Final report

1. Project details

Project title	Underground Pumped Hydro Storage (UPHS)
File no.	64020-1090
Name of the funding scheme	EUDP
Project managing company / institution	Aarhus Universitet
CVR number (Central business register)	31119103
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2. Summary

Based on the digital simulation studies in the project it can be concluded that the present UPHS design (2nd generation) needs to be improved to ensure a better control of the soil movements. The university of Aarhus and University of Karlsruhe are committed to be engaged with further geotechnical investigations of potential improvements and solutions for the next 6-12 months. The studies will be supported by the validated digital models developed in the EUDP project.

As a part of the project a small LAB model 5mx5m for preliminary studies was established in Skejby(AU). The primary test set-up was a test rig 20m x 20m, which was established in Foulum (AU) with the purpose to study performance, stress and wear out on a down scaled but representable UPHS system. During the test we could observe total energy loss of 5-10 % under ***stable operation****. However, with a* ***full size*** *and optimized system we may be able to achieve down to ca. 5 % loss under normal and stable operation. During the wear out test cycles we could due to soil disruption observe damaging stress on the membrane, which at the end was causing an abruption of the test membrane.*

Based on the observations of the membrane and soil behaviour the membrane design needs to be improved both with respect to the capability to levelize eventual asymmetries in the soil load and additional strength as a safety margin to mitigate stress impact. Based on the learnings from the project several potential solutions need to be studied in combination with the already planned simulations and design studies.

During the evaluation of the CAPEX related to the establishment of the UPHS system we can observe the soil work will be a substantial part of the cost of establishment. The present data indicates a CAPEX in the span 170.000 - 190.000€/(MWh (LCOS 116€/MWh) for a 112MWh plant, which is the on par/below a corresponding battery storage. In the project we have identified ways to bring down the CAPEX to future cost targets between 125.000 and 140.000€/MWh (LCOS 93€/MWh), which would correspond to a ca. 30 % lower cost of storage than a corresponding battery solution in 2030.

Based on the CAPEX calculation´s Use case studies have been carried out with the ***present energy data*** *in Denmark. A learning from the use case studies is that the UPHS is not an attractive business case with the present cost of energy in Denmark. However, this also will be the same conditions for corresponding battery solutions*

However, with the expectation of a more volatility future cost of energy and the effectuation of the planned cost optimizations, the UPHS system should be an economic attractive solution for future energy storage systems. Taking into account the establishment of the UPHS will be independent of raw material (e.g. Lithium for batteries) primary from out site EU/USA, may give the UPHS an advantage in the future energy storage market, where we may observe a lager focus on potential geopolitical conflicts.

Med udgangspunkt I de digitale simuleringsstudier der blev udført I projektet, kan det konkluderes, at det nuværende UPHS design (2nd generation), skal forbedres for at sikre en bedre kontrol af jordbevægelserne. Aarhus Universitet og Karlsruhe Universitet har givet tilsagn om at videreføre geotekniske undersøgelser af de potentielle forbedringer og løsninger i de næste 6-12 måneder. Disse studier vil blive understøttet af den i EUDP projektet udviklede og validerede model.

Som en del af projektet blev der etableret en mindre 5m x 5m LAB model til de indledende studier i Skejby (AU). Det primære test set-up var et testsystem på 20m x20m, der blev etableret i Foulum (AU), med det formål at undersøge performance, stress og wear-out på en nedskalleret men repræsentativ UPHS system. Under testene kunne der under stabile drift situationer observeres energitab på 5-10 %. Ved et full size og optimeret system kunne det under normale drift situationer være forventeligt at opnå tab på omkring 5 %. Under de cykliske Wear out test kunne vi grundet jordforskydningerne observere ødelæggende stress på membranen, som slutteligt bevirkede et brud på test-membranen.

Med udgangspunkt i observationerne af membranen og jordforskydningerne, vil det være nødvendigt at forbedre membrandesignet med hensyn til membranens evne til at udligne asymmetriske jordforskydninger og samtidig forøge membranens sikkerhedsmargin til at kunne absorbere stres påvirkninger. Med udgangspunkt i viden opnået i projektet, vil der være flere potentielle løsninger der skal undersøges i forbindelse med de allerede planlagte simulerings og design studier.

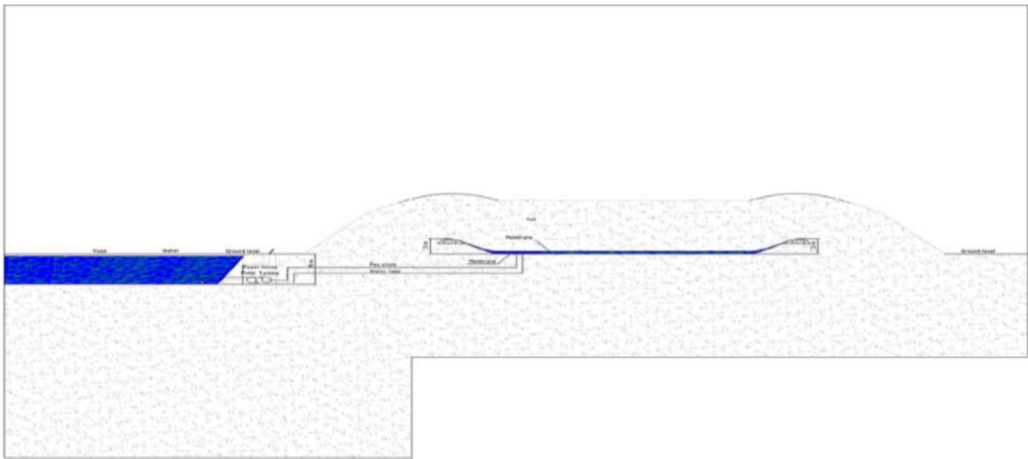
Under evalueringen af CAPEX relateret til etableringen af UPHS-systemet kan vi konstatere at jord arbejdet vil være en væsentlig del af etableringen. De nuværende data indikerer en CAPEX i området 170.000 - 190.000€/(MWh (LCOS 116€/MWh) for et 112MWh system, hvilket er det samme/mindre end et tilsvarende batteri lagrings system. I projektet har vi identificeret muligheder til at bringe CAPEX ned på en fremtidig kost i området 125.000 and 140.000€/MWh (LCOS 93€/MWh), *hvilket vil svare til en ca. 30% lavere lagrings omkostning end et tilsvarende batteri løsning i 2030.*

Med udgangspunkt i CAPEX beregningerne er use-Case blevet beregnet med de ***nuværende*** *energi data i Danmark. En læring fra disse use-casestudier, viser at UPHS systemet ikke er en attraktiv forretning med de* ***nuværende*** *energipriser i Danmark. Dette gælder dog også for tilsvarende batteri løsninger*

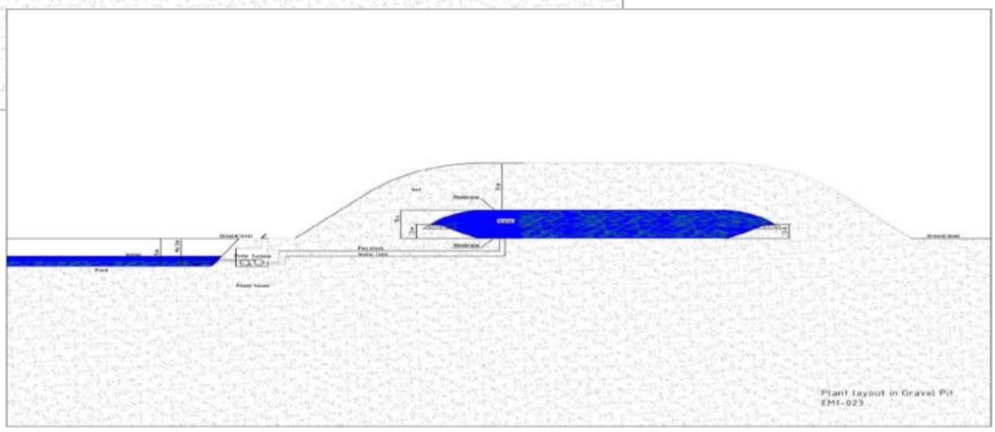
Med en forventning om fremtidige energipriser med større udsving og de planlagte kostoptimeringer kan UPHS systemet dog forventes, at blive en økonomisk attraktiv løsning for fremtidige energi lagrings systemer. Hvis man tager med i den samlede betragtning, at et UPHS-system grundlæggende vil være uafhængig af "råstoffer" (f.eks. Lithium til batterier), der primært kommer fra områder uden for EU/USA, vil dette måske give UPHS systemet en fordel i det fremtidige energi lagrings marked, hvor vi sikkert vil kunne se en større fokus på potentielle geopolitiske konflikter.

3. Project objectives

The objective of this project is to continue the development of a concept for large scale energy storage, with 15-25m topsoil covered underground water storage reservoirs in membranes (=energy storage), tube interconnected with a generator/turbine and pump units to open water reservoirs, suited for renewable energy systems. The energy membrane is a pumped hydro storage (PHS) concept for storing electric energy in an **underground** water reservoir. The system is called Underground Pumped Hydro Storage – **UPHS.** The technology has previous undergone two stages of development and this project covers the third phase, where the project group examines critical elements concerning geotechnical circumstances, design of the system, the membrane, cost optimization as well as business case and market adaptation.



UPHS principle of function. Upper illustration showing the energy storage empty (discharged by gravity of topsoil mass) and the lower illustration shows the energy storage full (charged by renewable power pumped water from lower reservoir)



The objectives include the construction and tests on a down scaled demonstration test and pilot plant. The specific objective tasks for reporting are:

Geotechnical simulation modelling
Design parameters for the UPHS-system
Examination and test of different membrane types
Construction and test of a 20 x 20-meter demonstration and field trial model with focus on:
Energy loss

Geometry of the membrane
Soil movement / displacement
Accelerated lifetime test and wear-out of the membrane
Cost optimization of the general system and individual components
Application possibilities at the end-users Vestas Wind Systems and European Energy
Calculation of business case and examination of market adaptation.

Furthermore, it is the objective for this project to mature the concepts and technologies for the next phase, which includes construction and test of a full-scale demonstration plant with fully commissioned pump and turbine.

4. Project implementation

The UPHS project was divided into 6 Work Packages:
WP1 – Project Management and Dissemination (Lead: AquaNamic / ECD)
WP2 – Geotechnical design and simulation (Lead: Aarhus University)
WP3 – Analysis, design and selection of Membrane (Lead: AquaEnergy, with AquaNamic / Solmax)
WP4 - Scale testing (Lead: Aarhus University)
WP5 - Cost calculation and optimization (Lead: PlanEnergi)
WP6 – Use and business cases (Lead: AquaNamic)

WP1 is reported here under section 4. project implementation. The main findings, results and conclusions of all WPs are collected and consolidated in the report sections: 5. Project results., 6. Utilisation of project results and 7. Project conclusion and perspective

Each Work package from 2 to 6 is also reported separately and added as appendices to the report in section 8 Appendices. The appendices and adjoined appendices are numbered according to their WP and constitute the core-system-technological reports with each WP objectives, implementation, findings and results.

WP1.
The outset for this third UPHS project was two previous stages of development from the matured idea in 2013 -2014, supported for initial investigations and tests by ForskEl, and Innobooster In 2020. The partner-consortium for this third EUDP granted project were formed with specific partner tasks to perform the first scaled demonstration and objectives.

Initially 8 partners joined the consortium applying for the EUDP grant, with an economic budget. **Aquanamic** is the initiator and IPR holder of the technological principle behind the UPHS and has through-out the project been the lead project progress management together with and supported by **EnergyCluster Denmark** conducting the overall progress plan and economic reporting to EUDP. **Aarhus University** has been the lead applicant and project holder and contact performing the project core tasks of geotechnical design, simulation and scale testing including investigations, measuring and analysis of geotechnical field test results and further perspectives. **Solmax** is a state-of-the-art developer and provider of membranes delivering the underground membranes and technological calculations as well as the actual construction of the lay-out of the membranes. **Aquaenergy** have added design, construction, and calculations of test side as well as technical and economic parameters for operation (LCOS), including the US based experiences and parameters. **Planenergi** has experiences from designing and construction of heat-dam-storages (water reservoirs) including energy and LCOS i.e cost calculations and optimisation of UPHS. **Vestas Wind Systems** and **European Energy** joined as partners in the project as possible operators and owners of UPHS facilities and plants including and validating the need and business case parameters behind large power energy storage. A ninth no-budget partner **Arkil** (large contractor, building, construction, and developer company) joined the project in 2021 performing the actual soil work at the test site, providing excavators, digging and physical construction work. Arkils skills and experience of soil and construction work was crucial for the actual building of the reservoirs, underground membrane bed and sloped sides of the bed, overburden top layer and final design. In close cooperation with the other design partners the lay-out was done by Arkil.

Management and coordination of WP have been conducted according to the application Gannt chart with scheduled milestones from September 2020 to June 2022, but with a slightly adjusted plan and granted EUDP extension request for the UPHS project to September 16th, 2022. 14 days, monthly or bi-monthly meetings between the partners have been conducted throughout the project period updating on progress for each WP. Resumés on progress combined with technical reports and presentations of the WP tasks performed have been shared between all partners throughout the entire project at mail exchanges or at a common established sharepoint platform. All partners have had access to the sharepoint. Meetings have been in person at the testsite, at the partners locations, but most meetings after kick-off have been conducted as virtual meetings. Separate Bi-partner meetings have been performed according to tasks and progress plan. Aquanamic has as IPR holder and general management had individual meetings with each partner if necessary to agree on and clarify the WP tasks. All partners have delivered according to agreement and plan, with a few delays for some, however all task-deliverables have been handed in.

EUDP annual status and midterm financial reports have been delivered in time for reimbursement and payout. Minor budget changes between the partners have been granted by EUDP. Especially AU and Planenergi has been short of budgeted time due to both the COVID 19 restrictions, but also for more extensive investigations performed.

One important milestone was selection and construction of the test site. During the planning and implementation phase, 4 different locations were investigated. The first being at a Test site at “nordjyllandsværket” were more heat-dams are being build and were the connection to the power grid over transformers for operational test purposes would be less costly and a possible add-on to the UPHS project. Unfortunately, the planned and promised site for the testsite were redecided for other purposes by Nordjyllandsværket. A second investigated Test site at GreenLab Skive industrial park where the UPHS could be built into existing and ongoing soil-work, had to be abandoned due to regulatory delays and permits to build. Finally test sites at Skejby Aarhus were not accepted and it was decided to build the test site at rented land on Aarhus Universities Research facilities at Foulum. The cancellations of the investigated test sites delayed the actual building of the site.
The project was unfortunately also impacted by the COVID-19 lockdowns in the period of the project. Hence, the establishment of the test set-up´s at both Skejby and Foulum were delayed. It caused the project to be extented beyond the original planned schedule for February-June 22 to September 22. It also had the consequences of a shorter test period, where the Geotechnical investigations and measurements could be performed. AU were forced to speed up physical tests and simulation-software adjustments.

Performance and conducting the tests at Foulum are described in WP2 WP3 and WP4 appendices.

The risk associated with the project were:

Risk	Probability	Impact	Mitigation
Wear out impact Lifetime of the membrane	Medium	High	Design & fault analysis. Definition of qualification test to ensure use of **relevant material**, **design** and **protection** for the membrane. Conduct Highly accelerated Lifetime test (HALT) to qualify the selected membrane material and design, before establishment of full-size demo plant.
Deformation of Soil during operation causing additional energy loss in membrane	High	Medium	Develop dynamic simulation program to support ideal design principles of the UPHS. Use of special sand and special constructions (such as different material in different locations) to ensure stability of the soil and minimize deformations that are irreversible and energy consuming.
Construction principles of UPHS causing the levelized cost of storage, i.e. the LCOS, to be to high	Low	Medium	Investigate and develop cost efficient technical methods to establish the UPHS. Compare to economic data for other alternative storage principles, ensuring that the design of the UPHS storage remains a competitive solution.
Stress on the membrane by *hydrodynamic* forces during “charging” and discharging	Low	medium	Conduct studies and simulation to ensure the right design to minimize hydrodynamic stress on the membrane. Eventual implementation of “diffusing” principles at the inlet of the membrane.

Table 1 Project risk assessment and mitigation

The Membrane burst in autumn 2022 due to stress of the membraned (duly reported in Appendix WP2-WP3-WP4). The burst was not expected but included in the risk assessment. At a post steering committee meeting with all partners, it was decided that AU should perform more simulations based on the test measurements and results of the first test period. The membrane should be investigated after excavation and removal of top-burden. Solmax and AU have analyzed the membrane burst.

Aknowledgement. Arkil Constructors must be acknowledged for their dedication to the project adding more time, skills and resources than first agreed in contract and at own costs. Their extra contribution was highly valuable and has contributed to the success of the final construction and physical layout. Arkil also supported the pump used at the demonstration site.

Professor Hans Henning Stutz and his team at Institute of Soil Mechanics and Rock Mechanics at Karlsruhe Institute of Technology, Germany (KIT) shall be acknowledged for contributing extensively (and free of charge) to the project after Hans Henning Stutz moved to KIT from Aarhus University in 2020. KIT has amongst others contributed with lab element testing of sands, in-depth numerical simulations of the UPHS system, dissemination of results and added valuable input to discussions.

University of Nottingham, UK was engaged during the project to perform centrifuge testing (physical model testing at reduced scale and elevated gravity) to supplement the field trial test at Foulum. Their contributions are acknowledged, which amongst others include; providing access to state-of-the-art facilities, development of a new test setup for the UPHS system, carrying out centrifuge testing, adding valuable input to discussions and dissemination of results.Project forward. It has been decided that the partners will be invited for a Project-scoping phase 3 and phase 4 meeting in late 2022. The conclusions and experiences from the final report will be the outset for a possible continuation of a 3rd and 4th phase. See conclusion and perspectives. The test site at Foulum will, if possible, for a period forward remain as a possible test site and not be restored to previous functions. The test site can be reused at a lower cost for next phase if is not restored, and already prepared with reservoirs and overburden soil. The Universities AU, KIT and Nottingham will under their own budgets try to refine the simulation tools.

Dissemination of the UPHS project has been on the short informational level of progress of the project to interested parties, e.g., the UPHS principle and perspectives at an energy storage workshop, ECDs annual meeting 2022. Moreover, the general UPHS principle has been displayed at on a sign erected at the test site at Foulum Research centre. More delegations of various Foulum visitors have been informed of the project principles. Dissemination through a planned timelapse video and video drone recordings were never edited for presentation purposes, due to the burst of the membrane in the autumn of 2022. Timelapse video recorded during the test period with both charging and discharging are performed and stored for both presentation purposes, but also for geotechnical research purposes of the dynamic working overburden soil. At Appendix WP2 and WP 3 still pictures of the test side are included. Further dissemination of the project results and tests will be utilized for planned 4th phase development and funding application.

Se list of dissemination´s in appendixes to WP1.2

5. Project results

*The project results are described in detail in the attached **WP reports**. However, in the following chapter the key results from each WP will be highlighted.*

The overall project purpose was to investigate both technical and economic feasibility of the UPHS concept and technology. As mentioned above this investigation was broken down into 5 sub-projects.

<u>WP2 Geotechnical design and simulation.</u>

To evaluate and optimise the performance of Underground Pumped Hydroelectric Energy Storage (UPHS) systems in sand, WP2 adopted numerical modelling. The main outcomes are:

a) There is a good agreement at the conceptual level between the computer simulations and the field test, providing a clear indication of the reliability of field trial observations and measurements as well as validation of the numerical framework.
b) The developed numerical models of varying complexity provide a tool for estimating the efficiency and deformation patterns of the UPHS system.
c) The models confirmed the high likelihood of geotechnical failure for the investigated configurations
d) There are indications that a limited maximum lift height to prevent large overburden deformations may not be the only requirement to achieve a large number of cycles.
e) The simulations predict substantial local reduction of the soil cover thickness which leads to tensile strains of the underground geomembrane reservoir bag during cyclic operations that can exceed the elastic regime.
f) The role of the soil type may be secondary compared with the lateral confinement and initial overburden configurations.
g) Numerical simulations indicated that by scaling-up the size of the UPHS, energy losses in the soil (expressed as the ratio of energy loss over stored energy) would reduce and hence **the efficiency of the system is predicted to increase**. Based on the results it seems feasible to design full prototype UPHS systems with an achieved efficiency of 90-95% per cycle (only considering energy losses stemming from the overburden soil); however, future works should address the overburden stability which has implications on the membrane stability.
h) There may be a necessity, but also a possibility, to implement a support system to increase the efficiency (and possibly stability) of overburdens at full prototype scale compared to small-scale (1:5-10) tested in the field.

The developed numerical models, validated by comparison with field trial results and providing conservative predictions, can be used in the future to design a revised overburden configuration that matches the expected performance of UPHS systems. Sub-WPs are listed as follows.

WP2.1	**Develop geotechnical simulation models**
WP2.2	**Characterise geotechnical design-parameters for the UPHS**
WP2.3	**Document the improvement techniques for potential DEMO-project of the UPHS**

Further in-depth numerical simulations are ongoing and will continue over the next 6-12 month at AU and KIT (University of Karlsruhe). The focus will be on; improving the numerical models, provide further in-sight into the system behaviour and to investigate a number of principle solutions/design modifications to overcome the critical issues highlighted from the field experiments and the numerical simulations.

WP3 Analysis, design and selection of Membrane

Through the down scaled models in both Skejby and Foulum (AU) we have had the opportunity to study the behavior of the membrane during operation. Through these tests we have gained valuable knowledge of the inter-relationship of bag design parameters, system performance and requirements for the bag material.

The bag material that was used for the tests in the project was polypropylene geomembrane, 2mm thick, without reinforcement layer, having high flexibility but not an especially high yield stress.

Unfortunately, during these experiments, the bag suffered a rupture. Leading up to the rupture, the overburden displayed cracks and a rearrangement of overburden material resulting in a thinning the overburden at the central region of the bag. However, as one of the objectives in the project was to study the stress mechanism, we could also claim that one of the objectives actually has been reached.

Based on the observations in the Foulum test rig we can see that the bag can experience loading that is unbalanced, non-uniform from location to location within the bag, or varying over the course of repeated filling/emptying cycles.

Key learnings for the future work are:

1) Improvements regarding support conditions and control of the motion of the overburden. (as mentioned in the WP2)
2) Another aspect of design improvement, a geomembrane with higher strength would be beneficial. For future work, it is recommended to use a material with higher strength.
3) Improvements in flow geometry for inlet/drainage connections to the interior of the bag.
4) A potential membrane design including compartments to control and mitigate unbalanced soil load

As an additional potential improvement with respect to the soil movement and the stress impact on the membrane we could as an alternative concept solution imagine an overburden that behaves more like a fluid than traditional soil does, by virtue of being intentionally wet and perhaps being made primarily of sand. A sufficiently fluid overburden would not suffer from the observed migration of overburden in an outward direction, because the overburden surface would be sufficiently fluid to remain essentially flat at all times. This improvement has not been studied in the present project but may be a part of the upcoming studies.

WP4 Scale testing

To characterise the performance of Underground Pumped Hydroelectric Energy Storage (UPHS) systems in sand, WP4 consisted of a physical test campaign, including both 1:40 scale small-scale lab testing (5 m x 5 m), 1:800 scale reduced-scale centrifuge test series, and a 1:10 scale field trial (20 m x 20 m).

Prior to the establishment of the main test rig, a small-scale lab set-up was established in Skejby (AU). Next page is an extract of illiustrations from the detailed WP4 report illustrating the test set-up in Skejby.

Based on the learnings from the LAB model, the main test rig in Foulum (AU) was established. Below the overview of the established test rig in Foulum (illustations is an extract from the attached detailed WP 4 report)

Fig. A4. 7: UPHS field trail. (a) Cross-section. (b) Construction of the UPHS; b1 installation of piezometers on base membrane, b2 arial view of test site showing basin on the left side and excavation pit and base membrane for the underground reservoir, b3 corner view of base geotextile and overlying base membrane, b4 adding of overburden sand on the underground geomembrane reservoir with top geotextile for protection, b5 view of final overburden surface (flat shaped) after compaction. Arial view of FT_C4 afterwards overburden construction and target survey points, with indications of local reference system selected transverse cross-sections A-A and B-B.

Tested overburdens were limited to coarse-grained sand with no reinforcements within it and at its surface. The main outcomes from the test system are:

a) a clear indication of the feasibility to construct the system in the field,
b) collected physical measurements of UPHS system energy efficiency
c) field trial observations and measurements used for validation of the numerical model in WP2
d) indications of a limited maximum lift height to prevent large overburden deformations
e) observations and measurements showing a risk of tensile strains of the underground geomembrane reservoir bag exceeding the elastic regime at inflation ratios above half of the target value
f) proof that the currently selected membrane material is not sufficiently robust to withstand mechanical actions at relatively high lift height when overburden deformations cause a significant reduction in overburden cover.

Collected physical measurements can be used in the future to estimate the expected performance of UPHS systems with similar configurations and, more importantly, design novel UPHS configuration systems (using reinforced ground and/or modular reservoir configurations with multiple inlets) that can overcome current limitations in lift height. Sub-WPs are listed as follows.

WP4.1a	**Small-scale lab model testing of circular and square membranes with no overburdens**
WP4.1b	**Reduced-scale lab testing at elevated gravity (centrifuge testing) of UPHS systems in dry sand**
WP4.2	**Field trials of UPHS systems in sand**

WP5 - Cost calculation and optimization

Conditions of works in this work package developed with the experiences made in the test rig in Foulum and the cooperation with Arkil. Prices and costs used are due to the interaction with key-manufacturers of hydro-electrical equipment, like Voith. The work to come to conclusions has been achieved in course of setting different combinations of membranes and optimizing of input variables and factors that influence the capacity and costs of an UPHS plant facility. For this purpose, an excel tool was established to address the influence of the different factors and variables.

One conclusion is that, based on preliminary indications with an liftheight/overburden height factor from 0,36 financial feasibility studies were carried out with a CAPEX span around 170.000 - 190.000€/(MWh (LCOS 116€/MWh) for a 112MWh plant. Those are based on the present knowledge of soil works and technical behaviour of soil, with a soil column of 25m, a lifting height of 9m (height of water column) and a penstock height of 6m.

Another conclusion is that, to achieve future cost targets between 125.000 and 140.000€/MWh (LCOS 93€/MWh) an improved water column and filling level inside the membrane should be obtained. Based on the calculation model we can e.g., observe that having a natural heigh difference of 10 meters combined with a lifting height of the soil on ca. 13 meter will bring the cost of the UPHS in the span between 125.000 and 140.000€/MWh.

During the project contact to key suppliers of hydro electrical equipment was established and overview of relevant material was generated and cost estimated. These cost estimates were integrated in the cost calculation. Due to the maturity of the project a further optimization of these cost could be expected. Also, the average round trip efficiency (ca. 79 %) used in the calculations may be optimized as these estimates are taken from systems with significant longer pipelines. For the total round-trip efficiency for the UPHS we have added an average loss of ca. 7-8 % from the soil movements. Hence, for the present calculation ca. 72 % has been used. With a stable full-size system, we may be able to aim for ca. 5 % loss in soil and with the shorter pipelines we may expect a higher efficiency as well. Hence, future total efficiency in the span from 75-78 % may be achievable.

Furthermore, due to the nature of the facility comes an additional potential to drive costs further down in course of a considerable combinations of the establishment of an UPHS plant with other construction projects, in where disposal of huge volumes of soil are a part of it. Instead of disposal in traditional means, another project may benefit from cost savings for transferring soil towards an UPHS construction. And in combination with eventual existent old gravel, coal or mining pits establishing an UPHS can be an interesting way of re-establishment or alternative form of renaturation with integrated energy storage.

WP6 – Use and business cases

The economic feasibility of the UPHS has been evaluated based on specific use case simulation studies and evaluation of other storage technologies. Since we have not been able to finalize the design of the UPHS in this concept and test study, we have used best estimated UPHS data for these studies. As the geotechnical studies at AU will proceed, also after the finalization of the EUDP project, we also intend to use the developed economical use case model for the updated UPHS data coming out of these future studies.

A business case (BC) is for **the time being** not attractive in Denmark. However, several factors may in the future turn the UPHS into a positive BC and an attractive energy storage solution. Key factors to ensure this will be:

1) A higher value factor. According to Danish Energy Agency and published in April 2022 (System scenarios, April 2022), the volatility in the Danish electricity market is expected to increase towards 2030, hence it could be expected that the value factor will be increased.
2) Further optimizations of the UPHS design enabling a lower CAPEX. As we have seen in WP 5 this should be possible.
3) Further optimization of the total round-trip efficiency.
4) Further we may see that future RE-projects will require “Mandatory” installation of storage-capacity.

Compared to other present available storage technologies, e.g. lithium battery storage systems, we can observe the UPHS could be a more economical favourable solution, of cause assuming that the UPHS technology will be matured.

Another key driver for the UPHS technology may be that the UPHS storage technology will not be depending on raw materials coming from outside EU/USA, which may be an advantage in the new geopolitical situation developing for the time being.

Hence, if the UPHS technology can be developed and matured it may be an attractive solution for a future energy storage solution.

6. Utilisation of project results

As mentioned in the application, the present EUDP project was covering the technical and economic feasibility study, enabling a dedicated design and demonstration program. Based on the achieved results we are now able to proceed with a more detailed design and demonstration phase. However, as mentioned in in the conclusions from the WPs we need to make further numerical simulation studies to validate relevant improvements of the design before we can actually enter into the next project phase.

Besides the valuable knowledge of the membrane/soil behaviour, which could be studied in the project, the following assets are available for the next project phase:

- A validated geotechnical simulation model to be used for the optimization of the soil load
- A CAPEX calculation model, which can be updated with key data for the soil work
- A use case model which can be used for economic feasibility studies.

All of the above-mentioned items can be used in the process to develop AquaNamic to a commercial set-up for the UPHS.

Due to the need for further design studies to determine and validate the proposed improved design-ideas for the soil/membrane solution, a formal market introduction and **commercialization** will be postponed (in chapter 7 we have resumed the plan and perspective of the potential commercialization)

When an improved design has been validated by AU, AquaNamic will engage with the project partners to set the framework for the next step of the commercialization of the UPHS.

Though the **present** business cases (based on the actual key data for both UPHS system and Grid data) are not attractive, we can still observe the overall importance of having access to a large energy storage facility, as this is linked to general energy-system trends over the coming years.

First, the value of this capability to operate an arbitrage revenue stream, is linked to the volatility in the market. As can be seen from the figure below which has been generated by EA energianalyze on behalf of the Danish Energy Agency and published in April 2022 (System scenarios, April 2022), the volatility in the Danish electricity market is expected to increase towards 2030, whereafter it might fall again. This conclusion is extracted from the steepness of the duration-curve.

Based on this observation the general UPHS business should become more attractive in the coming years.

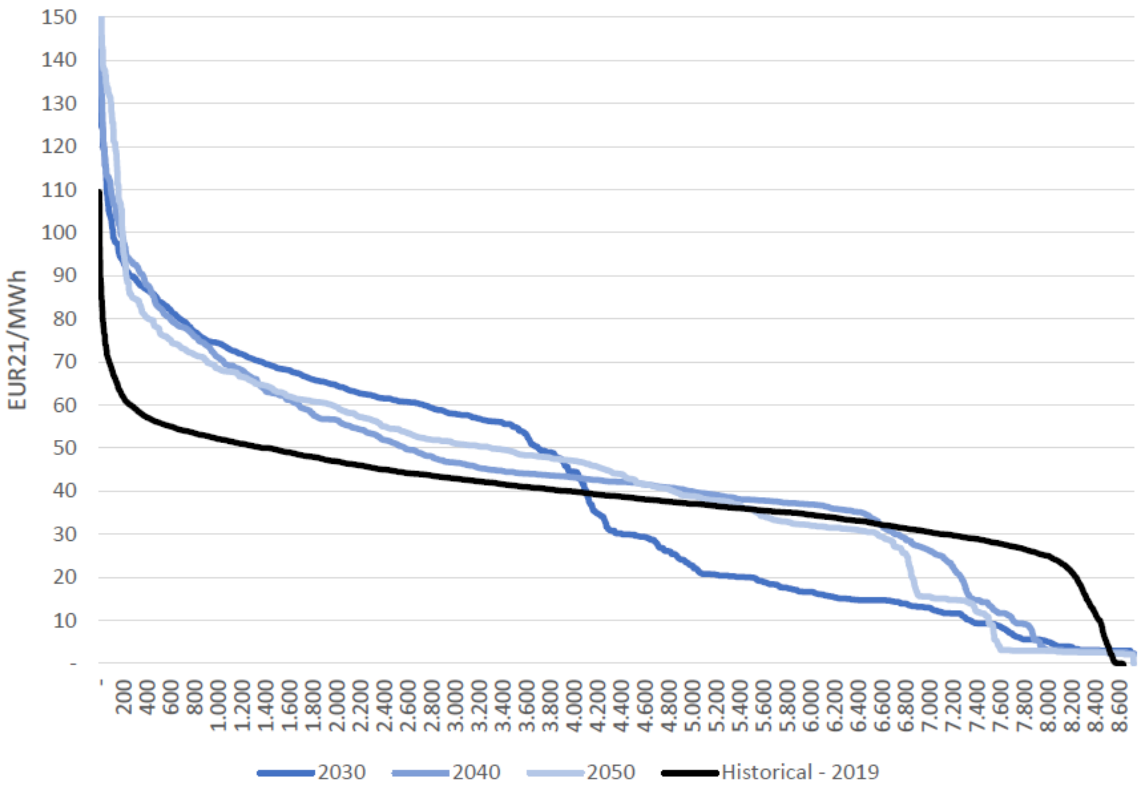


Fig. 1 Volatility in the Danish electricity market Danish Energy Agency and published in April 2022 (System scenarios, April 2022

Another observation relates to the availability of cheap electricity which is a precondition for the overall arbitrage business model. Since PtX installations are now being announced and planed for deployment in Denmark in quite large numbers, it's becoming clear that there's a competition among several future off-taker classes, who all base their business model on the availability of such cheap electricity. This observation may indicate that the **general UPHS business case** will not improve significantly under Danish conditions over the coming years.

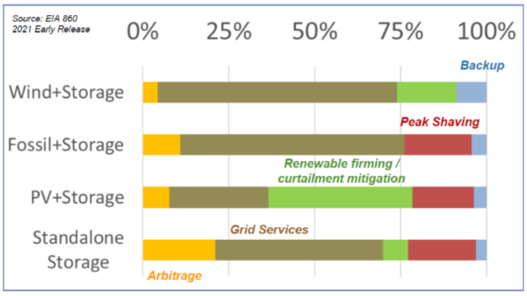
Based on this observation the general UPHS business could of cause become more challenged in the coming years. However, a **PtX may also need some kind of Energy Buffer to maintain a continuous production and here a UPHS may come in as solution**. Hence, it may be difficult to predict a specific measure for the opportunities and threats regarding the UPHS storage technology in Denmark.

Finally, there's an observation related to potential requirements for large storage units to be deployed in connection with RE generation projects, driven by requirements from the network operators (DSO and TSO) and balancing responsible parties for the project to limit the ramp-rate as seen by the grid withing narrow conditions. This could be accompanied with requirements for the generator to deliver a certain minimum expected capacity factor, which also may only be achieved by adding large scale storage and reducing the grid capacity for such projects. This trend is now seen in the US, as illustrated in the figure below provided by Lawrence Berkeley National Laboratory in August 2022 in their report "Hybrid Power Plants, Status of Operating and Proposed Plants, 2022 edition".

Breakdown of self-reported use cases for battery storage is somewhat similar whether a standalone battery or a hybrid, though there are a few key differences

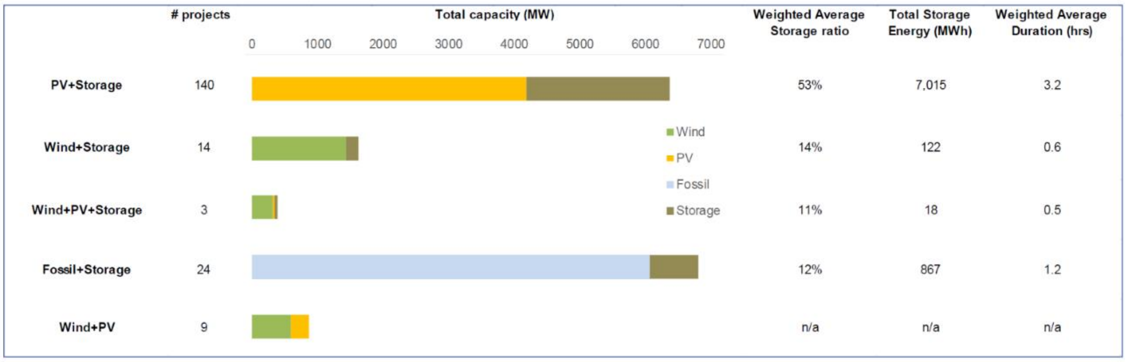
- Operators self-report use cases to EIA; individual plants can indicate multiple use cases
- Grid services are the most commonly reported use case, though renewable firming and curtailment mitigation is particularly important in PV+Storage hybrids
  - Wind+Storage has primarily targeted ancillary service markets
  - PV+Storage more often used to firm the PV capacity for resource adequacy purposes
- Backup power and arbitrage are least popular use cases reported by operators

Breakdown of battery use case among popular hybrid configurations and standalone storage



Grid services category includes the following: frequency regulation, load following, ramping/spinning reserve, load management, and voltage/reactive power support

PV+Storage hybrids are most numerous (140), and have by far the most storage capacity (2.2 GW) and energy (7 GWh) than other hybrids



Notes: Not included in the figure are 108 other hybrid / co-located plants with other configurations; details on those plants are provided in the table on slide 7. ***Storage ratio*** *is defined as total storage capacity divided by total generation capacity within a hybrid type.* ***Duration*** *is defined as total MWh of storage divided by total MW of storage within a hybrid type.*

Sources: EIA 860 2021 Early Release, Berkeley Lab

Based on this observation, the general UPHS business should become **more attractive** in the coming years since UPHS may replace batteries as used in the US, and since **market trends** driving co-location of generation+storage may also be applicable in Europe.

As a potential offtaker of this technology Vestas has followed the project with great interest and still sees a large potential in the technology. The project has also uncoverd a number of issues that need to be addressed before the actual feasibility of the technology can be analysed in detail. For the future work with this technology Vestas suggests the following targets:

1. Keep Capex and Opex significantly below competing battery technologies – aim to be 30% below the expected Lithium-Ion prices in 2030
   a. UPHS is a new storge technolgy and in its characteristics seems to have more in common with traditional Pumped Hydro rather than batteries. Pumped Hydro storage has a price point that is below half of that for Lithium-Ion which is the argument for setting an aggressive target for the CAPEX and OPEX price points
   b. Based on the current bloomberg predictions for the price point for Lithium ion in 2030 the UPHS techocligy should target a goal of 110 kEUR/MWh installed.
2. Focus on improving the technical capabilities

a. Flexibility is key in the energy system of the future and therefore it is vital that the UPHS technology is continued to be developed in that direction.
b. Focus on increasing the efficiency - aim for >80% to compete with regular PHS
c. Focus on the ability to hold energy for long periods of time without losses
d. Focus on investigating degradation – degradation is the single largest risk a storage operator has to deal with,and being a new technology this will cost a discount on the price for commercial operators.
e. Focus on ramp rates and the speed at which the flow can be reversed – aim for 30% of nominal power increase or reduction within 7,5 seconds to fulfill the FCR-D requirements in the Nordics.

Besides the above-mentioned observations, we may also include Geopolitical impact on different competing technologies. The UPHS will be mainly **independent of lithium** or manufacturing facilities coming from areas controlled by countries opposing western democracies. Hence, an UPHS competing, even if it only “on par”, with battery solutions may still be an attractive solution for EU and US.

7. Project conclusion and perspective

Based on the technical studies in the project we can conclude that the present design ideas need to be improved to ensure a better control of the soil movements. Investigations of potential improvements and solutions are already planned for the next 6-12 months.

The membrane design needs to be improved both with respect to the capability to levelize eventual asymmetries in the soil load and additional strength as a safety margin to mitigate stress impact. Based on the learnings from the project several potential solutions need to be studied in combination with the already planned simulations and design studies.

During the evaluation of the CAPEX related to the establishment of the membrane we can observe the soil work will be a substantial part of the cost of establishment. However, also ways to optimize the soil work have been identified, enabling the UPHS solution to be financial attractive.

A further optimization of the soil work by placing the UPHS off-shore, which have ***not*** *been investigated further in the present project, may be subject for a detailed investigation before the next project phase.*

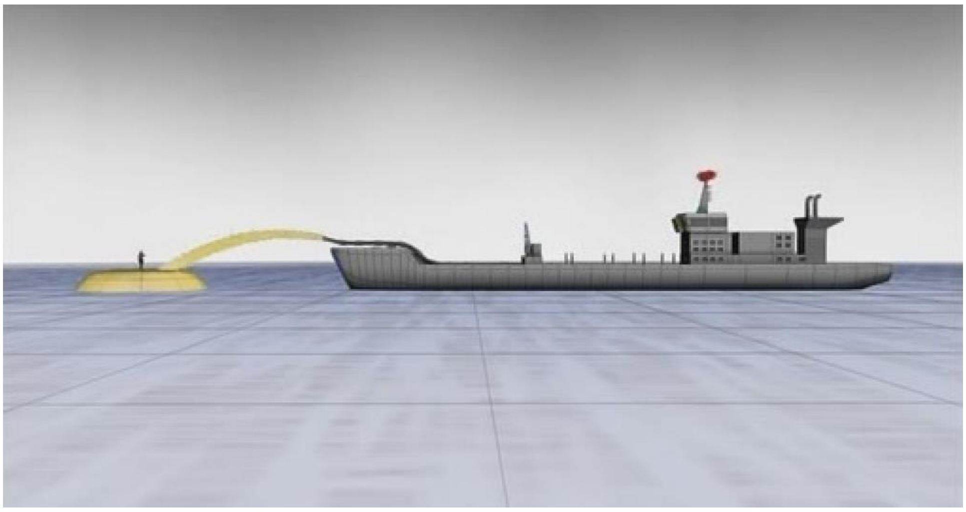
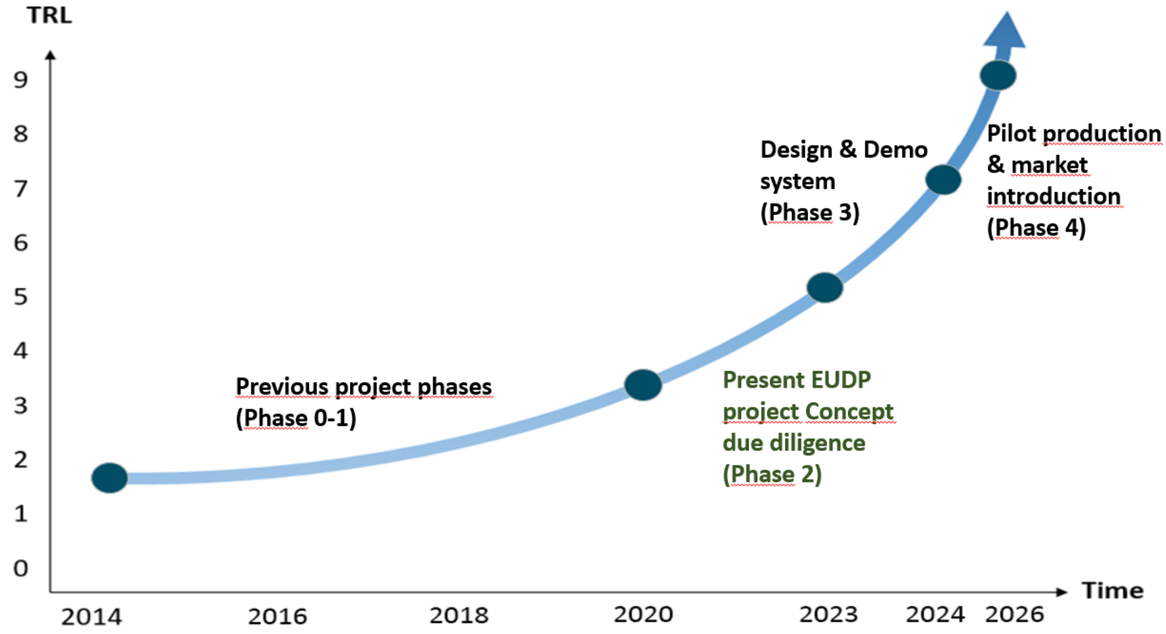


Fig 2. Illustration of an "off-shore" version of the an UPHS system. Turbine needs to be made of non-corrosive materials as it will be saltwater running through the system

Based on the CAPEX calculation´s simulation studies and comparation to competing storage systems have been made. Even with a marked introduction of alternative energy storage technologies and PtX technologies, we still consider the UPSH to be an attractive and economic feasible solution.

A learning from the use case studies is that with the present Danish energy marked storage systems are for the time being not an attractive business case. However, with the expectation of a more volatility future cost of energy, the different storage technologies will be attractive business cases.

Following resumes the way forward for the UPHS comercialization



Phase 0-1 - TRL1-4: Covering basic technology research on the **1st generation concept** of the membrane (ForskEL - program). Here, the basic technical feasibility of using a membrane for energy storage was made. Positive realization was that the energy loss in the soil was low (app. 1 - 3%). However, the investigations and tests also showed areas for improvements, e.g. measures to prevent "over-stretching" of the membrane during operation" and the relatively low energy density/m^3. Study of the **2nd generation** concept enabling higher energy capacity per m^3 and solutions for the identified "over-stretching" of the membrane during charging in the original concept.

Phase 2 - TRL4-6 covering the **present EUDP project**. The overall purpose was to conduct technical as well as economic feasibility studies on the proposed 2nd generation membrane. Results are to be found in this report and attached detailed WP status reports.

Phase 3 - TRL6-8 (planned 2023-24): Based on the results from Phase 2 and **additional design investigations rest of 2022,** an UPDATED test-rig with a **3rd generation** membrane and optimized soil construction needs to be established and validated. When the 3rd generation membrane has been validated a full-size demonstration system will be designed, engineered and constructed. During this phase we should be able to demonstrate the interactions between all technologies related to the UPHS. All related subsystems e.g. turbine/pump, generator and grid connection need to be established enabling operational charging and dis-charging of the energy. Target is to have 2-3 **demo plants** operating in parallel to speed up eventual learnings from the operation of the demo systems. Present stakeholders in the EUDP project have already expressed interest in participating in this phase in Denmark. Through the engagement with AquaEnergy(US) potential US stakeholders have already now been identified.

However, we need to have both the planned simulations at AU and University of Karlsruhe completed/validated and the corresponding improved membrane design ready before we enter a new application together with the present project team.

Phase 4 - TRL8-9 (2025-26): Commercial **Pilot production / Pre-launch** of 2-3 full size operational plants should be established. During this phase the manufacturing, installations and service facilities should be established to support the actual launch activities.

8. Appendices

Appendix WP1 UPHS – Management and dissemination

WP1.1 ; WP1.2

Appendix WP2 UPHS – Geotechnical design and simulation

WP2.1

Appendix WP3 UPHS - Membrane design

WP 3.1

Appendix WP4 UPHS – Scale testing

WP4.1; WP4.1-a; WP4.2; WP4.3

Appendix WP5 UPHS - Cost calculations and optimization

WP5.1; WP5.2

Appendix WP 6 UPHS - Use case studies

WP 6.1 ; WP6.2

Her lagrer vi energi under den jyske muld

Det er en vigtig del af den grønne omstilling, at vores daglige energiforbrug baseres på vedvarende energikilder som sol og vind.

Det betyder også, at vi er nødt til at kunne lagre noget af den grønne energi til de dage, hvor der hverken er solskin eller blæsevejr.

Underground Pumped Hydro Storage (UPHS) er et bud på et nyt lagrings-princip:

På dage med meget blæst eller solskin bruger vi overskudsstrøm fra solcelleanlæg og vindmølleparker til at fylde en stor, underjordisk membran med vand. Når vi pumper membranen op, løfter vi den jord, den ligger under. Og når vi mangler grøn energi, åbner vi for ventilen og lader vægten af jorden trykke vandet ud igen gennem en vandturbine, som leverer strøm op til 140MWh strøm til el-nettet.

Således kan vi med vand, tyngdekraft og jysk muld sikre vedvarende energi til dage uden sol og vind.

Foulum UPHS systemet er et mindre test system (20mx20m) støttet af EUDP, hvor vi i løbet af 2021-22 vil undersøge de grundlæggende teknologier.

Partnere:

AquaNamic, Aarhus Universitet AU Engineering, European Energy, Energy Cluster Denmark, Vestas, PlanEnergi, SOLMAX, Arkil, AquaEnergy

Finansieret af:

EUDP

Underground pumped hydro storage (UPHS) – EUDP project

Dissemination of results

A. Publications - from previous phase:

1. P. Norlyk, K. Sørensen, L. Andersen, K. Sørensen, H. H. Stutz. (2020). *Holistic simulation of a subsurface inflatable geotechnical energy storage system using fluid cavity elements*. *Computers and Geotechnics.* 127. https://doi.org/10.1016/j.compgeo.2020.103722

2. K. Sørensen, H. H. Stutz, P. Brødsgaard-Raptis and M. Luxhøj (2021). *Conceptual physical modelling of a subsurface geomembrane energy storage system*. Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering, Sydney 2021.

3. H. H. Stutz, P. Norlyk, K. Sørensen, L. V. Andersen, K. K. Sørensen, J. Clausen (2021). *Finite element modelling of an energy-membrane underground pumped hydroelectric energy storage system*. Proceedings of the 6th International Conference on Green Energy Technologies, Frankfurt, Germany, July 14-16, 2021.

B. Publications - from current phase:

4. A. Franza, K. K. Sorensen, H. H. Stutz, A. Pettey, C. Heron, A. M. Marshall (2022). *Field and centrifuge modelling of a pumped underground hydroelectric energy storage system in sand*. Proceeding of the 10th International Conference on Physical Modelling in Geotechnics 19–23. September 2022, KAIST, Daejeon, Korea.

5. G. Zamani, A. Franza, K. Sørensen, L. V. Andersen, H. H. Stutz (2023). *Large deformations of overburden soil induced by the inflation of an underground geomembrane-lined reservoir*. 10th European Conference on Numerical Methods in Geotechnical Engineering. (Abstract submitted and accepted).

6. Additional journal papers are planned.

C. Oral and poster presentations:

7. A. Franza, K. Sørensen, H. H. Stutz, L. V. Andersen, A. Pettey, C. Heron, A. M. Marshall (2021). *Geotechnical study of a pumped underground hydro electric energy storagage system in sand: a multi- method approach.* 3rd annual Danish Geotechnical Research Seminarar at AAU 11th Nov.2021, Danish Geotechnical Society (Poster session + Oral presentation).

8. L. Mugele, A. Franza, V. Gauger, K.K. Sørensen, H.H. Stutz (2022). *Underground pumped hydroelectric energy storage (UPHS) in sand – Ongoing numerical simulations and field experiments*. 32rd ALERT Workshop, 26th -28th Sep. 2022. Aussois (Poster session).

Appendix WP2 UPHS – Geotechnical design and simulation

Participants:	Aarhus University (AU), AquaNamic, AquaEnergy and Karlsruhe Institute of Technology (KIT)
Lead:	Aarhus University

1. Summary

To evaluate and optimise the performance of Underground Pumped Hydroelectric Energy Storage (UPHS) systems in sand, WP2 adopted numerical modelling. The main outcomes are:

a) There is a good agreement at the conceptual level between the computer simulations and the field test, providing a clear indication of the reliability of field trial observations and measurements as well as validation of the numerical framework.
b) The developed numerical models of varying complexity provide a tool for estimating the efficiency and deformation patterns of the UPHS system.
c) The models confirmed the high likelihood of geotechnical failure for the investigated configurations
d) There are indications that a limited maximum lift height to prevent large overburden deformations may not be the only requirement to achieve a large number of cycles.
e) The simulations predict substantial local reduction of the soil cover thickness which leads to tensile strains of the underground geomembrane reservoir bag during cyclic operations that can exceed the elastic regime.
f) The role of the soil type may be secondary compared with the lateral confinement and initial overburden configurations.
g) Numerical simulations indicated that by scaling-up the size of the UPHS, energy losses in the soil (expressed as the ratio of energy loss over stored energy) would reduce and hence the efficiency of the system is predicted to increase. Based on the results it seems feasible to design full prototype UPHS systems with an achieved efficiency of 90-95% per cycle (only considering energy losses stemming from the overburden soil); however, future works should address the overburden stability which has implications on the membrane stability.
h) There may be a necessity, but also a possibility, to implement a support system to increase the efficiency (and possibly stability) of overburdens at full prototype scale compared to small-scale (1:5-10) tested in the field.

The developed numerical models, validated by comparison with field trial results and providing conservative predictions, can be used in the future to design a revised overburden configuration that matches the expected performance of UPHS systems. Sub-WPs are listed as follows.

WP2.1	**Develop geotechnical simulation models**
WP2.2	**Characterise geotechnical design-parameters for the UPHS**
WP2.3	**Document the improvement techniques for potential DEMO-project of the UPHS**

Further in-depth numerical simulations are ongoing and will continue over the next 6-12 month at AU and KIT. The focus will be on; improving the numerical models, provide further in-sight into the system behaviour and to investigate a number of principle solutions/design modifications to overcome the critical issues highlighted from the field experiments and the numerical simulations.

2. Objectives

The main objectives achieved by this WP are listed as follows [between brackets the corresponding sub-WP],

- Develop and validate numerical models against field trial measurements in [WP2.1].
- Numerical quantification of energy loss due to soil deformation during cyclic charging / discharging of the UPHS system [WP2.2].
- During cyclic operations, numerically characterise the movements of the membrane and soil body, the stresses acting on the membrane as well as resulting strains within the membrane [WP2.2].
- Compare single-cycle versus multi-cycle analyses to understand relevant information that can be extrapolated from monitoring during initial operations of larger demos [WP2.2].
- For varying soil type, estimate of energy losses during charging and discharging and, thus, the efficiency of the system [WP2.3].
- Parametrically study the effect of overburden and membrane initial geometries on the behaviour of the UPHS system, focusing on single-cycle analysis [WP2.3].
- Provide preliminary indications on the feasibility to implement stabilizing techniques (e.g. use of reinforcements) used to minimize the energy loss and improve the geotechnical stability of the system [WP2.3].

3. Implementation

- The complexity of numerically modelling UPHS systems in the presence of large overburden deformations and relatively flexible geomembranes was initially underestimated. The development of the holistic refined numerical model required the entire time of the Postdoc #1. Due to the lack of conclusive outcomes, Postdoc #2 (focusing on the field trial) inititated the line of research relying on the simplified modelling, which was then transferred to the PhD student that carried out parametric/sensitivity studies summarised in this report. Building on the work of Postdoc #1, after the end of his contract, refined numerical results were obtained by the MSc student at the partner Karlsruhe Institute of Technology (KIT) whereto Prof. Hans H. Stutz, co-applicant, moved during the project. During the granted extension time, it was possible to compare advanced and simplified modelling techniques developed at AU and KIT, verified against each other and (partly) validated by the field trial observations. Consequently, the outcomes of WP2 focused on the development of validated numerical tools and the delivery of parametric/sensitivity analyses to identify the key behaviour of the UPHS in ground, rather than on the final design of an optimised UPHS system to be tested in future larger demos. This is reasonable considering the field trial outcomes that highlighted unforeseen challenges.
- Despite the attempts of Postdoc #2 and the MSc student, the development of a three-dimensional model considering the square geometry of the reservoir in the field was not successful due to convergency issues. Although square membrane modelling is possible, further work is needed to tackle this aspect. Considering the identified challenges with the geotechnical design, simpler axisymmetric conditions were adopted in the entire report on WP2.

3.1 Description of numerical modelling and tested configurations

Models. Both refined and simplified models based on the Finite Element (FE) method were developed using commercial software (Simulia Abaqus and Optum G2) [see Figure 1]. During single- and multi-cycle simulations, cycles up to maximum inflation ratios $R_V = V/V_n$ varying between 0.35 and 0.7 were tested (i.e. volume

V up to 35% and 70% V_n, respectively, where V_n is the nominal value obtained by doubling the volume associated with the initial membrane shape) if not differently stated. Note that the average lift $U_{avg} \approx V/A_0 = V/(\pi L^2/4) = R_v \times U_n$ relates to the volume ratio.

- The simulated problem geometries in axisymmetric conditions are comparable in refined and simplified numerical models; when comparing numerical predictions with the field trials (having a square shape) the transverse sections of the field trails were considered. For the material models, the refined numerical boundary value problem solved by Simulia Abaqus allowed implementing both the Mohr-Coulomb elastic−perfectly plastic as well as the hypoplastic soil constitutive models; contrarily, the Optum G2 simplified boundary value problem is limited to the Mohr-Coulomb constitutive model.
- When comparing with the field trials, the soil constitutive parameters were calibrated based on advanced laboratory tests of the Foulum sand, conducted at KIT; for the parametric and sensitivity studies, representative parameter values were selected.
- The greatest difference between the two models is the approach used to simulate the underground reservoir and geomembrane-lined bag. The refined Abaqus model explicitly modelled the reservoir: the upper and lower geomembranes are simulated using shell elements, a surface-to-surface contact with a frictional interface and hard contact (with a penalty method) is adopted between the membrane and the soil as well as between the upper and lower membrane layers, and incompressible fluid elements connect the reservoir to a nearby basin. The simplified model consisted of a rigid piston-based system displacing a base layer of incompressible solid elements directly in contact with the soil (the piston simulates the change in volume of the reservoir by upward and downward movements); therefore, the upper membrane layer is assumed as fully flexible and bounded by a rough interface to the soil (i.e. no slippage is possible) whereas no geomembrane bag closing is possible.
- Both models assume a constant pressure throughout the reservoir (i.e. no pressure gradient with the reservoir due to the water density). This reservoir pressure p^* is equal to the “overburden pressure” (i.e. a reaction of the water on the overburden), it is the result of the mass of the overburden as well as the overburden's internal strength and stiffness. This pressure p^* in the numerical model is comparable with the average pressure acting at the base of the reservoir in the field trials estimated as $p^*_{field} = p_{field} - U_{avg} \times \gamma_w = p_{field} - U_n \times R_v \times \gamma_w$.
- In the Abaqus model, the effects of geometric nonlinearities (due to large displacements and changes in overburden shape) are accounted for, whereas they are neglected in the Optum G2 model.
- Adaptive remeshing to deal with strain localisation was not used.

Tested configurations. In this report, all simulations were performed in axisymmetric conditions (for a circular membrane in plan view, obtained as a solid of revolution of the cross-section in Figure 1). Simulations are labelled using the nomenclature shown in Figure 2a based on cover *C*, side length *L*, and membrane depth *D*: for instance, for the field trial FT_C4 described in WP4 is referred to as *L20C4D0.6*. Also, the description of hill-shaped and flat-shaped overburden is shown in Figure 2b. The main analyses tested the following three geometries:

- Preliminary geometry **PR_C4=L20C4D1.2** [hill-shaped], having *L* = 20 m; *D* = 1.2 m, *C* = 4 m, *T* = 2 m; *A* = 0; *O* = 2 m; *β* = 26.6° (slope 1:2); *α* = 26.6° (slope 1:2). The nominal (target) lift height is $U_n = 2 \times D$ = 2.4 m, whereas the nominal fully inflated volume is V_n = 594.7 m^3.
- Field trial with 2 m cover **FT_C2= L20C2D0.6** [flat-shaped], having *L* = 20 m; *D* = 0.6 m, *C* = 2 m, *T* = 0; *A* = 0; *O* = N/A; *β* = 0; *α* = 26.6° (slope 1:2). The nominal (target) lift height is $U_n = 2 \times D$ = 1.2 m, whereas nominal fully inflated volume is V_n = 334.8 m^3.
- Field trial with 4 m cover **FT_C4= L20C4D0.6** [hill-shaped], having *L* = 20 m; *D* = 0.6 m, *C* = 4 m, *T* = 2 m; *A* = 0; *O* = 2 m; *β* = 26.6° (slope 1:2); *α* = 26.6° (slope 1:2). The nominal (target) lift height is $U_n = 2 \times D$ = 1.2 m, whereas nominal fully inflated volume is V_n = 334.8 m^3.

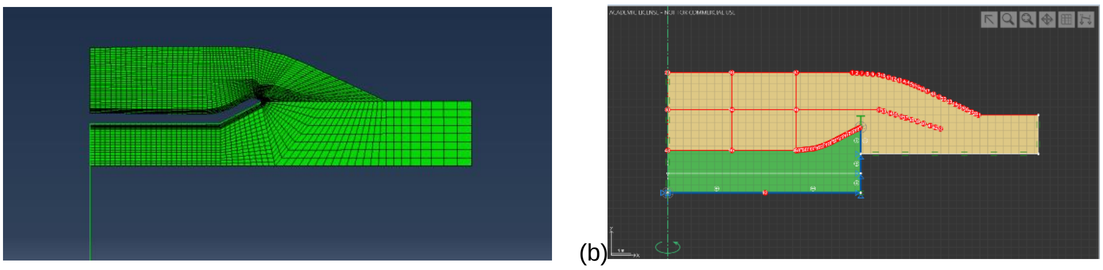


Figure 1 Geometries of the (a) refined Abaqus and (b) simplified Optum UPHS models for the preliminary geometry **PR_C4**.

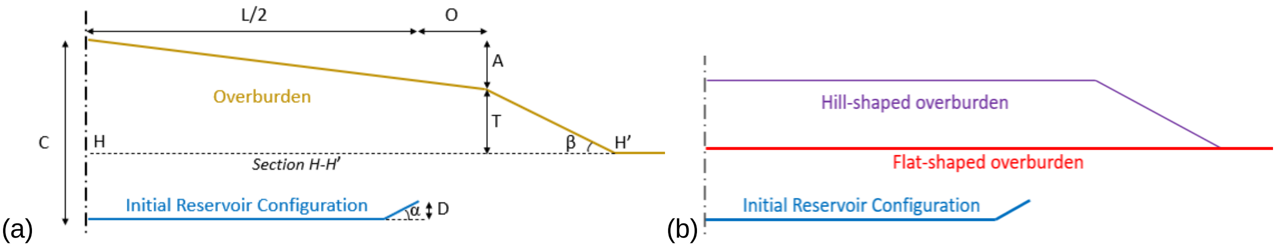


Figure 2 (a) Nomenclature adopted to describe the UPHS initial geometry. (b) Qualitative description of the overburden.

4. Results

From the interpretation of the outcomes of numerical modelling (WP2), the following indications are drawn:

- As confirmed by both field trials in WP4, for optimal UPHS systems, a nearly linear relationship is to be expected between the reservoir volume and the vertical displacement of the centre of the soil cover [see Fig. A2. 8]. In numerical modelling, minimal accumulation of strains (at the overburden and membrane) is associated with a nearly linear relationship between maximum settlements and horizontal movements of the overburden and the membrane and volume changes. During cyclic operation, any increase in maximum displacements of the UPHS system compared with initial cycles may be associated with incipient (or triggered) geotechnical failure of the overburden soil and/or membrane tensile straining. This observation on a steady response of the system over cycles has important implications for the future design of monitoring systems.
- Inspection of horizontal stresses in the overburden close to the membrane centre confirmed speculated mechanism of overburden top(bottom) under active(passive) horizontal stress state under inflation, and vice versa under deflation [see Fig. A2. 2, Fig. A2. 3, Fig. A2. 6].
- With respect to numerical results and their comparison with field trials:
  - The refined Abaqus model results compared qualitatively well with the field trials in terms of overburden surface displacements. As interpreted from the measurements collected during the field trials in WP4, during the initial cycles, the overburden surface and, thus, the membrane undergo balloon-shaped inflations with maximum uplift at the centre while the overburden surface moves outwards from the centre (the maximum horizontal movements are approximately 20% and 40% of the central settlements for the flat-shaped (FT_C2) and hill-shaped overburdens (FT_C4)) [see Fig. A2. 9 and Fig. A2. 10]. For the Abaqus results, these horizontal surface movements as well as overburden extension deformations in correspondence to the zone of cover reduction [see Fig. A2. 2] support the conclusion from WP4 that *"flat-shaped overburdens accommodate the balloon-shaped inflation of the membrane through shear-band formations at the edges and extension deformations of the central region. Contrarily, hill-shaped overburden undergoes more uniform deformations with outwards movements of the side soil and extensive deformations of the entire soil above the original surface level"*.

- For the modelling of the 2 m cover field trial FT_C2, the accumulations of the overburden deformations during cyclic operations may lead to a local reduction in overburden cover that, concurrently, favour further local uplift of the membrane. In particular, the axisymmetric numerical models indicated that, during the first inflation cycles, the ground displacement profiles follow a bell-shaped profile with a localised maximum central uplift [see Fig. A2. 3], whereas the field trial indicated that this bell occurred along the mid-length of the diagonal between the centre and a corner of the square membrane.
- Refined numerical modelling indicated that the building up of tensile strains in the relatively flexible membrane can be related to the percentage of cover thickness reduction [see Fig. A2. 7], possibly because of the transition from a balloon- to a bell-shaped membrane inflation mode.
- The comparison of numerical and field overburden pressure p^* versus inflation ratio R_V indicated an excellent agreement for the inflation behaviour, whereas numerical modelling (both Abaqus and Optum) predicted a stiffer unloading response of the overburden and, thus, slightly greater energy losses [see Fig. A2. 4, Fig. A2. 5, and Fig. A2. 11]. Considering the differences between the two numerical models (boundary conditions, soil material models), it is speculated that this difference within the pressure-average uplift relationship between the numerical results and the observations of the field trials could be due to geometrical effects (square vs circular membranes).

- For both single- and multi-cycle analyses of the preliminary configuration (PR_C4), the simplified Optum model was capable of providing predictions in close agreement with the refined Abaqus model, when both models adopted the Mohr-Coulomb constitutive model; this comparison was satisfactory both in terms of overburden displacements and overburden pressure as long as the inflation volume is below the upper threshold for monotonic inflation failure [see Fig. A2. 12, Fig. A2. 14, Fig. A2. 15, and Fig. A2. 17].
- The numerical model results suggested a variation of the deflated overburden shape with cycles characterised by both a reduction in the central cover thickness (as observed in the field trials in WP4) as well as the closing of the reservoir bag (with the contact of the upper and lower membranes over a short distance at mid-distance between centre and edges) [e.g. Fig. A2. 3 and Fig. A2. 17]. The closing of the reservoir bag happened following the cyclic accumulation of overburden strains and was associated, within the numerical modelling, with the kick-toe shapes of the pressure-volume relationship at the overburden [see Fig. A2. 5]. Differently from the field observations, where pressure-volume curves of the overburden were rather steady with cycle number, the numerical model results display a quick reduction of the overburden cover once the kick-toe is formed, possibly because of the link between the kick-toe pressure, the closing of the membrane, and the bell-shaped distortions of the overburden.
- With respect to the comparison of monotonic inflation, single-cycle, and multiple-cycle analyses, results of both the refined and the simplified numerical analyses showed that:
  - When monotonically increasing the reservoir volume, the overburden may undergo a failure at inflation volumes larger than the target values; this can be seen as an upper limit of the inflation volume, which should be lower to guarantee stability over cyclic operations. In particular, UPHS system failure at large monotonic inflations is characterised by: softening in the reservoir pressure-volume relationship predicted by the Abaqus model as a consequence of the outwards water pressure on the inclined bell-shaped membrane; an increase in the rate of central cover reduction for unit volume changes; triggering of membrane straining [see Fig. A2. 1]. Despite this, this type of analysis provides an upper limit on maximum inflation ratios. Cyclic analyses indicated that the maximum allowable volume is well below the value obtained from monotonic testing (for instance, simplified simulations indicate geotechnical instability for less than 10 cycles at $R_{V,max} = 35\%$).
  - When comparing single and multiple cyclic analyses, in agreement with field data, the energy performance of the UPHS system can be roughly estimated from single-cycle analyses, considering that a relevant shift in the pressure-volume curves is associated with unacceptable accumulation of overburden deformations [see Fig. A2. 11 and Fig. A2. 4].
  - Multi-cycle analyses are essential to evaluate the maximum and minimum allowable volumes to which the UPHS can be operated, avoiding the risk for the overburden failure due to accumulations of large irreversible strains, and, thus, excessive surface displacements [see Fig. A2. 7].

    - Single-cycle and monotonic analyses result in compressive meridional strains of the membrane (when a realistic friction coefficient or a perfectly rough/bounded membrane is assumed); therefore, they are not suitable to predict tensile strains in the membrane which would occur only at the failure state for monotonic inflation [Fig. A2. 8 and Fig. A2. 15]. Tensile meridional strains occurred over cyclic operations in both the refined and the simplified numerical modelling [see Fig. A2. 7 and Fig. A2. 8], which appears to agree with field evidence of elastomer strain gauges reading accumulating strains over several cycles.
- Regarding the effect of soil-membrane friction, interpretation of the simplified and refined numerical analyses indicates that the membrane is relatively flexible, and the friction is sufficiently high so that the membrane deforms according to the movements of the bottom layer of the overburden [see Fig. A2. 15]. However, monotonic Abaqus simulations implementing MC soil and a perfectly smooth interface indicated that the reduction in the coefficient of friction resulted in tensile strains (contrarily to the compressive strains in presence of friction) [see Fig. A2. 15]. Therefore, it is possible to speculate that a reduction in friction may lead to a greater potential for membrane tensile straining over cyclic UPHS operations (this aspect has not been furtherly investigated).
- As confirmed for multi-cycle analyses, the assumption of a fully flexible membrane perfectly bounded to the overburden by the membrane−soil friction adopted in the simplified Optum modelling is an operational first approximation, especially for numerical studies focused on the optimised design of the overburden [see Fig. A2. 17]. Considering that large membrane tensile strains occurred in the numerical modelling in conjunction with large deformations and reduction in cover of the overburden (e.g. refined model predicted for field trials FT_C2 membrane strains above the limit design strain level of 5% when the cover reduction ΔC was greater than 20% of the initial cover C), the design of optimal UPHS systems should rely on multi-cycle analyses.
- Numerical simulations confirmed field evidence that flat-shaped overburdens have a higher energy efficiency than hill-shaped overburdens [Fig. A2. 11]. In the numerical simulations, the efficiency tends to decrease with the maximum lift height (i.e. volume inflation) for a given overburden because of the asymptotic trend of the overburden pressure p^*. In qualitative agreement with trends in field trials, for $R_v = 35\% - 70\%$ corresponding to $U_{avg}/L = 2\% - 4\%$,but on the conservative side, energy losses estimated from the simplified modelling for the flat-shaped overburden are between 10%-15% of the stored energy, while for the hill-shaped overburden the energy losses range between 20%-30% [see Fig. A2. 11: Optum modelling results from 2-cycle analyses of the field trials FT_C2 and FT_C4: overburden pressure p^* vs volume ratio R_v. In the table, summarized mechanical and geometrical parameters as well as efficiency.]. The greater the inflation volume the greater the energy loss, because of a greater soil yielding associated with an asymptotic mobilised overburden pressure p* [see Fig. A2. 11: Optum modelling results from 2-cycle analyses of the field trials FT_C2 and FT_C4: overburden pressure p^* vs volume ratio R_v. In the table, summarized mechanical and geometrical parameters as well as efficiency.].
- Field trials indicated that (WP4) the target uplift U_n = 1.2 m (6% of the side length L; associated with R_v = 1) for the configurations L20C2 and L20C4 is mechanically not feasible. Importantly, numerical results confirmed the overburden instability when analysing an UPHS system constructed with unreinforced sand under multi-cycle operations, with geotechnical instability of the overburden (large displacements and irreversible strains) being triggered in numerical analyses for uplift heights as low as 2% of the side length L (a value at which the field trials were stable for less than 10 cycles). Additionally, numerical predictions currently slightly overestimate the energy losses recorded in the field. Consequently, it is possible to argue that the developed numerical models provide conservative predictions of the UPHS system behaviour and, if reaching an optimal design by numerical parametric study, this model would hold potential for optimal operation over a low number of cycles. On the other hand, it is not possible to conclude on the expected long-term performance.
- Regarding the scaling of the UPHS system to full prototype scale, simplified numerical modelling with single-cycle analyses indicated that the energy efficiency of the UPHS system could significantly increase by scaling the UPHS system by a factor of five in size from efficiencies of 75-80% (L20C20) up to 90-95% (L100C20) for both drained and undrained conditions [see Fig. A2. 19, Fig. A2. 20, Fig. A2. 21]. On the

other hand, the impact of the scaling on the distribution of displacements is minor, with a membrane balloon-shaped inflation to be expected also at full prototype scale.

- A sensitivity study of the soil type and properties conducted with single-cycle modelling in Optum provides the following:
  - The effects of friction angle and small apparent cohesion at full prototype scale (L100C20) on the energy efficiency of the UPHS system are minor [see Fig. A2. 20].
  - Simulations in Optum show that soil type (and thus soil stiffness and strength) has a limited impact on the overburden and membrane deformed shape (the former is affected by the overburden configuration, while the latter follows a balloon-shape prior to soil failure). Also, soil stiffness and strength parameters play a minor role in energy efficiency at a given normalised lift height: namely, increases in the cohesion and friction angle in drained coarse soil only slightly influence the energy storage capability with minimal effect on efficiency. An exception to be considered is stiff fine-grained soils with large undrained cohesion (however, this type of soil may not be applicable to UPHS systems where the overburden is excavated and constructed).
- Modelling in Optum with the MC soil constitutive model at constant soil stiffness and fixed strength parameters (i.e. constant Young's modulus and set friction angle), by enlarging (i.e. scaling up) field trial geometries (FT_C2 and FT_C4) by a factor of five suggest that enlarging small-scale (1:10) experiments and models to full prototype size would result in an improved UPHS system performance, both in terms of stability and efficiency, as the elastic regime of the soil behaviour would play a greater role at full-prototype scale than at small scale testing. However, a further study is needed for a refined assessment of the role of soil stiffness increase with effective stresses on the performance of UPHS systems being scaled up in size.
- Parametric monotonic inflation analyses were carried out reinforcing the soil with multiple levels of geogrids. Preliminary results indicated that to prevent failure of the soil in the central regions of the cover, geogrids should extend only above the membrane and not into the external soil, so that the central soil region would be reinforced with respect to the external shear bands without intersecting them. However, for the field trial configuration, results also indicated that mobilised stress within the geogrid (needed to reinforce the soil) may be close to the ultimate strength; therefore, it is likely that geogrids may accumulate plastic strains over cycles and possibly decrease their effectiveness in the long term.

5. Conclusion and perspective

5.1 Conclusions

Finite-element analyses were carried out in this WP to evaluate, numerically, the resilience of the UPHS system configurations tested in the field. The numerical analyses provided further insights into mechanical aspects of the soil and the membrane that could not be evaluated in the field, and evaluated the implications of varying the overburden configuration (shape and material properties) and scaling up the size of the system to full prototype dimensions. The following main conclusions are drawn:

- The developed numerical models can provide a first approximated description of UPHS system behaviour in terms of overburden and membrane movements as well as expected energy efficiency for a few cycle analyses. On the other hand, the developed models cannot be fully validated for life cycle assessments. Therefore, it is concluded that the developed models may be used for a revised geotechnical design of the UPHS system capable to withstand less than 10 cycles whereas further work is needed to develop modelling approaches capable to design the system for a lifetime span.
- The numerical simulations confirmed field evidence that target uplift heights of the UPHS system would result in unacceptable overburden deformations and a consequent reduction in the central cover thickness. This is due to extension of the soil in the horizontal directions, facilitated by the naturally low tensile strength

of soils. The numerical simulations confirmed the field evidence that the resilience and durability of UPHS systems are highly dependent on soil lateral confinement and, more generally, the overburden shape.

- The membrane is a relatively flexible material within the UPHS system. In the presence of adequate friction with the bottom of the overburden, tensile strains in the membrane are a direct consequence of the overburden deformations. In particular, the numerical analyses indicated that a reduction in cover thickness and bell-shaped membrane profiles are likely associated with unacceptable membrane tensile straining.
- Monotonic inflation analyses can provide indications on the likely deformation mode of the overburden (e.g. shear bands at the side vs bell-shape with tensile soil elongation at the centre); single-cycle analyses can be used to roughly estimate the efficiency; multi-cycle analyses are needed for resilience predictions considering deformations of the overburden and membrane straining.
- Simplified models (relying on the Mohr-Coulomb constitutive model and piston-based modelling with incompressible low shear strength elements) could be used to quickly identify potential optional configurations, whereas refined modelling (considering nonlinear soil behaviour and the potential closing of the reservoir) is needed to carry out long-term predictions on cyclic behaviour.
- Results suggest that regardless of soil type (soft clay, sandy soil) energy losses per cycle of full prototype UPHS may be within the range of 5%-15% of the stored energy depending on investigated normalised uplift ($U_{avg,max} \approx 4\%$). Energy losses (expressed in relation to the stored energy) are found to increase when: soil strength parameters increases, scale is decreased, uplift is increased.

5.2 Perspective

- Despite differences in the rate of overburden deformation for each cycle, results collected from numerical modelling in WP2 would suggest that kick-toe shapes of the deflection pressure−volume curve may be associated with unacceptable overburden deformation as the result of reservoir bag closing, which causes the intensification of the bell-shaped profile of the membrane inflation at subsequent cycles and overburden deformations. Actions are required in future design to prevent this kick-toe mechanism (e.g., by avoiding a low minimum volume during deflations in combination with lateral confinement of the soil).
- Sufficient evidence has been collected to speculate that both the UPHS system's geotechnical stability and its energy efficiency are affected by both maximum and minimum inflation volumes. Further attention should be paid to this aspect, while also considering realistic inflation/deflation cycles needed to accommodate energy grid requirements and energy price fluctuation.
- The complexity of numerical modelling of UPHS systems is significant, considering large strain problems and geometrical nonlinearities. Future work may consider the use of alternative modelling methods to FE models.
- The developed numerical models, providing conservative estimates of overburden deformations and energy losses, hold the potential for revised or improved geotechnical design now that there are clear insights from this project on the underlying UPHS system behaviour mechanisms.
- To provide a structural analogy, understandable to the common engineer, the overburden is currently behaving as a beam undergoing central bending-induced straining that accumulate with each cycle. Contrarily, optimal behaviour of the overburden would be associated with a rigid beam having failure localised at the sides as a vertical slip surface; however, to obtain this, preliminary results may suggest that unrealistic geogrids may be needed.
- Also, considering that in larger demos the membrane stiffness would be approximately similar whereas the overburden stiffness would increase with cover. Future modelling focusing on the overburden design could rely on simpler modelling approaches as the one adopted in Optum G2 or alternatively the use of a pressure distribution (neglecting the membrane stiffness). However, the effects of a relatively low coefficient of friction on the membrane straining is important and, in real applications, should be accounted for to avoid unconservative assessments.

5.3 Ongoing and Future works

- Currently, numerical simulations are ongoing at AU and KIT to develop (i) a 3D simulation model that has the potential to avoid the overconservative predictions of axisymmetric models, (ii) study in depth the response of UPHS systems at full-prototype for which there has been clear indication of increased efficiency (decreased energy losses in the soil), (iii) suggest a revised design concept based on reinforced UPHS system. This research is currently carried out by a PhD student at AU and an MSc project at KIT. Although this activity is research focused, it is expected that outcomes will provide the numerical tools for improved UPHS design, as needed for further developments.
- The experimental and numerical studies carried out in the current EUDP project highlight a number of critical issues related to the current design, which needs to be further addressed to improve the stability of the system and to allow for greater energy storage potential. Focus should be on providing both greater control of membrane and overburden movements, and with the in-depth knowledge gathered in this study a number of principle solutions have been outlined below. These solutions will over the next 6-12 month be further investigated through numerical simulations, and they will undergo a feasibility evaluation (from both mechanical and construction perspective) in order to postulate a numerically validated design of a full prototype reinforced UPHS system. If successful, it is envisioned to apply for a new project that will fund the field testing of a downscaled redesigned UPHS trial system.

Principle solutions to be further investigated:

- *Construction of perimeter confinement walls or multiple confining cells*, to prevent outwards (lateral) movements of the overburden soil.
- *Construction of the reservoir bag as multiple pockets* with internal welding or reinforcements to achieve a mattress-type behaviour with a nearly uniform reservoir uplift (as opposed to balloon-shaped inflations).
- Construction of system of closely spaced multiple reservoir bags with separate flow control systems to ensure a coupled uniform uplift of the overburden.
- *Central reinforcements of the overburden*, to increase the horizontal tensile strength of the central areas and, thus, minimise cover reduction.
- *Creation of a piston-like overburden* with a stiffness foundation element (e.g. raft) to stiffen and induce a uniform uplift of the overburden.
- *Redesign of overburden geometry towards an initial concave shape to counteract lateral outwards soil movement.*

Appendix WP 2. - 2.1

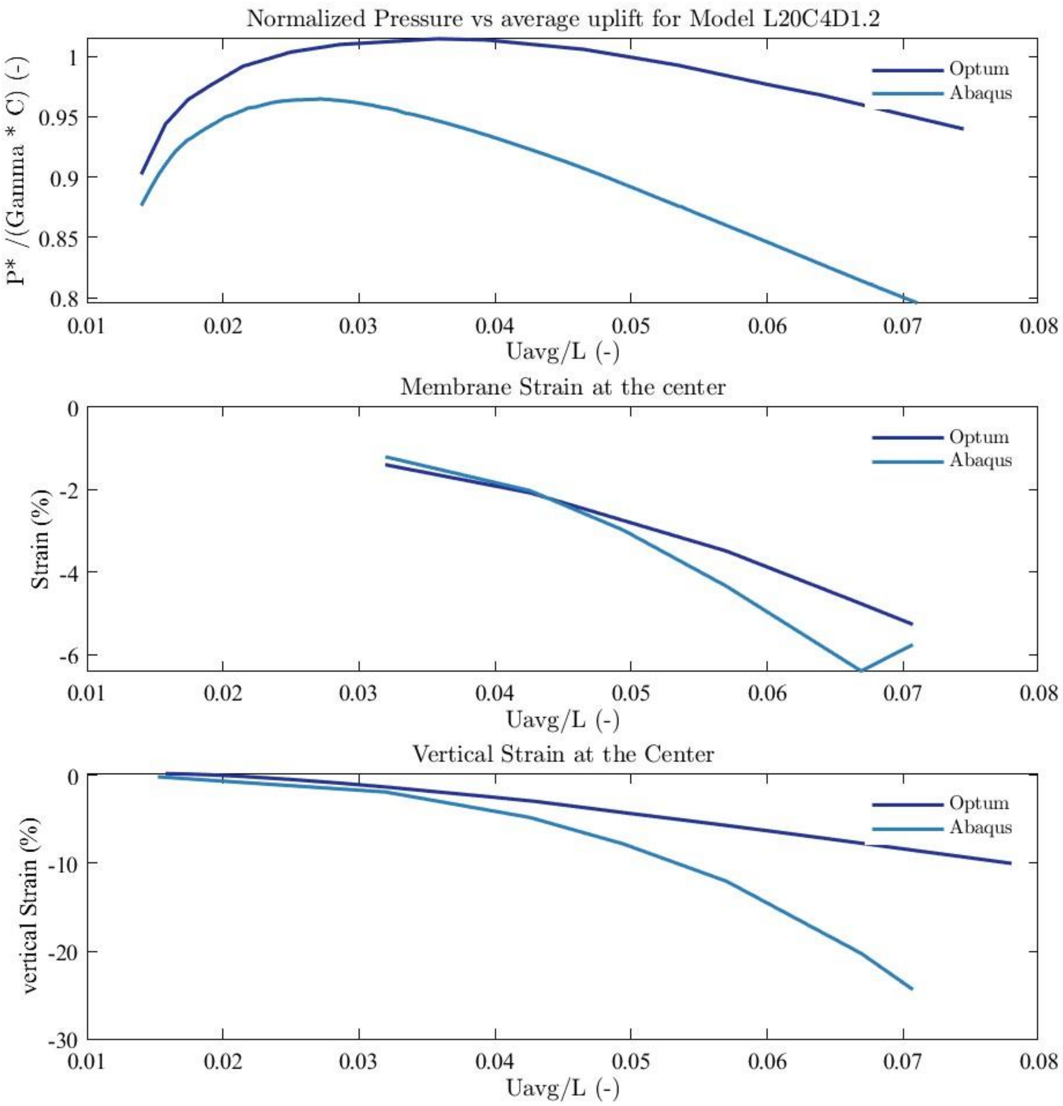


Fig. A2. 1: Abaqus and Optum modelling results of the monotonic inflation of the preliminary configuration (PR_C4): overburden normalized pressure, membrane strain and cover reduction vs average uplift to cover ratio.

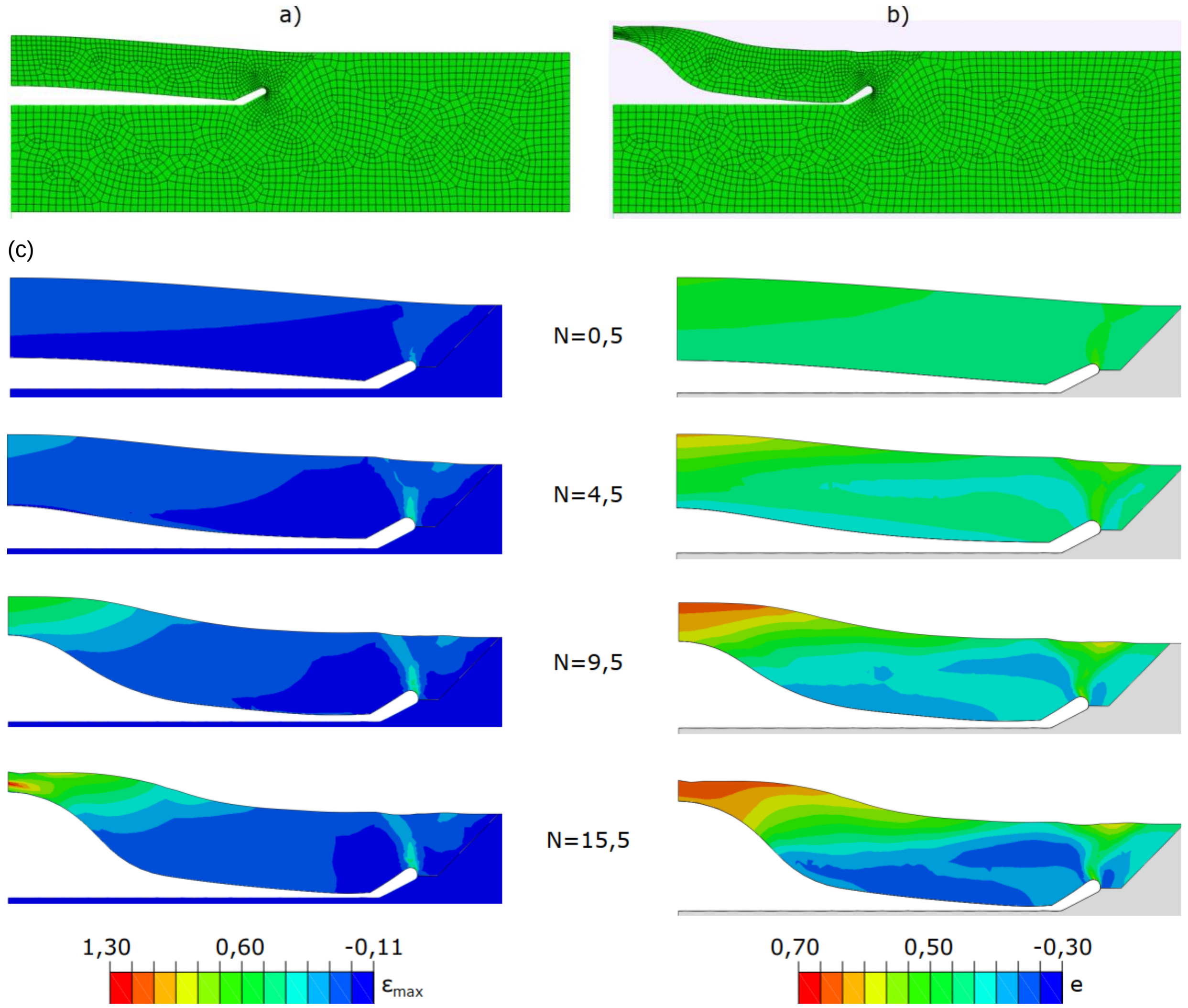


Fig. A2. 2: Abaqus modelling results of the field trial FT_C2 at Rv=35%: deformed shapes (a,b), maximum strain and void ratio for varying cycle number (c).

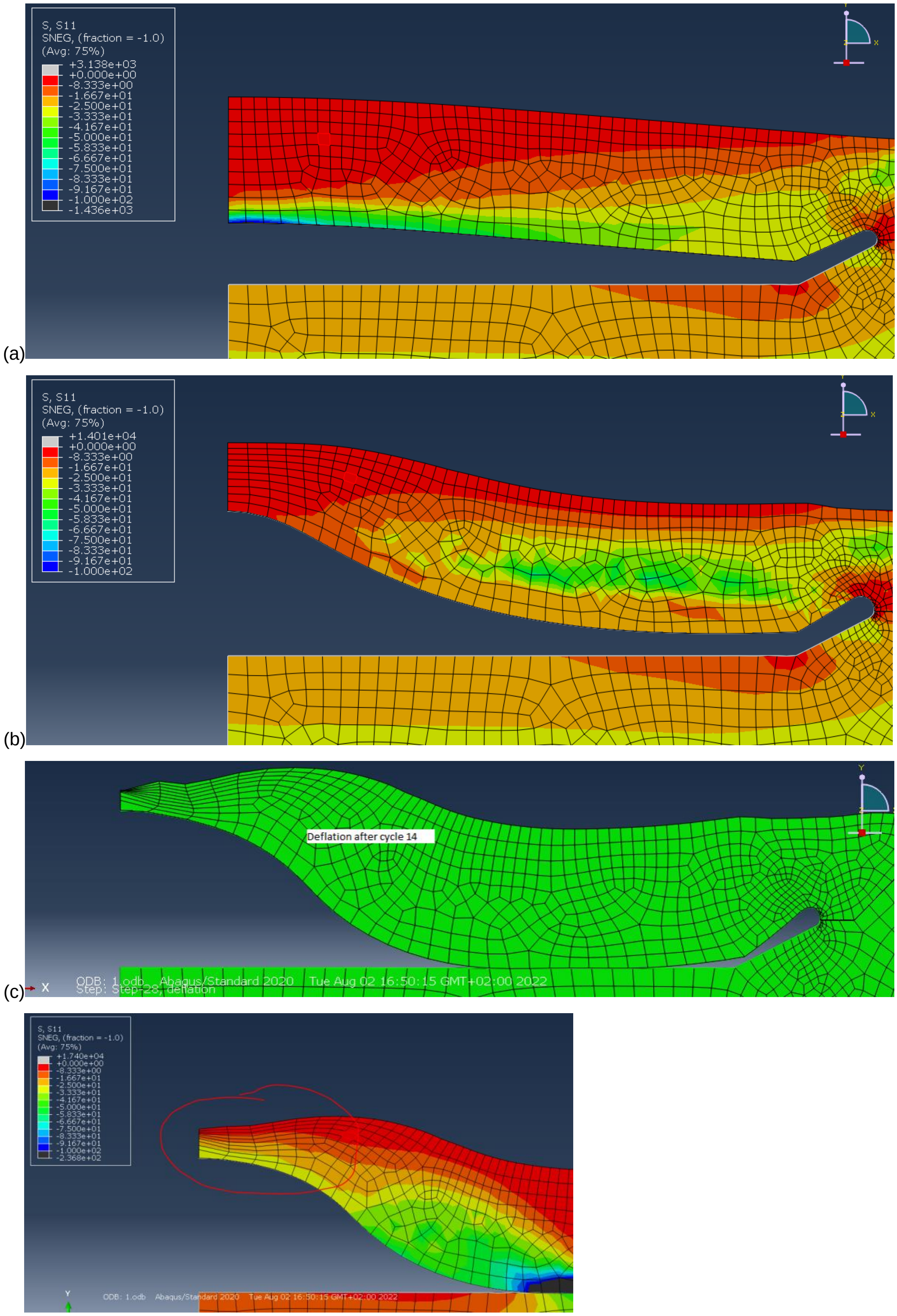


Fig. A2. 3: Abaqus modelling results of the field trial FT_C2: deformed shape and horizontal stresses at cycles (a) 1, (b) 8 and (c) 14.

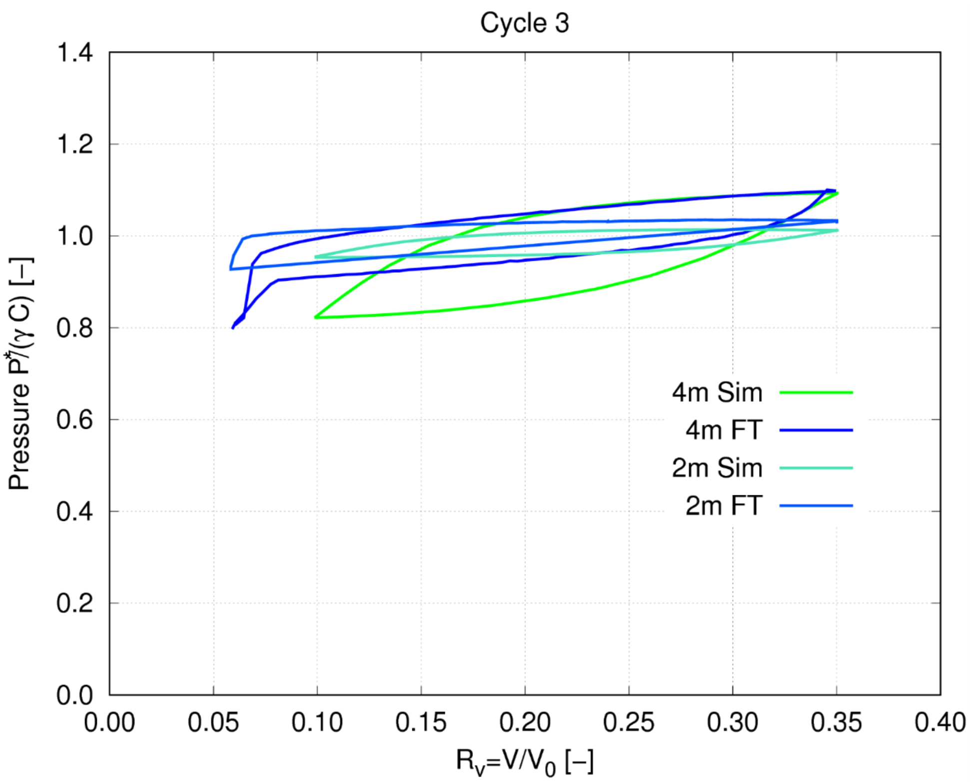


Fig. A2. 4: Abaqus modelling results of the field trial FT_C2 and FT_C4: overburden pressure p^* vs volume ratio R_v.

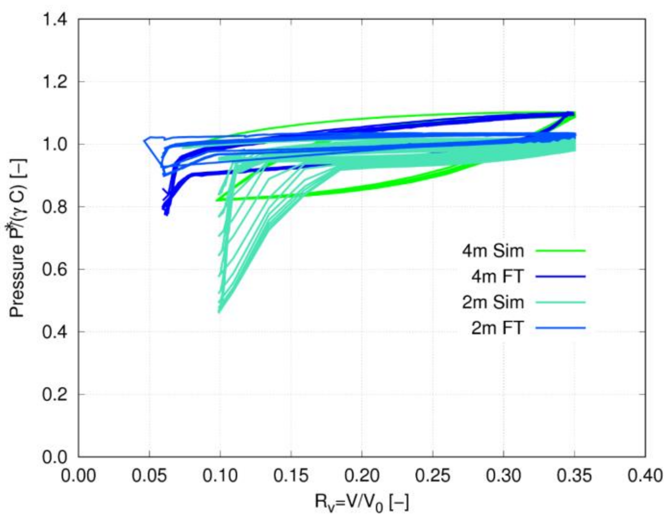


Fig. A2. 5: Abaqus modelling results of the field trial FT_C2 and FT_C4: overburden pressure p^* vs volume ratio R_v.

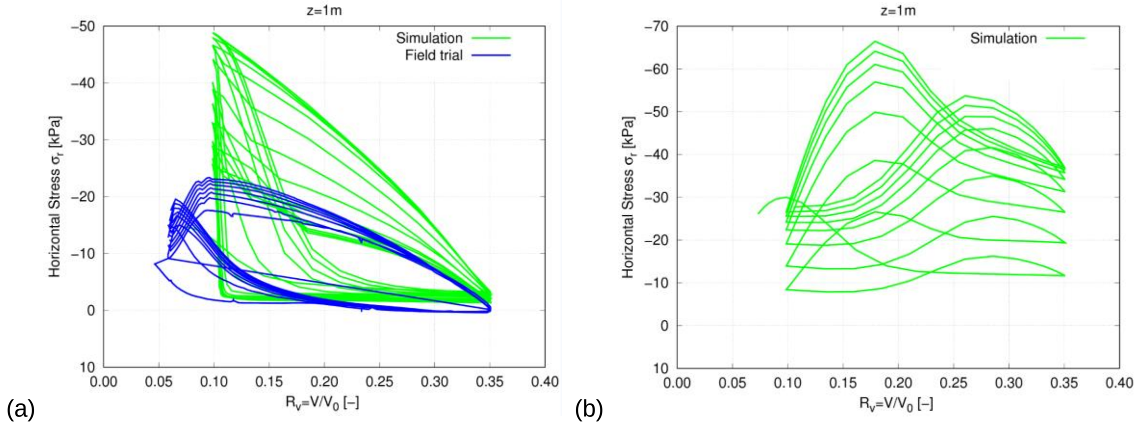


Fig. A2. 6: Abaqus modelling results of the field trial (a) FT_C2 and (b) FT_C4: horizontal stress at the centre axis vs volume ratio R_v for series 1 and A.

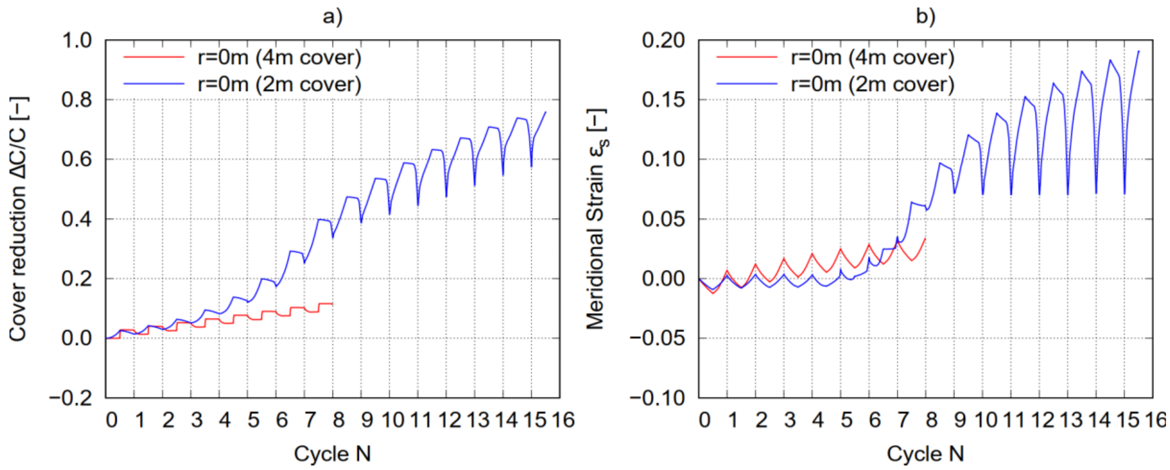


Fig. A2. 7: Abaqus modelling results of the field trial FT_C2 and FT_C4: a) reduction in cover C and b) maximum tensile strain of the membrane vs number of cycles.

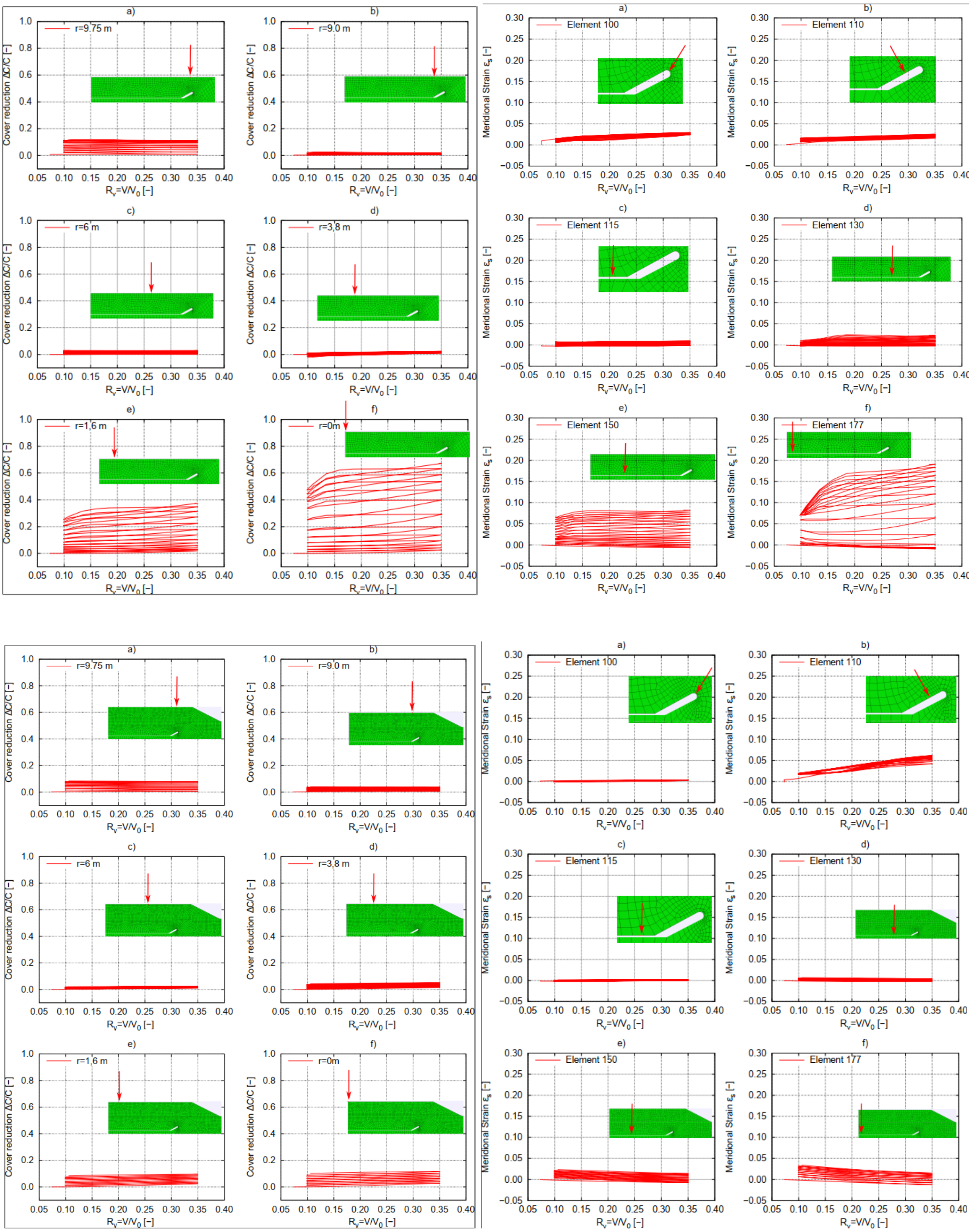


Fig. A2. 8: Abaqus modelling results of the field trial FT_C2 and FT_C4: reduction in cover and tensile meridional strain of the membrane at varying offset from the centre.

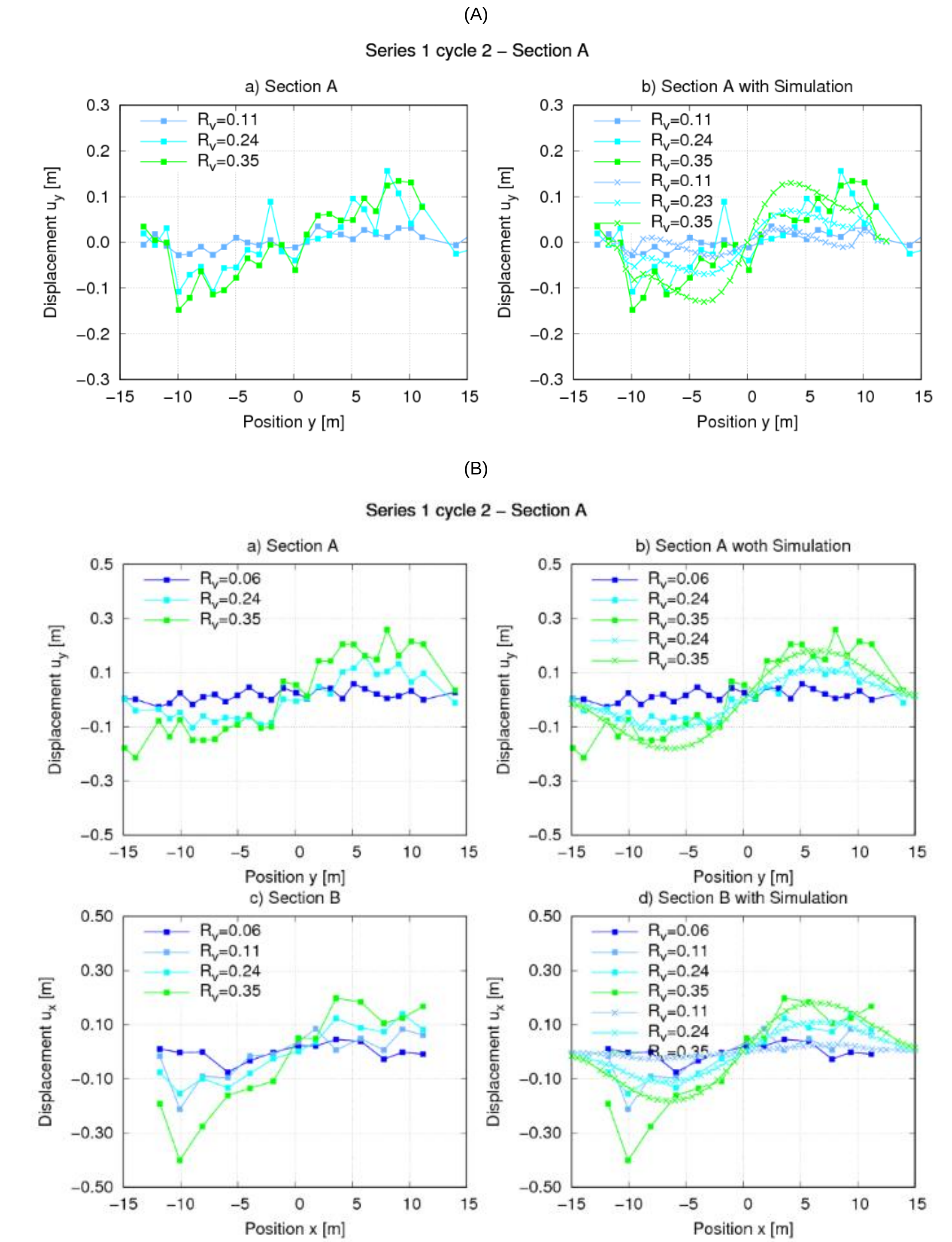


Fig. A2. 9: Abaqus modelling results of the field trials: comparison with horizontal displacement Ux or Uy measured along transverse section A during cyles 2 of the field trial (A) FT_C2 with 2m cover and (B) FT_C2 with 4m cover.

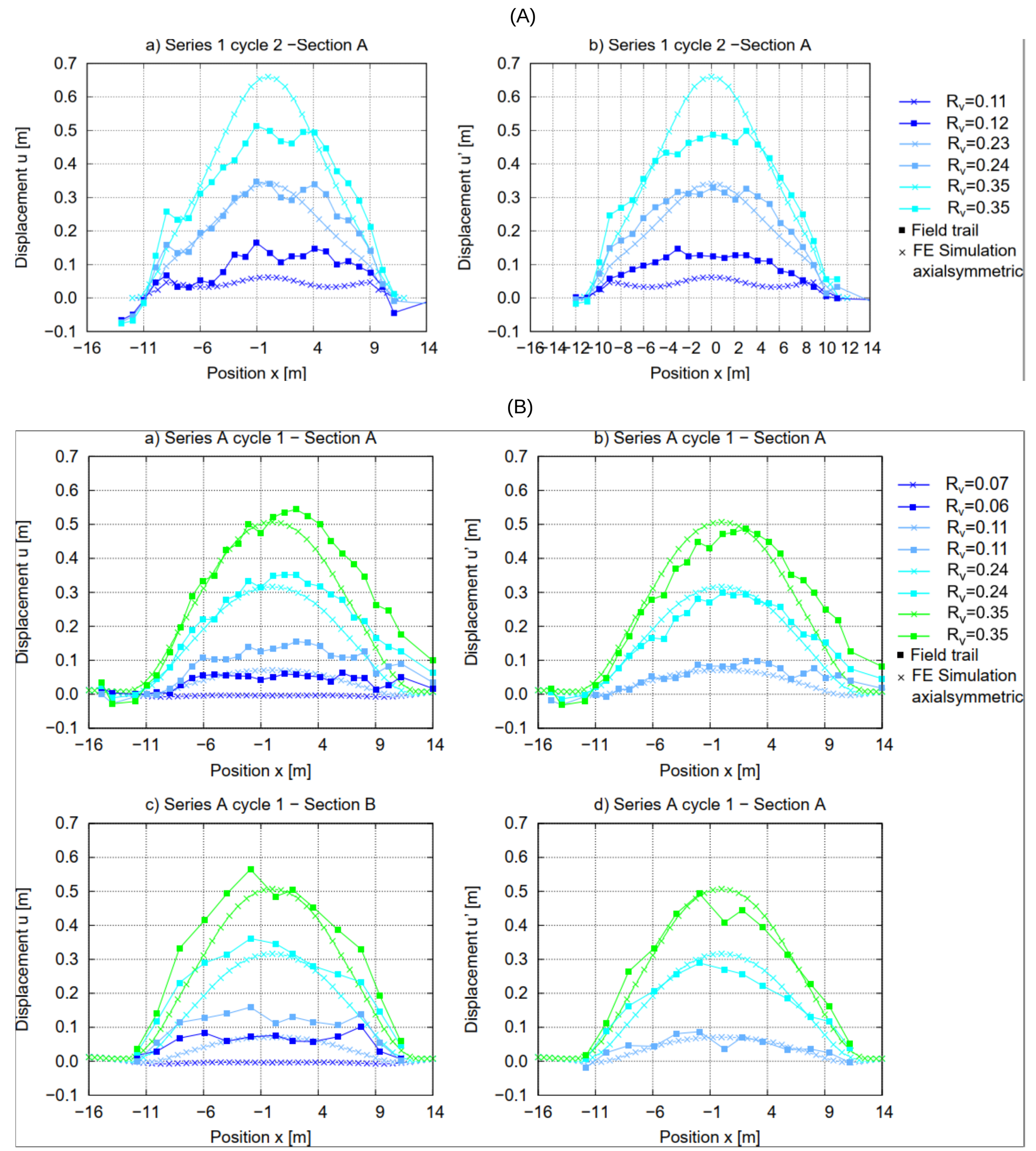
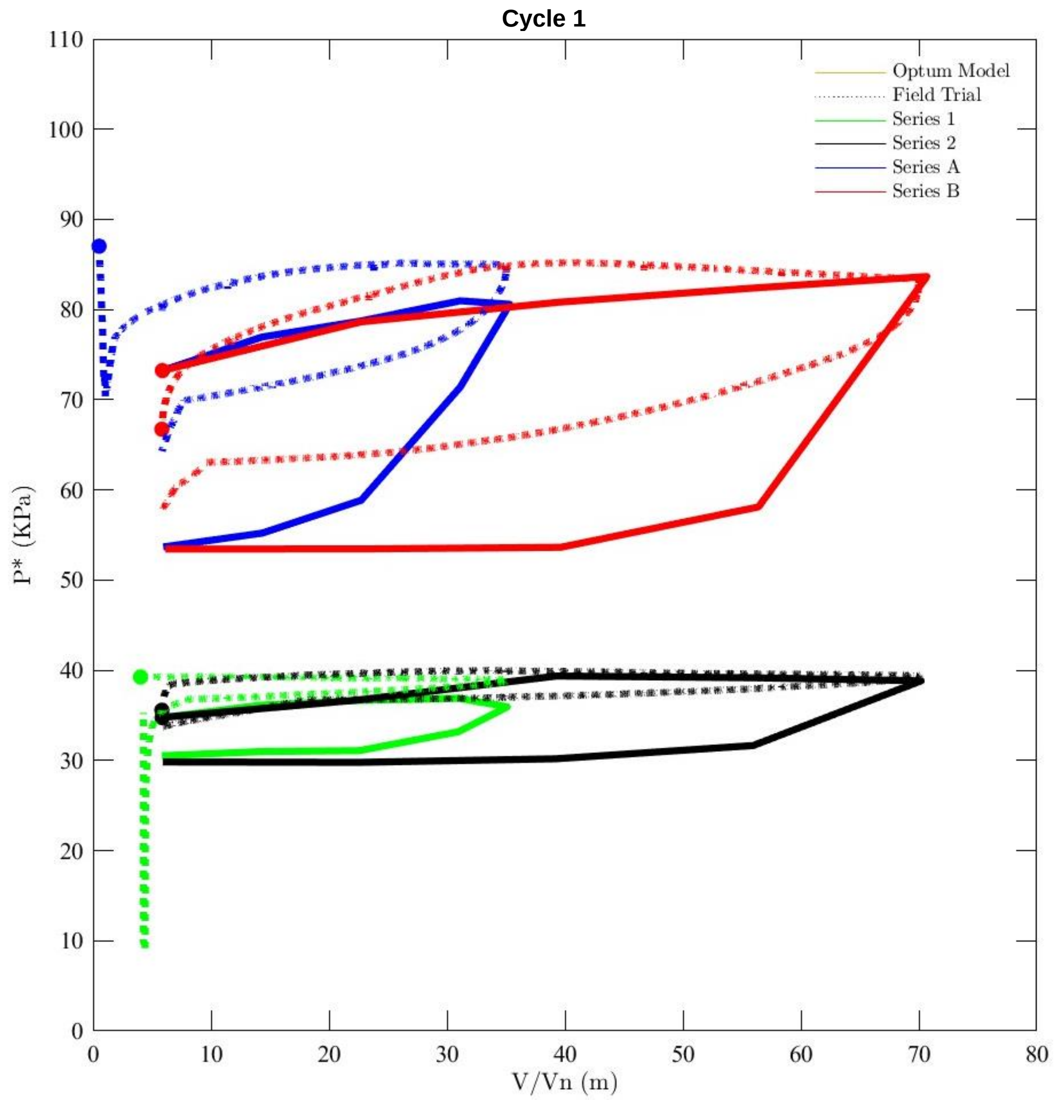


Fig. A2. 10: Abaqus modelling results of the field trials: comparison with vertical displacements U measured along transverse section A during the 1st cycle of the field trial (A) FT_C2 with 2m cover and (B) FT_C2 with 4m cover.



Model	series		L	C	D	T	A	O	Beta	Alpha	Name					
2m cover	1	Axysimmetric	20	2	0.6	0	0	inf	0	26.57	L	20	C	2	D	0.6
	2	Axysimmetric	20	2	0.6	0	0	inf	0	26.57	L	20	C	2	D	0.6
4m cover	A	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L	20	C	4	D	0.6
	B	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L	20	C	4	D	0.6

No. of Cycles	Material	E	nu	C	Phi	Psi	Gamma	K0	Drainage	Energy loss cycle 1	Energy loss cycle 2	Efficiency Cycle 1	Efficiency Cycle 2
2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	12.3	9.4	87.7	90.6
2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	17.5	15.0	82.5	85.0
2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	21.6	18.0	78.4	82.0
2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	27.8	25.8	72.2	74.2

No. of Cycles	Material	E	nu	C	Phi	Psi	Gamma	K0	Drainage	Energy loss cycle 1	Energy loss cycle 2	Efficiency Cycle 1	Efficiency Cycle 2
2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	12.3	9.4	87.7	90.6
2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	17.5	15.0	82.5	85.0
2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	21.6	18.0	78.4	82.0
2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	27.8	25.8	72.2	74.2

Fig. A2. 11: Optum modelling results from 2-cycle analyses of the field trials FT_C2 and FT_C4: overburden pressure p^* vs volume ratio R_v. In the table, summarized mechanical and geometrical parameters as well as efficiency.

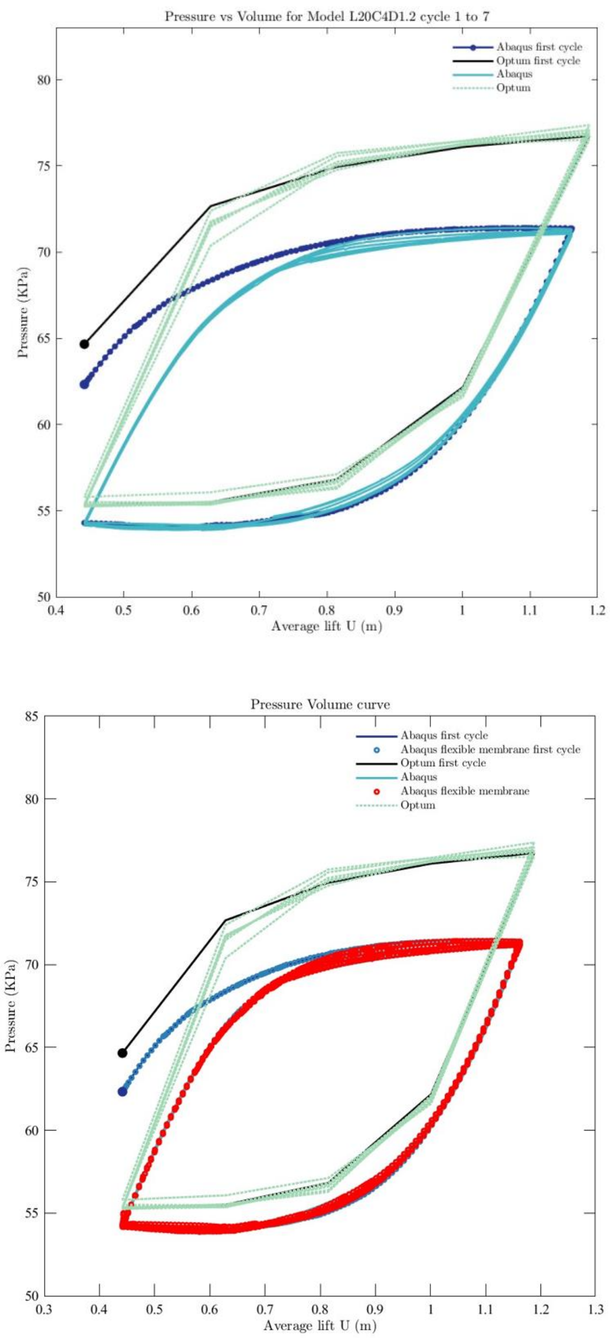


Fig. A2. 12: Optum vs Abaqus with both implementing MC soil, multi-cycle modelling for the preliminary geometry PR_C4: pressure p^* vs average lift.

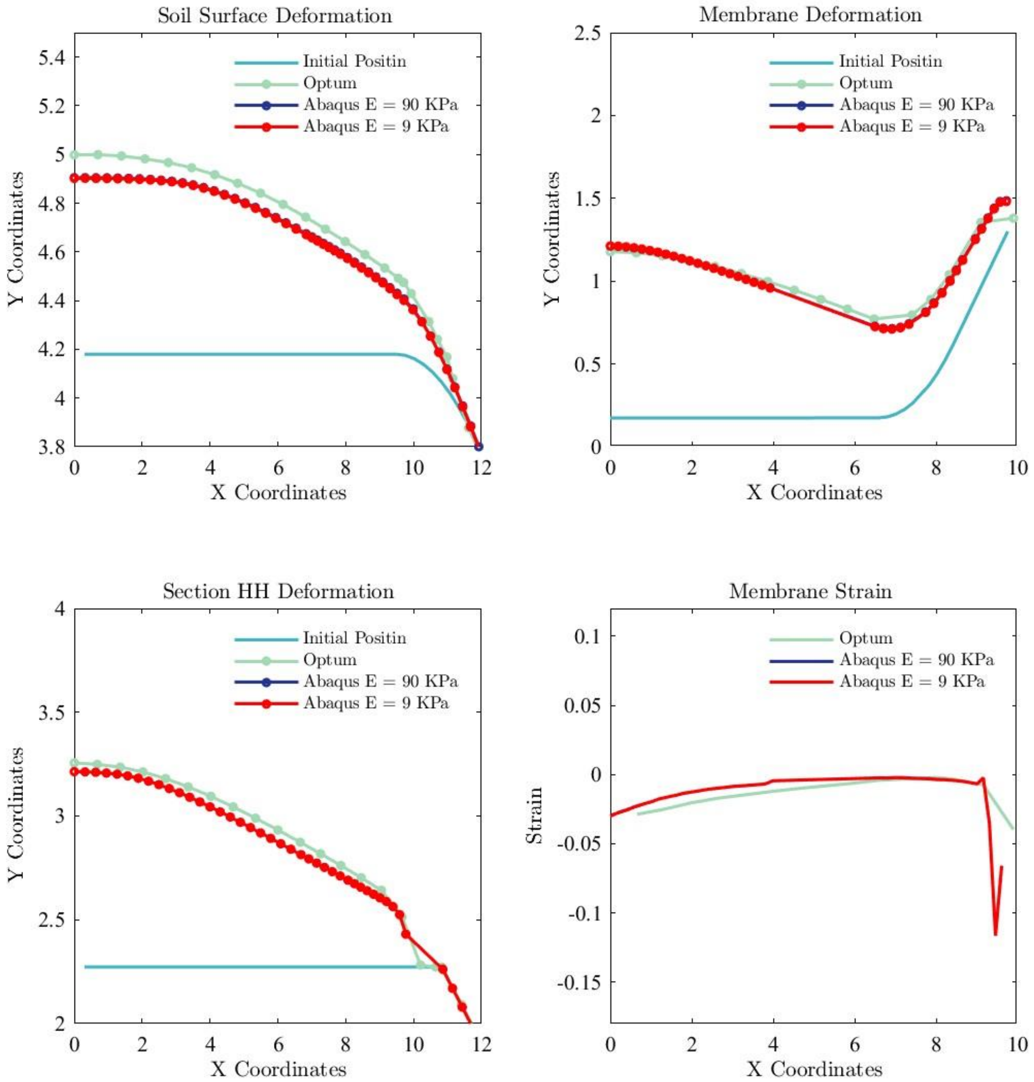


Fig. A2. 13: Evaluations of the influence of the membrane stiffness for single-inflation analysis: comparison of Optum vs Abaqus with both implementing MC soil (single-cycle analysis; PR_c4; Inflation volume of 245 m3 thus Rv=41% and Uavg/L=5%).

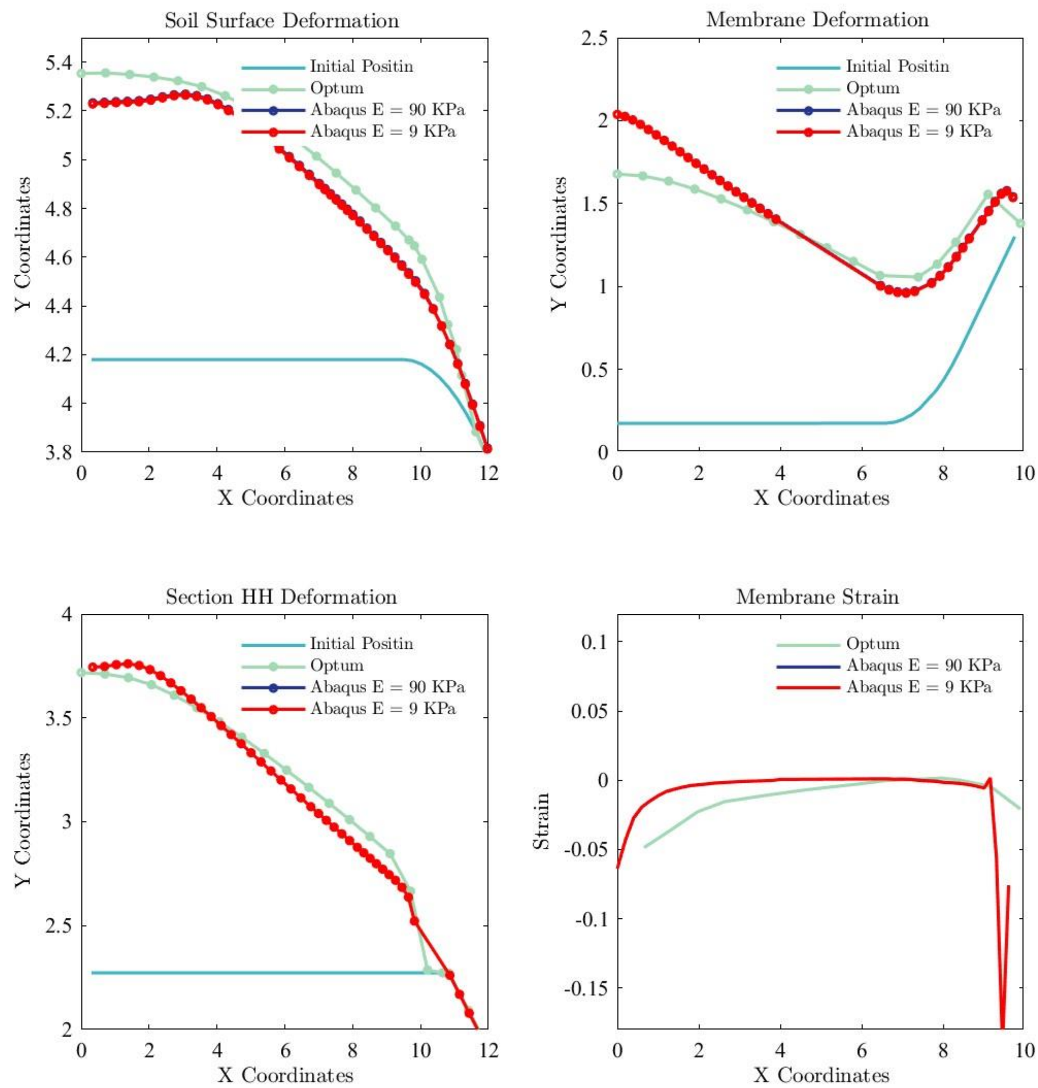


Fig. A2. 14: Evaluations of the influence of the membrane stiffness for single-inflation analysis: comparison of Optum vs Abaqus with both implementing MC soil (single-cycle analysis; PR_c4; Inflation volume of 332 m3 thus Rv=56% and Uavg=6.7%).

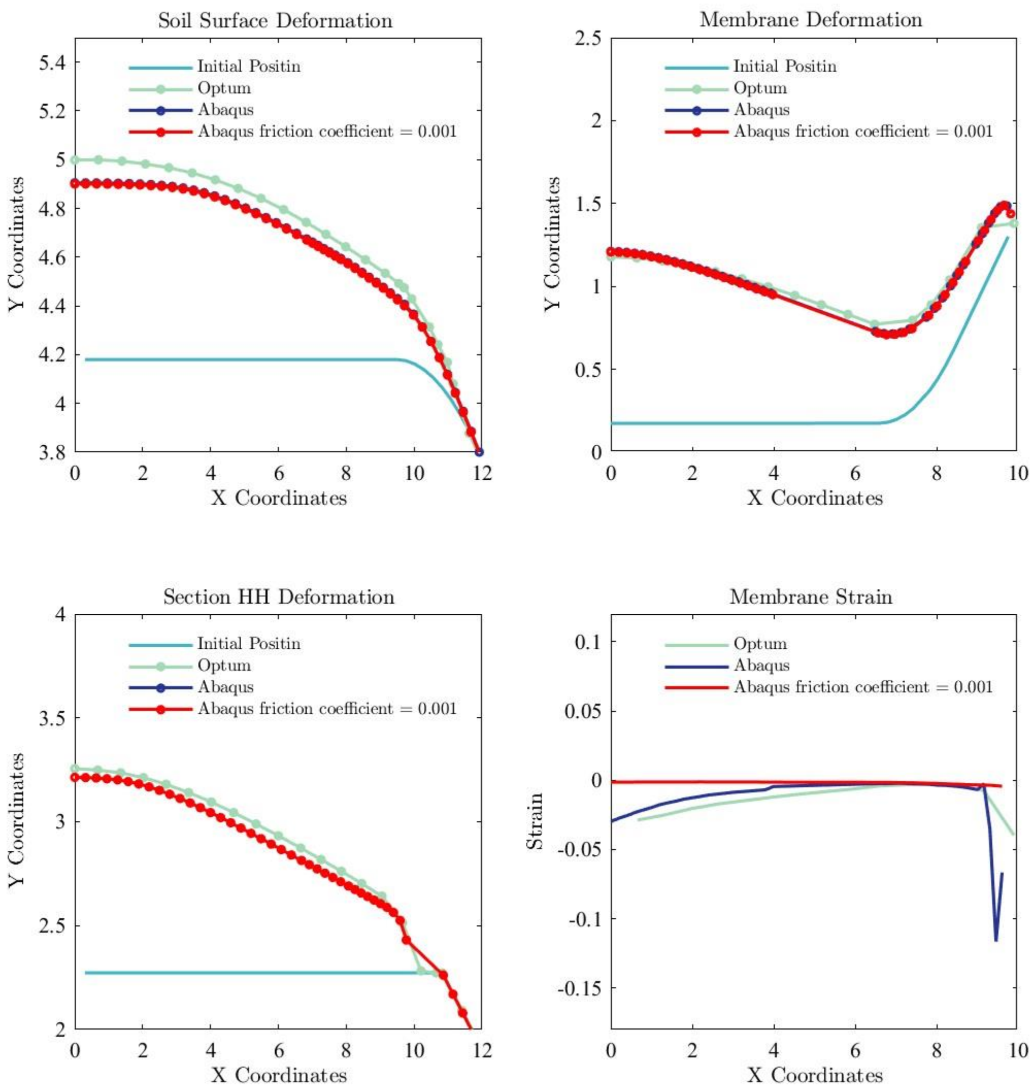


Fig. A2. 15: Evaluations of the influence of the coefficient of friction between soil and membrane, and comparison of Optum vs Abaqus with both implementing MC soil (single-cycle analysis; PR_c4; inflation volume of 245 m3 thus Rv=41% and Uavg/L=5%).

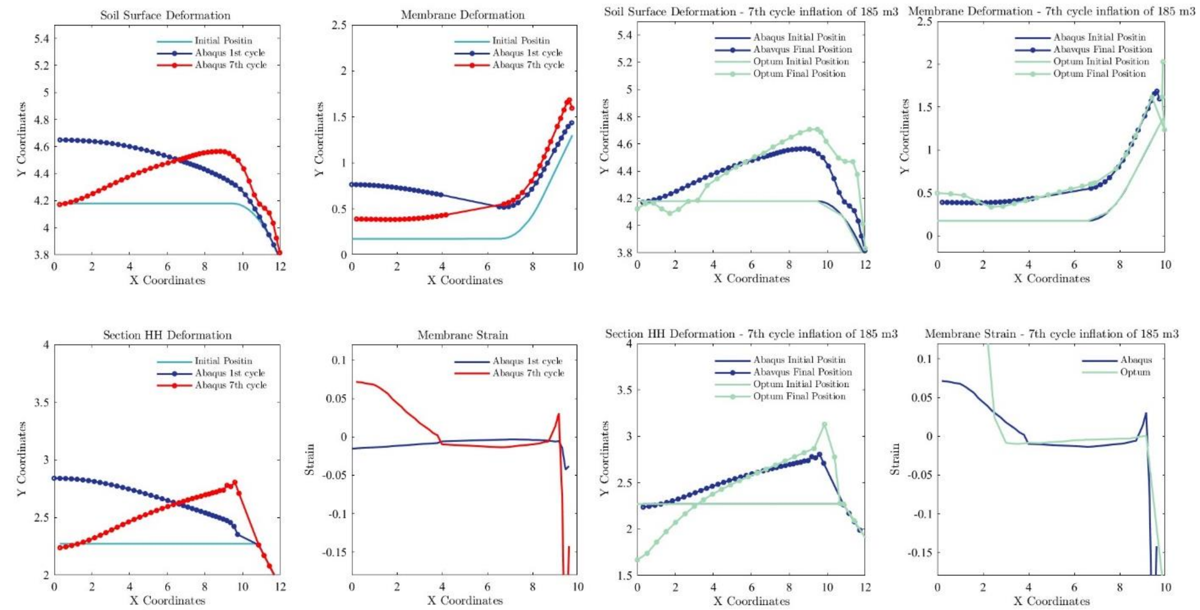
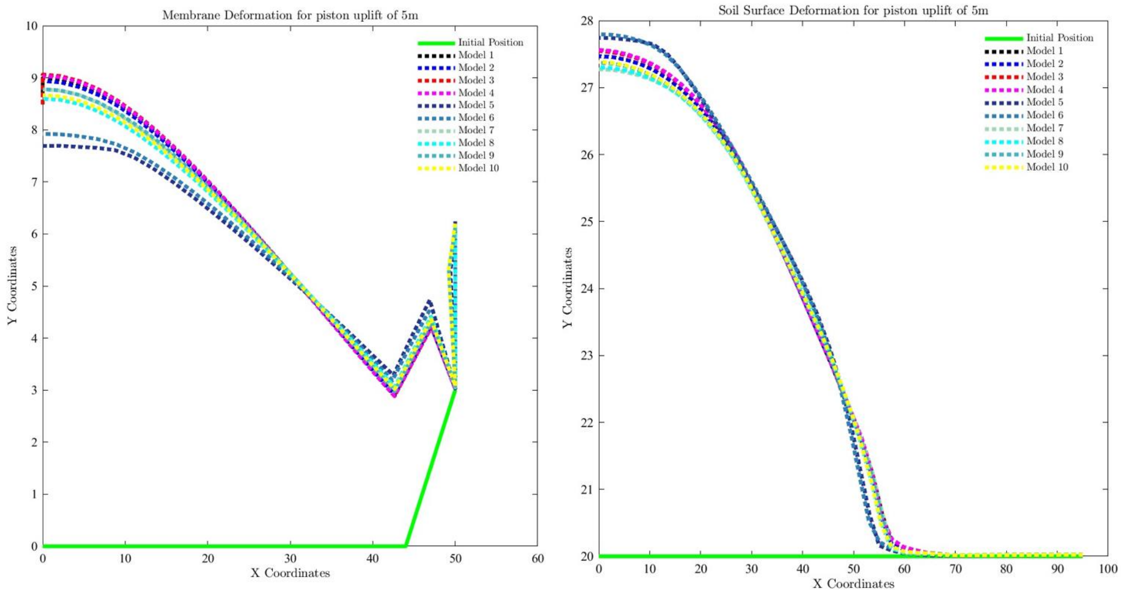
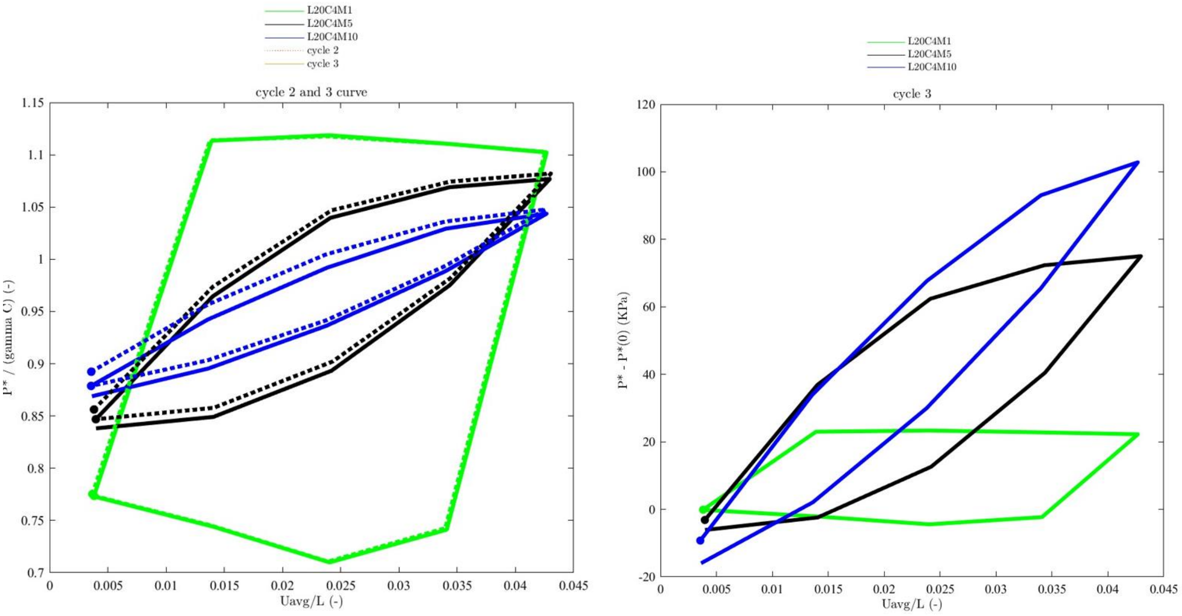


Fig. A2. 16: For the preliminary configuration PR_C4 obtained from Abaqus and Optum implementing MC soil: (left) comparison of inflated state at cycle 1 and 7; (right) comparison of inflated state at cycle 7 predicted by Abaqus and Optum. (multi-cycle analysis; PR_c4; max inflation volume of 185 m3 thus Rv=65% and Uavg/L=7.8%).



no.	Material type	C (Kpa)	Phi	E (Mpa)	Efficiency	Analysis Type
1	Drained Sand	0	35	10.6	91	Always drained
2	Drained Sand	5	35	10.6	91	Always drained
3	Drained Sand	0	45	10.6	89	Always drained
4	Drained Sand	5	45	10.6	91	Always drained
5	Undrained Clay	50	0	10.6	91	Drained/Undrained
6	Undrained Clay	100	0	10.6	92	Drained/Undrained
7	Undrained Clay	10	20	10.6	92	Drained/Undrained
8	Undrained Clay	20	20	10.6	91	Drained/Undrained
9	Undrained Clay	10	25	10.6	91	Drained/Undrained
10	Undrained Clay	20	25	10.6	90	Drained/Undrained

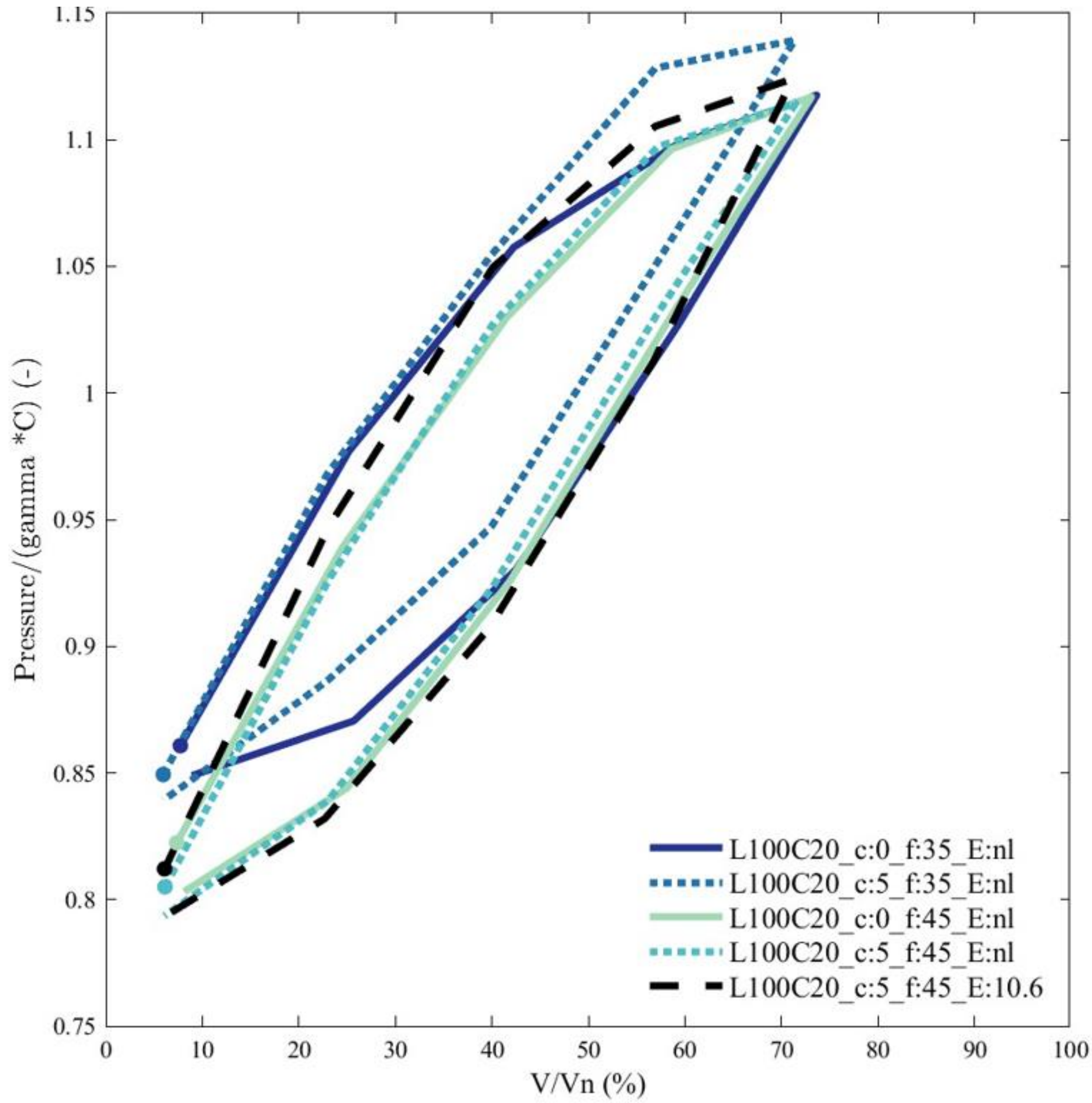
Fig. A2. 17: Sensitivity study in Optum of the effects of soil type on overburden surface and membrane inflated state at full prototype (L100C20D3M1, hill-shaped)



	Number of Cycle	1	2	3
L20C4D0.6M1= L20C4D0.6	Energy Loss (%)	28	26	26
	Efficiency (%)	72	74	74
L20C4D0.6M5= L100C20D3	Energy Loss (%)	12	9	9
	Efficiency (%)	88	91	91
L20C4D0.6M10= L200C40D6	Energy Loss (%)	7	4	4
	Efficiency (%)	93	96	96

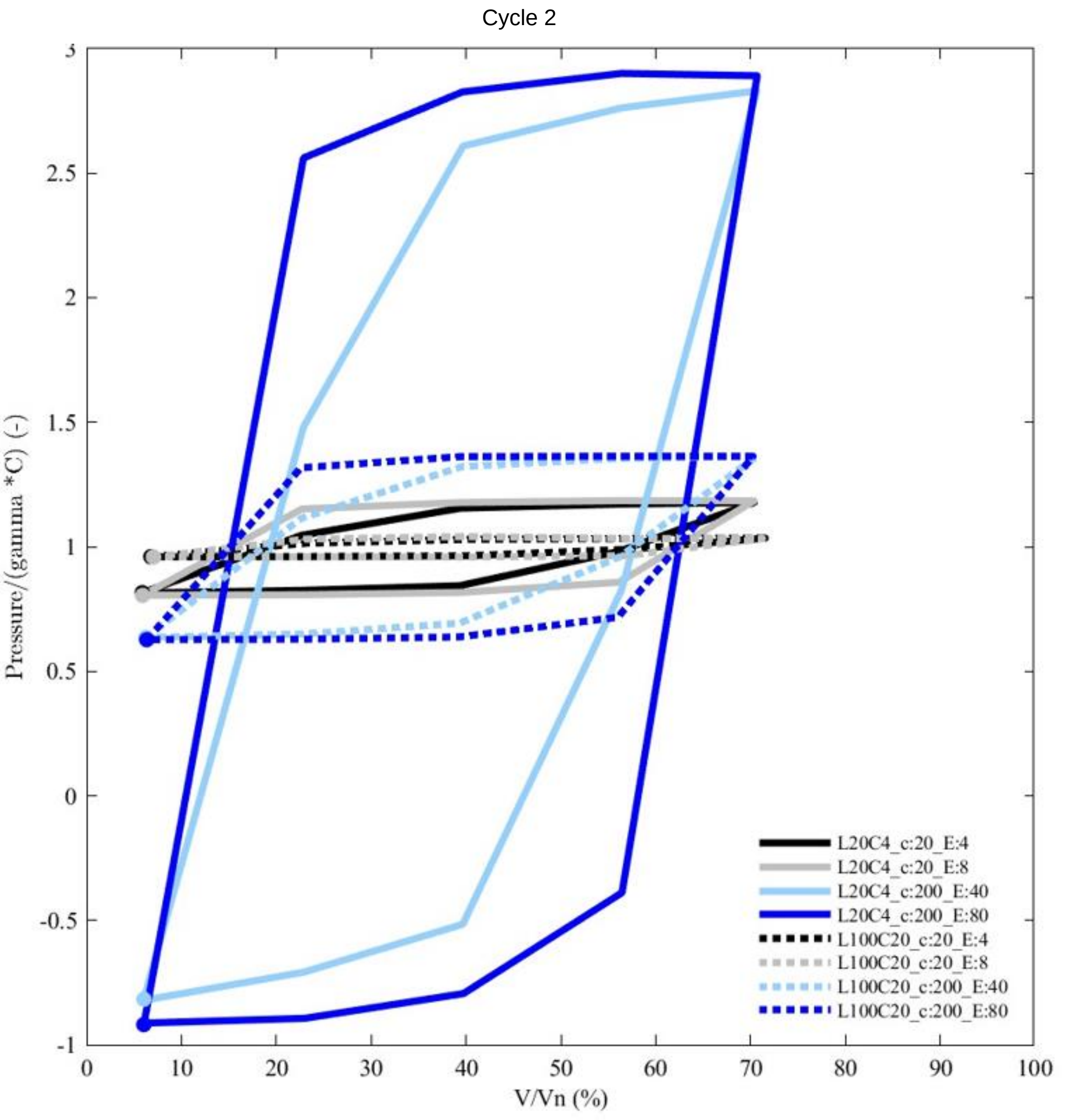
Fig. A2. 18: Evaluations of the influence of the enlarging a UPHS system from the hill-shaped configuration FT_C4in MC sand using Optum modelling: (left) normalized pressure and (b) variation in absolute pressure vs normalized average lift (configuration, three-cycle analysis; scaling by increasing gravity field as in centrifuge testing, Mx where x is scaling factor).

Cycle 2



no.	Material type	E (MPa)	c (kPa)	Phi (°)	Efficiency %	Analysis Type	Legend Label
1	Drained Sand	Stress Dependent	0	35	91	Always drained	L100C20_c:0_f:35_E:nl
2	Drained Sand	Stress Dependent	5	35	93	Always drained	L100C20_c:5_f:35_E:nl
3	Drained Sand	Stress Dependent	0	45	92	Always drained	L100C20_c:0_f:45_E:nl
4	Drained Sand	Stress Dependent	5	45	93	Always drained	L100C20_c:5_f:45_E:nl
5	Drained Sand	10.6	5	45	91	Always drained	L100C20_c:5_f:45_E:10.6

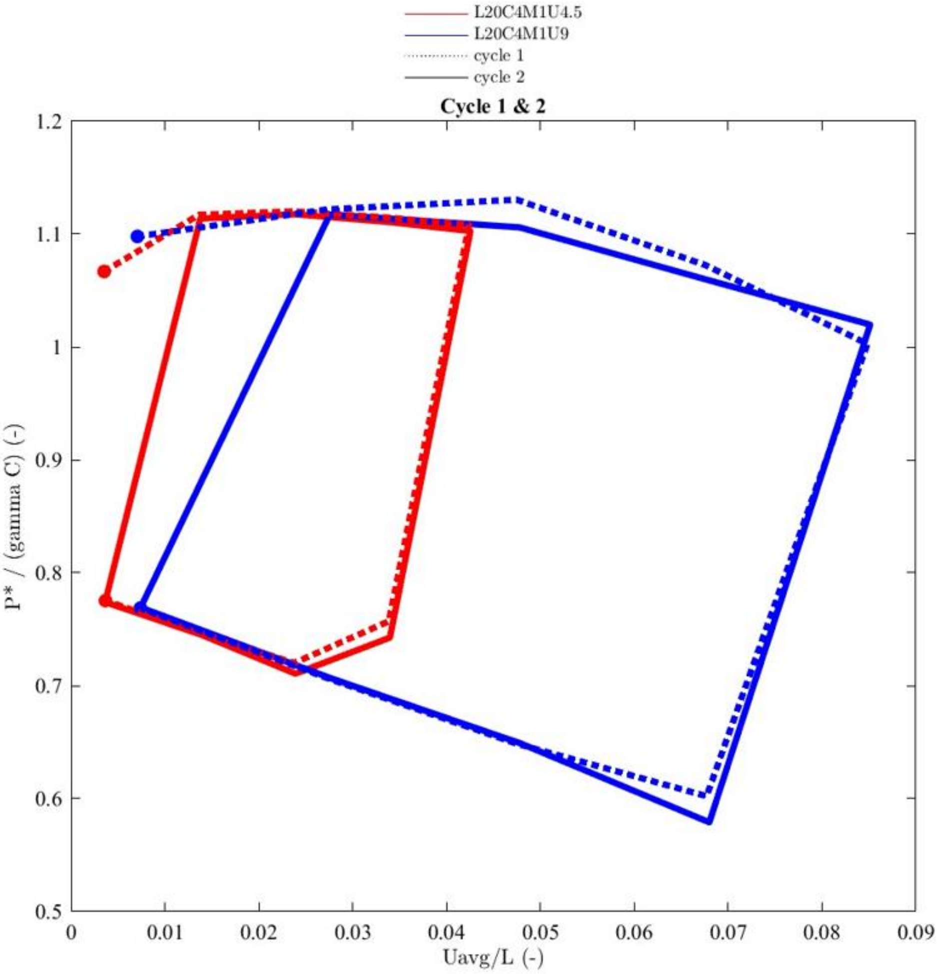
Fig. A2. 19: Optum modelling results of the effects of sand strength parameters on energy performance on full prototype (hill shaped; L100C20D3 , ie 5times FT_C4)



no.		c (kPa)	E (MPa)	Efficiency (%)	Analysis Type	Legend Label
1	Undrained Clay	20	4	83	Drained/Undrained	L20C4_c:20_E:4
2	Undrained Clay	20	8	77	Drained/Undrained	L20C4_c:20_E:8
3	Undrained Clay	200	40	44	Drained/Undrained	L20C4_c:200_E:40
4	Undrained Clay	200	80	38	Drained/Undrained	L20C4_c:200_E:80
5	Undrained Clay	20	4	95	Drained/Undrained	L100C20_c:20_E:4
6	Undrained Clay	20	8	93	Drained/Undrained	L100C20_c:20_E:8
7	Undrained Clay	200	40	68	Drained/Undrained	L100C20_c:200_E:40
8	Undrained Clay	200	80	58	Drained/Undrained	L100C20_c:200_E:80

Fig. A2. 20: Optum modelling results of the effects of clay strength and stiffness parameters on energy performance on full prototype (hill shaped; L20C4D0.6 and L100C20D3)

Cycle 2



Models	Number of Cycle	1	2
L20C4M1U4.5	Energy Loss (%)	28	26
	Efficiency (%)	72	74
L20C4M1U9	Energy Loss (%)	32	29
	Efficiency (%)	68	71

Fig. A2. 21: Optum modelling results of the effects of increasing normalized uplift height on energy performance on full prototype (energy loss and efficiency in %)

Cycle 2

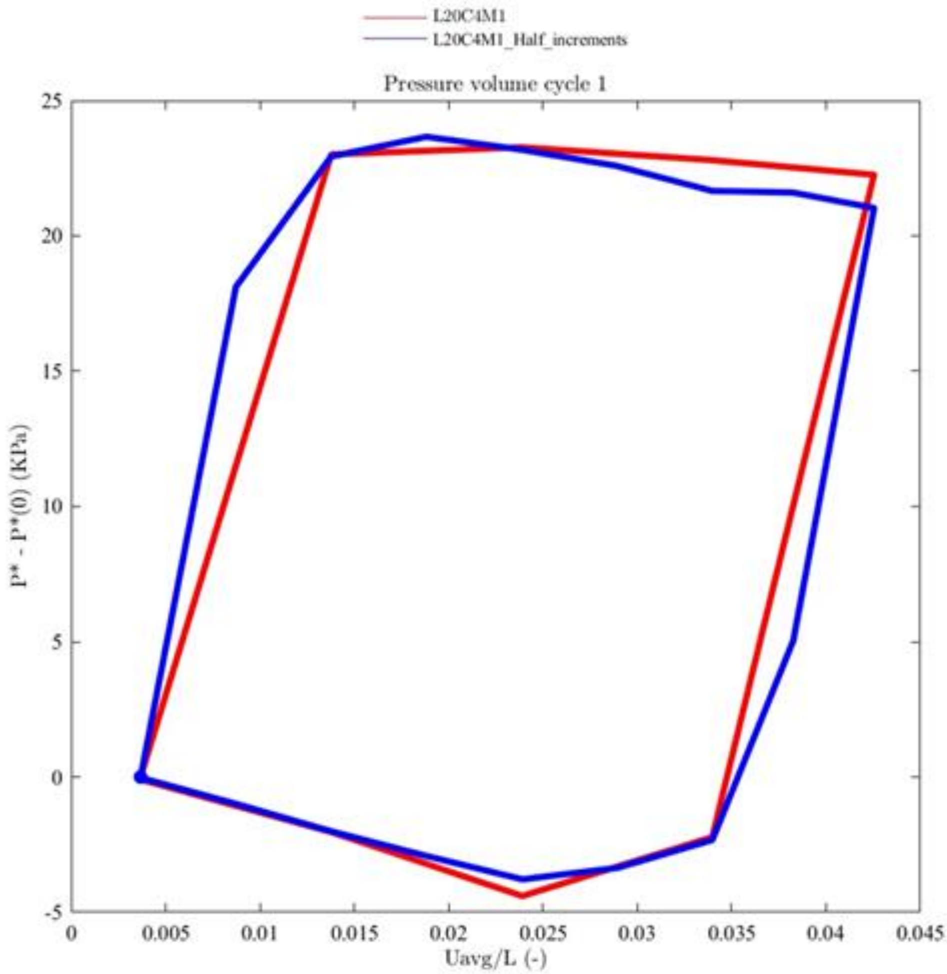


Fig. A2. 22: Optum modelling results of the effects of varying the step size in volume change on pressure volume curves.

Table A2. 1 List of Optum simulations

			L	C	D	T	A	O	Beta	Alpha	Name	N
Filed Geometry (FT_C2)	Task 0	Axysimmetric	20	2	0.6	0	0	inf	0	26.57	L 20 C 2 D 1	
Filed Geometry (FT_C4); different overburden	Task 2 - model 1	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Task 2 - model 4	Axysimmetric	20	6	0.6	4	0	2	26.57	26.57	L 20 C 6 D 1	
	Task 2 - model 7	Axysimmetric	20	4	0.6	2	0	-4	26.57	26.57	L 20 C 4 D 1	
Filed Geometry (FT_C2) ; with distributed load	Task 2 plus- 2m load	Axysimmetric	20	2	0.6	0	0	inf	0	26.57	L 20 C 2 D 1	
	Task 2 plus- 4m load	Axysimmetric	20	2	0.6	0	0	inf	0	26.57	L 20 C 2 D 1	
	Task 2 plus- 4m load 9	Axysimmetric	20	2	0.6	0	0	inf	0	26.57	L 20 C 2 D 1	
Effect of side slope of membrane	Task 3 - model 1	Axysimmetric	20	2	0.6	0	0	inf	0	16.70	L 20 C 2 D 1	
	Task 3 - model 2	Axysimmetric	20	2	0.6	0	0	inf	0	45	L 20 C 2 D 1	
Shear Band	Task 4 - shear Band	Axysimmetric	20	2	0.6	0	0	inf	0	26.57	L 20 C 2 D 1	
Geogrid	Task 5-Geogrids 1	Plane Strain	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Task 5-Geogrids 2	Plane Strain	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Task 5-Geogrids 3	Plane Strain	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Task 5-Geogrids 4	Plane Strain	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Task 5-Geogrids 5	Plane Strain	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
Different overburden geometry	Task 6_1	Axysimmetric	20	4	0.6	0	2	0	11.31	26.57	L 20 C 4 D 1	
	Task 6_2	Axysimmetric	20	4	0.6	0	2	2	9.46	26.57	L 20 C 4 D 1	
	Task 6_3	Axysimmetric	20	4	0.6	0	2	4	8.13	26.57	L 20 C 4 D 1	
Plane strain Vs Axisymmetric	Task 7- plane strain	Plane Strain	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
Different Geometries	Task 9_1	Axysimmetric	10	2	0.6	0	0	inf	0	26.57	L 10 C 2 D 1	
	Task 9_2	Axysimmetric	10	4	0.6	2	0	inf	90	26.57	L 10 C 4 D 1	
	Task 9_3	Axysimmetric	20	4	0.6	2	0	inf	90	26.57	L 20 C 4 D 1	
	Task 9_4	Axysimmetric	40	4	0.6	2	0	4	14.03	26.57	L 40 C 4 D 1	
	Task 9_5	Axysimmetric	40	2	0.6	0	0	inf	0	26.57	L 40 C 2 D 1	
	Task 9_6	Axysimmetric	40	4	0.6	2	0	inf	90	26.57	L 40 C 4 D 1	
	Task 9_7	Axysimmetric	40	8	0.6	6	0	inf	90	26.57	L 40 C 8 D 1	
Scaling Effect	Task 10_X5	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
Different uplift increments	Task 11	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
Scaling and Cohesion Effect	Task 12_1	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Task 12_2	Axysimmetric	100	10	3	10	0	10	26.57	26.57	L ## C 10 D 3	
	Task 12_3	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
Effect of stiffness	Effect of stiffness_1	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Effect of stiffness_2	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Effect of stiffness_3	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Effect of stiffness_4	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Effect of stiffness_5	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Effect of stiffness_6	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Effect of stiffness_7	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
	Effect of stiffness_8	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
Model with wall at the edge	Model wall	Axysimmetric	20	4	0.6	2	0	2	26.57	26.57	L 20 C 4 D 1	
sensitivity study	sensitivity study_1	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_2	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_3	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_4	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_5	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_6	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_7	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_8	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_9	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	sensitivity study_10	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
sensitivity study with stress dependent E	Stress dependent E_1	Axysimmetric	200	40	3	10	0	inf	90	26.57	L ## C 40 D 3	
	Stress dependent E_2	Axysimmetric	500	100	15	10	0	inf	90	26.57	L ## C ## D 15	
	Stress dependent E_3	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
	Stress dependent E_4	Axysimmetric	100	20	3	10	0	inf	90	26.57	L ## C 20 D 3	
Preliminary configuration Problem	Abaqus Validation	Axysimmetric	20	4	1.2	2	0	-0.5	24.5	24.5	L 20 C 4 D 1	
												*m

Name	No. of Cycles	Material	E	nu	C	Phi	Psi	Gamma	K0	Drainage	
L 20 C2 D 1	m or 4	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m or 4	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C6 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C2 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C2 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C2 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C2 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C2 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C2 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 10 C2 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 10 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 40 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 40 C2 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 40 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 40 C8 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L ## C 20 D 3	m or 2	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L 20 C4 D 1	m or 2	Drained Sand	10.6	0.33	5.9	32.6	2	17	0.46	Always Drained	
L ## C10 D 3	m or 2	Drained Sand	10.6	0.33	5.9	32.6	2	17	0.46	Always Drained	
L 20 C4 D 1	m or 2	Drained Sand	10.6	0.33	0	32.6	2	17	0.46	Always Drained	
L 20 C4 D 1	m or 2	Indrained Cla	4	0.33	20	0	2	17	0.46	rained/Undrained	
L 20 C4 D 1	m or 2	Indrained Cla	8	0.33	20	0	2	17	0.46	rained/Undrained	
L 20 C4 D 1	m or 2	Indrained Cla	40	0.33	200	0	2	17	0.46	rained/Undrained	
L 20 C4 D 1	m or 2	Indrained Cla	80	0.33	200	0	2	17	0.46	rained/Undrained	
L 20 C4 D 1	m or 2	Indrained Cla	4	0.33	20	0	2	17	0.46	rained/Undrained	
L 20 C4 D 1	m or 2	Indrained Cla	8	0.33	20	0	2	17	0.46	rained/Undrained	
L 20 C4 D 1	m or 2	Indrained Cla	40	0.33	200	0	2	17	0.46	rained/Undrained	
L 20 C4 D 1	m or 2	Indrained Cla	80	0.33	200	0	2	17	0.46	rained/Undrained	
L 20 C4 D 1	m	Drained Sand	30	0.25	2	36	7.5	18	0.41	Always Drained	
L ## C20 D 3	m or 2	Drained Sand	10.6	0.33	0	35	2	17	0.46	Always Drained	
L ## C20 D 3	m or 2	Drained Sand	10.6	0.33	5	35	2	17	0.46	Always Drained	
L ## C20 D 3	m or 2	Drained Sand	10.6	0.33	0	45	2	17	0.46	Always Drained	
L ## C20 D 3	m or 2	Drained Sand	10.6	0.33	5	45	2	17	0.46	Always Drained	
L ## C20 D 3	m or 2	Indrained Cla	10.6	0.33	50	0	2	17	0.46	rained/Undrained	
L ## C20 D 3	m or 2	Indrained Cla	10.6	0.33	100	0	2	17	0.46	rained/Undrained	
L ## C20 D 3	m or 2	Indrained Cla	10.6	0.33	10	20	2	17	0.46	rained/Undrained	
L ## C20 D 3	m or 2	Indrained Cla	10.6	0.33	20	20	2	17	0.46	rained/Undrained	
L ## C20 D 3	m or 2	Indrained Cla	10.6	0.33	10	25	2	17	0.46	rained/Undrained	
L ## C20 D 3	m or 2	Indrained Cla	10.6	0.33	20	25	2	17	0.46	rained/Undrained	
L ## C40 D 3	m or 2	Drained Sand	10.6	0.33	0	35	2	17	0.46	Always Drained	
L ## C ## D 15	m or 2	Drained Sand	10.6	0.33	5	35	2	17	0.46	Always Drained	
L ## C20 D 3	m or 2	Drained Sand	10.6	0.33	0	45	2	17	0.46	Always Drained	
L ## C20 D 3	m or 2	Drained Sand	10.6	0.33	5	45	2	17	0.46	Always Drained	
L 20 C4 D 1	m or 7	Drained Sand	10.6	0.33	5	37	2	17	0.41	Always Drained	
	***m = monotonic**										

Appendix WP3 UPHS - Membrane design

1. Project details

Project title	WP 3 UPHS - Membrane design
Lead	Aquaenergy
Project partners	AquaEnergy, AquaNamic, Solmax

2. Summary WP

In regard to the bag or membrane, WP3 investigates the inter-relationship of bag design parameters, system performance, requirements for the bag material, and the results of the experiments that were conducted. During the 20m x 20m field trial, the bag suffered a rupture. Leading up to the rupture, the overburden displayed cracks and also a rearrangement of overburden material resulting in a thinning of the overburden at the central region of the bag. It is now better appreciated that the bag can experience loading that is unbalanced, nonuniform from location to location within the bag, and varying over the course of repeated filling/emptying cycles. The bag material that was used was polypropylene geomembrane, 2mm thick, without reinforcement layer, having high flexibility but not an especially large yield stress Suggestions for improvements and future work are presented.

3. WP objectives

Based on the simulation studies (WP2) different membrane types and shapes of a specific membrane design should be proposed. One or more down-scaled membranes should be made for test in a special designed Wear-out test-rig (app. 20 x 20 meters with a lifting height of app. 1 m).

Solmax, AquaNamic, AquaEnergy, AU and TI (participating via “Boble-project” in 2020) will have to work together to analyse, develop and test the special design, including selection of material, thickness, form and type of welding. The dynamic behaviour of the membrane and the load on the membrane will be made available by AU.

Cross functional Workshops will be arranged to support the relevant knowledge sharing.

Before making the actual membrane(s) for the wear-out test-rig, a sub-set of special tests should be specified and conducted with respect to identified fault mechanisms; i.e. stretch test, grinding tests.

When the design of the membrane has been narrowed down to some potential “die hard candidates” for the wear-out test, Solmax will manufacture test samples to be used in the wear-out test-rig.

During wear-out test, it would be expected that participants in the WP would be present on site on a regular basis to evaluate the test results and inspection of the membrane.

4. WP implementation (resume of key activities and observations.

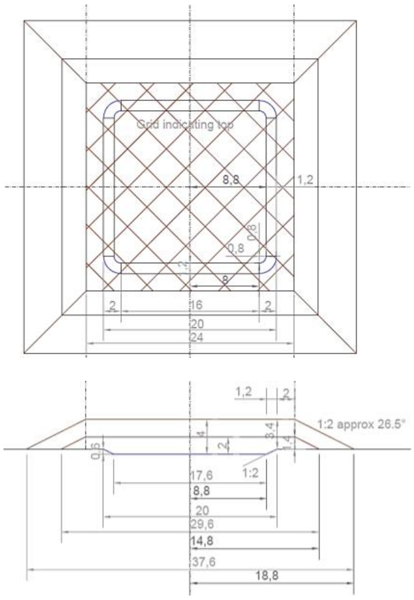
In preparation for and in support of the design of the 20m x 20m field trial, several preliminary smaller-scale tests were performed as described in WP4. These tests included: mechanical testing of membrane materials at SOLMAX and at DTI (Danish Technical Institute); indoor testing of smaller bags with sand at Skejby; and centrifuge testing at the University of Nottingham.

For the 20m x 20m field trial, details of construction and the test sequence are provided in WP4. Selected details of design and construction are discussed here, and are shown in Fig. A3.1, because of their relevance to the performance and integrity of the bag.

The bag was constructed having overall dimensions of about 20m x 20m, having a shape (when viewed from above) that was a square with rounded corners. The bag rested on a substrate that is a dish-shaped excavation having a flat bottom and a sloped portion near the edges. The design lift height was about 1.2m, with 0.6m of that being the excavated dish shape of the substrate and the other 0.6m being distance that the bag could fill above the top of the substrate.

The bag was constructed having a bag upper layer and a bag lower layer joined to each other at the midplane of the bag. The two layers had essentially the same dimensions as each other so that when the bag was completely empty, the two layers overlay each other. The bag lower layer rested on the substrate as a stationary rigid support. The bag upper layer was movable and flexible in order to raise and lower the overburden. The sloping sides of the substrate had a slope of 2:1 or approximately 26 degrees with respect to horizontal. As a result, when the actual length of the material of the bag upper layer is compared to the bag width dimension of the bag as viewed from above, there was about 4% slack (extra length) in the bag upper layer, resulting from the shape and dimensions of the substrate. Because of this slack, there are portions of the operating scenario (especially around 50% fill volume) in which the shape of the bag upper layer cannot be predicted deterministically from fundamental physical principles. The bag interior was in fluid communication with external equipment through one fill/drain pipe connection, which was installed within the substrate underneath the bag and penetrated through the bag lower layer at the geometric center of the bag.

In a first stage of the experimental sequence, 2m overburden was placed on top of the bag and the overburden was plowed flat when the bag was empty (a condition that is referred to in WP4 as flat-shaped). This 2m of overburden directly in contact with the bag was locally excavated sand. In a second stage of the experimental sequence, another 2m of overburden, again composed of sand, was added on top of the first amount of overburden, resulting in a total overburden thickness of 4m. The second increment of overburden was piled higher than the surrounding terrain, resulting in a top surface that is referred to in WP4 as hill-shaped. The sand is used because it is free of large possibly damaging objects that might be present in ordinary soil, and also it is believed that the sand near the bag upper layer is more flowable than ordinary soil. Between the sand and the membrane, the membrane was protected by geotextile.



On the left is the completed bag, not yet covered with any overburden. (Colored lines are added to highlight the edges of the sloped region of the substrate.) On the right, a portion of the discharge reservoir is visible.

Upper: Plan (top) view
Lower: sectional view

Fig. A3.1 (left)

Fig. A3.1 (right)

Bag material and construction

The bag was made of commercially available membrane material manufactured by Solmax. This material is widely used for containment liners and other large-scale applications. This material is polypropylene also containing a small amount of polyethylene. The material is purely polymer and does not contain any reinforcing layer or fiber. Its thickness as manufactured is 2 mm.

At 20°C, the material has a Yield stress or tensile stress of about 5 MPa and an Ultimate Tensile Strength of > 15 MPa. The material is quite flexible such that a sample that is pulled in uniaxial tension elongates by a factor of almost 10 up to the point of breakage, while thinning to about one-third or one-quarter of its original thickness. The material has a Ductile-Brittle Transition Temperature of about -40C.

Because the bag was larger than pieces of the material as manufactured, it was necessary to perform welds. In order to better simulate an eventual bag that would be even larger, material from rolls was cut into smaller pieces than necessary, and then was joined by welds. All joints between pieces of material were made at the construction site and were made by thermal welding. The welding procedures are double hot wedge welding as regular procedure, and extrusion welding for connection to structures (inlet) and in other detailed areas where hot wedge welding is not possible. The welds joining the bag upper layer and bag lower layer were performed using hot wedge welding achieving a so-called inverse weld.

Loading on the bag

In order to justify the design of the bag and understand the experimental results, it is necessary to understand the loads and reactions of loads experienced by the bag. In general, the pressure of liquid inside the bag is created mostly by the overburden that is positioned on top of the bag. However, in more detail, liquid pressure inside the bag also includes a contribution due to the hydrostatic pressure of the water itself. The local hydrostatic pressure of the water itself varies as a function of the elevation of any given location inside the bag. Also, in the experiment, it is likely that the thickness of the overburden varied among different places in the bag both because of details of initial construction and because of overburden rearrangement that occurred over the course of the experimental sequence. Because of these two variations and maybe other factors, it is likely that liquid pressure inside the bag might not be perfectly reacted by the overburden at every location and at every time. Whatever local load or pressure is not perfectly reacted by the overburden is a load that must be reacted by the bag upper layer itself, through a combination of local tension in the bag material and the local shape of the bag.

Fig. A3.2 (top) illustrates the pressure distribution in various places within the overburden and inside the bag itself, for an overburden that has a constant thickness. This illustration does not take credit for frictional restraint provided by the overburden. The overburden has frictional properties that might help to resist or react certain loads exerted by the bag in certain directions. Such frictional phenomena are believed to be important, but they are likely to be dependent on local overburden properties and on boundary conditions. Frictional properties of overburden are included in the modeling performed in WP2, and will be further analyzed in the future.

Fig. A3.2 (middle) is a simplified illustration that describes a membrane that contains hydrostatic pressure inside it, having no overburden. This situation is similar to a conventional pillow tank, such as is used for temporary storage of fuel or other liquids, with an important feature of a pillow tank being that it is not covered with overburden. The illustration shows such a container separated into two imaginary halves, with the horizontally-acting force due to internal pressure urging the two halves to separate from each other. In the absence of frictional overburden, what prevents such separation is tension in the membrane. It is believed that the tensile stress in the bag or membrane, resulting from unreacted hydrostatic pressure inside the bag, increases (faster than linearly) with the height of the bag, i.e., lift distance. This simple illustration lacks overburden and so it does not take into account frictional properties of the overburden, which might react some of that horizontal separating force. In the presence of frictional overburden, some of the horizontal force would be reacted by the overburden, but whatever such force is not fully reacted by the overburden would have to be carried by the membrane material in tension. The presence of cracks in the central region of the overburden, as observed during the experiments reported here, illustrates the overburden not fully resisting these horizontal outward forces.

It can be noted that at certain filling fractions, especially in the range of 50% full, the exact shape of the bag upper layer (in view of the slack that is present) is indeterminate and cannot be predicted from fundamental physical principles. It can also be noted that there is potentially an instability inherent in this situation. The existence of a lower density fluid underneath a larger density fluid could create the classic physical situation known as the Rayleigh instability, which encourages the lesser density fluid to locally rise upward into the region of the greater density fluid. In this report, an interface that is generally smooth without exhibiting this instability is described as a balloon shaped interface. An interface that does exhibit this instability, such as by a localized upward bubble or deformation of the membrane, is described as a bell-shaped interface as illustrated in Fig. 1 of WP5. Probably the most important factor acting to control or prevent this instability is the frictional behavior of the overburden material.

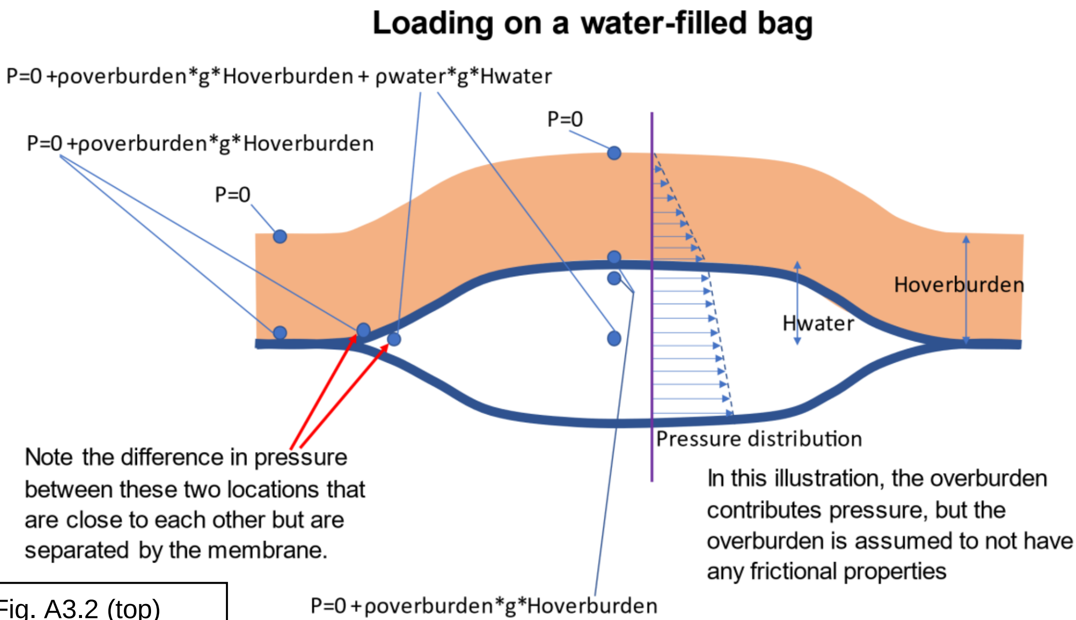


Fig. A3.2 (top)

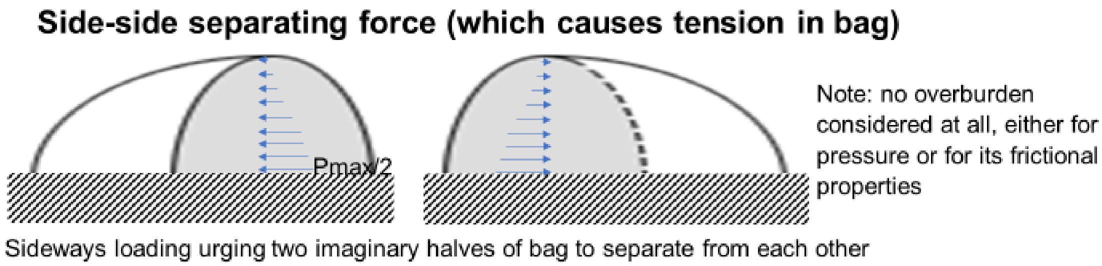


Fig. A3.2 (middle)

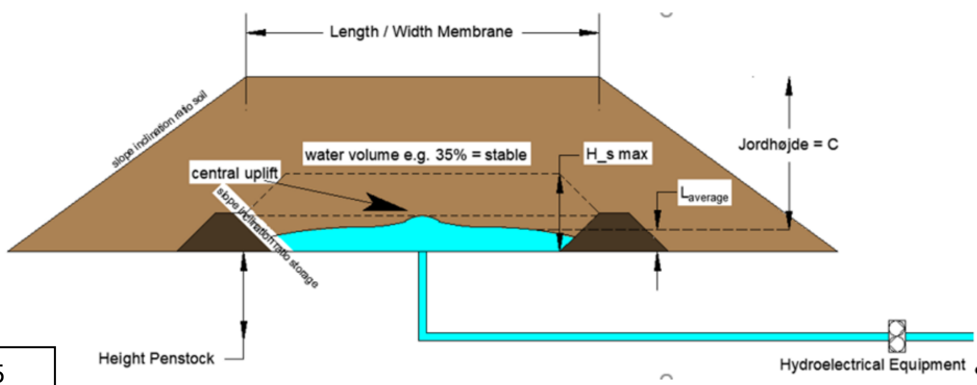


Fig. 1 of WP5

Figure containing the key measures of a "standard" one unit membrane system. Key annotation of the different measures has been indicated. Also, we see the indication of the ***potential*** *limitation of the lifting height.*

5. WP results (resume and discussion of results).

- *Describe the **obtained technological analysis and key results**. Did the project produce results not expected?*

The most important test result was that in the 20m x 20m field trial, the system suffered a rupture of the bag, after having operated at partial capacity and conditions for a number of cycles. The rupture occurred in the central region of the bag upper layer. Another important and probably related observation is that during this test series, there was re-arrangement of the overburden. Most visibly, cracks formed and grew in the surface of the 4m thick overburden. Also, there was measurable migration of overburden outward from the central region, which caused a reduction of the thickness of the overburden in the central region. Thus, it is possible that the cracks in the overburden, and the overburden migration, may have interacted with the bag in a way that contributed to the rupture.

Cracks in the overburden

Cracks in the overburden are documented in WP4, such as Fig. A4.7 in WP4. Nevertheless, selected observations can be pointed out here. Cracks in the overburden grew as time and the number of cycles progressed, and became worse at 70% filling of the bag compared to 35% filling of the bag. The bag rupture occurred when the overburden thickness was 4m. The depth of cracks is believed to be as much as 2-3 m extending into the 4m overburden thickness from the overburden surface toward the bag. The bag rupture occurred at 70% filling of the bag, which was the largest filling that was performed up until that time.

The cracks observed in the overburden were of two types:

- Peripheral cracks. These cracks followed a path around the periphery of the rounded-square shape of the bag. There were a series of peripheral cracks that were generally parallel to each other. It is thought that that the peripheral cracks are located near or approximately above the sloping portion of the substrate. Photographs show the same general shape pattern for the cracks and for the sloped portion of the substrate, although the exact the geometric relation has not been determined.
- Generally straight cracks extending generally along the two diagonals of the rounded-square bag shape. The two straight diagonal cracks intersect approximately perpendicularly to form an “X” pattern. The location of the intersection of the two diagonal cracks was approximately above the location of the rupture of the bag.

During the filling cycles to 35% of full volume, peripheral cracks did form, but the center-crossing diagonal cracks did not form. It can be noted that filling to only 35% of full volume would only involve the bag upper layer remaining dipped down into the substrate region. Thus, the overburden directly above the bag central region would not bulge above the bag midplane, but in this situation the overburden surface nevertheless bulges slightly upward in a convex shape. During the 70% filling cycles, peripheral cracks continued to grow, and also center-crossing diagonal cracks formed. It can be noted that filling to 70% of full volume both involves the bag upper layer bulging upward above the midplane and involves the overburden surface bulging more prominently in a convex shape. From visual observation, cracks observed in the overburden are estimated as being possibly as much as 2-3m deep out of the 4 m overburden thickness. When the bag ruptured, the bag had 4m of overburden on top of it (which was the full design amount of overburden) and was at or near 70% fill volume. In accordance with this planned test sequence, at the time the bag ruptured, the bag had never yet been filled beyond 70% of design volume.

Migration of overburden, in a radially outward direction, and thinning of overburden in the central region, are discussed in more detail in WP2 and WP4.

Fig. A3.3 a, b, c

(Upper Left) Overburden several days before the rupture, showing peripheral cracks in the overburden. (Photo taken by photographer at ground level) (Lower Left) Completed bag prior to overburden being placed on top of it, in which the completed bag follows the contour of the substrate including its sloped portion near its edge. (Photo taken by aerial drone) Note possible similarity of peripheral crack geometry and geometry of slanted portion of substrate. (Upper right) Close-up photo similar to Upper Left photo, taken by photographer at ground level. The cracks shown in Upper Left photo and Upper Right photo are peripheral cracks, and both of these photos were taken several days before the rupture.

Fig. A4.7 in WP4

Aerial photo showing periph-eral cracks and diagonal cracks.

Fig. A3.3 d

Photo taken the day before the bag rupture. In this photo, the orientation of sunlight and shadows is such as to make the overburden cracks (both peripheral cracks and straight-line diagonal cracks) especially visible. In this photo the bag was empty, as indicated by the fact that the water level is nearly full in the discharge reservoir in the rear of the photo.

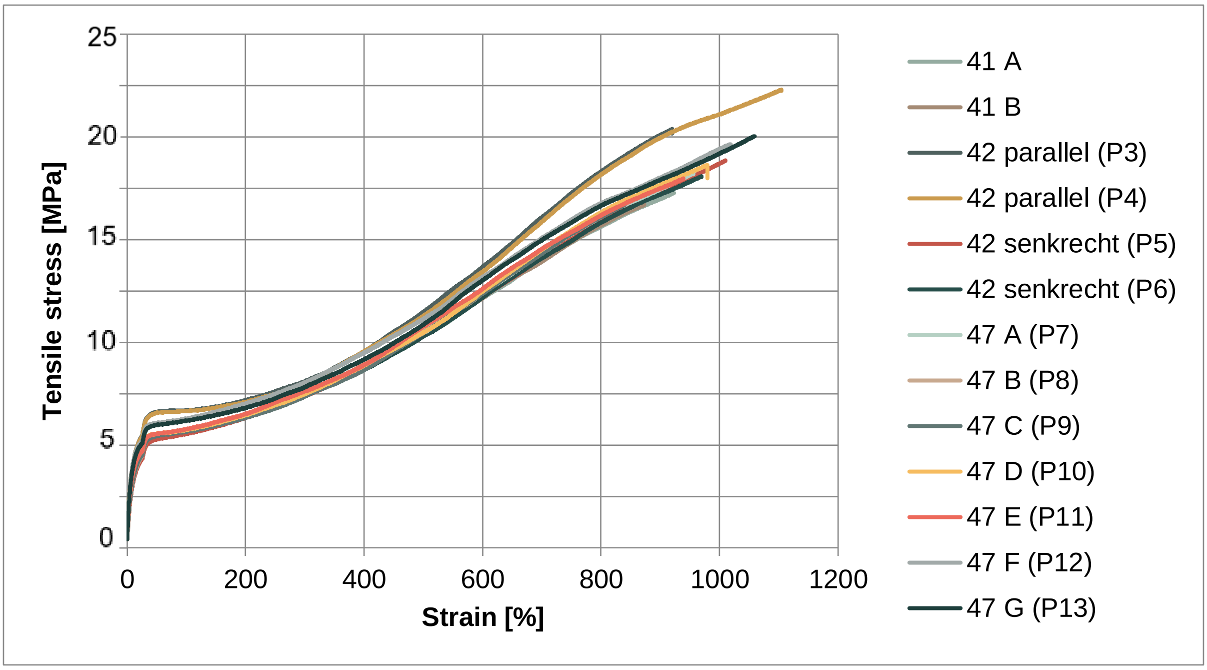
Rupture of the bag and results of examination of the bag near the rupture

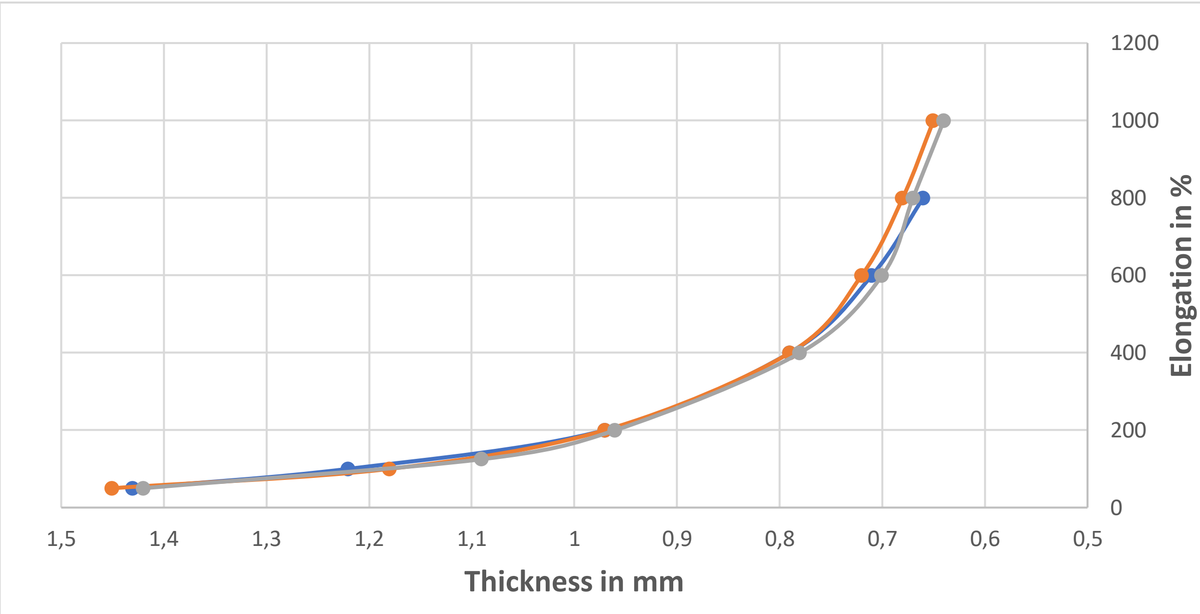
As already described, the rupture occurred at 70% fill volume with 4m overburden during the 18th cycle at that condition. Photographic documentation of the rupture is provided in WP4. It was found that the rupture occurred near the center of the bag upper layer in the form of a long straight rupture (3m long) and a shorter rupture (1.7m long) that intersected the long rupture approximately perpendicular to the long rupture. There also was a smaller tear, having a length of around 30-40 cm, going off from the shorter of the two ruptures. The two longer tears were generally aligned with the sides of the square shape of the bag, rather than being aligned with the diagonal cracks. It is believed that the intersection point of the ruptures was approximately below the intersection point of the diagonal cracks in the overburden.

For investigation purposes, after the rupture and after the removal of the overburden, portions of the bag were cut from the rest of the bag and were taken to a laboratory for analysis. The remaining thickness of the bag material was measured especially along the rupture but also at other places where bag material was intact. Places far from the rupture generally continued to have the initial material thickness of 2 mm. In various places near the rupture, the bag material had thinned out to smaller values. The smallest measured remaining bag thickness was about 0,5 mm in the ruptured zone. So, at the thinnest location, the remaining bag thickness was only one-quarter of the original as-manufactured bag thickness. This suggests that a substantial amount of stretching of the bag material occurred before the final rupture. The thinning measured next to the ruptured zone indicates that stretching of the bag material had occurred before the final rupture. In those areas thicknesses measured were mainly between 1,5 to 2,0 mm. Further detail is given in WP4. This amount of stretching suggests that the rupture was not due to brittle failure of the bag material. Also supporting this conclusion is the fact that the ductile-brittle transition temperature of the material is -40C, which is far lower than any temperature that the bag could have experienced during operation. Although the material had thinned in various places, the thinning was greatest near the intersection of the two main tears. This probably indicates that the stresses were greatest at that location, i.e., near the center of the bag.

In regard to the bag material, Fig. A3.4 (top) is a plot of uniaxial tensile test results of the bag material for various different specimens. The numbering of the specimens indicates the area of the sample from which the specimens were taken. All specimens were taken in the extrusion direction of the geomembrane, except samples 42 P5 and P6. The strength in technical direction is higher due to the alignment of the long chain polymers. In Fig. A3.4 (top), the vertical axis is plotted as tensile stress in units of MPa, based on the original dimensions of the material. The material has a yield stress or tensile stress of about 5 MPa and an Ultimate Tensile Strength of about 15-17 MPa.

Fig. A3.4 (bottom) is a plot of the thickness of the material (which was 2mm thick before any stretching) as a function of elongation. On this graph, the curves are for as-manufactured material that was stretched all the way to failure. The fact that all of the curves closely overlie each other suggests good consistency about the mechanical behavior of the material.





Figs. A3.4 (top and bottom)

Possible failure mechanisms and explanations

The fact that the rupture occurred after 18 identical filling/emptying cycles suggests that the failure was not due to a single instance of an initial overstress situation but more likely was due to a progressive process of some sort, quite possibly related to the overburden cracking and overburden rearrangement.

It is thought that, first of all, the likelihood or severity of overburden cracking might be related to or might described by a dimensionless ratio, namely the lift distance divided by the overburden thickness. For example, cracking occurred 70% of the nominal lift distance of 1.2m with a 4m overburden thickness, which is a ratio of 0.3. Overburden cracking did not occur, or was less severe, for smaller values of that ratio. Even if there were no further analysis or design changes, it is thought that a guideline based on this ratio could be used for future design.

With reference now to loading on the bag as illustrated earlier in Fig. A3.2 (top), in regard to reaction forces in the vertical direction, it is possible that, over the course of repeated cycles, outward migration of overburden occurs, lessening the reaction provided by the overburden near the center, thereby requiring the bag in that central region to react more of the pressure because the overburden was reacting less of the pressure-generated vertical force. This could encourage creation of a sort of upward-bulging bubble in the bag upper layer. It can be noted that water is less dense than the overburden. Even though the water is confined by the bag, there is still some ability of the bag and water to deform. Also the overburden, even though it is an aggregate of solid particles, has some ability to flow or behave as a fluid. Thus, there is the possibility of localized upward deformation or instability referred to here as a ”bell-shaped” deformation. It is possible that thinning of the overburden in the central region lessens the ability of the overburden to provide vertical reaction to the pressure inside the bag, requiring the bag itself to react that vertical force.

In regard to reaction forces in the horizontal direction, it is possible that, over the course of repeated cycles, cracking of the overburden reduces the ability of overburden to provide horizontal reaction to the type of forces illustrated in Fig. A3.2, requiring the bag itself to bear unreacted horizontal forces. The shape of the overburden surface, when the bag was filled as much as it was filled during the experiments, can be visually estimated to resemble an arc or dome. Thus the overburden surface when the bag is full is not flat-topped, nor is it elliptical, nor is it the exact opposite of the shape of the substrate (which is a flat-bottomed trapezoidal shape). It can be noted that the original placement of the overburden resulted in an overburden thickness that had some slope outside the bag, because of the hill-shaped contour of the 4m thick overburden. The 4m overburden thickness started out with a hill even when the bag was empty and became a more prominent hill or ”dome” at conditions of the maximum filling that was performed. It is speculated that the slope of the dome might have resulted in some rearrangement of overburden during successive cycles, i.e., motion of overburden away from the center of the bag toward the periphery. This could be due to gravity or as a result of local overburden deformation such as cracking caused by the bag motion, assisted by gravity. Future design guidance should include the soil characteristics such as internal friction properties, density/ compaction, and possible stabilisation features.

It can be noted that there are two phenomena, possibly interrelating with each other, that might have contributed to the rupture. In general, it is possible that in a local region the fluid pressure inside the bag might be less than perfectly reacted by the overburden. This could happen from construction nonuniformities, but more importantly it could happen if there are cracks in the overburden above that local region. Furthermore, the bag upper layer contains a slight amount (4%) of excess length of material (compared to the side-to-side dimension of the bag when viewed from above). This excess material may be available for the formation of ”bubbles.” It is believed that a factor which may resist the development of such instabilities is the frictional nature of the overburden itself. If a crack develops in the overburden, that crack may have two detrimental effects: it may lessen the amount of reaction that the local overburden offers against fluid pressure inside the bag, which may encourage formation of a local bulge or bubble in the bag; and if such a bulge occurs, the fractured overburden (especially near the intersection of the two diagonal cracks) may offer less frictional resistance to growth of such a bubble or instability or to the horizontally outward migration of overburden.

Another relevant phenomenon is that (with reference to a bag that is split into two imaginary halves by a vertical plane passing through the center of the bag) it is possible that the water inside the bag creates an outward-spreading force that essentially urges one half of the bag to spread sideways away from the other half of the bag, as illustrated in Fig. A3.2 (middle). This would create tensile stress at, among other places, the top center of the bag upper layer. A reaction against such sideways spreading force is provided by the frictional behaviour of the overburden, but the ability of the overburden to provide such restraint might be compromised by the peripheral cracks in the overburden. This in turn might increase the tensile forces having to be carried by the bag upper layer near its center (which is where the rupture occurred).

Therefore, it is possible that both the diagonal intersecting cracks and the peripheral cracks may have contributed to the bag rupture, in different ways. It is therefore desirable to reduce or prevent any form of overburden cracking behavior.

In regard to other possible contributors to the rupture, it also can be noted that near the location of the rupture, above the bag upper layer and separated from the bag upper layer by some of the overburden, there was a circular plate (diameter 40cm) with an upward-pointing pole attached to it. This structure was provided for purposes of locational measurement and visualization. It is believed that the circular plate was not the primary cause of the rupture in the bag but it might have contributed to the failure. In the future, some other arrangement will be used for measuring locations.

It is thought that the number of cycles executed during this experimental series was not large enough to produce enough abrasion of the bag material for abrasion to be the primary cause of the rupture. It also is thought that the number of cycles executed during this experimental series was not large enough for fatigue of the bag material to be a primary cause of the failure.

It can be noted that the rupture occurred in a piece of as-manufactured material, not at a joint between segments of the material.

In regard to still other possible contributors to the failure, it also can be noted that the rupture of the bag occurred during unusually cold weather when there was a slight presence of snow or frost on the ground, shortly before dawn. Accordingly, investigation was performed of the mechanical properties of the bag material at such temperature. However, the laboratory test results of the bag material show that even these temperatures were substantially above the ductile-brittle transition temperature of the bag material, and the material is still ductile even at -50C. It is not known if a freezing phenomenon within the overburden could have affected the deformation properties of the overburden. Taking all factors into consideration, it is believed that the cold temperatures, by themselves, probably were not a major cause of the rupture of the bag.

In regard to places in the bag other than near the rupture location, it is also possible to draw some inferences from measurements of the bag material thickness at such places. Primarily this information is about folds in places near the edge of the bag. It is difficult or impossible to predict or make calculations about the folding behaviour. It was found by measurement that there was some thinning of the bag material near some of the folds, which is believed to be due to the bending that was experienced by the bag. It is not known if this thinning is due to stretching or to abrasion, but it is believed that stretching is the more likely explanation because the number of potentially abrasion-producing cycles executed during this experimental series was fairly small.

6. WP conclusion and perspective (Conclusion of the membrane design

- *State the conclusions made in the project.(Outline our best conclusion on a MEMBRANE design)*
- ***<u>What are the next steps for the developed technology?</u>*** *(This is what we can use for the NEXT application (if we are lucky)*
-

There are several improvements in the design of the system that will be considered.

First of all, the design should reduce the amount of local motion or stress within the overburden, or should provide better distribution of the motion or stress that does occur. In view of the possible relationship between overburden cracking and overburden motion and abnormal loads on the bag, it is worthwhile to try to minimize both kinds of cracking that occurred, i.e., peripheral cracks and straight diagonal cracks.

In the 20m x 20m field trial reported here, the base of the membrane was 2-3.5 m below ground level. So with 2m overburden, lateral support was provided fully and robust reaction of horizontally outward forces by an immovable structure (the original undisturbed earth) was provided up to the midplane of the bag. When the overburden was built up to 4m, some of the uppermost 2m of overburden was in the form of a hill shape that did not offer robust support against outward horizontal motion of the overburden. One thought process for preventing rupture in the future is to provide, at locations higher than the midplane of the bag, better reaction against forces that try to expand the bag in the radially outward direction or cause overburden to move radially outward from its original location. It is possible to envision that the overburden be surrounded by a berm that is fairly immovable, i.e., solid or rigid compared to the deformable overburden, and the berm could extend even as high as the maximum height of the bag when full. This is shown in Fig. 1 of WP5 represented by the dark brown trapezoidal shape. The berm could be constructed to be more solid and immovable than the overburden itself.

It is also possible that stability of the overburden can be improved with a reinforcement such as a geogrid on top of the geomembrane or buried within the overburden. Perhaps such reinforcement could be placed at locations that experience relatively greater amounts of motion and change of shape. Another possible type of reinforcement is a hoop or ring buried within the overburden, centered above the center of the bag. Similarly, it would be possible to provide more than one hoop or ring arranged concentrically with respect to each other. Such a restraint would limit radially outward motion of overburden. The use of reinforcement in a future test should be considered, but details have not been analyzed or designed. It can be appreciated that it is only possible to manage deformation and overburden motion and hopefully keep them within desired limits in desired places, but some motion and deformation will always occur, because the nature of the UPHS system requires some motion and deformation.

There is also an observation in the current set of experiments that the presence or absence of over-burden cracking had some correlation with the dimensionless ratio of lift distance to the side-to-side dimension of the bag. Cracking generally did not occur if this ratio was less than 0,3, and cracking did occur for larger values of this ratio. Future designs and operating scenarios can take this ratio into consideration.

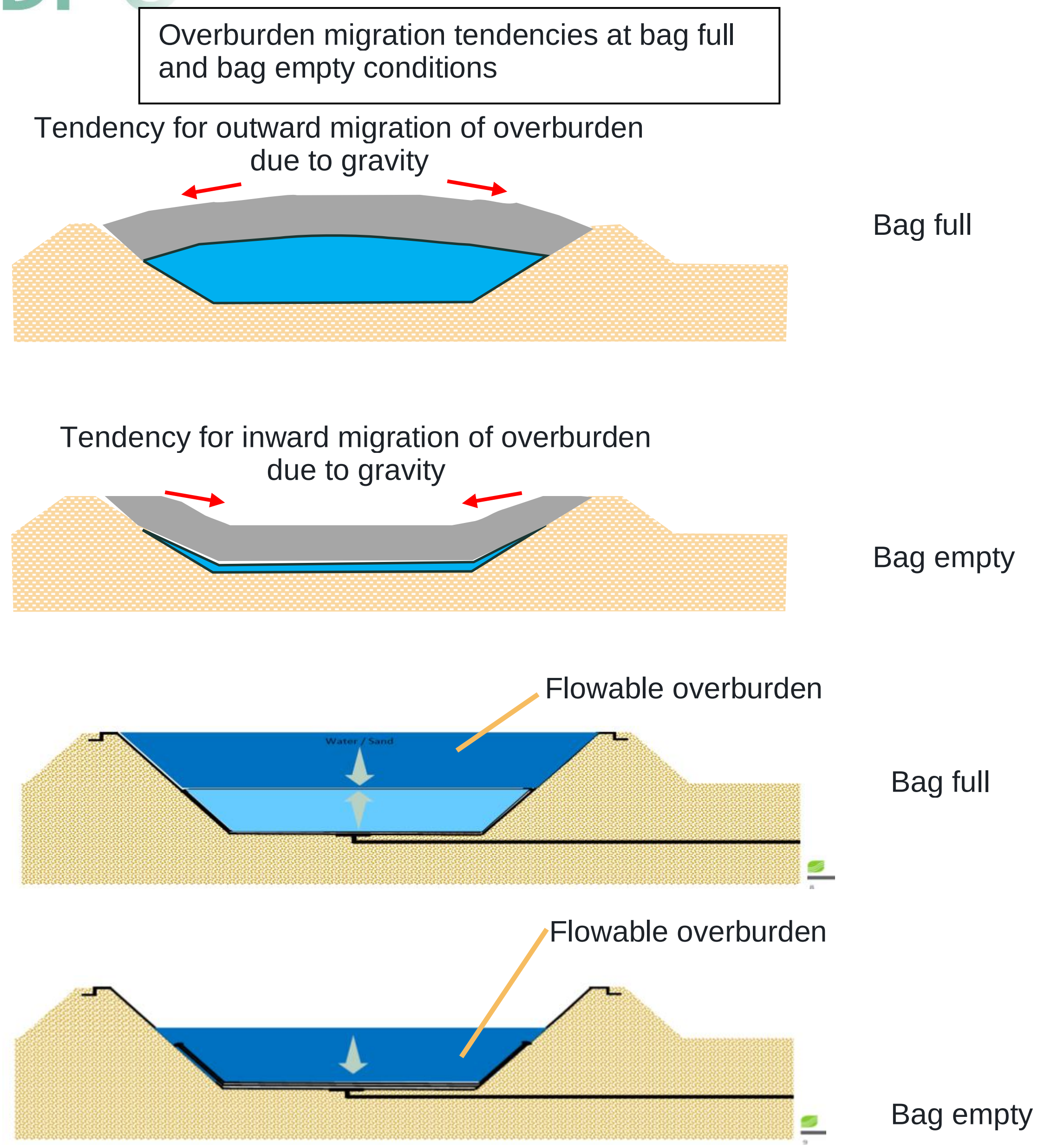
It is believed that the peripheral cracks that occurred in the overburden occurred approximately above the sloped region of the substrate. As constructed in the 20m x 20m field trial reported here, the sloped portion of the substrate had a slope of 2:1 or approximately 26 degrees relative to horizontal. During uplift (filling of the bag), it seems that the overburden surface takes a shape that is unrelated to the shape of the substrate and rather is determined by various other forces and is approximately a dome of somewhat uniform curvature. However, during settling (emptying of the bag), the bag upper layer and the overburden can be expected to settle into a shape that does closely follow the substrate shape. It could be considered that the slope of the slanted portion of the substrate could be made more gentle, and that a more gentle slope might result in less severe peripheral cracking of the overburden. Although the peripheral overburden cracks were not where the bag rupture occurred, it is still possible that peripheral cracking contributed to the rupture by creating voids that encouraged outward migration of overburden, and so reduction of peripheral cracking could have some benefit to the central part of the bag (where the rupture did occur) by providing more consistent frictional behavior of the overburden and by helping to prevent outward migration of overburden. Also, in regard to a phenomenon occurring specifically near the periphery of the bag (which is not where the rupture occurred), it is expected that a flatter inclination of the substrate would also help to protect against folding and accumulation of the geomembrane. Associated with such a design change, there would be some decrease in the volume of water contained by the bag, but the benefit would be improvement in the control of motion of the overburden. In general, future designs could put some effort into edge design details that reduce potential risk of critical folding and membrane stretching.

In regard to horizontally outward migration of overburden, the construction of the 20m x 20m field trial was such that the top surface of the overburden had an upwardly convex shape most of the time. In regard to bag empty conditions, the overburden surface was truly flat and level with adjacent soil, in the bag empty condition with 2m overburden thickness. Also, at the bag empty condition with 4m overburden thickness, the overburden surface was flat but the flatness of the overburden extended only a little bit beyond the bag, and further out than that the pile of overburden tapered down to the ground so that it offered imperfect restraint against outward motion. In regard to conditions in which the bag contained water, in both the 2m and 4m overburden thicknesses, any time the bag was filled to any extent, the overburden surface would bulge upward convexly. The upward bulge created a slope that would tend to cause overburden material to slide away from the central region due to gravity. It can be estimated, from geometry and from photography, that the slope could be as much as 5 to 10 degrees, for a simple convex bulge that is referred to as a balloon shape. Therefore, in all situations there was either some actual tendency, or at best zero tendency, for the overburden material to migrate outward away from the bag center, in response to gravity. It is further possible that the repeated motion or disturbance of the overburden due to bag filling/emptying could have made the overburden more mobile than it would be in a completely static situation, so that overburden would be more likely to slide in the outward direction that gravity incentivized. In the experiment as constructed, the incentivized direction for such motion was always outward or at best there was zero incentive.

In a more general sense, it can be realized that the incentivized direction of migration of overburden does not have to be always-outward, because there are a variety of shapes in which the overburden surface could be constructed. Given appropriate shape, it should be possible to provide an overburden surface that has a tendency for outward migration at certain conditions and a tendency for inward migration at other conditions. Furthermore, it is possible that these two tendencies could be arranged to approximately balance each other out so as to result in approximately zero overall migration over an extended period of operation. For example, the overburden surface could be such that when the bag is empty, the overburden surface is concave (dished) resulting in an inward migration tendency. The same overburden surface could be such that when the bag is full, the overburden surface is convex (bulged), resulting in an outward migration tendency that is weaker than what was observed in the current experiments. If the expected time duration at the bag empty condition approximately equaled the expected time duration at the bag full condition, then the geometry could be selected such that the height of the bulge at the bag full condition approximately equals the depth of the dish at the bag empty condition. For other situations, the bulge dimension and the dish dimension could be adjusted appropriately. So, it should be possible to achieve a situation in which the overburden slides a little bit in one direction during one phase of the cycle followed by a little bit of sliding in the opposite direction during another phase of the cycle, so that on average the overburden motion due to overburden surface slope is significantly smaller than what occurred in the just-completed set of experiments. This is illustrated in Figs. A3.5 a, b.

It is also possible to consider an overburden that behaves more like a fluid than traditional soil does, by virtue of being intentionally wet and perhaps being made primarily of sand. A sufficiently fluid overburden would not suffer from the observed migration of overburden in an outward direction, because the overburden surface would be sufficiently fluid to remain essentially flat at all times. This is illustrated in Figs. A3.5 c, d. Such a fluid overburden would have to be contained by a berm surrounding it. However, in such a situation there might be the possibility of a Rayleigh instability affecting the bag-overburden interface, as is illustrated in Fig. 1 of WP5.

If there are multiple bag modules as proposed in WP5, it is possible that the intact soil outside the construction could serve as a robust restraint against outward horizontal motion of overburden, or the boundary of one module could serve as such a restraint for an adjacent module. This could be influenced by the details of how the various modules are located with respect to each other and how the various modules are sequenced or operated. If the modules are operated approximately similarly and simultaneously, it is more likely that the edge of one module could serve as a suitable boundary condition for the next module. However, for modules that are outermost in a group of modules, there still remains a need to provide a suitable restraint, which might require construction of a berm. Similar to the concept of having individual modules, it might be possible to create a bag that has within it more than one discrete volume that is not in fluid communication with any other discrete volumes of the bag. The individual volumes could be supplied by separate plumbing.



Figs. A3.5 a, b, c, d

As yet another consideration in regard to overall system design, it can be kept in mind that cracking behavior of the overburden is probably indicative of dissipation of energy resulting from the motion of the overburden. In general, the four main contributors to energy loss or inefficiency in the round-trip process of energy storage and recovery are believed to be: pump losses; turbine losses; piping losses; and loss of energy associated with deformation of the overburden. Thus, a reduction in cracking behavior of the overburden would probably also lead to an improvement in round-trip efficiency of the overall system. A certain amount of efficiency loss is inherent in the pump and turbine and associated piping. Piping losses for UPHS are likely to be smaller than for conventional pumped hydro. It also is necessary that the total loss of efficiency from all sources should stay within a certain bound so that the system is economically attractive. These considerations define a tolerable limit on the amount of energy loss due to overburden deformation.

In another aspect of design improvement, a geomembrane with higher strength would beneficial. For future work, it is recommended to use a material with higher strength in order to withstand whatever uneven load distribution does occur. Materials containing fiber reinforcement in the form of an internal layer do provide higher strength of the membrane material compared to the purely polymeric material currently used. However, due to the flexing of the bag involved in the filling and emptying process, the bonding between the reinforcement and polymer is likely to be affected and could deteriorate. In this regard, the region of a weld would become the weakest point and the most critical part. A test should be conducted with a geomembrane that is monolithic, but of a material having a higher initial strength (such as LLDPE (Linear Low Density Polyethylene)), and possibly a greater thickness than was used in the current experiments. As yet another possible feature of a revised geomembrane, it would be possible to provide a geomembrane having a textured upper surface that would provide better frictional interaction between the membrane and the overburden immediately adjacent to it for better stability of the overburden.

Whatever other design changes are implemented, the next design should address some considerations about the water flow while filling the bag in order to create a more even stress distribution. Hydraulic simulations should be included in a further study. Perhaps the openings where the pipe joins the bag should be covered by grates or screens so that the openings have dimensions measured in, at most, centimeters, rather than the currently-existing opening in the form of a large exposed opening of the order of 10 cm in diameter. This could help to protect the bag upper layer whenever the bag upper layer rests directly on the water supply opening. It may be advantageous to split the water connection among several connection points. Even if the connection points all connect to the same interior space inside the bag, there could be separate controls or valves for the various connection points. This could be advantageous both for draining and for filling. In the current operations, the emptying of the bag was done down to an estimated remining volume of 6% of the total design volume, but it is not known how uniformly that volume of remaining water was distributed inside the bag. Maybe in the future we could consider more detail about how close to empty the bag can be drained.

Still other possible considerations could include possibly providing different overburden properties or composition in specific locations; and eliminating possible stress concentrations (such as the disc and the pole that were located close to the rupture location as a landmark for taking position measurements).

7. Appendices related to the WP

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Appendix WP3 - 3.1 UPHS

Relation of bag parameters to system design

It is worthwhile to explain here the relation of bag design parameters to system performance. A summary of this relationship is provided in Fig. A3.A1.

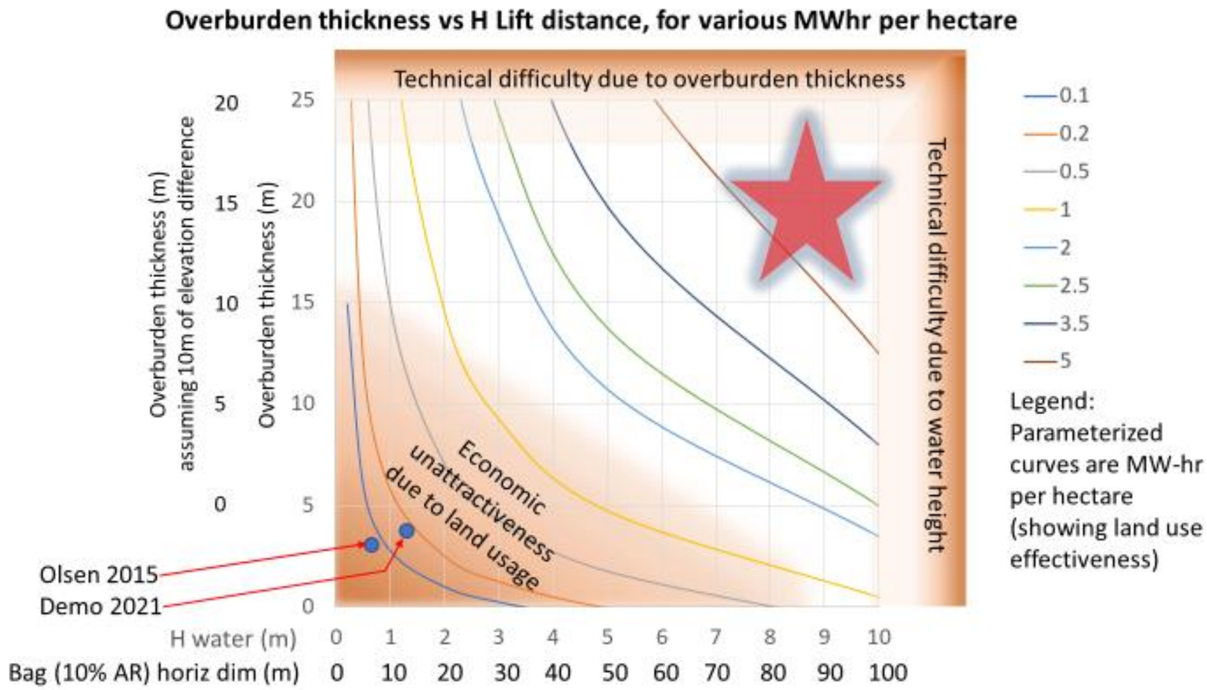


Fig. A3.A1: Relation of bag parameters to system design parameters

In general, in terms of usage of land, UPHS is not as compact as some other competing energy storage technologies. Therefore, it is desirable to keep in mind an ultimate goal of achieving a sufficiently large value of energy storage per unit of land occupied. This same parameter also is closely related to economic considerations. In this discussion and graph, the land that is referred to is the land area used for the water storage reservoir, not considering land that might be occupied by a discharge reservoir.

For the construction of this diagram, it is useful to realize that in physics and thermodynamics, energy is often represented as the product of a parameter representing pressure, multiplied by another parameter representing volume. In UPHS, one important design parameter is the thickness of the overburden. Because the overburden pressurizes the water in the bag, the overburden thickness is a parameter that approximately represents the pressure of the water in the bag. This overburden thickness can be thought of as pressure head expressed in units that are associated with overburden thickness (taking into account the overburden density).

Another important design parameter is the lift distance or the height of the bag when full. The volume of water contained in the bag is approximately proportional to the lift distance. The lift distance can be thought of as representing the volume of the bag per unit of land usage.

Therefore, in the graph presented here, the two main axes are lift distance (horizontal axis) (which is related to volume) and overburden thickness (vertical axis) (which is related to pressure).

In Fig. A3.A1 are plotted parameter curves for various constant values of MW-hr (energy stored) per hectare of land used for storage. It can be seen that these curves are approximately hyperbolas on the graph. The overall result of the calculation is that the energy storage per unit of land usage is well correlated with the product (lift distance)*(overburden thickness). Other variables have a more minor influence. It is believed that for practical and economic purposes and efficient usage of land, a desirable value of MW-hr per hectare is at least approximately 2.5 MW-hr/ha. This is based on very approximate feedback from potential customers. This is the green curve in Fig. A3.A1.

Another design parameter that could have some influence is possible elevation difference between the storage reservoir and the discharge reservoir. UPHS is intended to be used in locations that are not very mountainous, so in Fig. A3.A1 the calculations plotted using the primary axes are performed for equal elevations of storage reservoir and discharge reservoir. However, it would be advantageous to try to select sites, if available, that offer a modest amount of elevation difference, such as 5 to 10 meters. This reduces the overburden thickness needed for comparable performance. Accordingly, in Fig. A3.A1 a secondary vertical axis is also shown assuming an elevation difference of 10m between the storage reservoir and the discharge reservoir. Also, a secondary horizontal axis is shown to indicate that the aspect ratio of the bag (comparing the horizontal dimension to the lift distance) implies a bag horizontal dimension for a given lift height. An aspect ratio of 10% is shown, assuming that to be a reasonable and typical aspect ratio.

In Fig. A3.A1, certain regions of parameter space are shaded to indicate that they are believed to be impractical or less desirable. It is believed that for practical reasons, it is desirable for the lifting distance to be less than approximately 10m, and similarly it is desirable for the overburden thickness to be less than approximately 25m. Also, the lower left region of the graph is shaded as being undesirable due to its undesirably small value of energy storage per unit of land usage.

The light-colored central region of the graph is believed to be desirable for commercial operation. More particularly, the star indicates a possible commercial operating point or range for a commercial installation. Also shown on the graph are the operating point of the Olsen 2015 publication and intended operating point of the 20m x 20m field trial reported herein for the current project. For future stages of development, the goal is to move the operating point further to the right and vertically upward, i.e., larger overburden thickness and larger lift distance as indicated by the star.

An important design parameter is tensile stress in the bag. Literature exists for the somewhat analogous commercial product known as a pillow tank, which is used for temporary storage of liquids while typically not being covered with overburden. For a pillow tank, membrane stress is essentially based on the separating force illustrated in Fig. A3.2 (middle) (neglecting frictional restraint provided by the overburden in the situation of UPHS). It is believed that the tensile stress in the bag, resulting from unreacted hydrostatic pressure inside the bag, increases with the lift distance. For pillow tanks, the increase in this tensile stress is predicted to be faster than linear. It is hoped that in the present UPHS, frictional properties of the overburden provide some reaction force in the horizontal direction to mitigate this effect. The exact relationship between bag stress and other variables is being explored through analytical modeling etc. The expectation of eventually increasing the lift distance and other dimensions of the bag, beyond the values used here for the 20m x 20m field trial, also encourages the development of a stronger bag material.

WP4 UPHS – Scale testing

Participants:	Aarhus University, AquaNamic and Solmax
File no. Lead:	Aarhus University

1. Summary

To characterise the performance of Underground Pumped Hydroelectric Energy Storage (UPHS) systems in sand, WP4 consisted of a physical test campaign, including both 1:40 scale small-scale lab testing (5 m x 5 m), 1:800 scale reduced-scale centrifuge test series, and a 1:10 scale field trial (20 m x 20 m). Tested over-burdens were limited to coarse-grained sand with no reinforcements within it and at its surface. The main outcomes are:

a) a clear indication of the feasibility to construct the system in the field,
b) collected physical measurements of UPHS system energy efficiency
c) field trial observations and measurements used for validation of the numerical model in WP2
d) indications of a limited maximum lift height to prevent large overburden deformations
e) observations and measurements showing a risk of tensile strains of the underground geomembrane reservoir bag exceeding the elastic regime at inflation ratios above half of the target value
f) proof that the currently selected membrane material is not sufficiently robust to withstand mechanical actions at relatively high lift height when overburden deformations cause a significant reduction in overburden cover.

Collected physical measurements can be used in the future to estimate the expected performance of UPHS systems with similar configurations and, more importantly, design novel UPHS configuration systems (using reinforced ground and/or modular reservoir configurations with multiple inlets) that can overcome current limitations in lift height. Sub-WPs are listed as follows.

WP4.1a	**Small-scale lab model testing of circular and square membranes with no overburdens**
WP4.1b	**Reduced-scale lab testing at elevated gravity (centrifuge testing) of UPHS systems in dry sand**
WP4.2	**Field trials of UPHS systems in sand**

2. Objectives

Main objectives achieved by this WP are listed as follows [between brackets the corresponding sub-WP].

- Estimate the inflation mode of the geomembrane bag without overburden, with either circular or square shapes, useful for the numerical back-analysis of the membrane [WP4.1a].
- Prove the feasibility to obtain a watertight bag by welding geomembrane linings to obtain circular and square reversed-shaped bags [WP4.1a and WP4.2].
- Identify characteristic movements of the membrane and soil surface [WP4.1b and WP 4.2] during inflation and deflation cycles.
- Characterize soil behaviour and accumulated deformations under cyclic loading conditions; this allowed evaluating the degree of “demolition” and geotechnical stability of the overburden [WP4.1b and WP4.2].

- For varying overburden configurations, estimate energy loss during charging and discharging and, thus, the efficiency of the system [WP4.2].
- Obtain a high-quality dataset to validate numerical models developed in WP2 [WP4.1b and WP4.2].
- Assess potential membrane damage under cyclic loading conditions [WP4.2].
- Estimate membrane movements and assessment of membrane straining during cyclic operations [WP4.2].
- Estimate the wear-out mechanism on the membrane during multiple charging & discharging cycles, including the rupture mechanism that occurred during the field trial [WP4.2].
- Characterise the behaviour of the Foulum and Congleton sands used for the overburdens in the experiments by laboratory element testing of representative volumes under prescribed simple boundary conditions. This allows rational calibration of the material models used for validation in WP2 and their parameter estimation [WP4].

3. Implementation

3.1 Development of the project.

- The objectives of WP4.1a had to be revised with respect to the original proposal considering restrictions to the access of the AU lab. During the first half of the project, it was concluded that it was unfeasible to adapt the UPHS small-scale lab model from the previous concept project (i.e. phase 1) as part of WP4.1a.
- To compensate for the difficulties at the point above, AU engaged the University of Nottingham to perform centrifuge testing in the added WP4.1b. However, the complexity of performing testing at elevated gravity led to only a single reduced-scale experiment being performed. As a main consequence, the estimation of the energy loss of the UPHS for different soil types and densities, originally planned for WP4, was addressed only numerically in WP2.
- The complexity of delivering a robust numerical model in WP2 was higher than anticipated. This resulted in the need to design the configuration to be tested in the field trials [WP4.2] based on engineering judgment (i.e. based on the knowledge available). Despite this, preliminary numerical outcomes helped the design of the monitoring system and to identify critical aspects to be described by measurements. In this respect, the followed implementation (that focused first on advancing with numerical modelling prior to physical testing) was effective.
- Working-related restrictions due to the pandemic resulted in significant delays of WP4.2. However, granted project extension allowed for completion of the planned experimental campaign.
- Considering preliminary trial results clearly pointing to large overburden deformations and reduction in cover, during the final stages of the field trial [WP4.2] an additional test series to study the beneficial impact of using stabilizing membranes in the overburden was considered. Unfortunately, this additional test series could not be performed due to the occurrence of a rupture in the geomembrane-lined bag. Consequently, the preliminary study of the effect of internal reinforcements on the overburden was addressed numerically in WP2.

3.2 Risks.

Two main risks of this WP are: (i) risk for significant leakage and (ii) risk for sudden rupture of the geomembrane-lined bag.

- In field trials (and future demo construction) identifying leakage in the geomembrane reservoir bag is not possible prior to the construction of the overburden and first inflation, due to the need for pressurized water. In the field trials of WP4.2, it was decided to not proceed with the inflation of the membrane-lined bag with no overburden, because of the risk of membrane straining, as observed during small-scale lab testing of WP4.1a. No (significant) leakage occurred in the system during field trials of WP4.2

thanks to excellent technical work and practical experience gained during WP4.1a. However, no mitigation actions can be set in place in the future to mitigate this risk.

- Rupture of the membrane occurred during field testing in WP4.2, as a consequence (among other aspects) of significant overburden deformations and cover reduction. To mitigate this risk, a threshold on allowable cover reduction should be introduced in the future during cyclic operations of UPHS systems while an additional protective layer to the used geotextile should be considered in future.

3.3 Description of test setup, monitoring and performed testing.

Small-scale lab testing. Two reservoirs alone (with no overburden) scaled (1:4) with respect to the field trial setup were tested. A circular reservoir with a radius of 4 m and a square reservoir with a side length of 5 m (referred to as "CR" and "SR", respectively). Both reservoirs were assembled by welding patches of the geomembrane GSE ProFlex (Solmax) linings having 1.0 mm thickness. During testing, the reservoir underwent a full inflation and deflation cycle while surface movements were recorded and measured [see Fig. A4. 4 and Fig. A4.3].

Field trial. Five test series were conducted on a 20 m x 20 m buried square reservoir scaled (1:10) with respect to a prototype system. The reservoir was placed at a depth of approximately 2 m – 3 m below the original ground level, to investigate both flat-shaped (overburden cover; C = 2 m, label FT_C2) and hill-shaped (C = 4 m, label FT_C4) overburdens, the latter extending above original ground level. Geomembrane GSE ProFlex (Solmax) linings having 2.0 mm thickness were used for the reservoir. Following the initial shape of the fully deflated bag, the nominal (target) lift height is U_n =1.2 m, while the nominal fully inflated volume V_n = 428.6 m^3. During testing, cycles up to maximum inflation ratios $R_V = V/V_n$ varying between 0.35 and 0.7 were tested (i.e. volume V up to 35% and 70% V_n, respectively), corresponding to the average lift of U_{avg} = 0.42 m and 0.82 m, respectively.

Tab. A4. 1 summarises and discusses deployed monitoring techniques.

Reduced-scale centrifuge testing. A (very) small scale model with a geometrical ratio of 1:80 to the field trial with a cover of 2 m (FT_C2) was developed and tested at the University of Nottingham at a gravity field of 80g. In this way, full-scale stresses are generated in the reduced–scale model similar to the field trial and, thus, experiment results are comparable with the field trial. The reduced-scale physical model is an approximation of the trial [see Fig. A4. 5]: the reservoir consisted of a single latex layer fixed at the edges with a thickness of 0.5mm (selected to replicate the prototype stiffness of the field trial geomembrane lining), the reservoir inflation/deflation was controlled by a volume-controlled system of the water flow.

Further details on the physical campaign and performed experiments are provided in the Appendix.

4. Results

Tab. A4. 2 summarises for each series, volume ratios, the number of cycles, measured average energy loss, and observations on both the deformations of the overburden and membranes as well as the pressure-volume response of the UPHS system.

From the interpretation of the observed behaviours and measurements during all physical modelling (WP4.1-2), the following indications are drawn. Further details on the results of the physical campaign and performed experiments are provided in the Appendix.

- As confirmed by both small-lab testing and field trials, a nearly linear relationship is to be expected between the vertical displacement of the centre and reservoir volume [see Fig. A4. 4]. This has practical implications for monitoring and analytical design; for instance, for the field trial monitoring, if central displacement increases sharply in rate with volume changes, it would be associated with unacceptable performance (possibly due to incipient geotechnical failure of the overburden).
- During the field trial, leakage tests were performed by having the underground reservoir at an inflated state and constant volume for more than a week. Constant pressure values and nearly no significant surface displacements were measured during this period, which confirmed that creep and leakage in the field reservoir were negligible. This confirmed a high quality of the technical and welding works for the construction of the geomembrane-lined bag.
- During the field trial, the membrane underwent balloon-shaped inflations with maximum uplift at the centre; this confirmed the overall inflation mode also predicted by the numerical results in WP2. In particular, field trials and reduced scale centrifuge testing for an inflation ratio R_v lower than unit (i.e. below the target/nominal lift height) indicated that, during first inflation cycles, ground displacement profiles follow a parabolic profile with a maximum central uplift [see Fig. A4. 6 and Fig. A4. 14].
- On the other hand, ground movement data would suggest a complex (and asymmetric in the plan view) deflation shape of the membrane, with water deflation localised around the inlet at the smaller volumes during deflation [see Fig. A4. 15a]. The fact that the deflated shape is more complex than a simple uniform movement is also confirmed by the kick-toe shapes of the pressure-volume measurements in the field trials [see Fig. A4. 11], which are (likely) the consequence of the soil arching at low water volumes when the reservoir completely squeezed in a few areas as suggested numerically by WP2. This mechanism for the kick-toe is also suggested by timelapse recordings of the surface movements (of series 3).
- Flat-shaped overburdens accommodate the balloon-shaped inflation of the membrane through shear-band formations at the edges and extension deformations of the central region. Contrarily, hill-shaped overburden undergoes more uniform deformations with outwards movements of the side soil and extensive deformations of the entire soil above the original surface level [see Fig. A4. 8].
- Extension deformations in the horizontal direction happened during the inflation part of cycles and localised around the central region (i.e. close to the origin of the local reference system, the settlement plate). This is confirmed by both pressure cell measurements of nearly null horizontal stresses during inflations [see Fig. A4. 12] as well as observations of large cracks within the partially saturated soil around the central soil region [see Fig. A4. 8].
  - For the flat-shaped overburden, these extension deformations are the likely main mechanical cause of the reduction in cover in the central region, as the soil has minimal tensile strength (except for cohesion due to suction).
  - For the hill-shaped overburden, overburden deformations are possibly due to combined effects of outwards movements of the soil during inflation cycles and horizontal extension deformations including the entire soil above the original ground surface level.
- There is strong experimental evidence that flat-shaped overburden has higher energy efficiency than hill-shaped overburdens, considering measured pressure-volume curves. Also, the efficiency tends to decrease with the maximum lift height (i.e. volume inflation) for a given overburden. Energy losses associated with the field flat-shaped overburden in the field trial are between 3%-6% of the stored energy, while for the hill-shaped overburden energy losses range between 9%-15% [see Fig. A4. 13]. This is supported by energy losses lower than 10% in the reduced-scale centrifuge model [see Fig. A4. 6], despite extremely large uplift height in the reduced experiment, that achieved equivalent inflation lift double that experienced in the field trial. The higher efficiency of flat-shaped overburdens is possibly due to the entire cover of overburden being laterally confined and, thus, undergoing smaller deformations that are associated with frictional losses. In addition, there is experimental evidence that the efficiency of a given UPHS system is affected by: (i) the maximum inflation and (ii) the minimum deflation volume of the cycle, and (iii) the maximum inflation experienced by the system during its operations. It is interesting to note that the energy

performance of the system was not highly influenced by large accumulations of the overburden deformations and reduction in cover; therefore, a relatively small variation in the maximum and minimum pressures associated with cyclic operations could be used as an alarm system for larger demos (i.e. when cycling up to a constant maximum volume, reduction in reservoir pressure is an indication of geotechnical failure) [see results for series 2 and B in Fig. A4. 11].

- Field trials (WP4.2) and reduced-scale modelling (WP4.1b) provided strong evidence that the target uplift U_n = 1.2 m (6% of the side length L; associated with R_v = 1) is mechanically not feasible if having UPHS constructed as unreinforced sand, for both flat- and hill-shaped profiles.
  - If observing ground movements recorded in the reduced-scale modelling of WP4.1b during the first cycle up to R_v = 1.25, the unreinforced overburden is characterised by large accumulations of irreversible strains and reduction in cover that would inevitably lead to a geotechnical failure over cyclic conditions [see Fig. A4. 6].
  - The fact that the overburden undergoes an excessive reduction in cover during cyclic operations was confirmed by both series up to 70% of the nominal inflation ratio (R_v = 0.7) [see Fig. A4. 9]. Contrarily, as confirmed by GPS surveys and drone surveys, the overburden deformations appeared significantly smaller for maximum inflations of 35% (R_v = 0.35) [see Fig. A4. 8, Fig. A4. 15,Fig. A4. 16].
- The central and side regions of the overburdens underwent large irreversible deformations during cyclic operations. For both hill-shaped (FT_C4) and flat-shaped (FT_C2) overburdens in the field trial, the central regions underwent extensive cracking (due to partially saturated soil conditions), horizontal extension deformations, and thus a large reduction in soil cover; this reduction can result in asymmetric cover conditions on the reservoirs and eventually to the system failure; in fact, the membrane rupture happened in the central region of the field trial FT_C4, when inflating up to R_v = 0.7 and the cover reduction was approximately 50% of the initial cover (i.e. cover reduced to 2 m from the initial 4 m value). Contrarily, deformations at the side regions differed for the two overburdens: namely, the flat-shaped overburden displayed localised shear bands with a step change in ground elevation and relative movements above the membrane side; the hill-shaped overburden displayed outwards movements of the external soil and evidence of slope instability of the laterally unconfined soil [see aerial pictures Fig. A4. 8, Fig. A4. 9 as well as GPS survey data Fig. A4. 15, Fig. A4. 16].
- In UPHS systems, membrane-imposed displacements due to the change of the reservoir volume have to be accommodated by the overburden by a combination of displacements and deformations: namely, rigid body motions, widespread deformations (e.g. extended soil cracking and horizontal extension), and localised deformations (shear bands at the sides). This concept that the overburden has to undergo a combination of displacements and straining has been clarified for the first time by the experimental campaign. This has important implications for the conceptual design of the overburden, as discussed in the next section.
- WP3 characterised the geomembrane properties; importantly, a linear elastic regime with minimal accumulation of plastic cyclic deformations was estimated as long as the reached biaxial tensile strain is below 5%. Elastomer strain gauges provided an estimate of the membrane straining in the field trial, which can be above 5% in the presence of overburden deformations and cover reduction. In particular, measurements of volumetric strain from elastomer strain gauges, bonded to the top membrane of the reservoir bag, were collected during the field trial with a 2 m cover (FT_C2). Measured strain levels were within the elastic regime when cycling up to an average uplift U_{avg}= 0.42m (for R_v = 0.35, volumetric strains were varying with volume below a 5% limit biaxial strain), whereas the top layer of the geomembrane underwent straining that exceeded the elastic regime when the average uplift reached U_{avg}= 0.84m (for R_v = 0.70, strain gauges went out of range and thus likely exceeded the 5% volumetric strain) [see Fig. A4. 17].
- Membrane movements were estimated by using a settlement plate at the centre of the reservoir. This element plate was crucial to have a reference for membrane displacement measurements and, more importantly, to calculate the reduction in cover (from the difference in the position of the surface and top of the settlement plate).

5. Conclusion and perspective

5.1 Conclusions

This WP carried out an experimental campaign designed to evaluate both the construction feasibility and the engineering performance of UPHS in sand, in terms of mechanical deformations and storage efficiency. Selected monitoring techniques relate to the main objectives of the physical tests. Measurements of the UPHS displacements, soil and reservoir pressures, and how they relate to the changes in the reservoir volume were illustrated. Despite the fact that the system performance did not meet the envisioned lift height (i.e. density energy storage per square meter), results will help to propose a revised and improved design of future UPHS in sand.

- The field trials refuted the hypothesised perfectly reversed shape of the inflated membrane. Instead, the implications of balloon-shaped membrane inflations on overburden deformations (including outwards soil movements, the horizontal extension of the upper overburden, risk of excessive membrane tensile straining, and surface cracking) should be considered in future works. Also, due to localised deflection of the membrane around the central area, there is a risk for the obstruction of the inlet and dynamic reduction in water pressure.
- Multiple inlets would minimise the risk for inlet obstruction during deflation and, possibly, prevent the tick-toe shape of the pressure-volume curve at deflation, which is among the main causes of energy losses.
- Lateral confinement of the overburden is required to minimise energy losses in the overburden. Natural confinement is provided in flat-shaped overburdens (e.g. overburden obtained by pit excavation and perfect volume balance); contrarily, retaining or confinement strategies may have to be designed for hill-shaped overburdens.
- Envisioned target uplift heights of the UPHS would result in unacceptable overburden deformations and consequent reduction in the central cover. This is due to extension deformations of the soil in the horizontal directions, facilitate by the naturally low tensile strength of drained soils. To tackle this mechanical problem, reinforcements (i.e. geogrid) may be needed; however, it was not possible to test them in the field due to the membrane rupture.
- UPHS energy losses in the soil, membrane and reservoir are lower than 5% of the stored energy (excluding the pump-turbine and piping system) when the uplift movements do not result in detrimental overburden deformations and the soil is laterally confined.
- To the best interpretation of the physical results gathered in WP 4, if no prior large deformations happened in the overburden, it is concluded that the maximum average uplift height U_{avg} of a UPHS system with a geometrical shape similar to the configurations tested in the field is between 2% to 4% of the membrane side length, while U_{avg} greater than 4% should not be possible because of the likely deformation-induced failure of the overburden. For tested geometries, the maximum lift height was 21% of the cover thickness for the 4 m cover (FT_C4) and 42% of the cover thickness for the 2 m cover (FT_C2).
- It is also likely that geotechnical instability and large deformations of the overburden are associated with large tensile straining of the membrane; consequently, the resilience and durability of UPHS systems are highly dependent on the selected membrane and the mechanical behaviour of the overburden. In conclusion, the successful design of UPHS does require further geotechnical studies that go beyond the scope and available resources of this project.

5.2 Perspective

- As a practical perspective on the system construction, considering the need for a dry environment during membrane welding, water accumulation in the reserved shape membrane should be prevented by effectively sloping soils and a system (trenches + pumps) for water removal.

- Following WP4, it is hypothesized that an ideal UPHS system should have the overburden that acts as a rigid mass on the buried reservoir with only small internal movements, and the changes in volume of the underground reservoir shall be accommodated by localised relative movements (shear bands) at the side of the overburden; for this, sufficient strength of the central area is needed to localise relative movements (shear bands) at the side.
- Future works should aim to deploy monitoring and measurement systems that allow for a systematic three-dimensional characterisation of experiments/demos; this includes (among others): digital image correlations by webcam recordings and UAV (drone) surveys; ground-penetrating radar, which could be used to quantify the cover across the entire foot-print, distributed measurement of overburden and reservoirs stresses.
- It is key to set up a system for remote inspection of the system (e.g. webcams connected to the internet) and remote retrieval of the logging of the monitoring instrumentation. This allows for the quick estimation of the state of the UPHS system and to set up real-time (or quick) alarm systems.
- Physical testing is inevitably associated with errors due to scale effects. Reduced scale modelling is affected by testing soil grains at the prototype size and, thus, a decreased number of particles per unit area of surfaces; this aspect cannot be modelled when adopting continuum-based numerical models as the one adopted in this study. In the field trials carried out at Foulum, the sandy overburden was partially saturated by water, leading to negative pore water pressures and apparent cohesion; this is confirmed by extensive soil cracking observed at the surface and extending up to 1m depth. Therefore, differences between the small-scale field trials and full-scale prototypes should be expected (e.g. soil cracking would most likely extend up to 1 m depth also in 20 m prototype overburdens, thus leading to a lower impact of apparent cohesion in prototypes than field trials). For this reason and to quantify scaling effects, numerical modelling was carried out both at small- and full-scale geometries; this is discussed in report WP2.
- Future works should answer the following questions: How is it possible to increase the horizontal soil strength of the soil to deal with the balloon-shaped inflation of the membrane? How to effectively confine the soil? Can multiple inlets be used to optimise UPHS energy performance and resilience over cyclic deformations? How to effectively protect the membrane against rupture?
- A number of strategic solutions to tackle the critical issues highlighted by the field trial needs to be discussed and conceptually analysed before carrying out further trial testing. In WP2 and WP3 a number of principal solutions are listed which over the next 6-12 month will be further investigated using numerical simulations, and our aim is that these will bring forward new viable solutions to increase the stability of the system and increase the energy efficiency.

6. WP4 Appendices

6.1 Introduction to the energy and stability of the UPHS system (WP4.1)

The input E_i and output E_o stored energy can be calculated by integrating the pressure p at the base of the reservoir with respect to the volume from the initial V_i to the final volume V_f and vice versa, respectively, giving an energy loss ΔE and an efficiency $\eta = E_o/E_i$ for a given cycle.

$$\Delta E = E_i - E_o = \int_{V_i}^{V_f} p\, dV - \int_{V_f}^{V_i} p\, dV \qquad (1)$$

Key quantities that engineers should be able to estimate for UPHS system in sand is energy storage capacity of $E_{i,max}$ and efficiency η under inflation/deflation cycles can be affected by geometrical changes, irreversible (plastic) deformations of materials, friction losses within micro-scale intergranular contacts, the piping, and the turbine/pump system. What makes the design of UPHS energy storage a geotechnical problem is that, inevitably, meter-scale vertical movements of the reservoir lead to complex displacement patterns, as opposed to a uniform uplift of a rigid mass, and possibly large irreversible deformations of the overburden and the geomembrane-lined bag. These irreversible deformations can accumulate over the cyclic operation of the reservoir, with implications on both efficiency and stability. Additionally, macro-scale failure mechanisms in the soil mass, shown Fig. A4. 1(b), could lead to significant energy losses and (potentially) the instability and failure of the system. In summary, the key mechanical quantities describing the cyclic performance of UPHS systems in sand are: pressure-volume relationship at the reservoir (related to storage capacity and efficiency), movements and deformations mechanisms of all components, particularly overburden and upper reservoir.

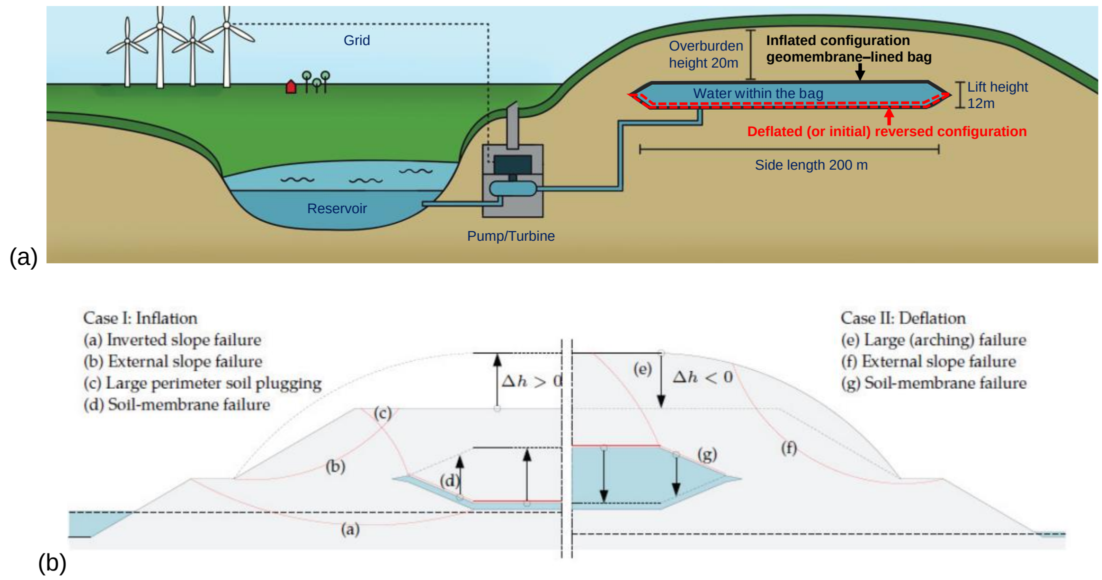


Fig. A4. 1: (a) UPHS concepct, (b) potential failure mechanisms.

6.2 Small-scale lab model testing (WP4.1-a)

Two reservoirs alone scaled with respect to the field trial setup with a circular and square shape (referred to as “CR” and “SR”, respectively) were tested by inflation with air and water:

- square reservoir **SR** has side lengths L = 5 m, corner radius of 1m, lift height U_{lift} = 0.6 m, membrane thickness t = 1 mm;t it scales with respect to the field reservoir FR by 1:4 for the plan geometry and 1:2 in membrane thickness, corner geometry and lift height.
- circular reservoir **CR** has diameter of 4m, corner radius of 2m, lift height of U_{lift} = 1.2 m, membrane thickness t = 1 mm. It scales with respect to the field reservoir FT by 1:1 scale for the geometry and lift height of the corners and 1:2 in membrane thickness, modelling the sides of the field reservoir.

Main results are shown in Fig. A4.2, Fig. A4.3 and Fig. A4. 4.

Fig. A4.2: Square reservoir alone inflated by air.

Fig. A4.3: Square and circular reservoir alone testing: (top) deflated configurations with highlighted transverse section being monitored; (centre-left) monitoring set-up; (centre-right) partly inflated state of the square membrane with associated folding; (bottom) fully inflate state of the reservoirs.

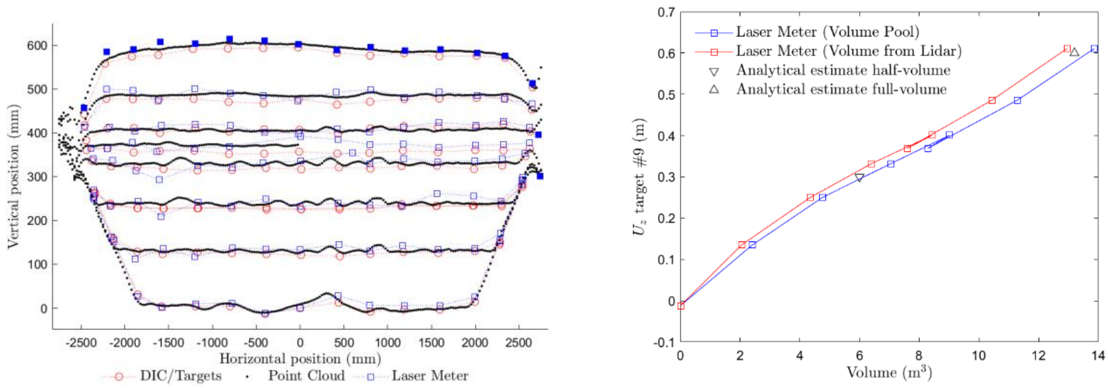


Fig. A4. 4: Point Cloud (PC) vs Digital image correlation (DIC) VS Laser Meter.

6.3 Reduced-scale centrifuge testing (WP4.2)

A 1/80th scale (of field trial) experimental package was tested at a nominal elevated-gravity field of 80 g in the University of Nottingham geotechnical centrifuge. The reservoir buried in sand is modelled as a single latex layer, filled with water, and fixed at the edges by a clamp system to an aluminium plate that models the bottom-fixed lining of the reservoir. The reservoir has side lengths L = 250 mm, a lift height U_{lift} = 7.5 mm, and cover C = 25 mm. Dry Congleton CNHST95 sand was air pluviated to achieve a loose relative density. The geomembrane is modelled as single latex layer, with a thickness of 0.5 mm to replicate the prototype stiffness of the field trial geomembrane lining. A volume-controlled system is used for inflight inflation/deflation of the water reservoir, consisting of a linear actuator, a piston, solenoid valves, an LVDT, and piping. A pore pressure transducer is used to measure the model-reservoir pressure P while its volume V can reach 1.5 V_0. Digital cameras are used to take images of the soil surface.

Following model preparation, the experimental set-up was mounted on the centrifuge, spun-up to 80 g, and then the reservoir volume was varied for three cycles having the sequence R_v = [0, 1.5, 0.5, 1.0, 0.5, 1.0, 0.5]. Cycle 1 up to 1.5 V_0 evaluates the stability, while cycles 2 and 3 up to 1.0 V_0 simulate service performance. The initial reservoir pressure was $P_0 \approx$ 36 kPa.

Fig. A4. 6a and b display the overburden surface during the first inflation, characterised by balloon and terracing shapes for R_v = 0.5 and 1.25, respectively, having concave and convex profiles at the centre. The surface soil above the edges of the reservoir was pushed outwards during cycle 1, affecting subsequent cycles.

Fig. A4. 6f plots the centrifuge P–R_v relationship. As for the field trial, cycle 1 displays a nearly linear increase in pressure with volume up to 1.35P_0 and a greater linear deflation rate that resulted in a minimum P = 0.8P_0. Interestingly, cycles 2 and 3 are nearly identical: inflation curves nearly linear, with $P > P_0$, and slopes similar to cycle 1; nonlinear deflation curves having a kick-toe shape and reaching the minimum pressure 0.8P_0 experienced during deflation cycle 1. The efficiency of cycles 2 and 3 is 92.2%.

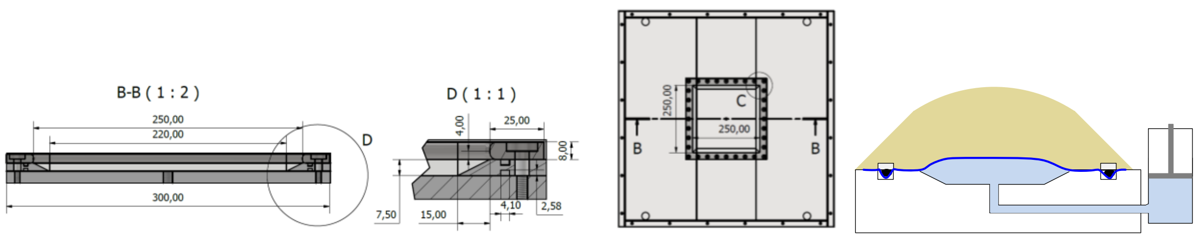


Fig. A4. 5: Drawings of the base plate and clamp system (in mm) and conceptual design of the model.

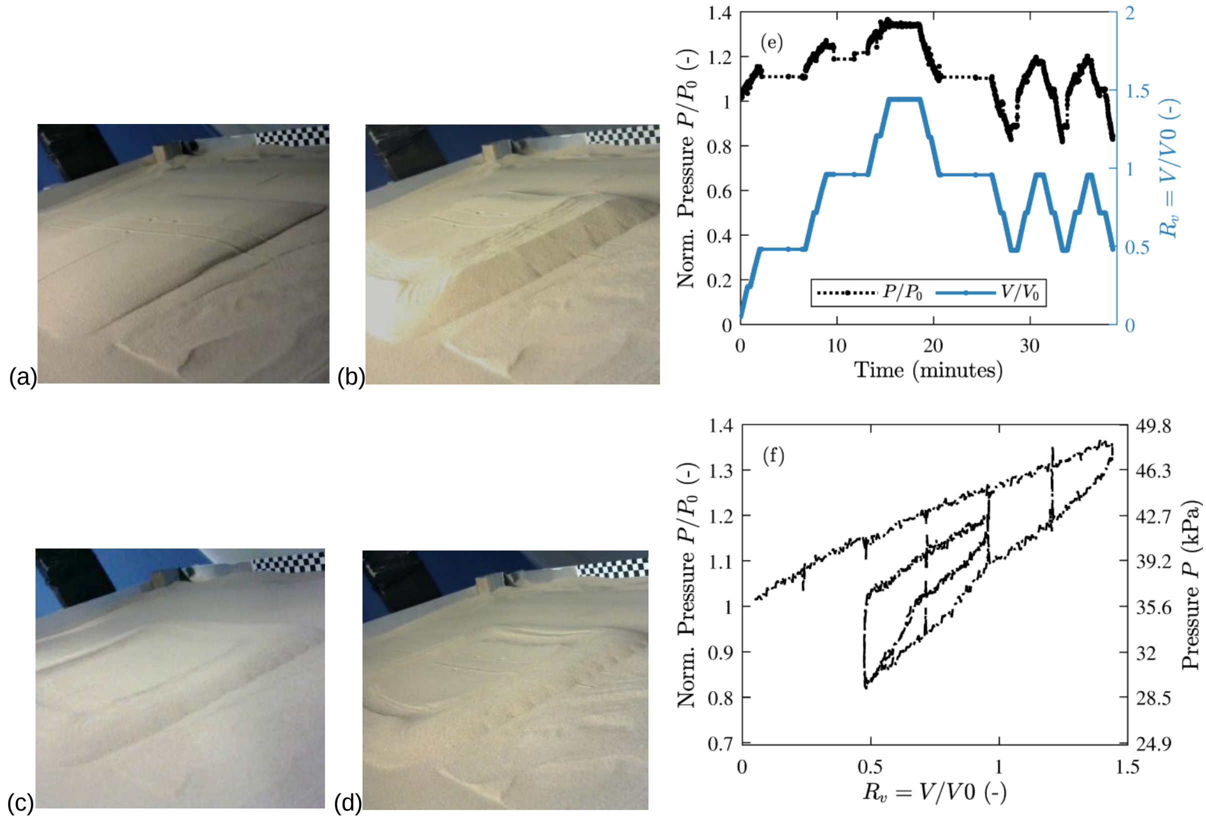


Fig. A4. 6: Overburden displacements during the first cycle at (a)-(b)-(c) R_v = 0.5, 1.25, 0.5 and (d) the final state at R_v = 0.5. Centrifuge measurements showing (e) reservoir pressure with volume ratio plotted against time as well as (f) pressure-volume ratio relationship.

6.4 (WP4) Field trials of UPHS systems in sand (WP4.3)

A 1:10 scale field trial of a full–size UPHS system shown in Fig. A4. 1(a) was carried out at Aarhus University in Foulum, Denmark. At the site, boreholes reported 0.5 m of topsoil, 0 - 2.5 m sand till, below which is a uniform medium layer of meltwater sand. The water table is below the reservoir depth. The setup consist of an underground reservoir and water basin with a trench in between for the automatic loop pumping system (pipes, pump, valves) to control and measure the in/out reservoir flow of water. Fig. A4. 5 display the cross-section and pictures of the construction sequence. First, earthworks were carried out to excavate the pits hosting the lined basin and the geomebrane lined reservoir bag. The buried underground reservoir is square and it has a single inlet/outlet located centrally at the lower layer of the bag, a side length L = 20 m, corner radius of 2 m, lift height U_lift = 1.2 m, 1:2 slopes at the edges, soil cover C = 2 m or 4 m (FT_C2 first tested, then followed by earthworks and testing of FT_C4). This is associated with a nominal volume V_0 = 428.6 m^{3}corresponding to a fully inflated reverse shape configuration with U_{lift} = 1.2 m. Reservoirs pressures P_A and P_B were measured by piezometers located within the underground reservoir at its base next to the central inlet while P_C is at one of the bag corners; the central pressure P_A used by the pumping control system is logged at a frequency of 0.1 Hz whereas a stand-alone datalogger reads P_B and P_C at 0.016 Hz. To protect the geomembrane, a geotextile layer was placed around the bag. The overburden was constructed using excavated sand in 0.8 m thick compacted layers for the 2 m cover, whereas soil the 4m overburden was constructed levelling the overburden surface at the end of trial FT_C2 without layered compaction. Classification testing on representative samples of the overburden sand gave; specific gravity G_s = 2.65 g/cm³, d_{50} = 0.30 mm, and d_{60}/d_{10} = 4.7, e_{min} = 0.369, and e_{max} = 0.699. A relative density I_D ≈ 72% of the overburden after compaction is estimated from a measured average in-situ dry density ρ_d = 1813 kg/m3 and bulk density ρ = 1973 kg/m3 using nuclear density method. The geomembrane is polypropylene-polyethylene GSE ProFlex (Solmax) having 2.0 mm thickness.Note that reservoir pressures P due to water and soil stresses are estimated as $P = P^* +$ (101.325 kPa$-P_{atm}$), where temperature compensated pressure values measured by the piezometers (P^*) are corrected by the fluctuation in the barometric atmospheric pressure P_{atm}, remotely obtained from the local automatic weather station number 6069. The reservoir volume V is obtained by the integration of the in/out water flow.

Tab. A4. 1 Experimental objectives and type of monitoring technique used.

Objective	**Deployed monitoring technique** *[within brackets discussion of their performance]*
Small-scale lab testing: Reservoir alone tests SM and CM	
Prove the feasibility to weld membrane linings cut into designed shapes to two obtained a waterproof bag, with upper and lower layers initially resting on a concave shaped base.	• **Laser meter** to track displacements of targets with respect to a steady point [*reliable technique to measure in run-time local and cross-section movements during operation; not suitable for full monitoring due to lack of automatization in the data acquisition*]. • Simple **2D Digital Image Correlation (DIC)** to track surface targets at given cross-sections [*Digital image series taken at relatively high frequency allow for a continuous; post-processing can be scaled based on needed information and if needed implemented in run-time; simple mapping of mm/pixel based on initial target position/distance is sufficient considering large displacement problem*]. • Collection of point clouds derived from a **terrestrial laser scanner** sensor [*capable of high-level description of the displacement field; multiple scanning may be required for out of sight surfaces; equipment/readings may be detrimentally affected by harsh environmental conditions; 3D DIC using digital images taken from an unmanned air vehicle more suitable technique*].
Field trial: Buried reservoir tests SM_C2 and SM_C4	

<table>
<tr><td>Evaluate volume of water and pressures within both the reservoir and the basin.</td><td rowspan="3">• Installation of a flowmeter along the pipe connecting reservoir and basin [integration of flow rate led to volume agreeing with variation in basin level; an electrical fault damaged the flowmeter that had to be substituted and led to a interruption of the trial].
• Installation of piezometers within the reservoir and at the basin [piezometers were found to be resilient to the construction stages; despite this, having redundancy in piezometer is advisable; all pressure measurements must be corrected for the barometric pressure fluctuation].</td></tr>
<tr><td>Measure stored and recovered energy in the reservoir to quantify the efficiency of the system.</td></tr>
<tr><td>Check the water-filled bag has no leakage when pressurised by the overburden.</td></tr>
<tr><td>Quantify displacements and deformations of the surface of overburden during cyclic changes in reservoir volumes</td><td>• Laser meter to track displacements of targets with respect to a steady point [as for tests SM and CM].
• Simple 2D DIC to track surface targets at given cross-sections using digital images taken by external DSLR cameras placed on tripods and permanent outdoor webcams [as for tests SM and CM; the use of permanent IP rated outdoor webcams to be preferred to temporary cameras on tripods].
• GPS surveying of targets [simple technique to obtain georeferenced displacements of targets and tiles regardless of environmental conditions; it was not systematically implemented during the early stage of the trial].
• UAV surveys providing a collection of point clouds derived from 3D DIC and an unmanned air vehicle (UAV) [cost effective solution to gather aerial records as well as georeferenced point clouds and target/tiles incremental displacements on a daily/weekly base; atmospheric considerations needed for UAV flight test planning; post-processing time make this technique not suitable for quick state evaluations; GPS surveys needed in connection to UAV surveys to georeference the point cloud].
• Settlement profiler pulled through a flexible buried pipe [deformations of the buried pipe obstructed the profile; buried horizontal inclinometer or flexible shape arrays may be more effective solutions at a greater cost].</td></tr>
<tr><td>Measure the elevation of the upper layer of the reservoir bag, which also allow quantifying the variation in the overburden cover (using surface overburden position data).</td><td>• Settlement plate resting on reservoir with target located at the heading [simple solution to evaluate the reduction in cover; only suitable at the centre where overburden and reservoir tilt are limited; base plate should be circular and placed above reinforcement geotextile or elastic layer to minimise reservoir bag distress; for extremely large deformations of the overburden, tilt of the plate may distress the underneath geomembrane; ground-penetrating radar (GPR) should be used instead if possible].
• Settlement profiler pulled through a buried pipe resting on the top of the reservoir bag [as discussed at the above row].</td></tr>
<tr><td>Estimate the risk for plastic accumulation of deformations of the membrane linings due to tensile straining and/or strain concentrations around corners and weldings.</td><td>• Elastomer strain gauges for volumetric strain estimate, bounded to the membrane for large strain measurement [strain gauges had to be protected against water contact by application of bitumen tape and silicone; attention to the arrangement of cables ; strain gauges reached output signal above their associated with approximately 5% volumetric strain] .
• Fibre optic sensors, bounded to the membrane for small strain measurement [fibre optic sensing should be considered only for underground reservoirs experiencing small deformations (which is not the case of relatively shallow underground reservoirs): for the field trial FR, defornmations of the overburden and reservoir lead to strains above their applicability range].</td></tr>
<tr><td>Estimate the impact of external environmental and temperature conditions on the UPHS system.</td><td>• Remote retrieval of temperature, relative humidity and barometric pressure from the nearby weather station [for 1:10 field trials, barometric pressure should be used to correct the pressure readings].
• Use of vibrating wire instrumentation (e.g. pressure cells, piezometers) with embedded temperature sensors.</td></tr>
<tr><td>Qualitatively describe overall UPHS behaviour from still and video recording during operations.</td><td>• Permanent outdoor webcams capable of live streaming as well as run in timelapse function in addition to dedicated site time-lapse camera [essential to limit the need for labour intensive visual inspection and records of overburden deformations; digital images could be used for 2D and 3D DIC].</td></tr>
</table>

Tab. A4. 2 Summary of field trial test series and energy performance.

Series	C	# cycles	$R_{v,min}$-$R_{v,max}$	Average energy loss	Description of overburden deformations and membrane straining	Description of pressure-volume relationship
1	2 m	9	6%-35%	3.4%	Steady overburden: -Slightly asymmetric uplift of the overburden in the plan view -Balloon shape membrane inflation with maximum uplift close to the centre -Minimal central cover reduction -Shear bands above the membrane edges	- Steady curves over cycles - Nearly linear inflation and deflation relationship, expected at small volumes for a volume ratio R_v < 10% - Kick-toe during deflation at small R_v values - Low energy losses
2	2 m	7	6%-70%	5.6%	Cyclic accumulatios of overburden deformations: -Asymmetric uplift of the overburden in the plan view -Localisation of the inflation along one of the diagonals -Extreme reduction in cover in the central area and in the region of maximum uplift along the diagonal	- Slightly reduction in maximum pressure over cycles. - Nearly linear relationship between pressure and volume (due to overburden resistance being fully mobilised), except for the tick-toe shape during deflation.
3	2 m	47	6%-35%	5.5%	-Asymmetric uplift of the overburden in the plan view, -Accumulation of uplift at one of the side (this is likely due to accumulation of water, considering observations of water trapped in this region prior to operation of Series A)	- Pressure-volume relationship similar to Series 1, both in terms of slopes of the linear part of inflation and deflation curves as well as maximum mobiles . Differences , except for a kick-toe mechanism during the deflation at approximately R_v = 15%
A	4 m	46	6%-35%	9.1%	-Symmetric uplift of the overburden in the plan view, with maximum uplift at the centre -Balloon shape membrane inflation with maximum uplift -Significant reduction in the cover reduction, possibly increasing over cycle number.	- Relatively steady curves over cycles, with a progressive reduction in the deflation kick-toe mechanism and with (nearly) constant values of maximum mobilised pressure. - Relatively linear pressure-volume relationships, expect at the change of flow direction when a steep increase and reduction in pressure is associated with inflation and deflation, respectively. - Mechanism at the point above resulted in medium energy losses.
B	4 m	17	6%-70%	14.9%	-Slightly asymmetric uplift of the overburden in the plan view -Over a few cycles, extreme reduction in central cover and outwards lateral movements at the bottom side of the overburden (where the elevation of cover confinement by the excavated pit was lower). -Membrane rupture at inflation state of the 18th inflation cycle, possibly a combined result of large membrane deformations, the presense of local rigid zone close the membrane caused by the settlement plate, and the significant reduction in cover.	- Highly nonlinear trend of pressure-volume relationship for R_v greater and lower than 50% during inflation and deflation, respectively. This is possibly due to full soil resistance being mobilised and, consequently, a reduction in the increase in slope for a given volume change. - Large energy losses associated with nonlinear pressure trends. - Minor formation of a kick-toe at the deflation curves. - Clear reduction in pressures over cycles (i.e. downwards shits of p vs R_v curves).

Fig. A4. 7: UPHS field trail. (a) Cross-section. (b) Construction of the UPHS; b1 installation of piezometers on base membrane, b2 arial view of test site showing basin on the left side and excavation pit and base membrane for the underground reservoir, b3 corner view of base geotextile and overlying base membrane, b4 adding of overburden sand on the underground geomembrane reservoir with top geotextile for protection, b5 view of final overburden surface (flat shaped) after compaction. Arial view of FT_C4 afterwards overburden construction and target survey points, with indications of local reference system selected transverse cross-sections A-A and B-B.

(a) FT_C2 field trial with cover C = 2 m

(b) FT_C4 field trial with cover C = 4 m

Fig. A4. 8: (a) At the reservoir volume of 300 m3 on the 6th Jan 22, aerial/side views of the overburden, initiation of the side shear band during first inflation, and reduction in the central cover from the settlement plate. (b) Initial configuration of the 4 m cover overburden (left) and deformed overburden view on the 31st Mar 22.

(a) FT_C2 field trial with cover C = 2 m

(b) FT_C4 field trial with cover C = 4 m

Fig. A4. 9:Aerial view of the state of the overburden at "geotechnical failure", at the end of series (a) 2 and (b) B.

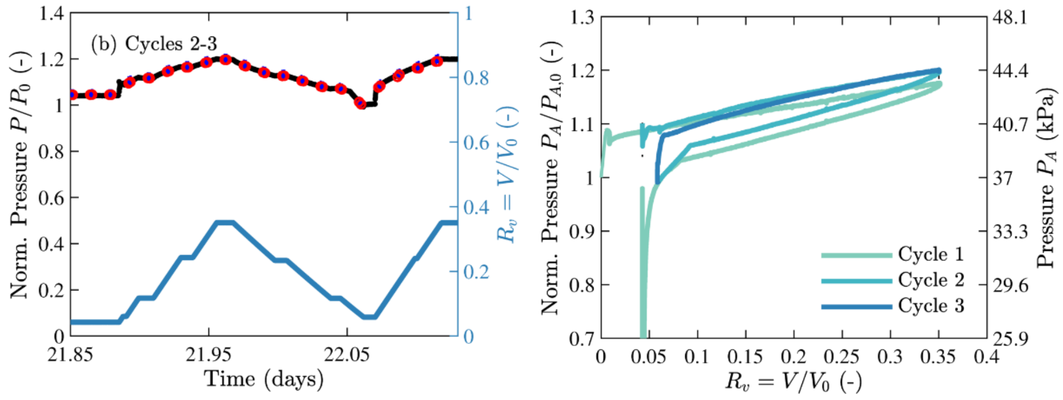


Fig. A4. 10: Results from cycles 1-3 of FR_C2 up to 150 m3 inflation: (left) normalised pressure and volume ratio of the reservoir against time; (right) normalised pressure against volume ratio.

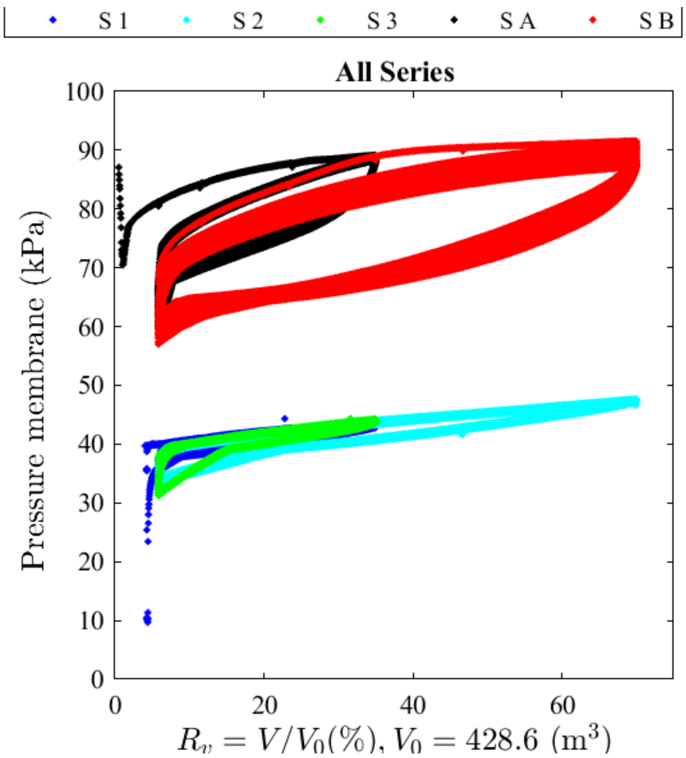


Fig. A4. 11: Results of reservoir pressure vs volume ratio for the entire field trail dataset (both FT_C2 and FT_c4).

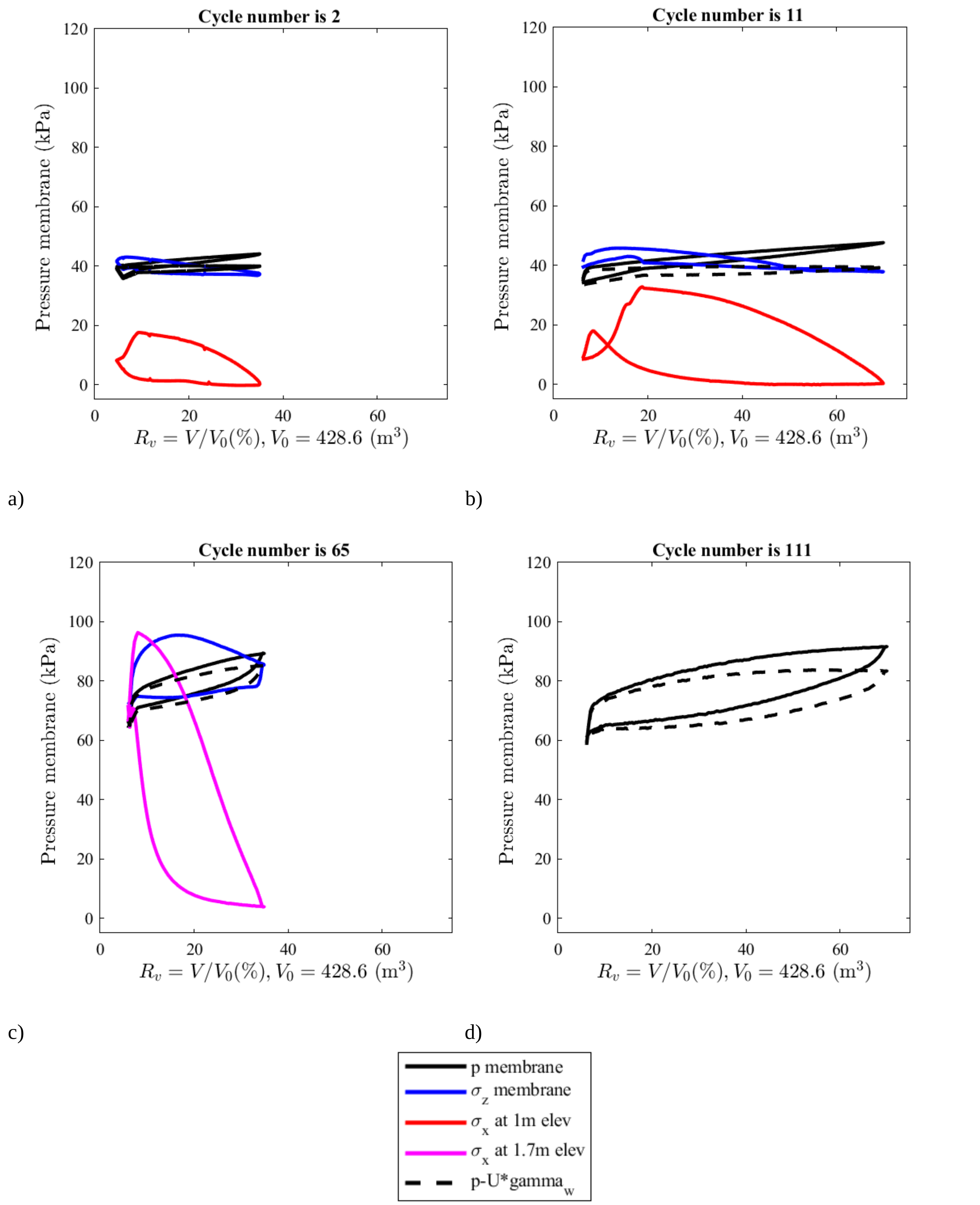


Fig. A4. 12: Comparison of pressure p (at the bottom of the reservoir) and pressure cell measurements of vertical and horizontal total stresses for cycles 2 of series (a) 1, (b) 2, (c) A, (d) B.

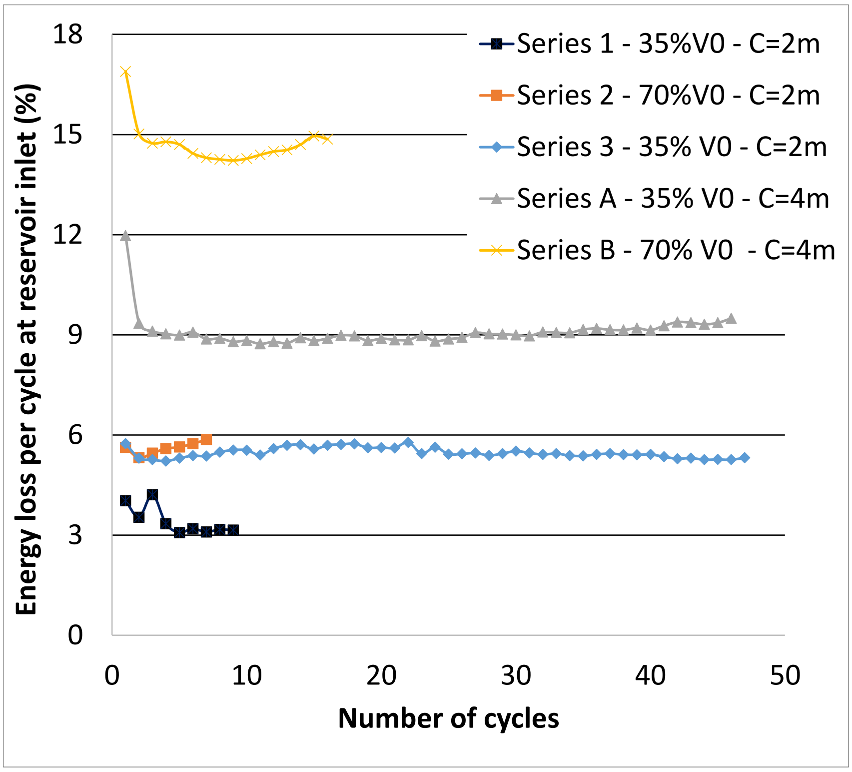


Fig. A4. 13: Field trial results: percentage energy loss (estimated from pressure-volume curves at the inlet) vs number of cycles for each test series (both FT_C2 and FT_c4).

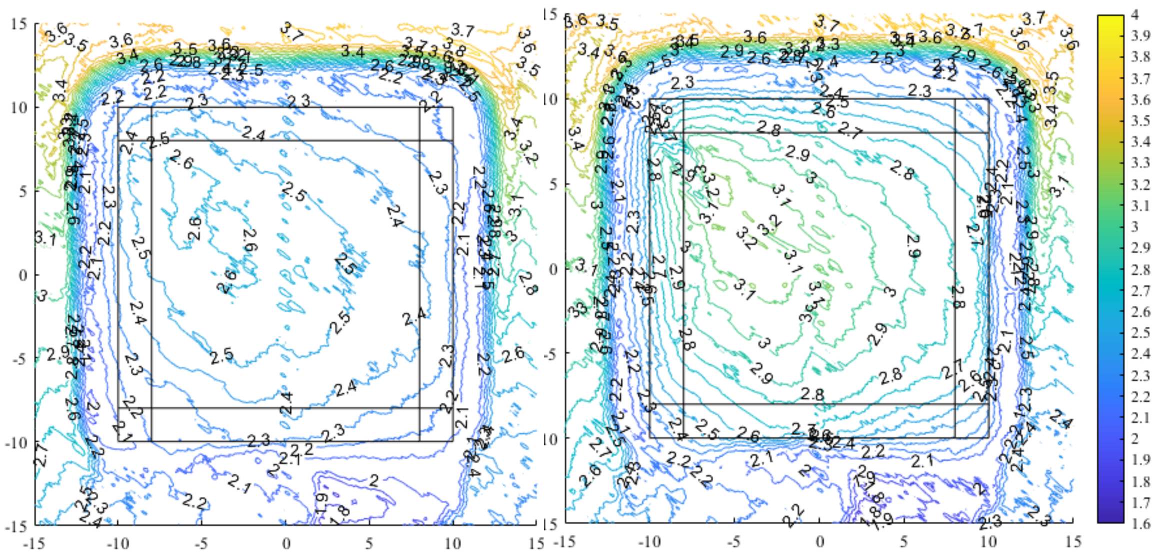


Fig. A4. 14: Georeferenced UAV survey (drone based) in local coordinates. Contours of difference in height from the 51.7 m elevation level of: (left) FR_C2 during cycle 3 series 1 at R_v=35%; (right) cycle 1 series 3 at R_v=70%.

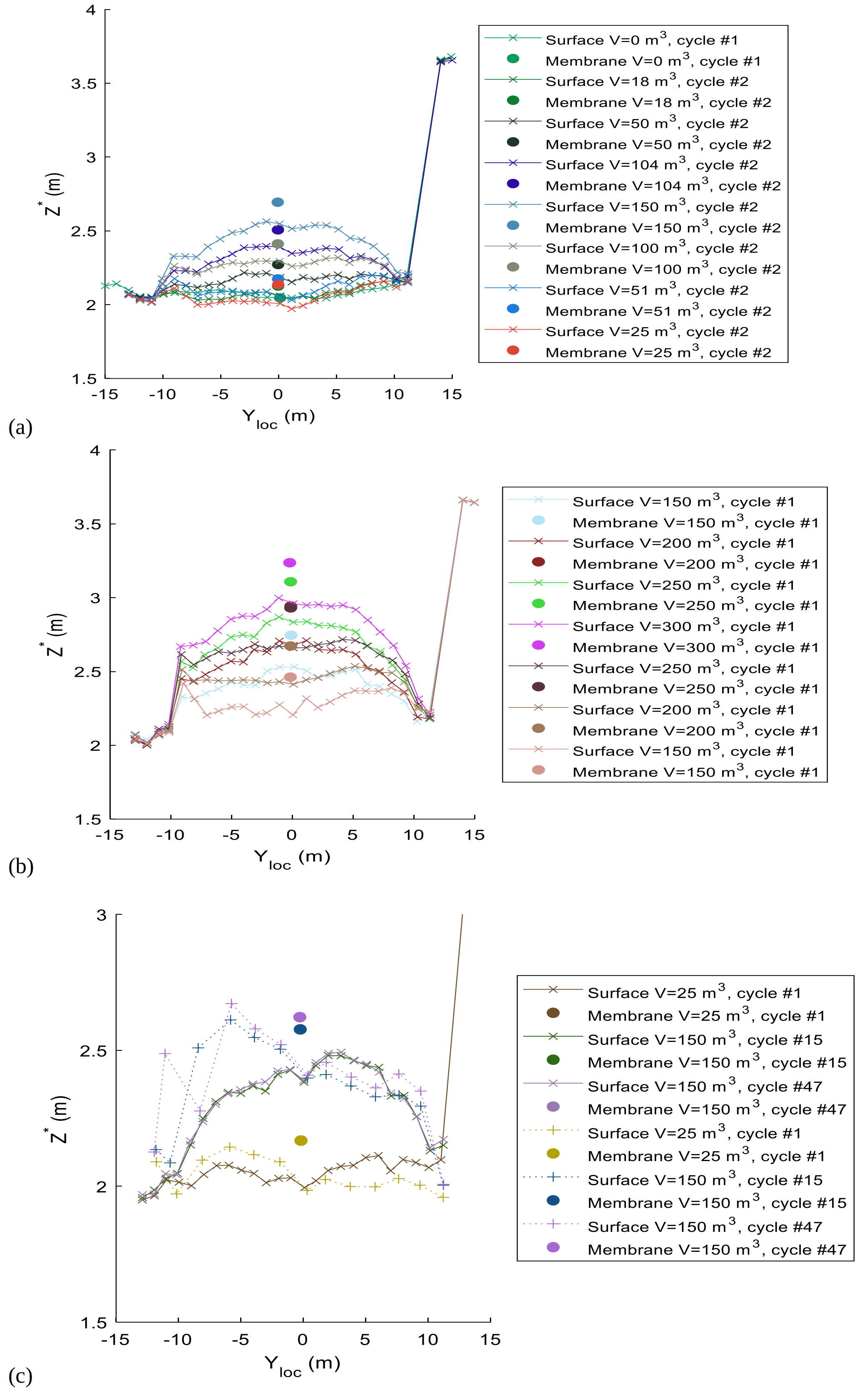


Fig. A4. 15: GPS survey along the transverse section A-A of FT_C2 during for the 2m cover overburden: (a) cycle 2 of series 1, (b) cycle 1 of series 2, and (c) cycles 1 15 and 47 of series 3 (note, for series 3 also data long section B-B added). Difference between crosses and circle markers indicate reduction in cover.

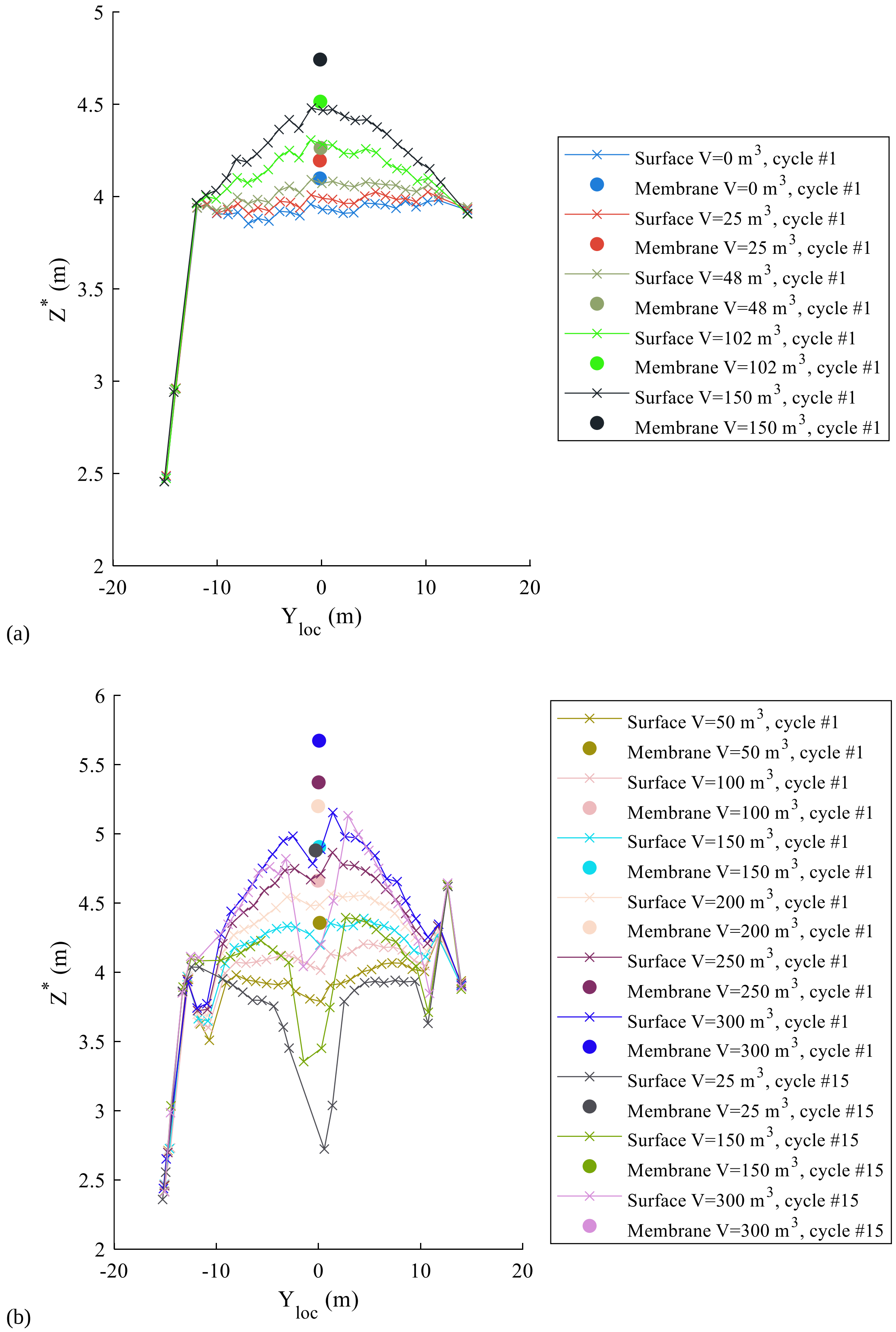


Fig. A4. 16: GPS survey along the transverse section A-A of FT_C4 during for the 4m cover overburden: (a) cycle 1 of series A and (b) cycles 1 and 15 of series B. Difference between crosses and circle markers indicate reduction in cover.

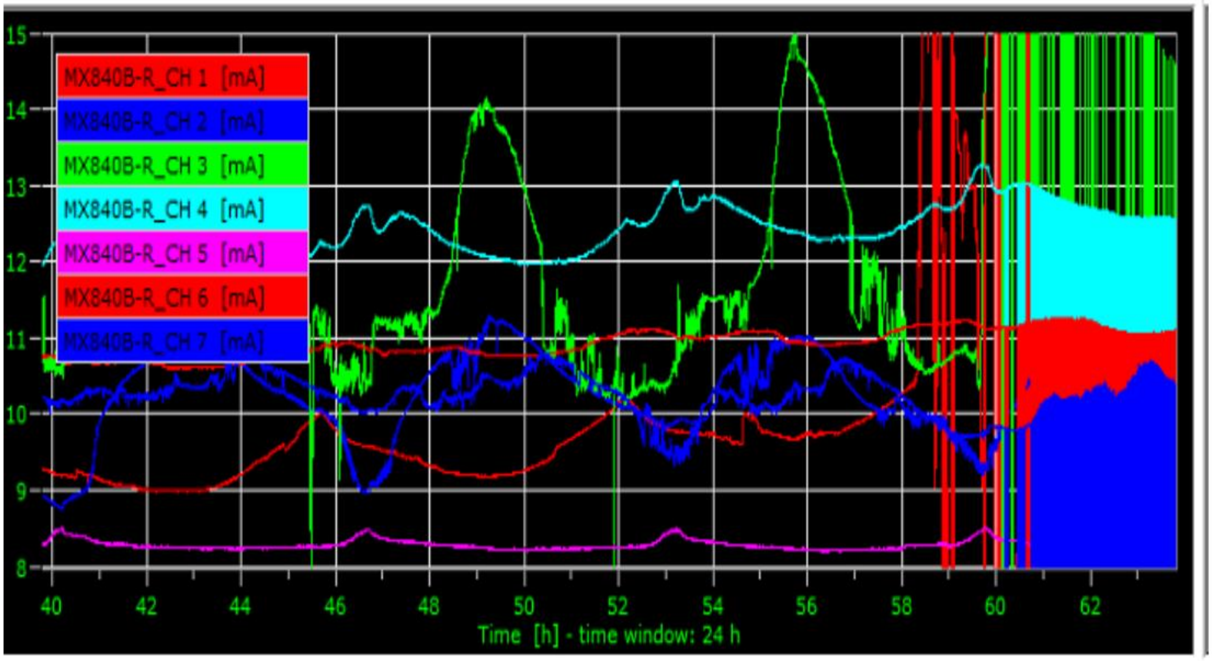
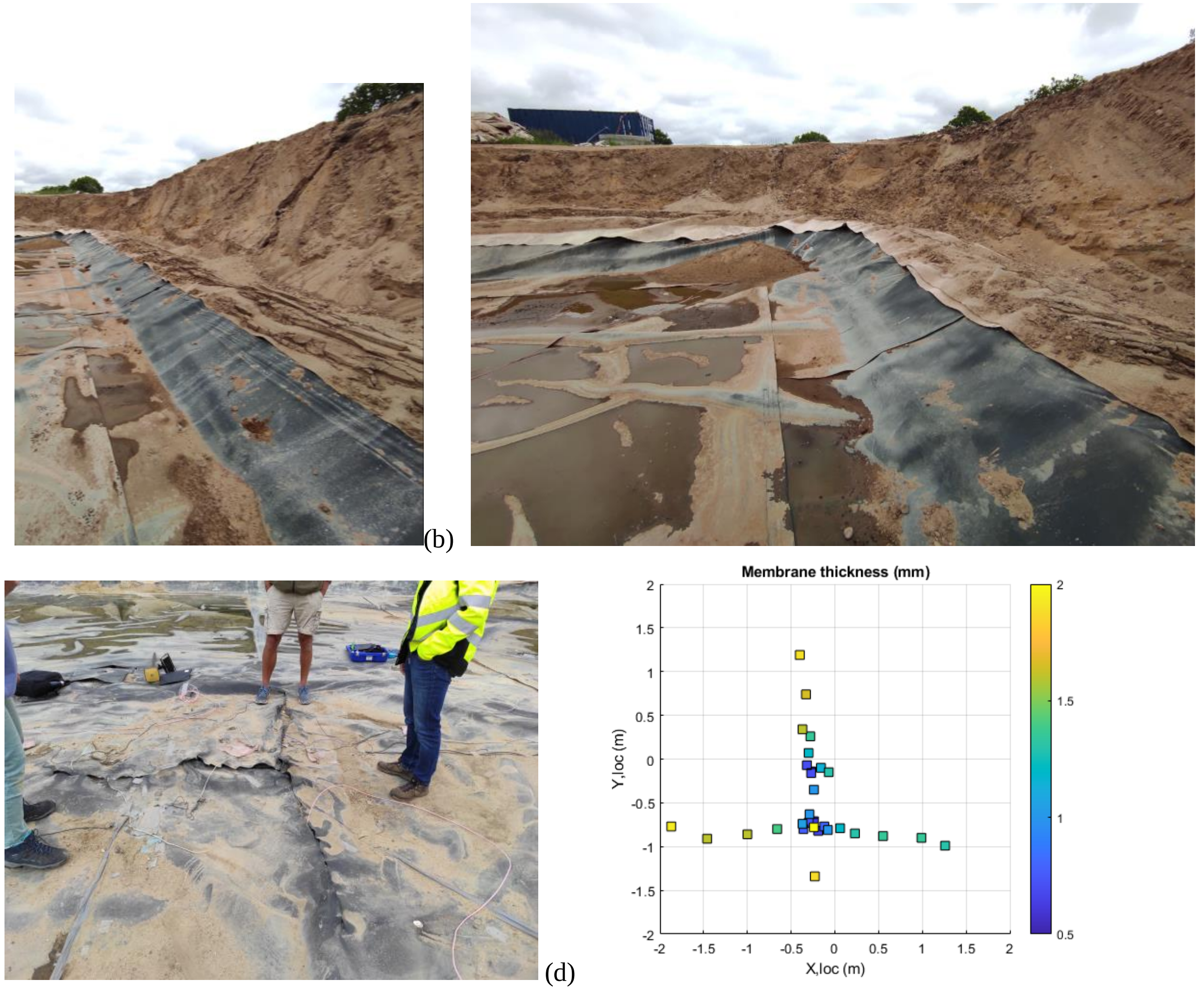


Fig. A4. 17: Output signals in mA (range between 4-20) from selected strain gauges during series . Note the factory calibration is 0.427mA / %volumetric strain.

(a) (b)



(c) (d)

Fig. A4. 18: Survey of membrane wearing, folding, and straining at the end of the field trial: (a) and (b) records of folding at the edge zones. (c) central zone of rupture, (d) measurements of membrane thickness in the central zone post field trial testing.

WP 5 Cost calculations and optimization

1. Project details

Project title	UPHS: WP 5 Cost calculations and optimization
File no.	
Name of the funding scheme	
Project managing company / institution	
CVR number (central business register)	
Project partners	PlanEnergi/AquaNamic…
Submission date	11 September 2022

2. WP Summary

Describe the objectives of the project, the obtained results and how they will be utilized in the future.

The short description should be in two versions:

- *English version*
- *Danish version*

Each version should be brief, no more than 2000 characters (including spaces).

Conditions of works in this work package developed with the experiences made in the test rig in Foulum and the cooperation with Arkil. Prices and costs used are due to the interaction with key-manufacturers of hydro-electrical equipment, like Voith. The work to come to conclusions has been achieved in course of setting different combinations of membranes and optimizing of input variables and factors that influence the capacity and costs of an UPHS plant facility. For this purpose, an excel tool was established to address the influence of the different factors and variables. In course of this it was possible to gather a few conclusions.

One conclusion is that, based on preliminary indications with an L/C factor from 0,36 financial feasibility studies were carried out with a CAPEX span around 170.000 - 190.000€/(MWh (LCOS 116€/MWh) for a 112MWh plant. Those are based on the present knowledge of soilworks and technical behaviour of soil, with a soil column of 25m, a lifting height of 9m (height of water column) and a penstock height of 6m.

Another conclusion is that, to achieve future cost targets between 125.000 and 140.000€/(MWh (LCOS 93€/MWh) an improved water column and filling level inside the membrane should be obtained.

Furthermore, due to the nature of the facility comes a potential to drive costs further down in course of an considerable combinations of the establishment of an UPHS plant with other construction projects, in where disposal of huge volumes of soil are a part of it. Instead of disposal in traditional means, another project may benefit from cost savings for transferring soil towards an UPHS construction. And in combination with eventual existent old gravel, coal or mining pits establishing an UPHS can be an interesting way of re-establishment or alternative form of renaturation with integrated energy storage.

Betingelserne for arbejdet i denne arbejdspakke er udviklet på baggrund af erfaringerne fra testanlægget i Foulum og samarbejdet med Arkil. De anvendte priser og omkostninger skyldes samspillet med nøgleproducenter af hydroelektrisk udstyr, som Void. Arbejdet med at nå frem til konklusioner er blevet udført i forbindelse med indstilling af forskellige kombinationer af membraner og optimering af inputvariabler og faktorer, der påvirker kapaciteten og omkostningerne ved et UPHS-anlæg. Til dette formål blev der udarbejdet et Excel-værktøj til at behandle de forskellige faktorers og variablers indflydelse. I løbet af dette var det muligt at samle nogle få konklusioner.

En af konklusionerne er, at der på grundlag af foreløbige indikationer med en L/C-faktor fra 0,36 blev gennemført finansielle gennemførlighedsundersøgelser med en CAPEX-spændvidde på omkring 170 000-190 000 EUR/(MWh (LCOS ...). Disse er baseret på den nuværende viden om jordarbejder og jordbundens tekniske adfærd med en jordsøjle på 25 m, en løftehøjde på 9 m (vandsøjlehøjde) og en højde på 6 m for vandledningen.

En anden konklusion er, at der for at nå fremtidige omkostningsmål på mellem 125 000 og 140 000 EUR/(MWh (LCOS ...) bør opnås en forbedret vandsøjle og fyldningsniveau inden for membranen Endvidere er der på grund af anlæggets karakter mulighed for at reducere omkostningerne yderligere i forbindelse med en betydelig kombination af etableringen af et UPHS-anlæg med andre byggeprojekter, hvor bortskaffelse af store mængder jord er en del af det. I stedet for at bortskaffe jorden på traditionel vis kan et andet projekt drage fordel af omkostningsbesparelser ved at overføre jorden til et UPHS-anlæg. Og i kombination med eventuelle eksisterende gamle grus-, kul- eller minegruber kan etableringen af et UPHS-anlæg være en interessant måde at genetablere eller en alternativ form for renaturering med integreret energilagring.

1. WP objectives

Task 5.1 - Civil, geotechnical specification and other relevant installations (PlanEnergi)

Based on input from WP2, WP3 and WP4 a detailed specification for excavation, relevant building, pipelines and connection to grid should be made, covering following deliveries:

- Drawings to capture the specific design of a full-size plan;
- Drawings to capture the design of the DEMO-system;
- Relevant calculations;
- List of equipment to be installed;
- Budget for establishment of a full-size plant and DEMO system;
- Calculation of LCOS and other relevant key numbers;
- Check of cost with relevant suppliers of services.

The specification should enable an entrepreneur to establish the DEMO plant.

Task 5.2 - Specification of Hydro system for the UPHS (AquaNamic, AquaEnergy)

Based on the size and shape of the UPHS, a specific requirement for the hydro equipment should be made, including following deliveries:

- Selection of pumps;
- Selection of turbine;
- Selection of generator;
- Other electrical equipment to be used for grid connection.

3. WP implementation

Below the key input from relevant WPs and other relevant background material serving as basis material for the implementation in the WP5

Geotechnical input and key parameters related to WP2, WP3 and WP4

The basic geotechnical design of the "moving" soil construction has been defined in WP2 and to a certain degree been validated in WP4 through both LAB test and Field test of a down scaled test rig. Below the outline of "one membrane unit" based on key inputs from WP2:

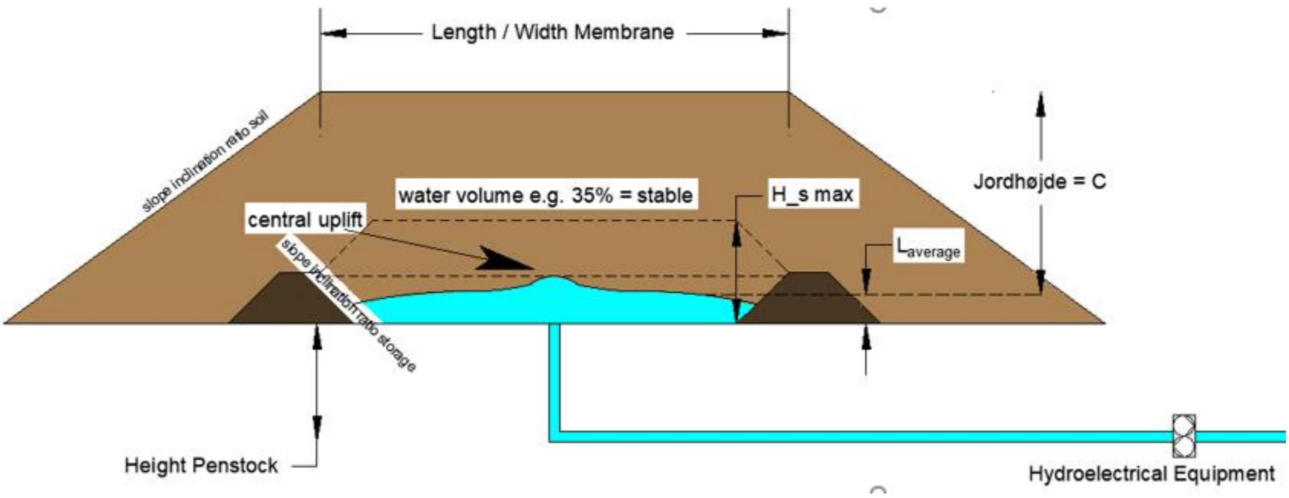


Fig 1 Figure containing the key measures of a "standard" one unit membrane system. Key annotation of the different measures has been indicated. Also, we see the indication of the potential limitation of the lifting height.

The conducted field tests in Foulum (by AU) indicated a stability limit around a ratio of 0,3 to 0,36 of the average lifting height ($L_{average}$) compared to the soil level (C).

Besides the above-mentioned inputs to regarding the lifting height we also could observe the measured efficiency. Assuming that we can keep the soil stable during operation we currently can see around **6-8 % loss** in the soil.

Design optimizations based on practical experience with Arkil during the establishment of the test rig.

A potential way to optimize the cost related to the establishment of the UPHS system will be to make multiple membranes, in a way where soil could be moved directly from one excavation to the soil load on the next module, depending on if and how deep a module is located below terrain level. Also, this will give the opportunity to utilize the same hydro electrical equipment for more membrane systems.

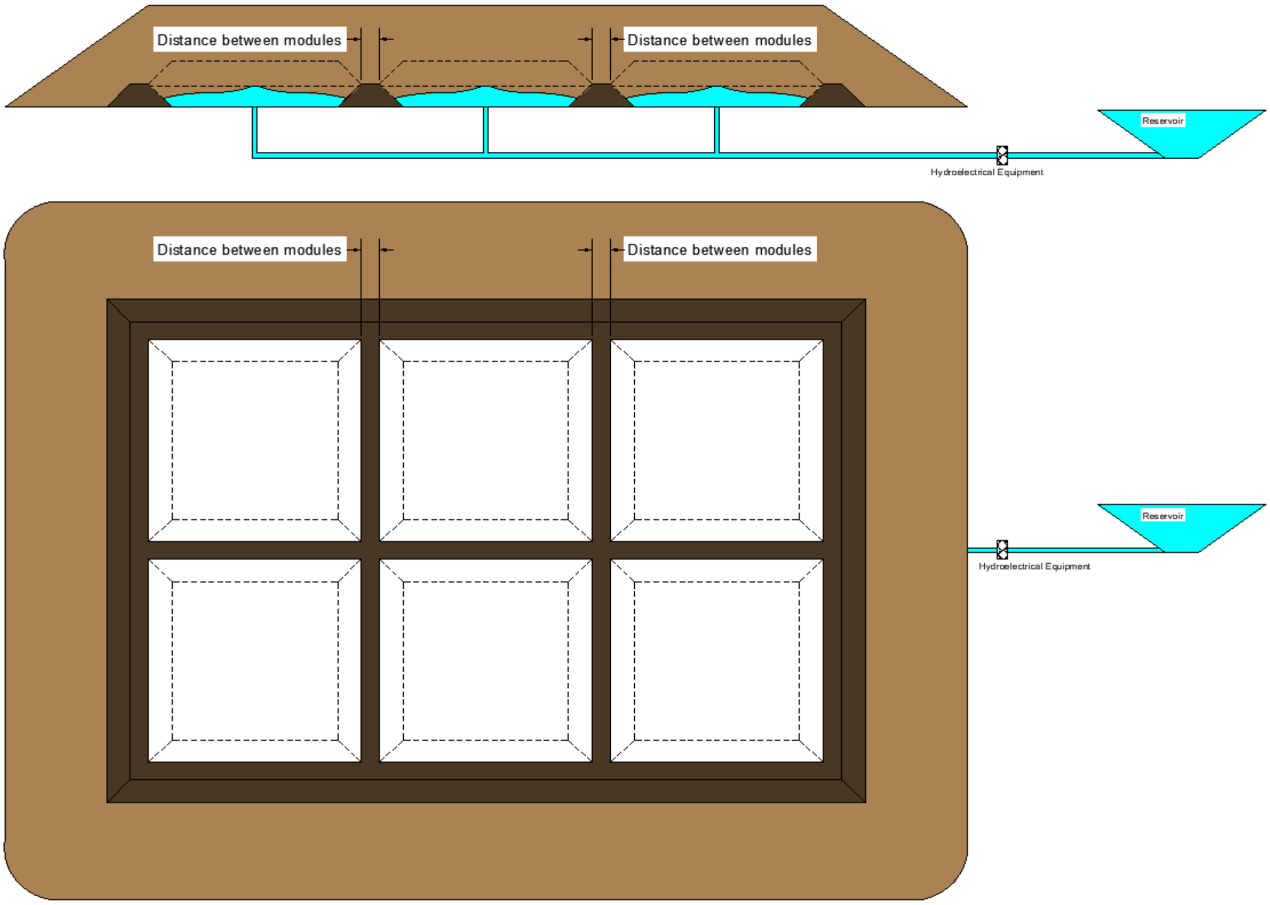


Fig. 2 Example of a system with 6 modules

The height of soil on top of the membrane causes the main influence on the capacity of a system. A typical column of 20m to 25m can be assumed as a standard for a large plant. Furthermore, the side length of 1 module / membrane can lay between 60m to 120m or even bigger (depending on the design). The amount of soil to be built up on top of only 1 module can easily exceed 300.000m3 and more, after the membrane has been implemented.

The costs to stack up a very large amount of soil depends highly on the sequence and efficiency. The implementation of soil shall undergo in such a way that every m3 of soil does not need to be moved more than once, coming either from a local excavation or by truck-delivery. However, at project start the desired area needs to be prepared and some soil needs to be removed. The calculation tool considers costs for removal of soil, once it is decided to locate the storage bottom below terrain level and for building-in in a traditional way (distribution by excavator and compaction every 30cm). The amount of building in is assumingly bigger, than the amount to be removed. Therefore, a percentage distribution is possible to address as partial removal of soil before membrane placement. This amount of soil would be hauled up temporarily to be built on top later on, therefore it is moved twice and the stated unit prices are both considered then.

Of course, also the source of soil plays a role. Either the soil is originated at the desired location of a plant and simply needs to be moved around, like e.g., it could be in a gravel pit. Another option could be a connection of other soil-intense construction, that are to be planned and during which a disposal of large volumes of soil becomes applicable. Including costs for soil delivery is very unpredictable, as this depends highly on the final location of the plant, potential distance to delivery sites, amount of soil and vehicles needed to deliver etc.

For a very large plant of e.g., 100MWh or 200MWh the amount of soil can reach a few million m3. International shipping by vessel, with unloading the cargo nearby the project site might even be an option then. Also, it may be interesting to investigate more efficient methods to implement soil, than the traditional ones (e.g., blowing in).

Resuming key inputs for the Hydro electrical system

The different elements in the Hydro electrical system for the UPHS is presented in the block diagram below:

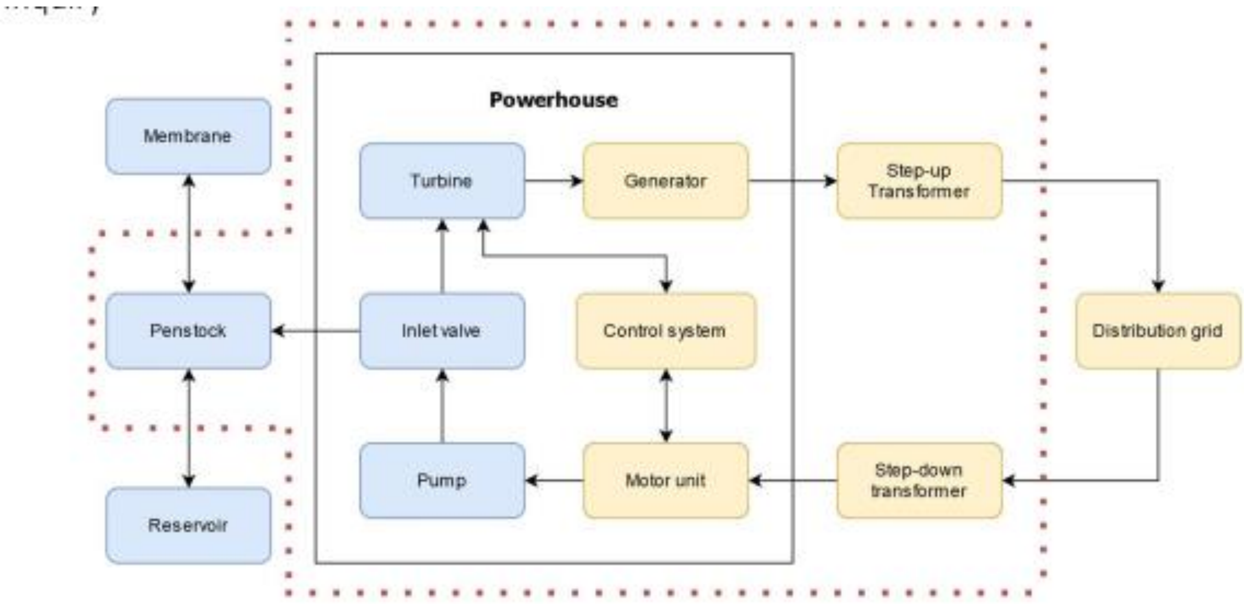


Fig. 3 The dotted line contains the key elements in the hydro electrical system

During the project we have engaged with different suppliers to investigate the cost basis for the hydro electrical system:

1) Voith Hydro (one of the leading industrial partners for hydro electrical systems. Germany)
2) Andritz Hydro (also a major supplier of hydro electrical systems. Austria),
3) Amjet Turbine systems (US located company specialized in composite turbines for low head applica-tions). See annex xx
4) A mix of different suppliers where we have tried to configure the hydro electrical system based on different individual sub-suppliers.

The different solutions have all advantages and dis-advantages.

The Amjet system is e.g. made of composite material and could therefore be used with saltwater enabling the UPHS to be located by the ocean. However, for the time being the turbines are only dimensioned for "low-head" applications and will not suit the UPHS key applications. If the Amjet turbine can be developed into also high head applications, the solution may be attractive due to the possibility to use salt water in the system.

A "self-configuration" of the hydro electrical parts from different suppliers would enable cost savings compared to a "turn-key" delivery from e.g. Voith or Andritz. The risk will be that we lose some of the total overall efficiency.

However, on a short term Voith or Andritz will be preferred and for the economic feasibility studies we have used the inputs from Voith Hydro.

Below the we see some of the material supplied by Voith.

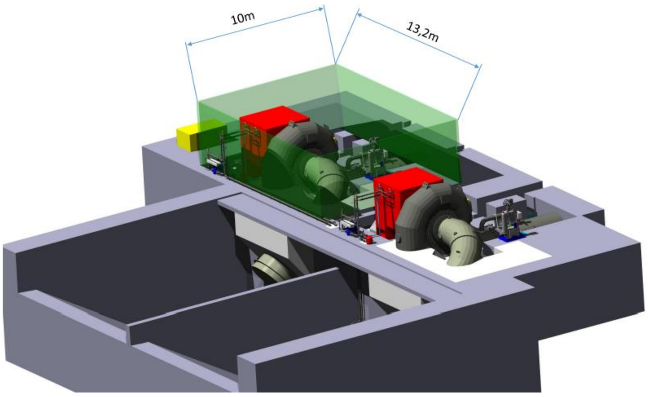


Fig. 4 The Turbine and generator of a hydro electrical system supplied by Voith and the corresponding physical outline.

The corresponding **budget** cost supplied by Voith (table below).

Project: AquaNamic UPSP

Base Data			Non-Binding Price Estimation *			
Planz Size [m²]	Number of units	Turbine Power [MW]	Pump-Turbine incl. auxiliaries	Motor-Generator	eBoP	Overall
120	1	3.2	EUR 1.230.000,--	EUR 495.000,--	EUR 260.000,--	EUR 1.985.000,--
150	1	4.9	EUR 1.230.000,--	EUR 645.000,--	EUR 290.000,--	EUR 2.165.000,--
225	3	3.7	EUR 3.100.000,--	EUR 1.785.000,--	EUR 500.000,--	EUR 5.385.000,--
330	5	4.8	EUR 4.980.000,--	EUR 3.225.000,--	EUR 780.000,--	EUR 8.985.000,--

*** Incl. scope of supply:**
Reversible Francis pump-turbine with runner diameter 1480 mm (for all plant sizes)
Turbine inlet valve DN 2000 PN 10 incl. bypass line and foot plate
Hydraulic governor incl. piping and oil filling
Complete set of electric equipment - incl. automation control system, MV switchgear, AC/DC distribution, main transformer, auxiliary transformer, cabling (excl. frequency converter if needed, depending on desired operation mode for 1-unit solution only)
Cooling water system
Engineering, documentation, packing

Excluded:
Shipment to site
Erection and commissioning

Fig. 5 Budget Hydroelectrical Equipment by Voith

We can observe that going up in size the hydro electrical system will be more cost efficient. Hence, this has been in-cooperated in the calculations.

Based on data from the U.S. Energy Information Administration (EIA) Pumped storage hydroelectrical facilities in US operated with an average monthly round-trip efficiency of **79%.** Hence, for further economical calculations we will use this number for the UPHS as well. This may be a conservative estimate as the UPHS would have significant shorter pipelines compared to a traditional pumped hydro system.

4. WP results

Enabling a systematic calculation of CAPEX and evaluation of impact of the different cost drivers an excel calculation model has throughout the project been established and improved. Below a closer description of the different elements of the cost model.

For the calculations an excel sheet has been established in where the different influencing parameters for the capacity and the costs have been included. The usage of the excel sheet is possible in connection with the specific tool of "What-If-Analyses" and "Goal Seek". With the help of this purpose, it is possible to define the design framework for a desired storage capacity and to connect its various dependencies, also in terms of cost.

The first page of the excel sheet contains a general introduction to the calculation method for the energy capacity. Different influencing parameters are stated, can manually be changed or are a result of the calculation formulars in the respective cells, according to the color of the cells

(yellow)	Manual Input for dimensions
(orange)	not-to-be-changed cells / variables
(green)	Energy Results
(blue)	Use Problemløser (NOT Malsøgning)

Energilagringsdimensionering firkant og rektangel

Jord / Soil	Jordhøjde	H_j [m]	25,0	
	Jordvolume	m3	214.299	
	Pressure ...	Pa	490500	
	... in Meter Water Column	m	50,00	
Waterstorage / Membrane	Longest Length	A [m]	92,58	
	Longest Width	B [m]	92,58	
	Length above the min water level	A@H_s min [m]	63,38	
	Ratio / Slope / Inclination		1 : 2,0	26,57°
	½ Højde / ½ Water Level h1 / h2	h1 / h2 [m]	7,50	
	Vandsøjle, max / Max Water Level	H_s max [m]	15,00	
	Længde ("nedre") / Shortest Length	a [m]	62,58	31,29
	Bredde ("nedre") / Shortest Width	b [m]	62,58	
	Total Water Volumen	m3	54.850	
	Minimum Water Level	H_s min [m]	0,2	
	Circulating Water Volume	**m3**	**54.056**	
	Extra Liner Anchor Trench	m	3	
	Liner Area	m2	7.378	
Lift-Height to Cover Ratio	Inflation of Total Water Volume Membrane	[%]	60%	!
	$L_{average}$ = Average Height of Water Level	$L_{average}$ [m]	9,00	
	Cover = C = Jordhøjde	H_j [m]	25,00	
	H_s max / H_j < 0,36 for a stable system	[ ]	0,36	

Energilagringskapacitet MAX kapacitet

Energy Calculation PlanEnergi	Jordhøjde	C or H_j [m]	25,0
	$L_{average}$ = Vandsøjle =	$L_{average}$ [m]	9,00
	Penstock minus Head Loss	H_p [m]	0,0
	Densitet, jord	kg/m3	2.000
	densitet, vand	kg/m3	1.000,0
	Gravitationskonstant	m/s2	9,81
	Epot, vand, considering H_s min	GJ	4,667
	Epot. jord, considering H_s min	GJ	37,000
	Energilagringskapacitet i Vand, C_tot	**kWh**	**1.296,3**
	Energilagringskapacitet i Jord, C_tot	**kWh**	**10.277,8**
	Total energilagringskapacitet, C_tot	**kWh**	**11.574,07**
	Virkningsgrad, turbine	%	72%
	Effektiv energilagringskapacitet, C_eff	**kWh**	**8.333,33**
Penstock	Bassinhøjde, over turbine	h0 or H_p [m]	0,0
Calculation Effective Head	Maximum gross Head	m	59,0
	Minimum gross Head	m	50,2
	Mean Gross Head	m	54,6
	Head Loss	m	0,00
	Mean effective Head	m	54,6
	Mean net Head	m	54,6
	Minimum Water Level Reservoir	m	0,0
	Maximum Water Level Reservoir	m	0,0

Fig. 6 Calculation method

In a pumped hydro storage, the volume and potential height difference of the upper water pond towards the reservoir is the system's capacity main driver. The setup of an underground pumped hydro storage, on the other hand, consists of 2 different aspects that have a superior effect the capacity. One is the capacity from the overburden soil and the other one is the capacity from the underground water membrane. Of course, also the height of the penstock has an impact, however it is considered 0 in the calculations here, as it highly depends on the desired location of the plant.

At unchanged water column inside the storage and unchanged height of overburden soil, the capacity relation from the length / width of the membrane is considered exponential. This relationship is further clarified by showing the percentage distribution of the influence from the capacity of the water and from the capacity of the soil on the total system. As the side length of the membrane increases, the influence of the water volume on the overall system also increases. However, the increase of this influence is larger for side lengths between ~40m to ~120m than for larger side lengths. For example, the influence of the water capacity of a membrane with 150m side length is 87% and with 500m side length 86%. This specific value can of course change due to changes in the water column (here 15m), the bottom height (here 25m) or the L/C factor (here 0.36).

However, the distribution remains exponential. Going from there forward one conclusion was that the construction of a large plant benefits by dividing the total capacity into several modules that are linked together.

In the following figure the relation and influence of water and soil on the system capacity is shown.

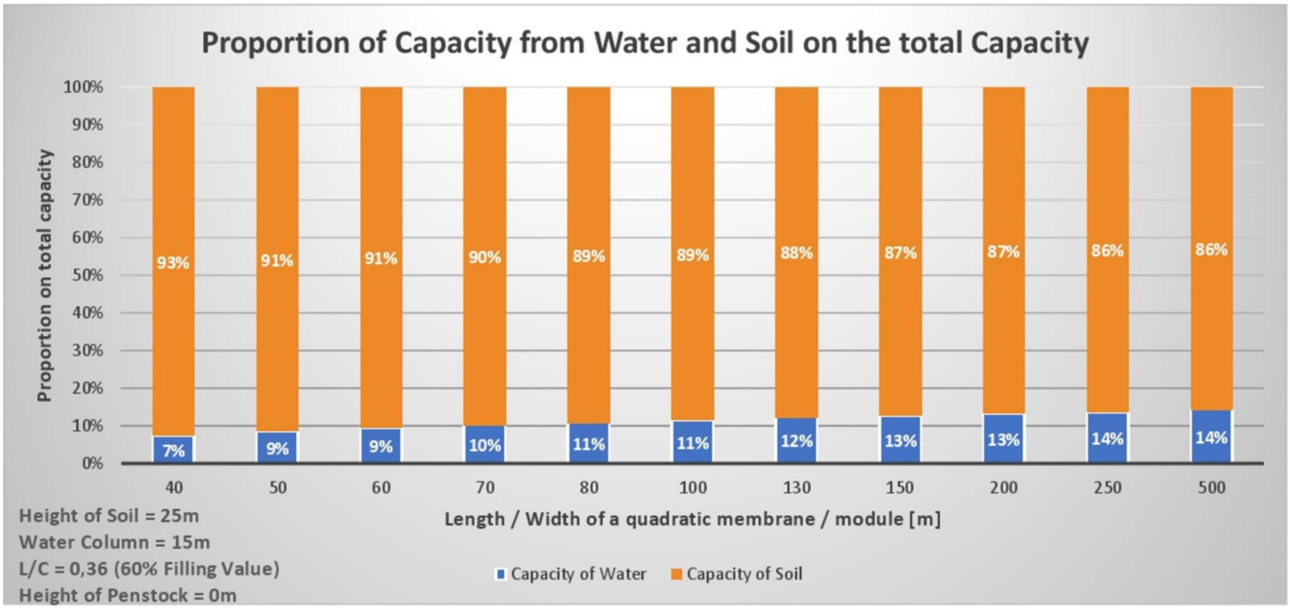
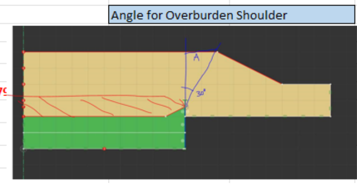


Fig. 7 Proportion of capacity from soil and water on entire system capacity

In general, the simplest and cheapest variation is a storage made of 1 module. The desired capacity influences then the dimensions of the module. Since a high-capacity requirement could lead to a very large module, the table also offers the possibility of calculating a different quantity of modules in their dimensions, which can then form a total capacity in addition.

With this approach also maintenance aspects would assumingly be addressed better, as for example a leakage in the membrane can cause a shutdown of a module for an uncertain period.

Phyiscal Basic Values	Density Top Soil	kg/m3	2.000				
	Density Water	kg/m3	1.000				
	Gravitational constant	m/s2	9,81				
System Stability Factors	**Filling Level of Membrane - %**	**[%]**	**60%**	**70%**	**80%**	**90%**	**Changes in this value have highest impact on total costs**
	Resulting Average Height of Water = $L_{average}$	$L_{average}$ [m]	9,00 m	10,50 m	12,00 m	13,50 m	
	$L_{average}$ / C < 0,36 = stable system		0,36	0,42	0,48	0,54	experiences from Foulum: ratio < 0,3 = stable system ; ratio = 0,36 technically possible to reach
Primary influencing variables	**Quantity of Modules (= quantity of individual storages)**		**6,0**	**6,0**	**6,0**	**6,0**	
	Length/Width Membrane Storage	**a** [m]	129,99 m	119,15 m	110,40 m	103,15 m	
	Height of Soil = C = Jordhøjde	**C** [m]	25,00 m	25,00 m	25,00 m	25,00 m	
	Max. Height of Water	**H_s max** [m]	15,00 m	15,00 m	15,00 m	15,00 m	
Secondary influencing variables	Height Penstock	**h0** or **H_p** [m]	10,00 m	resulting penstock height in relation to depth below terræn (D43)	6,00 m		
	Head Loss	[m]	1,00 m				
	Min. Water Level in the storage when empty	**H_s min** [m]	0,10 m		Angle for Overburden Shoulder		
	Slope Inclination Ratio Storage		1 : 1,0				
	Slope Inclination Ratio Soil over terræn		1 : 2,0				
	Distance between Modules	[m]	2,00 m				
	Efficiency Turbine /Total RTE	[%]	72%	7% loss in soil /7			
	Depth below terræn	[m]	4,00 m				
	Slope Inclination Ratio Soil under terræn		1 : 1,0				
	Angle for Overburden Shoulder	[°]	0				



Qty of Modules	no angle	angle from D43
6,0	622.939 m3	622.939 m3
6,0	2.387.551 m3	2.387.551 m3
6,0	2.191.986 m3	2.191.986 m3
6,0	2.048.469 m3	2.048.469 m3

Fig. 8 Different influencing parameters

With regards to the different influencing parameters (fig. 8), the table is split up in main elements:

- **Physical Basic Values**
  - Density
  - Gravity Constant
- **System Stability Factors** – with regards to the experiences from Foulum made by AU
  - Filling Level of Membrane in %
    - In connection to the height of overburden soil (C) and the max. height of water inside the membrane (H_s max), this leads directly to a visualization of the resulting average height of water inside the membrane and the $L_{average}$ / C – value
    - If the $L_{average}$ / C exceeds a certain value the color changes from green to red
- **Primary influencing variables** – these values have major influence on capacity and costs
  - Quantity of modules
  - Length / Width of one membrane module (a)
  - Height of Soil on top of one membrane module (C)
  - Max. Height of Water inside one membrane module (H_s max)
- **Secondary influencing variables** – these values have more or less minor influence on capacity and costs
  - Height of penstock (h0 or H_p) – height differences between bottom of storage and reservoir
    - in relation to the depth below terrain there is another field showing the resulting height of penstock
  - Head loss – energy loss due to friction etc. in the pipes
  - Min. Water Level in the membrane storage when empty (H_s min) – represents the remaining water level inside the membrane once it is discharged.
  - Slope inclination ratio storage – the slope angle inside the storage
  - Slope inclination ratio soil over terrain – the slope angle of the overburden soil *(depends on soil conditions and has no effect on capacity, only on the costs)*
  - Distance between modules – in case of more than 1 module, the closer the modules are located to each other, the less costs are required for the soil(works) between each module *(has no effect on capacity, only on the costs)*
  - Efficiency, turbine *(set to 72% = 7% loss in soil and 79% in hydro system)*
  - Depth below terrain – in case the storage bottom can be implemented below terrain level *(influences costs on soil and resulting height in penstock)*
  - Slope inclination ratio soil under terrain – the slope angle for implementation below terrain level
  - Angle for overburden shoulder – in case of more than 1 module. To minimize interaction of the overburden soil from each module with each other, the auxiliary calculation is shown aside. *(has no effect on capacity, only on the costs)*

Calculation Blocks

Capacity								
Total Capacity	[kWh]	**112.000 kWh**	**112.000 kWh**	**112.000 kWh**	**112.000 kWh**			
Quantity of modules		**6,0**	**6,0**	**6,0**	**6,0**	this influences the outer circumference of the plant and is **MANUALLY** considered in row 52		
Module Capacity	[kWh]	**18.667 kWh**	**18.667 kWh**	**18.667 kWh**	**18.667 kWh**			
Total Costs								
Total Costs	[€]	**20.651.798 €**	**18.401.577 €**	**16.713.928 €**	**15.401.568 €**			
Costs - € / MWh	[€/MWh]	**184.391 €/MWh**	**164.300 €/MWh**	**149.232 €/MWh**	**137.514 €/MWh**			
Soilworks (no purchase of soil!)						**Base for Unit Price**		
Soil - Volume	[m3]	3.200.753 m3	2.743.687 m3	2.400.551 m3	2.133.471 m3	Soil Removal	UP = 25,00 DKK/m3	means, to remove soil and store it on a pile for
	[m3/module]	533.459 m3/module	457.281 m3/module	400.092 m3/module	355.579 m3/module	Building up of Soil	UP = 28,00 DKK/m3	means, to remove soil and build up in one run
	under terræn	422.346 m3	356.136 m3	306.820 m3	268.717 m3	**MANUAL VALUE inserted for Amount of SIDES - See comment**		
	over terræn	2.778.407 m3	2.387.551 m3	2.093.731 m3	1.864.754 m3	**MANUAL VALUE inserted for Amount of SIDES - See comment**		
Soil - Unit Price / m3	[€/m3]	3,21 €/m3	3,21 €/m3	3,21 €/m3	3,21 €/m3	roportion of volume to removal and Pile up of 1st Modul		
Soil - Total Costs	[€]	10.276.435 €	8.808.327 €	7.706.206 €	6.848.402 €	25%		means, quantity of soil to be removed and stor
% approach of given UP for up to 200.000m3	[%]	85%	85%	85%	85%	means, for a larger quantity than 200.000m3 a deduction in UP should be possible		

Fig. 9 Calculation Blocks - Capacity, Total Costs and Soilworks

Following the influencing parameters, the blocks for the capacity, total costs and soilworks are stated. From the initial influencing parameters, the capacity calculation is made in total and per each module, depending on the quantity of modules for a system. With the “What-If-Analysis” and “Goal Seek” Tool it is also possible to calculated backwards from a desired capacity to the initial influencing parameters to see what different possibilities are there.

The total costs for a system are shown directly in the next block, to enable a simple visual connection from the total costs to the costs per MWh.

Soilworks

This is followed by a block for the Soilworks, in where no costs to purchase or dispose soil material are considered. The soilworks only consider pure implementation works on site: excavating, on-site movement, piling on a temporary heap and refilling in layers.

Arkil’s cost indications for the removing/excavating and temporary piling are 25 DKK/m3 (cell I55). For removing/excavating and refilling in layers are 28 DKK/m3 (cell I56) given. Both unit prices are given for an amount of up to 200.000m3. Possible reductions of 10% – 15% could be the case if an extremely large amount of soil (e.g., 7.000.000m^3) must be moved and therefore even bigger machinery can be applied. This mentioned reduction can be considered by the user manually by filling a %-value in the row *% approach of given UP for up to 200.000m3* (cell D61). The method of soil implementation is rather standard for soil construction, which means a distribution of soil in layers of ca. 30cm height, with e.g., help of excavators, and compaction of these layers until the desired soil column is reached.

The rows *under terræn* and *over terræn* refer to if the user decides to lower the height of the storage in comparison to the surrounding terrain level. For such soil needs to be excavated and the resulting amount is shown in the row *under terræn*.

One cell shows the description *“Proportion of volume to removal and Pile up of 1st Module”* (cell H60) which refers to the work step of soil to be removed and stored temporarily before implementation of first geosynthetics. This typically is an approach for excavation soil, thus this %-value is only included in the calculation that consider a value bigger than zero (X > 0) at *Depth below terræn* (cell D43). The intention behind this is to enable consideration of the costs for the soil that must be moved twice. If the storage is built on plane ground only the unit price for removing and refilling (Cell I56) affects the costs. Costs to prepare this plane ground (removal of topsoil, flattening out of area, …) are not considered.

The %-value states the part of the area of the 1st module, in where the soil is therefore moved twice. The calculation of the Unit Price is then the % of the volume (m3) x 25dkk/m3 (to remove soil) + 100% of the volume (m3) x 28 dkk/m3 (building up of soil). For more than 1 module this is considered as a part of the first module in the unit price.

This is a very theoretical approach in the excel file, with the intention to enable the user to get indications of possible optimizations of the unit price and total price through help of implementation with reduced steps / rotations.

Geosynthetics						
Area	[m2]	101.384 m2	85.179 m2	73.129 m2	63.836 m2	
Unit Price / m2	[€/m2]	33,03 €/m2	33,03 €/m2	33,03 €/m2	33,03 €/m2	
		reduced UP	reduced UP	reduced UP	reduced UP	
Total Costs Geosynthetics	[€]	3.348.716 €	2.813.449 €	2.415.463 €	2.108.500 €	
% approach of given UP for 25.000m2	[%]	90%	90%	90%	90%	means, for a larger quantity than 25.000m2 a deduction in UP should be possible
Penstock						
approx. Length	[m]	440 m	407 m	381 m	359 m	
Estimate Unit Price / m	[€/m]	1.300 €/m	1.300 €/m	1.300 €/m	1.300 €/m	
		estimate DN1600 PE	estimate DN1600 PE	estimate DN1600 PE	estimate DN1600 PE	
Estimate Total Costs Penstock	[€]	571.960 €	529.680 €	495.561 €	467.274 €	
% approach of estimated UP	[%]	100%	100%	100%	100%	
Hydroelectrical Equipment						
Turbine power	[MW]	11,10 MW	11,10 MW	11,10 MW	11,10 MW	
Costs per MW	[€/MW]	412.365 €/MW	412.365 €/MW	412.365 €/MW	412.365 €/MW	
Overall Costs	[€]	4.577.250 €	4.577.250 €	4.577.250 €	4.577.250 €	
% approach of estimated costs per MW	[%]	100%	100%	100%	100%	
Risks / Unforeseen / Reservoir etc.						
	[%]	**10%**	**10%**	**10%**	**10%**	

Alternative hydroelectrical equipment		
3,20 MW System	UP = 465.625 €/MW	1.490.000 €
4,90 MW System	UP = 441.837 €/MW	2.165.000 €
11,10 MW System	UP = 485.135 €/MW	5.385.000 €
23,80 MW System	UP = 377.521 €/MW	8.985.000 €

Fig. 10 Calculation Blocks - Capacity, Total Costs and Soilworks

In the next calculation blocks the geosynthetics, penstock, hydroelectrical equipment and risks are considered.

The unit price for the geosynthetics is the sum of the different items required in course of implementing geosynthetics for the membrane storage taken from Solmax' proposal. Beside the membrane material and works itself, this also means materials for protection and their implementation etc. Similarly, to the soilworks, in the below line the user can enter a qualified guess in terms of deductions once the dimensions considerably increases, compared to the quantity on which the unit prices was made.

As geosynthetics are polymer products which are made during oil processing prices can be rather volatile and be influenced by global politics and supply chain issues. (esp. in the current times)

Risks and unforeseen expenses are recommended to be 10% in the calculations.

Maintenance

For maintenance it is considered that in course of lifting and sinking after 12 years the membrane requires to be changed and in course of that it is assumed that soilworks in a range of 70 to 80% of the initial volume must be carried out. The costs for such were set to 10 million €.

5. WP conclusions and perspective

The present development in batteries (NMC) indicates that the costs will approach about 150 €/kWh and for infrastructure, inverter etc. approx. 300 €/kW.

For a 5.0 MW / 37 MWh system it will reach 7.0 million EUR corresponding to 190 000 €/MWh.

As a rule of thumb, the $L_{average}$ / C – ratio should be kept below 0.3 to maintain a stable soil cover. However, the higher ratio the better CAPEX. Simulations and tests have indicated that a ratio of 0.36 would be acceptable. For the example design this ratio is equivalent to a lifting height of 9 meters with 25 meters of topsoil column, which is equal to 60% of filling level of the membrane (15m lifting height = 100% of Filling level).

In the following figures the correlation of costs, membrane filling and $L_{average}$ / C ratio for a 112 MWh plant are shown. The plant consists of six membranes (6 module plant) with a resulting penstock height of 10 meter.

To be a present competitive solution CAPEX must be in the area of or below 200 €/MWh. As it can be observed from the figure below the costs are higher than the target value of 200 €/MWh unless the $L_{average}$ / C ratio moves into the unstable area. For a future competitive solution, e.g., in 2030, a CAPEX must be in the area of 110.000€ and 140.000€.

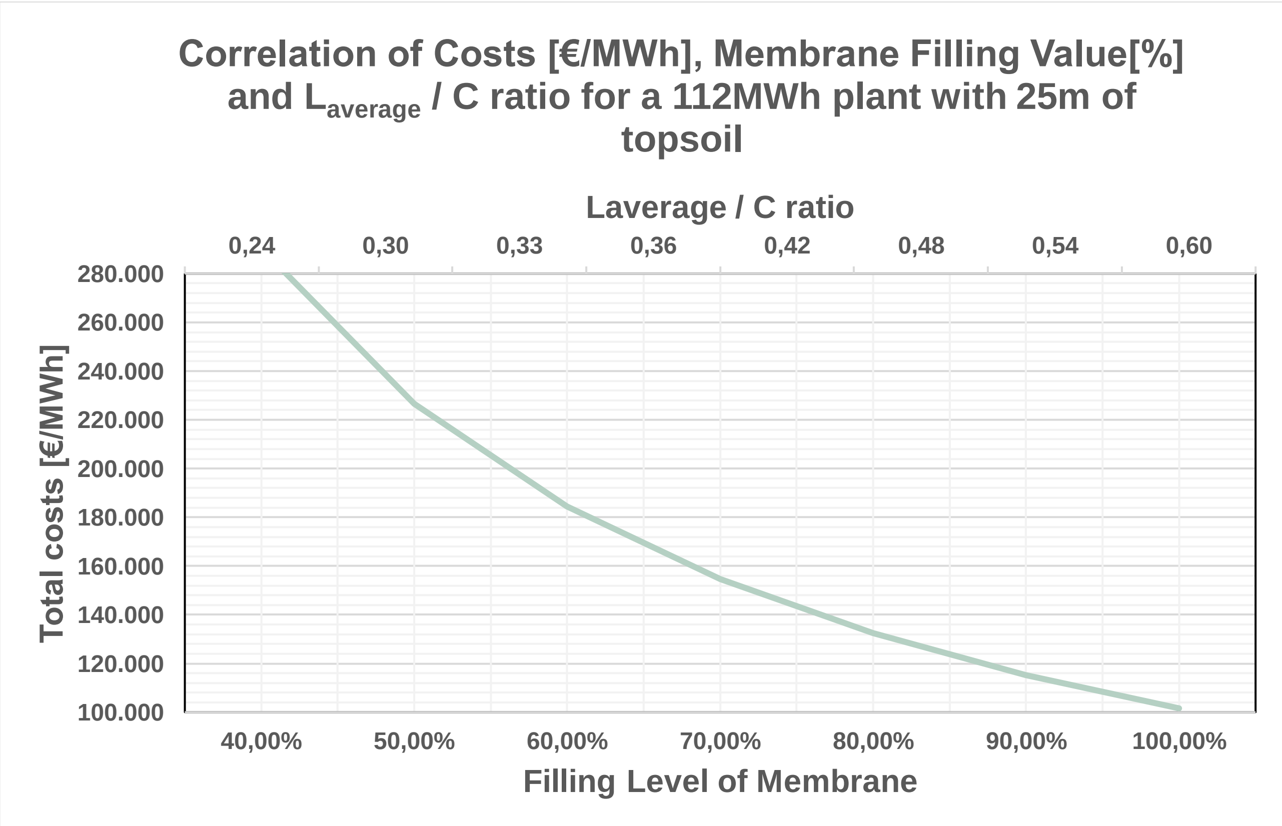


Fig. 11 A total price relation with *$L_{average}$ / C* ratio and *Filling Level of Membrane*.

Similarly to the figure shown beforehand, the L/C ratio is the main influencing factor on both, the system stability and the costs. An increase of filling level of membrane (= increase of water column) leads to an increase of L/C ratio. For example, an increase from 60% to 70% of filling level leads to 20.000€ less costs per MWh. Another 10% more water reduces the costs for more 15.000€ per MWh. At 90% filling level (plus 30%, L/C = 0,54) the costs are 40.000€ per MWh less, compared to a filling level of 60%. However, the CAPEX is can be influenced by the amount of modules used and it improves by increasing a plants capacity. Furthermore, an increased L/C ratio leads to more beneficial outcomes, since a smaller area per module (side/length) with corresponding effects on the quantities of the individual components results in further cost reductions.

In general, the distribution of cost elements is rather similar, no matter of the size of the plant or the amounts of modules, however the priciest component (soilworks) benefits, if the water column can be increased – see below figure.

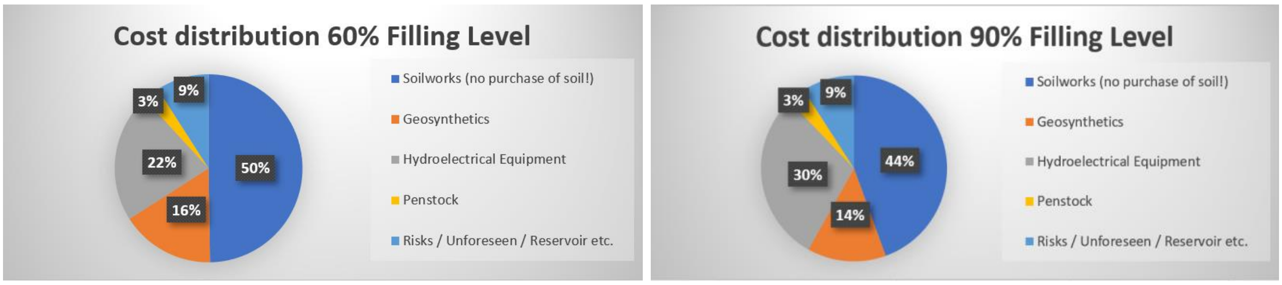


Fig. 12 cost distribution for a 112MWh plant with 6 membranes, filled at 60% and at 90%

For any construction about half of the costs go on earthworks. For an increased number of modules more pipes are required leading to higher costs for the penstock. Also, the costs for geosynthetics are likely to be increased then. On the other hand, the portion of costs for the hydroelectrical equipment rather decreases with increased capacity.

In the appendix are more comparisons and evaluations made, about the cost-influence on a 100MWh, 112MWh and a 200MWh plant with different numbers of membranes and if a single input value changes.

For example, increasing the inclination of the outer slope can lead to cost savings. It is technically not a simple issue to facilitate such, as it depends on geotechnical parameters of the chosen soil. However, an increased inclination leads to less soil volume required without impacts on the capacity, which then soil also may have to be stabilized then. Using geosynthetics for soil stabilization can be a method. Additional costs for such are not considered yet.

More than 50% of the costs are apportioned to the soil works. Furthermore, the height of soil has, in combination with the water column, a direct impact on the capacity (L/C ratio). To investigate this further and find sustainable technical solutions to increase this value can therefore be a very interesting question to look at.

Perspective

The UPHS technology can be an interesting alternative way of storing energy like a pump hydro storage, but for areas with less diverse elevations. Locating the plant nearby the sea can be a logical cause from there, as also the calculation does not consider costs for a reservoir, but water can rather be use from natural sources. A further optimization is required in the soil behaviour and technical stability, since it was shown how a small change can causes quite huge positive impacts on the CAPEX. Beside that also other cost influencing variables have potential to be investigated in order to optimize, as the excel tool gives information about.

Below are a few more optimization ideas mentioned:

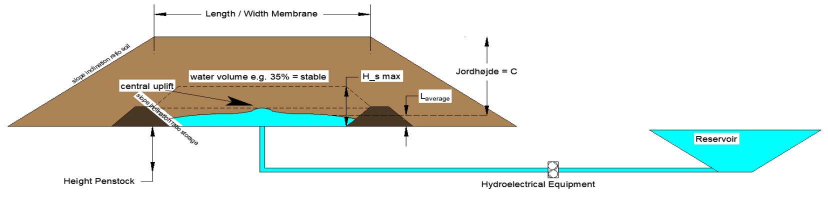
- Optimization of Soil installation
    - Blowing soil in position instead of traditional installation
    - Less compaction
    - Increase of layer thickness from e.g., 30cm to e.g., 50cm etc. to reduce implementation time per m3 and increase output per m3.
- Increase inclination of outer soil-edge from 1:2 (27°) to e.g., 1:1 (45°) or more.
    - May require reinforcement (with geosynthetics), therefore cost decrease is not linear to the decrease of volume, but assumingly still significant.

6. Appendices

Annex 1 → excel tool with several pages of calculations, information, diagrams, …

Annex 2 →Price information from suppliers

This Sheet contains the calculation principle for the UPHS (capacity and dimensions)



Energilagringsdimensionering firkant og rektangel

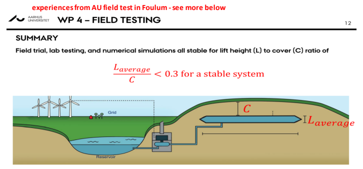
Jord / Soil	Jordhøjde	**H_j** [m]	25.0	
	Jordvolume	m3	214,299	
	Pressure ...	Pa	490500	
	... in Meter Water Column	m	50.00	
Waterstorage / Membrane	Longest Length	**A** [m]	92.58	
	Longest Width	**B** [m]	92.58	
	Length above the min water level	**A@H_s min [m]**	63.38	
	Ratio / Slope / Inclination		1 : 2.0	26.57°
	½ Højde / ½ Water Level **h1 / h2**	**h1 / h2** [m]	7.50	
	Vandsøjle, max / Max Water Level	**H_s max** [m]	15.00	
	Længde ("nedre") / Shortest Length	**a** [m]	62.58	*31.29*
	Bredde ("nedre") / Shortest Width	**b** [m]	62.58	
	Total Water Volumen	m3	54,850	
	Minimum Water Level	**H_s min** [m]	0.2	
	Circulating Water Volume	**m3**	**54,056**	
	Extra Liner Anchor Trench	m	3	
	Liner Area	m2	7,378	
Lift-Height to Cover Ratio	Inflation of Total Water Volume Membrane	**[%]**	60%	!
	$L_{average}$ = Average Height of Water Level	$L_{average}$ [m]	9.00	
	Cover = C = Jordhøjde	**H_j** [m]	25.00	
	H_s max / H_j < 0,36 for a stable system	**[ ]**	0.36	

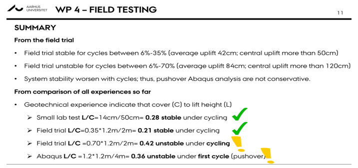
Energilagringskapacitet — MAX kapacitet

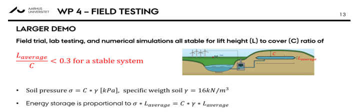
Energy Calculation PlanEnergi	Jordhøjde	**C** or **H_j** [m]	25.0	
	$L_{average}$ = Vandsøjle =	$L_{average}$ [m]	9.00	
	Penstock minus Head Loss	**H_p** [m]	0.0	
	Densitet, jord	kg/m3	2,000	
	densitet, vand	kg/m3	1,000.0	
	Gravitationskonstant	m/s2	9.81	
	Epot, vand, considering H_s min	GJ	4.667	
	Epot. jord, considering H_s min	GJ	37.000	
	Energilagringskapacitet i Vand, C_tot	**kWh**	**1,296.3**	
	Energilagringskapacitet i Jord, C_tot	**kWh**	**10,277.8**	
	Total energilagringskapacitet, C_tot	**kWh**	**11,574.07**	
	Virkningsgrad, turbine	%	72%	
	Effektiv energilagringskapacitet, C_eff	**kWh**	**8,333.33**	
Penstock	Bassinhøjde, over turbine	**h0** or **H_p** [m]	0.0	
Calculation Effective Head	Maximum gross Head	m	59.0	
	Minimum gross Head	m	50.2	
	Mean Gross Head	m	54.6	
	Head Loss	m	0.00	**this value is used to calculate the Pipe Dimension**
	Mean effective Head	m	54.6	
	Mean net Head	m	54.6	
	Minimum Water Level Reservoir	m	0.0	*assuming water can be taken from the sea*
	Maximum Water Level Reservoir	m	0.0	*assuming water can be taken from the sea*

experiences from AU field test in Foulum - see more below

The value 0,30 has been increased to 0,36 in this file !



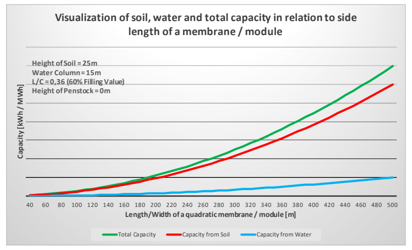


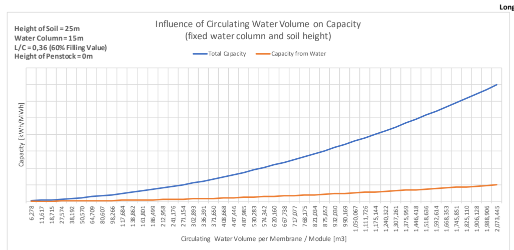


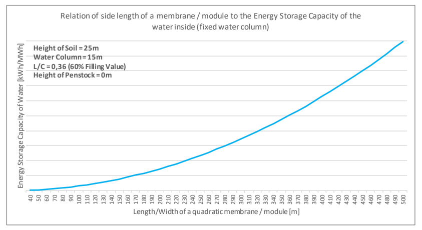
C (m)	L (m)	gamma (kN/m3)	C*L*gamma	L/C
15	12	16	2880	0.80
30	6	16	2880	0.20

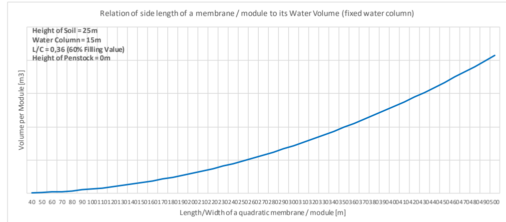
Tables / Diagrams

Longest Length of a Membrane [m]	C_tot	Vand, C_tot	Jord, C_tot	Circulating Water Volume
40	2,069	151	1,918	6,278
50	3,276	279	2,998	11,657
60	4,765	449	4,316	18,715
70	6,536	661	5,875	27,574
80	8,589	916	7,674	38,192
90	10,925	1,213	9,712	50,570
100	13,542	1,552	11,990	64,709
110	16,441	1,933	14,508	80,607
120	19,623	2,356	17,266	98,266
130	23,085	2,822	20,263	117,684
140	26,830	3,330	23,500	138,862
150	30,857	3,880	26,978	161,801
160	35,167	4,472	30,694	186,499
170	39,758	5,107	34,651	212,958
180	44,631	5,783	38,848	241,176
190	49,786	6,502	43,284	271,154
200	55,223	7,263	47,960	302,893
210	60,943	8,067	52,876	336,391
220	66,944	8,912	58,032	371,650
230	73,227	9,800	63,427	408,668
240	79,792	10,730	69,062	447,446
250	86,639	11,702	74,938	487,985
260	93,769	12,716	81,052	530,283
270	101,180	13,773	87,407	574,342
280	108,873	14,871	94,002	620,160
290	116,848	16,012	100,836	667,738
300	125,106	17,196	107,910	717,077
310	133,645	18,421	115,224	768,175
320	142,466	19,688	122,778	821,034
330	151,569	20,998	130,571	875,652
340	160,954	22,350	138,604	932,030
350	170,622	23,744	146,878	990,169
360	180,571	25,181	155,390	1,050,067
370	190,802	26,659	164,143	1,111,726
380	201,316	28,180	173,136	1,175,144
390	212,111	29,743	182,368	1,240,322
400	223,188	31,348	191,840	1,307,261
410	234,547	32,996	201,552	1,375,959
420	246,189	34,685	211,504	1,446,418
430	258,112	36,417	221,695	1,518,636
440	270,317	38,191	232,126	1,592,614
450	282,805	40,007	242,798	1,668,353
460	295,574	41,866	253,708	1,745,851
470	308,625	43,766	264,859	1,825,110
480	321,959	45,709	276,250	1,906,128
490	335,574	47,694	287,880	1,988,906
500	349,471	49,721	299,750	2,073,445

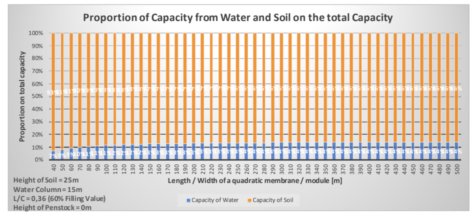




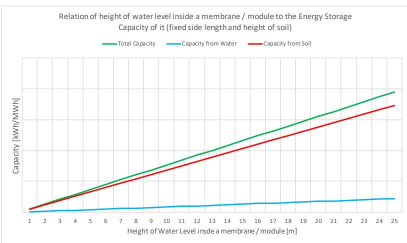




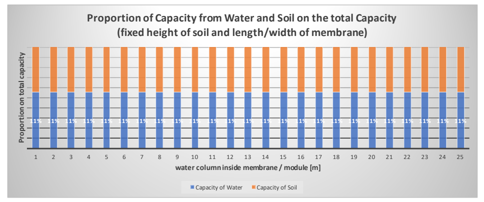
Longest Length of a Membrane	C_tot	Vand, C_tot	Jord, C_tot
40	100%	7%	93%
50	100%	9%	91%
60	100%	9%	91%
70	100%	10%	90%
80	100%	11%	89%
90	100%	11%	89%
100	100%	11%	89%
110	100%	12%	88%
120	100%	12%	88%
130	100%	12%	88%
140	100%	12%	88%
150	100%	13%	87%
160	100%	13%	87%
170	100%	13%	87%
180	100%	13%	87%
190	100%	13%	87%
200	100%	13%	87%
210	100%	13%	87%
220	100%	13%	87%
230	100%	13%	87%
240	100%	13%	87%
250	100%	14%	86%
260	100%	14%	86%
270	100%	14%	86%
280	100%	14%	86%
290	100%	14%	86%
300	100%	14%	86%
310	100%	14%	86%
320	100%	14%	86%
330	100%	14%	86%
340	100%	14%	86%
350	100%	14%	86%
360	100%	14%	86%
370	100%	14%	86%
380	100%	14%	86%
390	100%	14%	86%
400	100%	14%	86%
410	100%	14%	86%
420	100%	14%	86%
430	100%	14%	86%
440	100%	14%	86%
450	100%	14%	86%
460	100%	14%	86%
470	100%	14%	86%
480	100%	14%	86%
490	100%	14%	86%
500	100%	14%	86%



Height of Water Level [m]	C_tot	Vand, C_tot	Jord, C_tot	Circulating Water Volume
1	526	59	467	54,056
2	1,315	147	1,168	54,056
3	2,104	236	1,869	54,056
4	2,894	324	2,569	54,056
5	3,683	412	3,270	54,056
6	4,472	501	3,971	54,056
7	5,261	589	4,672	54,056
8	6,050	678	5,372	54,056
9	6,839	766	6,073	54,056
10	7,628	854	6,774	54,056
11	8,418	943	7,475	54,056
12	9,207	1,031	8,176	54,056
13	9,996	1,120	8,876	54,056
14	10,785	1,208	9,577	54,056
15	11,574	1,296	10,278	54,056
16	12,363	1,385	10,979	54,056
17	13,152	1,473	11,679	54,056
18	13,941	1,561	12,380	54,056
19	14,731	1,650	13,081	54,056
20	15,520	1,738	13,782	54,056
21	16,309	1,827	14,482	54,056
22	17,098	1,915	15,183	54,056
23	17,887	2,003	15,884	54,056
24	18,676	2,092	16,585	54,056
25	19,465	2,180	17,285	54,056



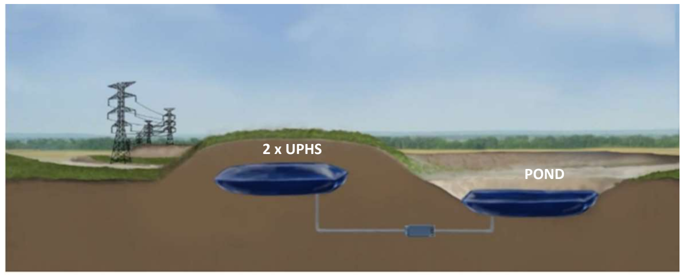
Height of Water Level [m]	C_tot	Vand, C_tot	Jord, C_tot
1	100%	11%	89%
2	100%	11%	89%
3	100%	11%	89%
4	100%	11%	89%
5	100%	11%	89%
6	100%	11%	89%
7	100%	11%	89%
8	100%	11%	89%
9	100%	11%	89%
10	100%	11%	89%
11	100%	11%	89%
12	100%	11%	89%
13	100%	11%	89%
14	100%	11%	89%
15	100%	11%	89%
16	100%	11%	89%
17	100%	11%	89%
18	100%	11%	89%
19	100%	11%	89%
20	100%	11%	89%
21	100%	11%	89%
22	100%	11%	89%
23	100%	11%	89%
24	100%	11%	89%
25	100%	11%	89%



SOLMAX

-CONFIDENTIAL-

Boundary conditions			System sketch
2 x UPHS			
-	**Geometry**	**rectengular**	
-	**Volume* - 1 Bubble**	**122.000 m³**	
-	**Slope inclination**	**1 : 2,00**	
-	**Edge length (top)**	**100,00 m**	
-	**Edge length (bottom)**	**64,00 m**	
-	**Depth****	**9,00 m**	
POND			
-	**Geometry**	**rectengular**	
-	**Volume**	**128.000 m³**	
-	**Slope inclination**	**1 : 2,00**	
-	**Edge length (top)**	**125,00 m**	
-	**Edge length (bottom)**	**75,00 m**	
-	**Depth**	**12,50 m**	



Item / Short description	Product	Quantity	Unit	EP	Cost estimation Total
SOLMAX material incl. installation					
- protection bottom layer UPHS	Non-woven geotextil 1.200 g/m² - without shipping costs due missing location	24.692	m2	7,90	195.066,80
- bottom layer UPHS	SOLMAX ProFlex 2.0 mm - without shipping costs due missing location	24.692	m2	9,80	241.981,60
- top layer UPHS	SOLMAX ProFlex 2.0 mm - without shipping costs due missing location	24.692	m2	10,90	269.142,80
- protection top layer UPHS	Non-woven geotextil 1.200 g/m² - without shipping costs due missing location	24.692	m2	8,10	200.005,20
- protection bottom layer POND	Non-woven geotextil 1.000 g/m² - without shipping costs due missing location	21.101	m2	6,70	141.376,70
- bottom layer POND	SOLMAX HD 2.0 mm black - without shipping costs due missing location	21.101	m2	7,90	166.697,90
SUM material incl. installation					**1.214.271,00**

Expected installation time:

- 2 x UPHS	1962 working hours	1 installation crews	14	weeks, can be speed up by more installation crews
- POND	680 working hours	1 installation crews	5	weeks, can be speed up by more installation crews

In the estimated costs not included:

- freight costs for the delivery of the material
- building site facility - approx. 5% of the sum costs - not considered due missing location
- project management - approx. 2% of the sum costs - not considered due missing location
- penetrations / connection of the in- and outlets incl. prefabrication units or other special unit parts
- possible floating cover on top of the POND to avoid dirt in the water plus balasting to collect and remove the rainwater from the cover
- costs for Standby due to reasons beyond SOLMAX control, e.g.: no installation possible due to bad weather and any 3rd party influence or else
- extra mobilization technicians in case of interuption due to non -SOLMAX- responsibility

Further not included services which shall be provided by purchaser, to facilitate field installation works, at no cost for SOLMAX:

- earthwork preparation inclusive of excavation and backfilling of anchor trenches, surface shall be inspected by SOLMAX epresentative prior to laying and shall be free of stones or sharp objects that may damage the liner;
- concrete structures, pipe penetrations, etc., shall be completed prior to any lining installation;
- filling material for approx. 10.000 sand bags, filled (ca. 5kg / each), for temporay ballast
- permanent wind ballast placement well coordinated with SOLMAX installation progress
- storage area adjacent to the working area
- heavy equipment (excavator, crane, TLB / Merlot / Manitou) for unloading; material handling, roll transport and -deployment, etc. +operator + fuel
- material unloading and transport to storage yard (near heat storage pond) coordinated with SOLMAX installation progress
- power supply (30 kVA, 400V) close to each installation area
- dewatering of jobsite during the construction period
- waste disposal management
- office such as equipment storage container (40'') for SOLMAX

* Volume UPHS considers two full truncated pyramids. In reality it will be less due to the edge design.

** The high of the UPHS is 2 x depth.

WP 6 UPHS - Use case studies

1. WP details

WP title	UPHS: WP 6 Use case studies
WP partners	Vestas/EuropeanEnergy/AquaNamic

2. WP Summary

The economic feasibility of the UPHS has been evaluated based on specific use case simulation studies and evaluation of other storage technologies. Since we have not been able to fix the design of the UPHS in this concept and test study, we have used best estimated UPHS data for these studies. As the geotechnical studies at AU will proceed, also after the finalization of the EUDP project, we also intend to use the developed economical use case model for the updated UPHS data coming out of these future studies.

BC is for ***the time being*** *not attractive in Denmark. However, several factors may in the future turn the UPHS into a positive BC and an attractive energy storage solution. Key factors to ensure this will be:*

1) *A higher value factor. According to* Danish Energy Agency and published in April 2022 (System scenarios, April 2022), the volatility in the Danish electricity market is expected to increase towards 2030, hence it could be expected that the value factor will be increased.
2) *Further optimizations of the UPHS design enabling a lower CAPEX. As we have seen in WP 5 this should be possible.*
3) *Further optimization of the total round trip efficiency.*
4) *Further we may see that future RE-projects will require "Mandatory" installation of storage-capacity.*

Compared to other present available storage technologies, e.g. lithium battery storage systems, we can observe the UPHS could be a more economical favourable solution, of cause assuming that the UPHS technology will be matured.

Another key driver for the UPHS technology may be that the UPHS storage technology will not be depending on raw materials coming from outside EU/USA, which may be an advantage in the new geopolitical situation developing for the time being.

Hence, if the UPHS technology can be developed and matured it may be an attractive solution for a future energy storage solution.

3. WP objectives

Task 6.1 Economical and business analysis from asset owner perspective

The overall goal of this task is to establish a financial model capable of assessing the financial performance of this energy storage solution.

Key input to the model will involve the following items:

- CAPEX – which include all cost of realization of the energy storage facility, including electricity generators capable of delivery both electricity and ancillary services to the grid;
- OPEX - which include all cost related to operation of the plant in terms of land-lease, financial costs, insurance, service and maintenance cost, etc.;
- Income from Power sales as given by the operational strategy and electricity market price;
- Income from ancillary services sold on market conditions based on participation in auctions, where these services are understood to include frequency-controlled normal reserve (FCR-N), reactive power, black start and other grid-forming services;
- Lifetime and uncertainty estimate for those key parameters that are representing this installation in the model.

It is evident from this listing, that several key questions are still unknown. This is not only related to CAPEX and OPEX, but also in relation to a realistic operational strategy that must be developed, while respecting the actual capacity of the storage facility (in terms of MWh), power of the generator (in terms of MW) and experimentally verified capability to deliver ancillary services (in terms reactive power, response time etc.).

The operational model must also be developed and optimized in an iterative process comparing various financial returns with different strategies and related CAPEX estimates.

European Energy will be instrumental in developing the financial model provided relevant input, and this will be generated during the other workpackages in terms of actual CAPEX and OPEX.

Task 6.2 Economical and business analysis from asset producer perspective

The overall goal of this task is to evaluate the technical and economic viability of the UPHS technology as an active component in the electricity system. This will be done by building a high-level simulation model that captures the key characteristics of the energy storage solution as seen from the electricity markets. These characteristics need to be identified as part of the project and are expected to mature over the project duration.

- This high-level model will be used to estimate the revenue potential of a UPHS system by generating charging and discharging timeseries. These will be generated by exposing the high-level model to multiple scenarios. The scenarios will be developed as part of the project and could as an example be applying the UPHS as a stand-alone solution in the power market or combining it with wind and/or solar. The UPHS ability to tap into multiple markets at the same time, also known as value stacking, will also be evaluated based on the results from the other work packages. Towards the end of the project, it will be investigated, whether real life control of the prototype from Vestas' central control infrastructure is feasible to subject the prototype to real-life operational signals.

4. WP implementation

Vestas and European Energy into this project with the roles of "problem owners". Both companies sell sustainable energy solutions across the world and energy storage is a rapidly increasing market and an increasing demand for energy storage will be expected

The content of WP 6 has been relying of inputs and interactions from primary WP5. Based on preliminary UPHS system data delivered to EE and Vestas beginning of 2021 preliminary system models were developed. These models have continuously been improved during the project (in the **annex 6.1** and 6.**2** we have attached descriptions and results from these models).

As mentioned in the previous WPs, we were not able to achieve a validation of a geotechnical "stable" UPHS system. Hence, some of the key numbers for the simulation studies were estimated.

However, based on the present UPHS estimations and optimizations from WP 5 following key data were used for the use case studies.

Soil load: 25 m

Lifting height: 9 meter. (corresponding to lifting height/Soil load = ca. 0,3)

Total storage capacity: 112 MWh

Capex: 22 mil EUR

Cost € / MWh: 197.000

Membranes: 6 pcs (each ca. 130x130 m)

Soil load: ca. 25 m

Lifting height of membrane: ca. 9 m

Turbine size: ca. 11 MW (Note can be adapted to a lager size if this will give a significant economical advance)

Total round trip efficiency: 72-73 %

Allocated RISK: 10 % of total cost.(added in the CAPEX)

Total estimated lifetime of the UPHS: 24 years

Mid-life preventive maintenance in year 12: 10 mil EUR.

Yearly soilwork maintenance: 50.000 EUR.

Yearly maintenance of hydro electrical equipment and system: 25.000 EUR

Even though the above-mentioned numbers are not finally validated in the geotechnical simulations studies, we have chosen to use these in the simulation use cases, enabling a bench mark towards other energy storage systems.

Besides the actual key data of the UPHS system a number of key data for the grid was also determined and used in the simulation cases. (e.g. grid export limits, price limits, price delta for arbitrage, operational usage of the storage..). The detailed descriptions can be found in annex 6.1.

5. WP results

The first conclusion when looking at the business cases with UPHS included and based on the **actual** grid data, demonstrate a difficult and unattractive business case with a **negative profit of 12.8 mEUR** for the full-size installation.

It's important to emphasize, that a systematic optimization of the Energy Storage Management model have not been made, to ensure that the most optimal configuration of parameters related to the operational strategy are selected for the chosen configuration. Many trials have been made, but learnings and experience from this manual optimization operation has not been systematically explored.

The work presented in the attached reports shall still be considered work-in-progress. Several elements shall be investigated further, before any final conclusions can be drawn.

The most important single factor will be an improved understanding of on the **Value Factor** that achievable with a system like this. Whereas a calculation of this factor in the first place relies on the ability to model a realistic operational strategy for the storage system, something which is well explored in the developed Energy Storage Management model, it's still necessary to look further into the Value Factor estimation. To perform this analysis, it's necessary to have access to energy pricing forecast which not only addresses the baseload price expectations, but also provide insights in the market volatility as such.

Without this analyze, it's difficult to make clear conclusions, but it's a good guess, that the Value Factor calculated in the present version of the report is **greatly underestimated**. This is indicated by the huge impact of time-period historical year) selected for the storage management analysis.

By running the BC calculations with **20 % variations** of selected critical parameters, the following output can be calculated:

UPHS	Unit	Sensitivity-20% on energy loss	Sensitivity-20% on value factor	Sensitivity-20% on Storage Capex	Sensitivity-20% on Opex
Site specific					
Area (lease)	[ha]	100.0	100.0	100.0	100.0
GHi estimate	[kWh/m2/a]	1013.6	1013.6	1013.6	1013.6
Technology concept					
Substructure	[-]	FT (26x2P)	FT (26x2P)	FT (26x2P)	FT (26x2P)
Energy Yield					
Specific energy yield (Yf)	[kWh/kWp]	1,175	1,175	1,175	1,175
Grid connection					
Connection body	[DSO,TSO]	DSO	DSO	DSO	DSO
DSO voltage-level	[A_høj etc.]	A_høj+	A_høj+	A_høj+	A_høj+
Grid connection specific fee	[tDKK/MW]	458	458	458	458
Project sizing					
Grid capacity assumed	[MVA]	79.25	79.25	79.25	79.25
Project KPI					
Total installed DC power	[kWp]	95,560	95,560	95,560	95,560
Energy Yield Assessment	[GWh]	112.31	112.31	112.31	112.31
Power ratio dc to grid	[kWp/kW]	1.21	1.21	1.21	1.21
CapEx					
CAPEX in total	[EUR/kWp]	*815.13*	*815.13*	*769.09*	*815.13*
Total CAPEX (fixed and variable)	[MEUR]	77.89	77.89	73.49	77.89
-hereof OTHERS incl. grid-fee paid	[MEUR]	26.88	26.88	22.48	26.88
Power Sales					
Energy export to the grid	[GWh]	108.6	107.8	107.8	107.8
PPA sales price	[EUR/MWh]	75.00	75.00	75.00	75.00
Selected Merchant price (10y avg.)	[EUR/MWh]	91.6	109.9	91.6	91.6
Value Factor after peak-shift & arbitrage (vs. reference)	[%]	1.009	1.211	1.009	1.009
Losses and curtailment					
Energy loss between generator and PCC	[%]	2.843%	3.554%	3.554%	3.554%
OpEx					
Annual operational expenses (sum of all years)	[mEUR]	80.61	81.14	80.42	51.61
Annual Operational costs by revenue	[%]	34.4%	30.3%	34.6%	22.2%
Business case					
Unleveraged project IRR	[%]	5.7%	7.5%	6.3%	7.0%
Profit (inv. value - CAPEX)	[mEUR]	-12.22	-2.40	-8.39	-5.14

The most important observation related to this table, is the very limited impact of energy loss reduction (Round-Trip-efficiency).

In contrast, it's clear that the **value factor** of the storage solution is **key to competitiveness** as it raises the business case by almost 10 mEUR.

Also **20% reduction in Capex and/or Opex** are seen to be quite important.

Hence, an increase of the value factor (20%) and a reduction of the CAPEX (20%) would give a **positive** BC

As for the scaling, further work is needed to assess if the arbitrarily chosen PV site size is well selected for a standard unit of this storage system.

Initial analysis has been made to evaluate the impact of generator and/or pump sizes, which still need to be included in the reporting.

Finally, it needs to be emphasized, that other revenue streams may be possible to tap into when considering ancillary services and grid balancing. This has not been considered in this report.

Besides the actual numbers coming out of the simulation studies we can also validate the UPHS economical feasibility towards "competing" technologies. E.g. batteries. To put the estimated parameters into context we made a comparison, using the newest numbers from Lazard[1] for a 11MW/112MWh, these values are made by scaling the available numbers for a 4-hour grid scale battery storage system. Such a battery would have a CAPEX of approx. **28,5 Mio EUR**. The reduction in capacity that have been made to the estimates do not render the technology uncompetitive.

The expected O&M costs for such a battery system would approximately be 100kEUR/year. Here again the estimates for UPHS still seem attractive, however these numbers are very uncertain due to the soil stability issues that have been observed at Foulum.

The main drawback of UPHS is the round-trip efficiency which is approximately 10 percentage points lower for UPHS than a corresponding lithium-Ion battery. Traditional pumped hydro storage has a similar efficiency to that of lithium ion so compared to both technologies there is need for improvement. This improvement can either come as a significant cost reduction on CAPEX so that the additional losses in OPEX are acceptable or simply by improving the efficiency.

6. WP conclusions and perspective

Though the **present** business cases (based on the actual key data for both UPHS system and Grid data) are not attractive, we can still observe the overall importance of having access to a large energy storage facility, is linked to general energy-system trends over the coming years.

First, the value of this capability to operate an arbitrage revenue stream, is linked to the volatility in the market. As can be seen from the figure below which has been generated by EA energianalyze on behalf of the Danish Energy Agency and published in April 2022 (System scenarios, April 2022), the volatility in the Danish electricity market is expected to increase towards 2030, whereafter it might fall again. This conclusion is extracted from the steepness of the duration-curve.

[1] Lazards-levelized-cost-of-storage-version-70-vf.pdf https://www.lazard.com/media/451882/lazards-levelized-cost-of-storage-version-70-vf.pdf

Based on this observation the general UPHS business should become more attractive in the coming years.

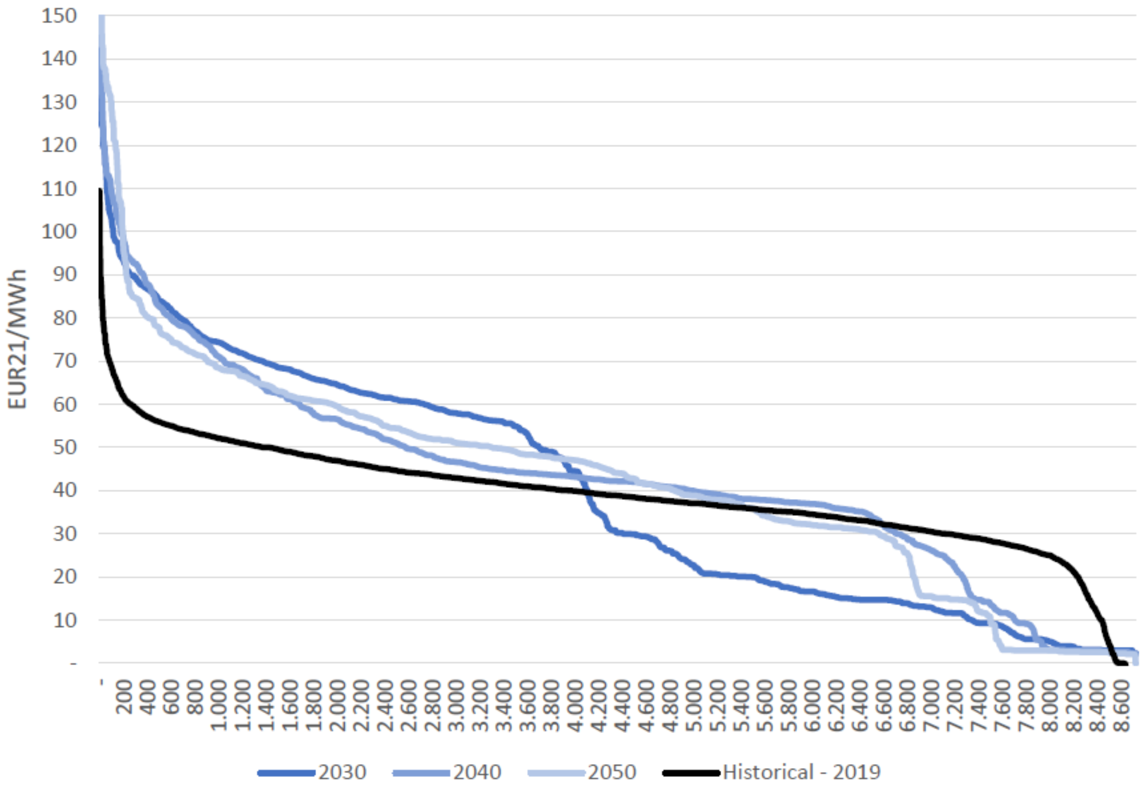


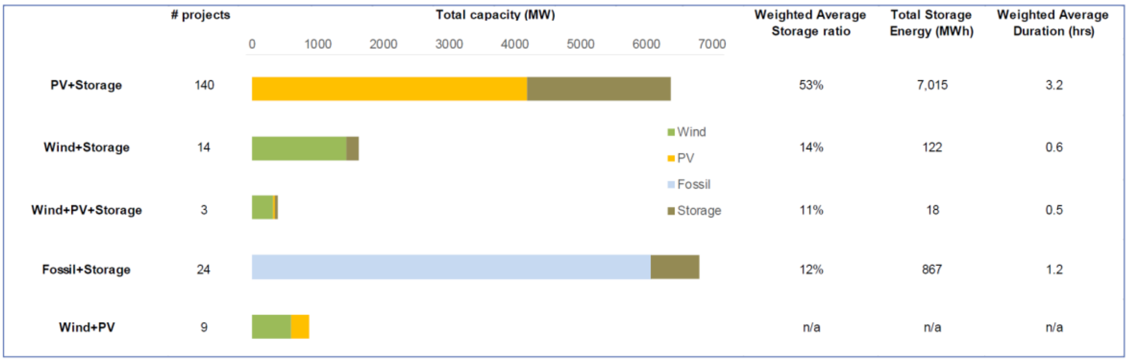
Fig. 1 Volatility in the Danish electricity market Danish Energy Agency and published in April 2022 (System scenarios, April 2022

Another observation relates to the availability of cheap electricity which is a precondition for the overall arbitrage business model. Since PtX installation are now being announced and planed for deployment in Denmark in quite large numbers, it's becoming clear that there's a competition among several future off-taker classes, who all base their business model on the availability of such cheap electricity. This observation may indicate that the **general UPHS business case** will not improve significantly under Danish conditions over the coming years.

Based on this observation the general UPHS business could of cause become more challenged in the coming years. However, a PtX may also need some kind of Energy Buffer to maintain a continuous production and here a UPHS may come in as solution.

Finally, there's an observation related to potential requirements for large storage units to be deployed in connection with RE generation projects, driven by requirements from the network operators (DSO and TSO) and balancing responsible parties for the project to limit the ramp-rate as seen by the grid withing narrow conditions. This could be accompanied with requirements for the generator to deliver a certain minimum expected capacity factor, which also may only be achieved by adding large scale storage and reducing the grid capacity for such projects. This trend is now seen in the US, as illustrated in the figure below provided by Lawrence Berkeley National Laboratory in August 2022 in their report "Hybrid Power Plants, Status of Operating and Proposed Plants, 2022 edition".

PV+Storage hybrids are most numerous (140), and have by far the most storage capacity (2.2 GW) and energy (7 GWh) than other hybrids



Notes: Not included in the figure are 108 other hybrid / co-located plants with other configurations; details on those plants are provided in the table on slide 7. ***Storage ratio*** *is defined as total storage capacity divided by total generation capacity within a hybrid type.* ***Duration*** *is defined as total MWh of storage divided by total MW of storage within a hybrid type.*

Sources: EIA 860 2021 Early Release, Berkeley Lab

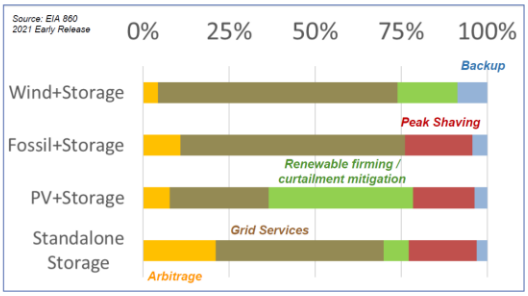
Based on this observation, the general UPHS business should become **more attractive** in the coming years since UPHS may replace batteries as used in the US, and since **market trends** driving co-location of generation+storage may also be applicable in Europe.

.As a potenial offtaker of this techoolgy Vesats has followed the project with great interest and still sees a

Breakdown of self-reported use cases for battery storage is somewhat similar whether a standalone battery or a hybrid, though there are a few key differences

- Operators self-report use cases to EIA; individual plants can indicate multiple use cases
- Grid services are the most commonly reported use case, though renewable firming and curtailment mitigation is particularly important in PV+Storage hybrids
  - Wind+Storage has primarily targeted ancillary service markets
  - PV+Storage more often used to firm the PV capacity for resource adequacy purposes
- Backup power and arbitrage are least popular use cases reported by operators

Breakdown of battery use case among popular hybrid configurations and standalone storage



Grid services category includes the following: frequency regulation, load following, ramping/spinning reserve, load management, and voltage/reactive power support

large potential in the technolgy. The project has also uncoverd a number of isues that need to be adressed before the actual feasibility of the technoligy can be analysed in detail. For the future work with this technolgy Vestas sugests the follwing targets:

1. Keep Capex and Opex signficantly below competeting battery technolgies – aim to be 30% below the expecetd Lithium-Ion prices in 2030
   a. UPHS is a new storge technolgy and in its characteristics seems to have more in common with traditional Pumped Hydro rather than batteries. Pumped Hydro storage has a price point that is below half of that for Lithium-Ion which is the argument for setting an aggressive target for the CAPEX and OPEX price points

b. Based on the current bloomberg predictions for the price point for Lithium ion in 2030 the UPHS techocligy should target a goal of 110 kEUR/MWh installed.

2. Focus on impooving the technical capabilaities
    a. Flexibilit is key in the energystsystem of the future and therfor it is vitale that the UPHS technology is continued to be developed in that direction.
    b. Focus on increasing the efficiancy - aim for >80% to compete with regular PHS
    c. Focus on the ability to hold enegry for long periods of time with out losses
    d. Focus on investigating degradation – degradation is the single largest risk a storage operator has to deal with, and being a new technology this will cost a discount on the price for comemrcial operators.
    e. Focus on ramprates and the speed at hich the flow can be reversed – aim for 30% of nominal power increase or reduction within 7,5 seconds to fulfill the FCR-D requriemnts in th e nordics.

Besides the above-mentioned observations, we may also include Geopolitical impact on different competing technologies. The UPHS will be mainly independent of lithium or manufacturing facilities coming from areas controlled by countries opposing western democracies. Hence, an UPHS competing, even if it only “on par”, with battery solutions may still be an attractive solution for EU and US.

7. Appendices

Annex 6.1: EE simulation study

Annex 6.2: Vestas simulation study

EUROPEAN ENERGY

Financial viability of UPHS

Elements of a commercial assessment of the technology and concept under development.

24 August 2022
Jan Vedde

Gyngemose Parkvej 50 – 2860 Søborg

Introduction

European Energy is partner in the EUDP supported project “Underground Pumped Hydro Storage” with responsibility as subtask leader of Task 6.1 “Economical and business analysis from European Energy” with expected outcome to be delivered according to the Commercial Milestone 6.3. titled “Description of and resume of Use cases and Business Cases”.

The overall goal of this task is to establish a financial model capable of assessing the financial performance of this energy storage solution. This assessment will be based on both financial data and technical specifications of the storage solutions, but also need to be considered in a specified context or use-case which will determine both the operational strategy applied and opportunities to stack revenue from various business opportunities under a set of ever-changing market conditions.

Use-case

The reference use-case investigated in this analysis relate to the combination of the Energy Storage solution with a utility scale PV project in Denmark. As alternatives, also combinations with wind projects and installations outside Denmark will be discussed. The reference PV case is based on a generic 100 MWp project to be constructed in Denmark in 2023.

Revenue streams considered

The following opportunities for revenue generation has been considered. In all cases, a decision to store generated energy in the UPHS system will depend on an assessment of the availability of free storage capacity in the system. While considering different opportunities for management of the operational decisions, priority will be given to the *negative-price* scenarios and *peak-shaving* opportunities, since in such hours the alternative income can be considered as zero. The second priority of storage to be considered is arbitrage, where the calculated income from the generated energy, is estimated to be higher in the future compared to a sales opportunity within the production hour.

Negative pricing

Whenever the forecasted electricity price is negative, it will be more attractive to store the energy as compared to selling with a negative income. For this reason, it’s always of priority

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to ensure empty capacity in the energy storage system for energy expected to be generated during hours of negative (or very low) pricing.

Following this decision to store energy in the system, also a decision to sell the energy at a later time once the electricity prices have raised to a higher or very high level, is given.

Peak-shaving: inverter clipping

Since the energy to be stored must be available in form of AC-electricity, all energy that may be made available by the solar panels must be converted from DC into AC to be made useful (either through direct sales or indirect through sales from the storage system).

In case the capacity of the inverter is less than the dc-energy provided as input to the inverter, the excess energy will be lost and cannot be recovered. Technically this will be done with the inverter MPPT, which will set the input voltage at some distance from the maximum MPPT voltage level.

Peak-shaving: grid-curtailment

Since new grid-connection fees will be applicable in Denmark for all new projects, where significant payments will be requested by both the local utility and Energinet, and since these payments will be related to the amount of AC-grid-capacity requested, there's a strong incentive to reduce the amount of grid-capacity requested for the project. Since a reduction in grid capacity will reduce the amount of energy exported, a business opportunity can be identified related to a reduction of grid-capacity requested in exchange for a loss of energy-export, where the energy-export loss may be recovered through the Energy Storage solution proposed.

Whereas the revenue generation related to sale of the curtailed energy which would otherwise be lost is core to use-case and considered directly in the developed Energy Storage Management model, the avoided up-front cost of grid-access payment is considered in the financial modelling which bundles the overall RE-project economy with the storage modelling.

Arbitrage

The more complex operational strategy relates to arbitrage, where a decision is made to not sell the energy generated as-produced on the spot-market but rather to store the energy in the expectation that sales prices later will be higher.

To decide if the available storage capacity should be use for arbitrage during any given hour, it's necessary to consider the several alternatives. Not only is it required that the sales-price within a foreseeable future will be significantly higher than the prices which can be obtained during the production-hour, but also the over-price expected shall be able to off-set the lack of revenue which will follows from the storage related energy loss referred to as Round-trip-efficiency-loss.

License to operate and RfG compliance

When grid-connecting large RE generating projects based on intermittent energy sources, a range of national conditions for grid-connection must be met. Such conditions may include direct or indirect requests to establish a hybrid connection with both energy storage and generator capacity, based on local demands for limited ramp-rate variations of the power feed to the grid or requirements for certain capacity factor targets to be meet. In these situations, the business-case for UPHS inclusions will be defined according to the opportunity profit on the direct generator business-case which may be defined in the financial modelling as the difference between a business case with and without UPHS included.

Ancillary service market opportunities

The most frequent reason to install battery electrical energy storage today, is related to opportunities to generate revenue in the ancillary service market. As participation in the market is very dependent on local and actual market conditions and therefore are difficult to quantify without inclusion of extensive analysis of the actual business operational risks, and as the technical capability of the UPHS solution is still not fully determined with respect to reaction time and ability to be active in this market, this potential revenue stream is not considered in the present description.

Energy storage management

An energy storage management model has been developed in Excel to enable simulation of various operational strategies.

Generator modelling

Since the it's important for an assessment of the value of a storage solution to consider in detail the relationship between actual energy generation from renewable sources and the actual electricity spot-price, and since it's difficult to simulate this relationship for markets for the coming years, it's decided to base the generation profiles on historical data from existing Danish PV and WTG projects. Hereby the correlation between actual generation and actual prices can be considered correct – at least historically.

Since the existing projects may be smaller in size and for the sake for relevance, it's been decided to scale the generator profile to a relevant level which for the generic project examples will be equivalent to a 100 MWp solar site. To avid complexity related to scaling of profiles which may already be inverter-clipped or otherwise curtailed, only PV projects installed since 2019 can be considered (before overplanting was normal) and the scaling is referenced to the maximum exported amount of energy as seen in the EnergiNet datahub, where hourly exported generation is available in unites of kWh delivered to the grid per hour.

The reference project used in the scaling exercise is named "Sol6", but also three other PV projects and some WTG projects have been investigated to access the variability.

Spot-price modelling

Hourly spot prices are collected from Nord Pool for both DK1 and DK2 in units of DKK/MWh. Since the reference project was inaugurated in December 2019, we have production data available for 2½ year. Not only electricity prices but also volatility in the market has seen to be quite different over this span of time. To capture the more promising market opportunities energy storage operations have been simulated for year 2021 as reference and the last year (July 1st, 2021 – June 30th, 2022) and year 2020 as alternatives.

Operational strategy

Hourly day-ahead prices are generally known one day before the operation takes place. Since the modelling of the storage system is based on historical prices, it's possible to consider the actual spot-prices as a fully enlightened operational planner – that is no element uncertainty or estimation is considered when taking future prices into consideration.

The modelling progress hour-by-hour such that a decision shall be made in each hour if the generation (of above 0) shall be sold at the current market-price or if the energy shall be stored for later sale. In this model the duration of the *planning period* (the period considered when making decision on sell or store) is a free input parameter, typically set to 24-32 hours.

Also, during the hour, a decision shall be made if some of the energy already stored shall be sold now or kept for later sale. For this decision a parameter has been introduced to describe the number of top-ranking pricing periods during the upcoming planning period, where power sales from the storage shall be considered.

For both types of decision, boundary conditions related to the capacity of pumps, turbines, storage system and grid-export access shall be considered.

Additional parameters to guide the operational strategy will be the minimum over-price (*price-delta*) considered, to decide to store energy. This over-price reflect difference between the sales-price foreseen within the planning period les the sales prices offered during the hour of generation.

The reference sets of operational parameters are listed below.

Parameter set	Hour-ahead selling decision perspective	Sales price priority to induce discharge decision	Power-price limit considered negative	Price delta for arbitrage
	[h]	[#]	[DKK/MWh]	[DKK/MWh]
OP1	22	3	4	50

Energy storage system

The UPHS storage system is described in detail in other WP so in this context only some key technical and financial characteristics are listed as being used in the reference case. Three different configurations of the system have been investigated.

For the basic solution with 6 membranes, 5 m height distance to pond, 25 m overlay soil and 9 m lifting height, a storage capacity of 120 MWh can be calculated.

Further characteristics on the electrical equipment, efficiencies are summarised in the tables below and financial data in the next table.

Parameter set	Storage concept description	Storage capacity	Initial capacity	Lower capacity	Charging power	Discharging power	Charging efficiency	Discharging efficiency
	[-]	[MWh]	[MWh]	[MWh]	[MW]	[MW]	[%]	[%]
ESS1	M=6; Vd=5; Hs=25; Lh=9	120	0	1	11	11	85.0%	85.0%
ESS2	M=6; Vd=5; Hs=25; Lh=9	120	0	1	**22**	**22**	85.0%	85.0%
ESS4	M=6; Vd=5; Hs=25; Lh=9	120	0	1	44	44	85.0%	85.0%
BESS1-1		1			1	1	90%	90%
BESS1-2		1			2	2	90%	90%

Storage concept description	Battery CapEx	Reinvestment	Reinvestment yearly interval	Recovery value	Battery Opex	Battery Opex escalation	Interest rate for LCOS calculation
[-]	[EUR]	[EUR]	[Year]	[EUR]	[EUR/year]	[%/a]	[%]
M=6; Vd=5; Hs=25; Lh=9	22,000,000	10,000,000	12	2,000,000	75,000	2.0%	2.0%

Energy storage modelling

By running the energy storage model using the above-described input parameters, the following data are provided as basic characterising data.

Scaled generation and grid export - reference case

Project calculation	Unit	Reference
Storage concept description	[-]	Grid: 79.25MW, UPHS: ESS2-OP1
Generator project – reference		
Project code	[-]	Sol6
Start date	[yyyy-mm-dd]	2021-01-01
Reference generator power	[MWh/h]	42.90
Generator project - modelled		
Modelled generator power	[MW]	95.56
Grid export power limit	[MW]	79.25
Energy storage system design		
Storage capacity	[MWh]	120
Storage charging power	[MW]	22
Storage discharging power	[MW]	22
Energy storage operating strategy		
Hour-ahead selling decision perspective	[h]	22
Sales price priority to induce discharge decision	[#]	3
Power-price limit considered negative	[DKK]	4
Price delta for arbitrage	[DKK]	50
Output – reference operation (as if no storage is installed)		
Generation - scaled total (no storage)	[MWh]	112,314
Energy loss (due to neg. price and grid limitation)	[%]	6.04%
Income direct energy export (excl neg. price and curtailment)	[mDKK]	58.77
Capture Price (excl neg. price and curtailment)	[DKK/MWh]	556.9
Value Factor reference (vs. baseload)	[-]	0.851

The maximum expected generation is 95.56 MWh/h, but this maximum export capacity is only required during a single hour of the year and does not need to determine the grid capacity in the agreement with the utility. According to the RfG compliance requirements a grid capacity 81.25 MWh/h is required to fulfil the RfG. This is due to the requirements set in the RfG to deliver a certain amount of reactive power, which reduces the amount of active power that can be connected. In the specific case the grid access has been further reduced by additional 2 MW, to save cost related to the grid-fee. By decreasing the grid access capacity by these extra 2 MW the total energy loss observed from both negative pricing (where the export is reduced to zero) and the curtailment in the grid, is determined as 6%. This energy should have priority to be stored for later sales when sufficient grid access is available.

The sections describing the “Energy storage system design” and “Energy storage operating strategy” are summaries of previous described input data and are identical to all cases. The section “Output - uncurtailed & no storage” provide information on reference operation, that is the expected energy export sales under the given curtailment conditions and given the power prices during the period in question.

By dividing the total income by the total sales volume, the capture price is calculated (in this case 556.9 DKK/MWh). This number can be compared to the baseload price (unweighted average) and seen to be significantly lower than this (index 85), which reflects the fact that prices often are high during winter and during night, when the solar PV cannot deliver energy to the grid – unless through a storage solution.

Energy export with storage: 1. negative prices & grid curtailment

Additional output from the simulation model is given in the table below, where only the first priority storage operation has been considered.

Output - energy storage of neg. price & curtailed energy		
Energy export - direct (excl. peak shifted)	[MWh]	106,338
Energy export - indirect (peak shifted)	[MWh]	2,848
Income - direct sales (peak shift excluded)	[mDKK]	58.77
Income - battery sales (peak shifted)	[mDKK]	1.83
Income - direct & indirect sales (peak shifted)	[mDKK]	60.60
Energy loss (peak-shift recovered)	[%]	2.78%
Equivalent Full Cycles (due to peak shift)	[#]	28
Capture price (after peak shift)	[DKK/MWh]	555.0
Value Factor after peak-shift (vs. reference)	[-]	0.997
Capture price improvement after peak-shift	[-]	-0.34%

Most of the energy are still sold directly to the market (106.3 GWh, 58.8 mDKK), but in addition 2.8 GWh of energy representing an income of 1.8 mDKK are also sold after being stored in the UPHS in an equivalent storage system loading of 28 full cycles.

Compared to the reference case without storage, the loss of energy is now reduced from 6.0% to 2.8%. This reduction reflects the energy “recovered” for later sale (from negative pricing and grid curtailment) whereas the remaining loss of 2.8% reflects the limitation in pump-power installed, which limits the amount of energy that can be stored.

Energy export with storage: peak-shift & arbitrage

By activating the full “intelligence” of the Energy Storage Management calculation which involve arbitrage decisions algorithms, further revenue can be generated and added to the direct export and peak-shaved energy sales.

Output - peak shift & arbitrage

Energy export - direct (peak shift & arbitrage subtracted)	[MWh]	103,227
Energy export - indirect (peak shifted & arbitraged)	[MWh]	5,096
- Balance: Gross energy loss	[MWh]	3,127.6
Income - direct sales (peak shift & arbitrage excluded)	[mDKK]	57.23
Income - battery sales (peak shifted & arbitrage included)	[mDKK]	3.64
Income - direct & indirect sales (peak shifted & arbitrage)	[mDKK]	60.87
Energy storage loss (operating peak shift & arbitrage)	[%]	3.55%
Equivalent Full Cycles (storing peak shift & arbitrage)	[#]	51
Capture price (peak shift & arbitrage)	[DKK/MWh]	562.0
Value Factor after peak-shift & arbitrage (vs. reference)	[-]	1.009
Capture price improvement after peak-shift & arbitrage	[-]	0.91%
LCOS – summary		
LCOS	[EUR/MWh]	14.94

This income now consists of 57.2 mDKK from the direct sale of 103.2 GWh but in addition also 5.1 GWh of energy will be sold from the UPHS which for the spot prices in 2021 would generate additional 3.6 mDKK in revenue such that the total income of 60.9 mDKK now is 2.1 mDKK higher than the reference without UPHS installed.

The equivalent number of full load cycles have been increased to 51 and the capture price is now 562.0 DKK/MWh which represents a small increase in capture price of 0.9%.

Finally, the LCOS has been calculated based on the financial numbers listed above, resulting in a LCOS estimate just below 15 EUR/MWh.

Technical - financial modelling

The calculations presented so far, does not answer the question if the storage solution represents a positive business case. To address this question, it's necessary to consider the storage system in the context of a full energy generating project, that can act as source for the energy to be stored and the framework for energy sales in general.

In the example described in this document, the selected storage case is evaluated as an element in a generic Danish PV project framework.

PV project basics

The generic PV project has been developed for other purpose and is characterised below.

UPHS	Unit	Reference Grid:79.25MW NO UPHS	Reference Grid:79.25MW UPHS:Aqua M6-P22
Site specific			
Area (lease)	[ha]	100.0	100.0
GHi estimate	[kWh/m2]	1013.6	1013.6
Technology concept			

Substructure	[-]	FT (26x2P)	FT (26x2P)
Energy Yield			
Specific energy yield (Yf)	[kWh/kWp]	1,175	1,175
Grid connection			
Connection body	[DSO,TSO]	DSO	DSO
DSO voltage-level	[A_høj etc.]	A_høj+	A_høj+
Grid connection specific fee	[tDKK/MW]	458	458
Project sizing			
Grid capacity assumed	[MVA]	79.25	79.25
Project KPI			
Total installed DC power	[kWp]	95,560	95,560
Energy Yield Assessment	[GWh]	112.31	112.31
Power ratio dc to grid	[kWp/kW]	1.21	1.21
CapEx			
CAPEX in total	[EUR/kWp]	*584.91*	*815.13*
Total CAPEX (fixed and variable)	[MEUR]	55.89	77.89
-hereof OTHERS incl. grid-fee paid	[MEUR]	4.88	26.88
Power Sales			
Energy export to the grid	[GWh]	105.0	107.8
PPA sales price	[EUR/MWh]	75.00	75.00
Selected Merchant price (10y avg.)	[EUR/MWh]	90.8	91.6
Value Factor after peak-shift & arbitrage (vs. reference)	[%]	1.000	1.009
Losses and curtailment			
Energy loss between generator and PCC	[%]	6.040%	3.554%
OpEx			
Annual operational expenses (sum of all years)	[mEUR]	52.03	80.42
Annual Operational costs by revenue	[%]	23.1%	34.6%
Business case			
Unleveraged project IRR	[%]	11.5%	5.5%
Profit (inv. value - CAPEX)	[mEUR]	14.79	-12.79

This table summarise both information on several different topics, covering information related to the site, technology, grid connection, CapEx, OpEx, energy yield & sales as well as power sales expectations.

The conclusion in terms of business case, include information on the project IRR and the expected profit in both absolute (m€) and relative (to the investment value) terms.

Reference case conclusion

The first conclusion when looking at the business cases with UPHS included, demonstrate a difficult and unattractive business case with a negative profit of 12.8 mEUR for the full-size installation.

It's important to emphasize, that a systematic optimisation of the Energy Storage Management model have not been made, to ensure that the most optimal configuration of parameters related to the operational strategy are selected for the chosen configuration. Many trials have been made, but learnings and experience from this manual optimization operation has not been systematically explored.

Alternative configurations

As alternative configurations to explore comparing to the reference case based on Sol6 and year 2021, below alternatives based on other solar projects, other investigating periods and examples with Wind projects have been included.

Other time-periods

It's obvious that the earnings and price volatility depends very much on the observation period, and below the same calculations have been performed for three different 1-year periods starting January 1st 2020, January 1st 2021 and July 1st 2021. It's well known, and easily observable that the latter periods do include more high-price spot prices.

Project calculation	Unit	Alt_2020	Alt_2021	Alt_2021H2
Generator project - reference				
Project code	[-]	Sol6	Sol6	Sol6
Start date	[yyyy-mm-dd]	2020-01-01	2021-01-01	2021-07-01
Reference generator power	[MWh/h]	42.90	42.90	42.90
Generator project - modelled				
Modelled generator power	[MW]	95.56	95.56	95.56
Grid export power limit	[MW]	79.25	79.25	79.25
Output - reference operation (as if no storage is installed)				
Generation - scaled total (no storage)	[MWh]	120,151	112,314	116,470
Energy loss (due to neg. price and grid limitation)	[%]	7.61%	6.04%	5.20%
Income direct energy export (excl neg. price and curtailment)	[mDKK]	21.14	58.77	115.71
Capture Price (excl neg. price and curtailment)	[DKK/MWh]	190.5	556.9	1,048.0
Value Factor reference (vs. baseload)	[-]	1.020	0.851	0.960
Output - peak shift & arbitrage				
Energy export - direct (peak shift & arbitrage subtracted)	[MWh]	109,905	103,227	107,947
Energy export - indirect (peak shifted & arbitraged)	[MWh]	5,427	5,096	4,951
- Balance: Gross energy loss	[MWh]	4,214.0	3,127.6	2,666.5
Income - direct sales (peak shift & arbitrage excluded)	[mDKK]	20.79	57.23	112.78
Income - battery sales (peak shifted & arbitrage included)	[mDKK]	1.57	3.64	7.71
Income - direct & indirect sales (peak shifted & arbitrage)	[mDKK]	22.36	60.87	120.49
Energy storage loss (operating peak shift & arbitrage)	[%]	4.01%	3.55%	3.07%
Equivalent Full Cycles (storing peak shift & arbitrage)	[#]	54	51	49
Capture price (peak shift & arbitrage)	[DKK/MWh]	193.9	562.0	1,067.2
Value Factor after peak-shift & arbitrage (vs. reference)	[-]	1.018	1.009	1.018
Capture price improvement after peak-shift & arbitrage	[-]	1.78%	0.91%	1.84%
LCOS - summary				
LCOS	[EUR/MWh]	14.03	14.94	14.34

With the above Energy Storage key operational results (Value Factor increase, Total energy loss) transferred to the financial model, the below results are found.

UPHS	Unit	Alt_2020	Alt_2021	Alt_2021H 2
Site specific				
Area (lease)	[ha]	100.0	100.0	100.0
GHi estimate	[kWh/m2/a]	1013.6	1013.6	1013.6
Technology concept				
Substructure	[-]	FT (26x2P)	FT (26x2P)	FT (26x2P)
Energy Yield				
Specific energy yield (Yf)	[kWh/kWp]	1,257	1,175	1,219
Grid connection				
Connection body	[DSO,TSO]	DSO	DSO	DSO
DSO voltage-level	[A_høj etc.]	A_høj+	A_høj+	A_høj+
Grid connection specific fee	[tDKK/MW]	458	458	458
Project sizing				
Grid capacity assumed	[MVA]	79.25	79.25	79.25
Project KPI				
Total installed DC power	[kWp]	95,560	95,560	95,560
Energy Yield Assessment	[GWh]	120.15	112.31	116.47
Power ratio dc to grid	[kWp/kW]	1.21	1.21	1.21
CapEx				
CAPEX in total	[EUR/kWp]	*815.13*	*815.13*	*815.13*
Total CAPEX (fixed and variable)	[MEUR]	77.89	77.89	77.89
-hereof OTHERS incl. grid-fee paid	[MEUR]	26.88	26.88	26.88
Power Sales				
Energy export to the grid	[GWh]	114.8	107.8	112.3
PPA sales price	[EUR/MWh]	75.00	75.00	75.00
Selected Merchant price (10y avg.)	[EUR/MWh]	92.4	91.6	92.5
Value Factor after peak-shift & arbitrage (vs. reference)	[%]	1.018	1.009	1.018
Losses and curtailment				
Energy loss between generator and PCC	[%]	4.011%	3.554%	3.067%
OpEx				
Annual operational expenses (sum of all years)	[mEUR]	82.12	80.42	81.54
Annual Operational costs by revenue	[%]	32.9%	34.6%	33.4%
Business case				
Unleveraged project IRR	[%]	6.6%	5.5%	6.3%
Profit (inv. value - CAPEX)	[mEUR]	-7.29	-12.79	-9.01

It's seen that the negative profit is lowest in the first period, reflecting the higher amount of energy generated which is unrelated to the storage system and the market conditions.

Other projects

It's obvious that the earnings also depend on the reference project selected and used for the scaling. Below the same calculations have been performed for three different solar projects.

Project calculation	Unit	Alt_Sol7	Alt_Sol8	Alt_Sol9
Generator project - reference				
Project code	[-]	Sol7	Sol8	Sol9
Start date	[yyyy-mm-dd]	2021-01-01	2021-07-01	2021-01-01
Reference generator power	[MWh/h]	26.38	36.33	17.22
Generator project - modelled				
Modelled generator power	[MW]	95.56	95.56	95.56
Grid export power limit	[MW]	79.25	79.25	79.25
Output - reference operation (as if no storage is installed)				
Generation - scaled total (no storage)	[MWh]	114,661	132,007	67,218

Energy loss (due to neg. price and grid limitation)	[%]	5.69%	4.72%	2.62%
Income direct energy export (excl neg. price and curtailment)	[mDKK]	61.13	134.29	44.95
Capture Price (excl neg. price and curtailment)	[DKK/MWh]	565.3	1,067.7	686.7
Value Factor reference (vs. baseload)	[-]	0.863	0.978	1.049
Output - peak shift & arbitrage				
Energy export - direct (peak shift & arbitrage subtracted)	[MWh]	105,630	123,107	62,958
Energy export - indirect (peak shifted & arbitraged)	[MWh]	5,045	5,390	2,956
- Balance: Gross energy loss	[MWh]	3,085.8	2,563.4	588.0
Income - direct sales (peak shift & arbitrage excluded)	[mDKK]	59.47	131.26	43.56
Income - battery sales (peak shifted & arbitrage included)	[mDKK]	3.67	8.67	2.36
Income - direct & indirect sales (peak shifted & arbitrage)	[mDKK]	63.14	139.93	45.92
Energy storage loss (operating peak shift & arbitrage)	[%]	3.48%	2.66%	1.94%
Equivalent Full Cycles (storing peak shift & arbitrage)	[#]	50	54	29
Capture price (peak shift & arbitrage)	[DKK/MWh]	570.5	1,089.0	696.7
Value Factor after peak-shift & arbitrage (vs. reference)	[-]	1.009	1.020	1.015
Capture price improvement after peak-shift & arbitrage	[-]	0.93%	2.00%	1.46%
LCOS - summary				
LCOS	[EUR/MWh]	14.62	12.59	24.55

In this case the second project seems to promise a better outcome both in terms of LCOE and capture price improvement.

Wind projects

A Battery Storage Management calculation has also been made with three selected wind profiles as input.

Project calculation	Unit	Alt_Vind1	Alt_Vind4	Alt_Vind9
Generator project - reference				
Project code	[-]	Vind1	Vind4	Vind9
Start date	[yyyy-mm-dd]	2020-12-30	2021-01-01	2020-12-30
Reference generator power	[MWh/h]	3.47	3.18	3.47
Generator project - modelled				
Modelled generator power	[MW]	95.56	95.56	95.56
Grid export power limit	[MW]	79.25	79.25	79.25
Output - reference operation (as if no storage is installed)				
Generation - scaled total (no storage)	[MWh]	270,348	118,926	231,549
Energy loss (due to neg. price and grid limitation)	[%]	10.14%	6.12%	8.00%
Income direct energy export (excl neg. price and curtailment)	[mDKK]	136.80	62.25	126.65
Capture Price (excl neg. price and curtailment)	[DKK/MWh]	563.2	557.5	594.5
Value Factor reference (vs. baseload)	[-]	0.862	0.852	0.910
Output - peak shift & arbitrage				
Energy export - direct (peak shift & arbitrage subtracted)	[MWh]	242,137	109,334	211,594

Energy export - indirect (peak shifted & arbitraged)	[MWh]	8,720	4,778	8,234
- Balance: Gross energy loss	[MWh]	18,005.1	3,723.6	10,179.3
Income - direct sales (peak shift & arbitrage excluded)	[mDKK]	134.35	60.33	124.04
Income - battery sales (peak shifted & arbitrage included)	[mDKK]	8.15	3.70	7.91
Income - direct & indirect sales (peak shifted & arbitrage)	[mDKK]	142.49	64.03	131.96
Energy storage loss (operating peak shift & arbitrage)	[%]	7.21%	4.05%	5.06%
Equivalent Full Cycles (storing peak shift & arbitrage)	[#]	87	47	82
Capture price (peak shift & arbitrage)	[DKK/MWh]	568.0	561.1	600.3
Value Factor after peak-shift & arbitrage (vs. reference)	[-]	1.009	1.006	1.010
Capture price improvement after peak-shift & arbitrage	[-]	0.86%	0.64%	0.97%
LCOS - summary				
LCOS	[EUR/MWh]	6.45	14.18	7.36

It can be seen that the LCOS is significantly lower than for the solar projects also related to the much higher use that's made of the UPHS.

Other markets

Beside the Danish market there's also opportunities to deploy the UPHS solution in other countries. To investigate such opportunities, we also have applied the Energy Storage Management modelling to a wind park in Texas, making use of scaled power generator data from a Vestas wind turbine and associated local hourly spot-prices. For simplifications of comparison the same general calculation context has been used, including transferring the USD based prices to DKK.

Project calculation	Unit	Texas	Reference-PV
Storage concept description	[-]	M=6; Vd=5; Hs=25; Lh=9	M=6; Vd=5; Hs=25; Lh=9
Generator project - reference			
Project code	[-]	Vind0	Sol6
Project name	[-]	Texas	Hanstholmvej
Start date	[yyyy-mm-dd]	2019-01-01	2021-01-01
Reference generator power	[MWh/h]	0.06	42.90
Generator project - modelled			
Modelled generator power	[MW]	95.56	95.56
Grid export power limit	[MW]	79.25	79.25
Energy storage system design			
Storage capacity	[MWh]	120.0	120.0
Storage charging power	[MW]	22.0	22.0
Storage discharging power	[MW]	22.0	22.0
Energy storage operating strategy			
Hour-ahead selling decision perspective	[h]	22	22
Sales price priority to induce discharge decision	[#]	3	3
Power-price limit considered negative	[DKK]	4	4
Price delta for arbitrage	[DKK]	50	50
Output - reference operation (as if no storage is installed)			
Generation - scaled total (no storage)	[MWh]	351,288	112,314
Energy loss (due to neg. price and grid limitation)	[%]	4.83%	6.04%

Income direct energy export (excl neg. price and curtailment)	[mDKK]	90.38	58.77
Capture Price (excl neg. price and curtailment)	[DKK/MWh]	270.3	556.9
Value Factor reference (vs. baseload)	[-]	1.010	0.851
Output - energy storage of neg. price & curtailed energy			
Energy export - direct (excl. peak shifted)	[MWh]	335,014	106,338
Energy export - indirect (peak shifted)	[MWh]	6,550	2,848
Income - direct sales (peak shift excluded)	[mDKK]	90.48	58.77
Income - battery sales (peak shifted)	[mDKK]	2.49	1.83
Income - direct & indirect sales (peak shifted)	[mDKK]	92.98	60.60
Energy loss (peak-shift recovered)	[%]	2.77%	2.78%
Equivalent Full Cycles (due to peak shift)	[#]	65	28
Capture price (after peak shift)	[DKK/MWh]	272.2	555.0
Value Factor after peak-shift (vs. reference)	[-]	1.007	0.997
Capture price improvement after peak-shift	[-]	0.69%	-0.34%
Output - peak shift & arbitrage			
Energy export - direct (peak shift & arbitrage subtracted)	[MWh]	330,206	103,227
Energy export - indirect (peak shifted & arbitraged)	[MWh]	9,306	5,096
- Balance: Gross energy loss	[MWh]	9,723.7	3,127.6
Income - direct sales (peak shift & arbitrage excluded)	[mDKK]	89.53	57.23
Income - battery sales (peak shifted & arbitrage included)	[mDKK]	3.52	3.64
Income - direct & indirect sales (peak shifted & arbitrage)	[mDKK]	93.04	60.87
Energy storage loss (operating peak shift & arbitrage)	[%]	3.35%	3.55%
Equivalent Full Cycles (storing peak shift & arbitrage)	[#]	92	51
Capture price (peak shift & arbitrage)	[DKK/MWh]	274.1	562.0
Value Factor after peak-shift & arbitrage (vs. reference)	[-]	1.014	1.009
Capture price improvement after peak-shift & arbitrage	[-]	1.38%	0.91%
LCOS - summary			
LCOS	[EUR/MWh]	4.77	14.94

The first observation is, that the overall energy generation is about three times higher for the same peak-power. Also the relative energy loss due to grid curtailment and negative prices is lower, mostly due to fewer hours with negative pricing. This is also visible from the overall high value-factor of 1.01, which indicate that the capture price of 270 DKK/MWh is almost identical to the baseload price.

The earning based on direct energy sales is 90.48 mDKK and can be boosted with 2½ mDKK when using the UPHS. This reduces the relative energy loss from 4.8% to 2.8% as the otherwise curtailed energy can now be sold and increases the average value of the sales by 0.7%.

When also applying arbitrage, the total income remains more or less unchanged at 93 mDKK reflecting an increase of overall energy loss increase to 3.35% due to RTE of 85%^2 whereas the capture price can be improved with 1.4% from 272 to 274 DKK/MWh by using the market opportunities.

Sensitivity analysis

The number of parameters characterizing the UPHS solution and operational behaviour are quite limited, and it's quite easy to assess the impact of various alternative parameter settings which may represent areas for further technical/financial optimisation or qualification of preliminary estimates.

The following sensitivity analysis have been performed by using the 3rd case "Aqua M6-P11 Grid:79.25MW", as reference:

1. Project data	Aqua M6-P11 Grid:79.25MW	Alt1: 20% on energy loss	Alt1: 20% on Value Factor	Alt1: 20% on Storage CapEx	Alt1: 20% on OpEX
3.6 Energy storage solution					
Storage concept	M6-P11	same as ref.	same as ref.	same as ref.	same as ref.
Storage concept description	M=6; Vd=5; Hs=25; Lh=9	same as ref.	same as ref.	same as ref.	same as ref.
Overall energy loss due to storage	2.95%	20% rel reduction	same as ref.	same as ref.	same as ref.
Value Factor vs. uncurtailed (Psonly & arbitrage)	1.069	same as ref.	20% rel increase	same as ref.	same as ref.
Storage CapEx	22,000,000	same as ref.	same as ref.	20% rel reduction	same as ref.
Reinvestment	10,000,000	same as ref.	same as ref.	20% rel reduction	same as ref.
Reinvestment yearly interval	12	same as ref.	same as ref.	same as ref.	same as ref.
Recovery value	2,000,000	same as ref.	same as ref.	20% rel reduction	same as ref.
Storage Opex	75,000	same as ref.	same as ref.	same as ref.	20% rel reduction
Storage Opex escalation	2.00%	same as ref.	same as ref.	same as ref.	same as ref.
Interest rate for LCOS calculation	2.00%	same as ref.	same as ref.	same as ref.	same as ref.

By running the calculation with these modifications, the following output can be calculated:

UPHS	Unit	Sensitivity-20% on energy loss	Sensitivity-20% on value factor	Sensitivity-20% on Storage Capex	Sensitivity-20% on Opex
Site specific					
Area (lease)	[ha]	100.0	100.0	100.0	100.0
GHi estimate	[kWh/m2/a]	1013.6	1013.6	1013.6	1013.6
Technology concept					
Substructure	[-]	FT (26x2P)	FT (26x2P)	FT (26x2P)	FT (26x2P)
Energy Yield					
Specific energy yield (Yf)	[kWh/kWp]	1,175	1,175	1,175	1,175
Grid connection					
Connection body	[DSO,TSO]	DSO	DSO	DSO	DSO
DSO voltage-level	[A_høj etc.]	A_høj+	A_høj+	A_høj+	A_høj+
Grid connection specific fee	[tDKK/MW]	458	458	458	458
Project sizing					
Grid capacity assumed	[MVA]	79.25	79.25	79.25	79.25
Project KPI					
Total installed DC power	[kWp]	95,560	95,560	95,560	95,560
Energy Yield Assessment	[GWh]	112.31	112.31	112.31	112.31
Power ratio dc to grid	[kWp/kW]	1.21	1.21	1.21	1.21
CapEx					
CAPEX in total	[EUR/kWp]	*815.13*	*815.13*	*769.09*	*815.13*
Total CAPEX (fixed and variable)	[MEUR]	77.89	77.89	73.49	77.89
-hereof OTHERS incl. grid-fee paid	[MEUR]	26.88	26.88	22.48	26.88
Power Sales					
Energy export to the grid	[GWh]	108.6	107.8	107.8	107.8
PPA sales price	[EUR/MWh]	75.00	75.00	75.00	75.00
Selected Merchant price (10y avg.)	[EUR/MWh]	91.6	109.9	91.6	91.6
Value Factor after peak-shift & arbitrage (vs. reference)	[%]	1.009	1.211	1.009	1.009
Losses and curtailment					
Energy loss between generator and PCC	[%]	2.843%	3.554%	3.554%	3.554%
OpEx					
Annual operational expenses (sum of all years)	[mEUR]	80.61	81.14	80.42	51.61
Annual Operational costs by revenue	[%]	34.4%	30.3%	34.6%	22.2%
Business case					
Unleveraged project IRR	[%]	5.7%	7.5%	6.3%	7.0%

Profit (inv. value - CAPEX)	[mEUR]	-12.22	-2.40	-8.39	-5.14

The most important observation related to this table, is the very limited impact of energy loss reduction (Round-Trip-efficiency).

In contrast, it's clear that the value factor of the storage solution is key to competitiveness as it raises the business case by almost 10 mEUR.

Also 20% reduction in Capex and/or Opex are seen to be quite important.

Discussion

The work presented in this report shall still be considered work-in-progress. Several elements shall be investigated further, before any final conclusions can be drawn.

The most important single factor will be an improved understanding of on the Value Factor that achievable with a system like this. Whereas a calculation of this factor in the first place relies on the ability to model a realistic operational strategy for the storage system, something which is well explored in the developed Energy Storage Management model, it's still necessary to look further into the Value Factor estimation. To perform this analysis, it's necessary to have access to energy pricing forecast which not only addresses the baseload price expectations, but also provide insights in the market volatility as such.

Without this analyse, it's difficult to make clear conclusions, but it's a good guess, that the Value Factor calculated in the present version of the report is greatly underestimated. This is indicated by the huge impact of time-period historical year) selected for the storage management analysis.

As for the scaling, further work is needed to assess if the arbitrarily chosen PV site size is well selected for a standard unit of this storage system.

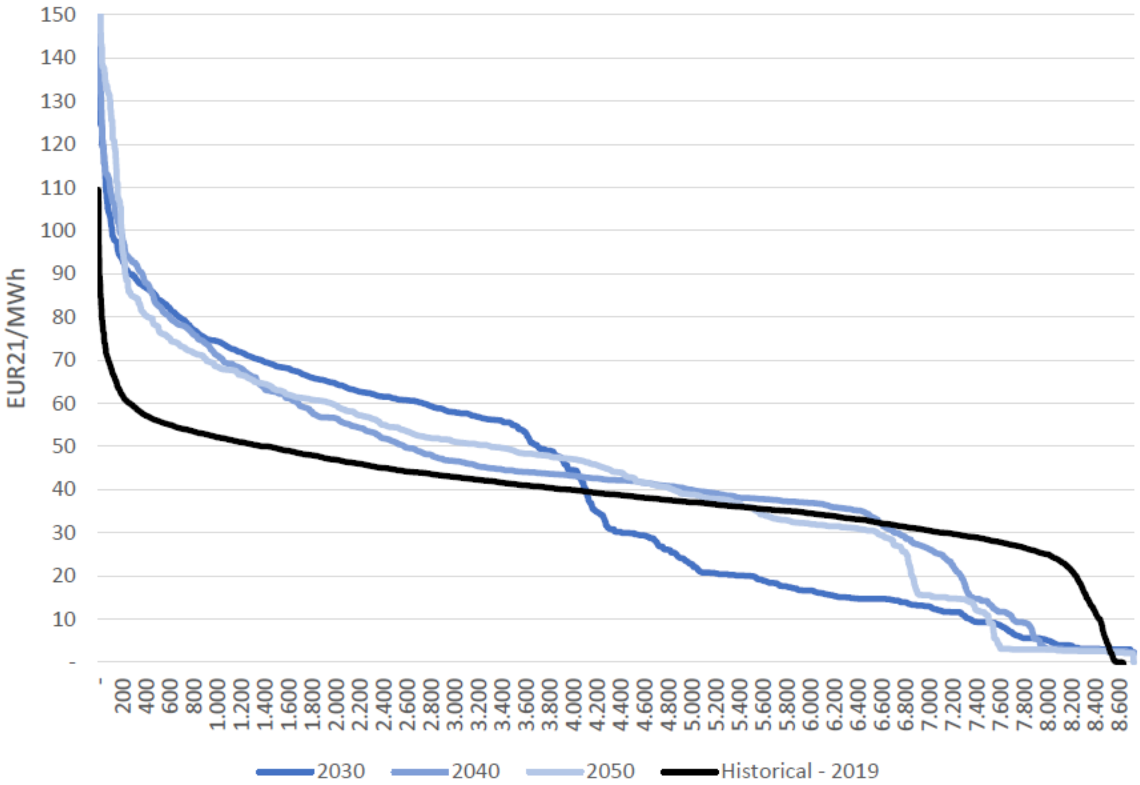
Initial analysis has been made to evaluate the impact of generator and/or pump sizes, which still need to be included in the reporting.

Finally, it needs to be emphasized, that other revenue streams may be possible to tap into when considering ancillary services and grid balancing. This has not been considered in this report.

Outlook

The overall importance of having access to a large energy storage facility, is linked to general energy-system trends over the coming years.

First, the value of this capability to operate an arbitrage revenue stream, is linked to the volatility in the market. As can be seen from the figure below which has been generated by EA energianalyse on behalf of the Danish Energy Agency and published in April 2022 (System scenarios, April 2022), the volatility in the Danish electricity market is expected to increase towards 2030, whereafter it might fall again. This conclusion is extracted from the steepness of the duration-curve.



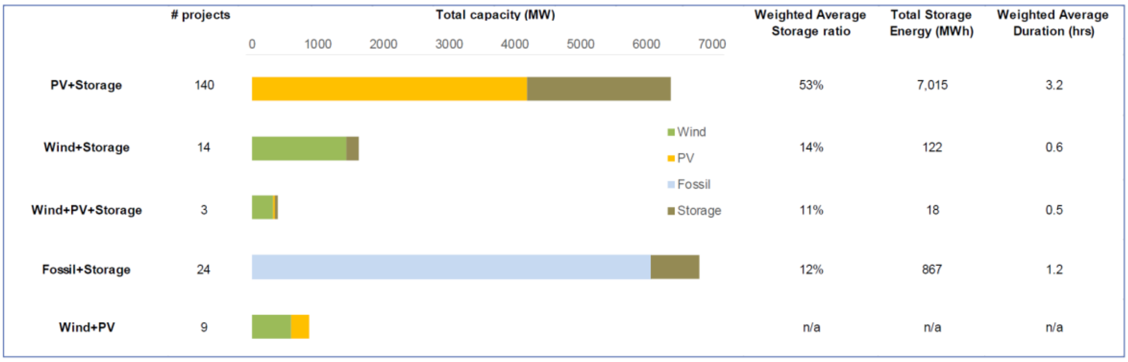
Based on this observation the general UPHS business should become more attractive in the coming years.

Another observation relates to the availability of cheap electricity which is a precondition for the overall arbitrage business model. Since PtX installation are now being announced and planed for deployment in Denmark in quite large numbers, it's becoming clear that there's a competition among several future off-taker classes, who all base their business model on the availability of such cheap electricity. This observation may indicate that the general UPHS business case will not improve significantly under Danish conditions over the coming years.

Based on this observation the general UPHS business should become more challenged in the coming years.

Finally, there's an observation related to potential requirements for large storage units to be deployed in connection with RE generation projects, driven by requirements from the network operators (DSO and TSO) and balancing responsible parties for the project to limit the ramp-rate as seen by the grid withing narrow conditions. This could be accompanied with requirements for the generator to deliver a certain minimum expected capacity factor, which also may only be achieved by adding large scale storage and reducing the grid capacity for such projects. This trend is now seen in the US, as illustrated in the figure below provided by Lawrence Berkeley National Laboratory in August 2022 in their report "Hybrid Power Plants, Status of Operating and Proposed Plants, 2022 edition".

PV+Storage hybrids are most numerous (140), and have by far the most storage capacity (2.2 GW) and energy (7 GWh) than other hybrids



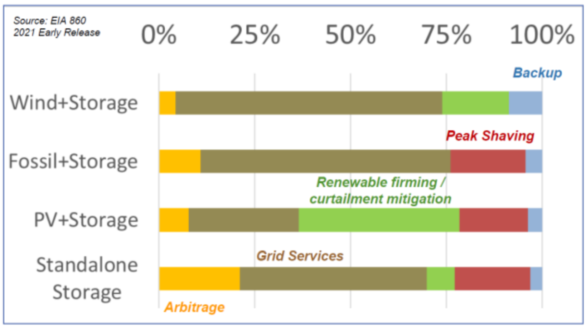
Notes: Not included in the figure are 108 other hybrid / co-located plants with other configurations; details on those plants are provided in the table on slide 7. ***Storage ratio*** *is defined as total storage capacity divided by total generation capacity within a hybrid type.* ***Duration*** *is defined as total MWh of storage divided by total MW of storage within a hybrid type.*

Sources: EIA 860 2021 Early Release, Berkeley Lab

Breakdown of self-reported use cases for battery storage is somewhat similar whether a standalone battery or a hybrid, though there are a few key differences

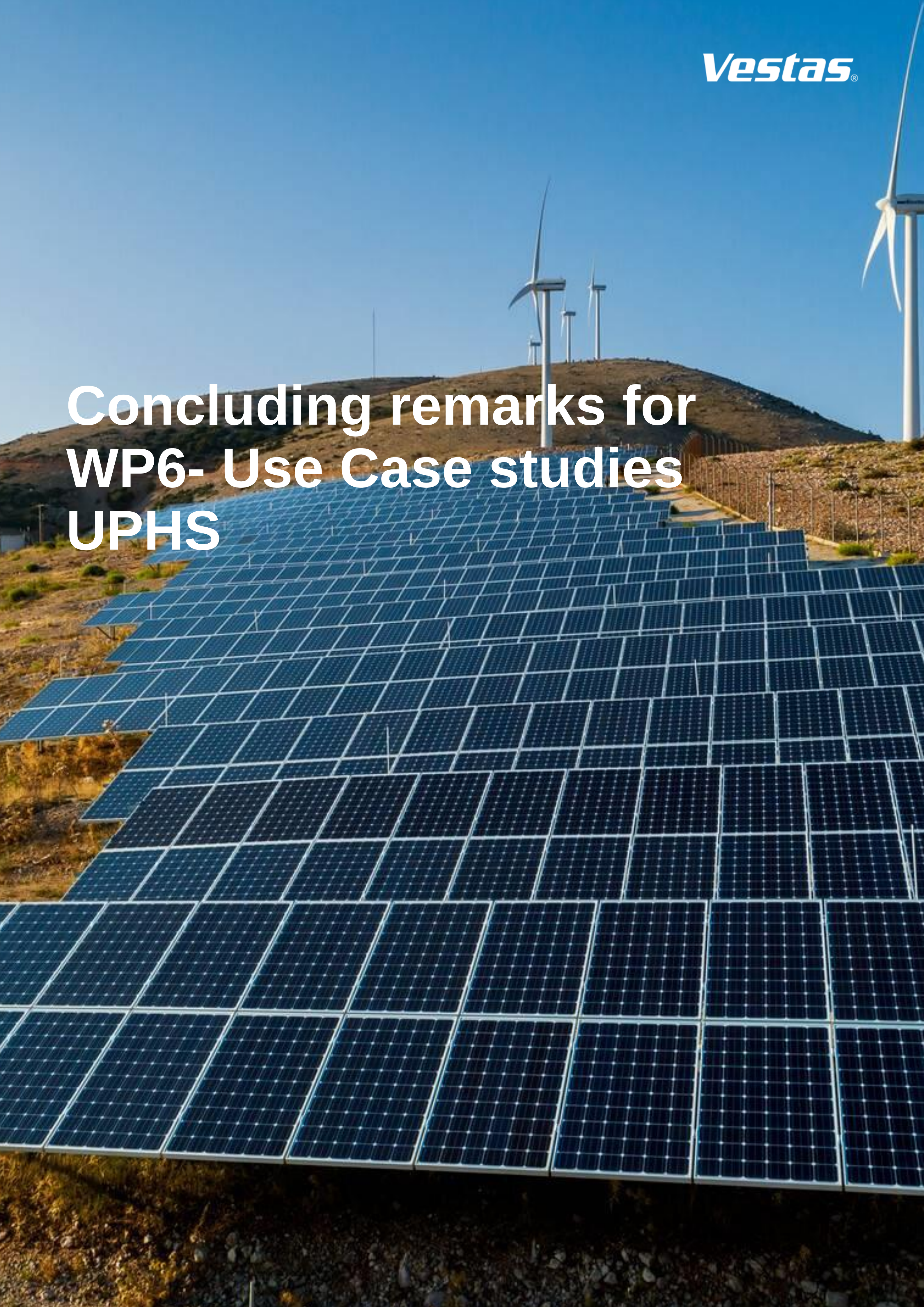
- Operators self-report use cases to EIA; individual plants can indicate multiple use cases
- Grid services are the most commonly reported use case, though renewable firming and curtailment mitigation is particularly important in PV+Storage hybrids
  - Wind+Storage has primarily targeted ancillary service markets
  - PV+Storage more often used to firm the PV capacity for resource adequacy purposes
- Backup power and arbitrage are least popular use cases reported by operators

Breakdown of battery use case among popular hybrid configurations and standalone storage



Grid services category includes the following: frequency regulation, load following, ramping/spinning reserve, load management, and voltage/reactive power support

Based on this observation, the general UPHS business should become more attractive in the coming years since UPHS may replace batteries as used in the US, and since market trends driving co-location of generation+storage may also be applicable in Europe.



Concluding remarks for WP6- Use Case studies UPHS

Contents

Data results from the project

Achieved results

As described in the other work packages the test setup at Foulum did not provide the results that were anticipated in the beginning of the project. This is the nature of research and innovation and while Vestas still sees great potential in the technology it has become clear that there is still quite some work to be done before the technology is mature and commercially applicable.

In the original application the intent for WP6 was to deliver the following:

D6.1: A list of parameters needed for the high-level model that must be supplied by the other WPs

D6.2: Timeseries describing expected charging and discharging patterns under the investigated scenarios

D6.3: A brief report describing:

D6.3.1: UPHS' applicability in the investigated scenarios

D6.3.2: Estimates of the revenue generation potential under the investigated scenarios

D6.4: An assessment of the feasibility of controlling the prototype in real life operations

Regarding the work done in WP6 it has been attempted to address the above deliverables, however as the parameters provided by the other work packages have not been proven in the Foulum demo it has been decided to focus on what needs to be improved rather than deliver economic feasibility conclusions on the available data, as this will not give a realistic picture due to the uncertainties that are still present. The main challenge is the lack of practical experience in the charging and discharging speeds, the regulating characteristics of the system while in operation and the speed at which the system can be reversed (going from full charge power to full discharge power). These parameters are paramount for assessing the applicability of the system in high value markets where speed is the key.

D6.1

Here is the list of Parameters that as requested by WP6 to the project in condensed form.

- Max and min gradient for charging and discharging of a full-size system
- Range of power to energy ratios available and associated price points
- Range of technically feasible sizes
    - Associated costs
    - Associated energy content
    - Associated efficiencies

D6.2 & D6.3.2 & D6.4

For these deliverables it has not been possible to achieve meaningful concrete results due to the lack of proven parameters from the test site in Foulum.

A Storage valuation tool has been developed and incorporated into Vestas' existing toolbox for siting and site evaluation. This tool has been made so that it allows conventional storage technologies and UPHS to be evaluated as stand alone revenue generation so not coupled directly to a renewable power site. The model takes generic parameters to characterize the storage asset such as initial and end of life state of charge (SOC), round trip efficiency, the C rate which is the ratio of Power to energy and the energy content of the asset. The tool also takes values of OPEX and CAPEX and includes these in the financial evaluation of the specified asset towards the selected energy markets and services. When performing these alanaylsis the tool models the storage asset and the cycles it would experience under the market conditions and therethrough can take degradation into account as well. Due to the lack of results from Foulum a UHS specific degradation model has not been implemented. A couple of screenshots are provided in the appendix.

D6.3.1

In the following the initial pre-project estimates and the post-project estimates will be discussed and Vestas will give their view on which areas are the most important ones to focus on for future work incl. target ranges for key cost points that need to be achieved by the technology to ensure economic feasibility in the future.

Pre project vs. post project estimates

	Pre-Project				Post-Project
Pump/turbine, MW	**2,3**	**5,6**	**13**	**28**	**11**
Physical size, m	120x120	150x150	225x225	330x330	6 pcs 130x130
Storage volume, m³	200.000	315.000	710.000	1.525.000	912.600
Storage capacity, MWh	22	48	107	231	112
Total investment, EUR	4.000.000	8.000.000	14.000.000	30.000.000	22.000.000
Investment, EUR/MWh	181.800	166.500	130.800	129.900	197.000
LCOS, EUR/MWh	61	51	48	47	?
ESOI	800	800	800	800	?
Necessary space, ha	4,5	6,5	15	29	?

Table 1 Cost of Storage for difference sizes of UPHS compared to corresponding battery solutions, revealing a competitive LCOS

In addition to the above characteristics the project group has made the following estimates based on the continued simulation work:

- Total round-trip efficiency: 72-73 %
- Total estimated lifetime of the UPHS: 24 years
- Mid-life preventive maintenance in year 12: 10 mil EUR.
- Yearly soil work maintenance: 50.000 EUR.
- Yearly maintenance of hydro electrical equipment and system: 25.000 EUR

UPHS viewed as a problem owner

Vestas enterd into this project, together with European Energy in the role of a problem owner. We sell and build sustainable energy solutions across the world and energy storage is a rapidly incresasing market and we expectt there to be a rapidly increasign demand for energy storage in the future.

To put the estimated parameters into context we make a comparison, using the newest numbers from Lazard[1] for a 11MW/112MWh, these values are made by scaling the available numbers for a 4-hour grid scale system. Such a battery would have a CAPEX of approx. 28,5 Mio EUR. The reduction in capacity that have been made to the estimates do not render the technology uncompetitive.
The expected O&M costs for such a battery system would approximately be 100kEUR/year. Here again the estimates for UPHS still seem attractive, however these numbers are very uncertain due to the soil stability issues that have been observed at Foulum.

The main drawback of UPHS is the round-trip efficiency which is approximately 10 percentage points lower for UPHS than a corresponding lithium-Ion battery. Traditional pumped hydro storage has a similar efficiency to that of lithium ion so compared to both technologies there is need for improvement. This improvement can either come as a significant cost reduction on CAPEX so that the additional losses in OPEX are acceptable or simply by improving the efficiency.

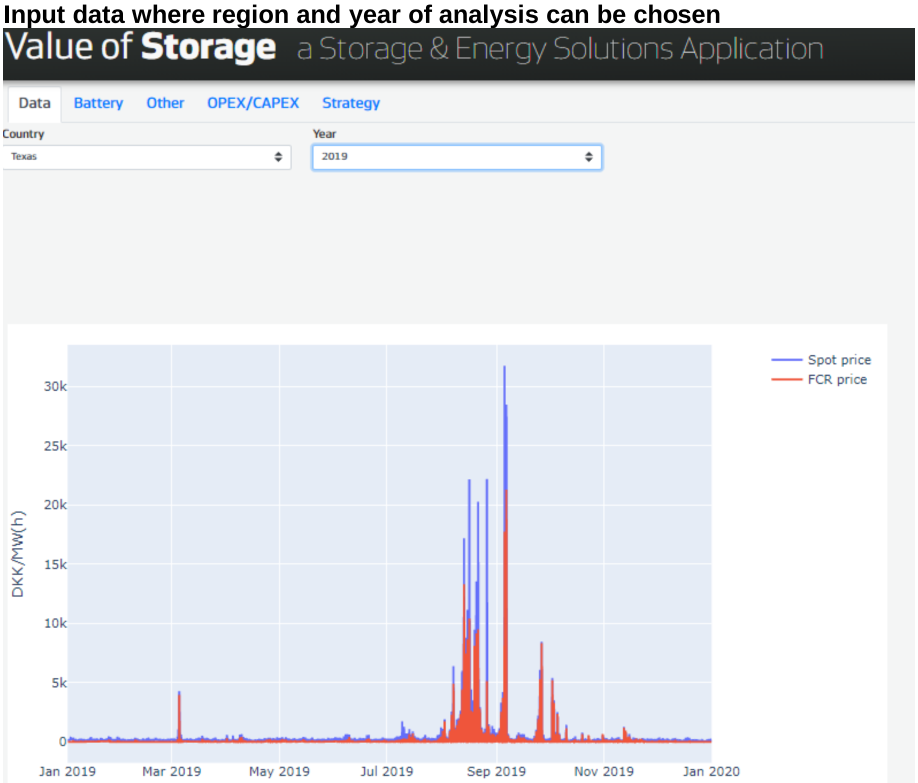
As a potenial offtaker of this techoolgy Vesats has followed the project with great interest and still sees a large potential in the technolgy. The project has also uncoverd a number of isues that need to be adressed before the actual feasibility of the technoligy can be analysed in detail. For the future work with this technolgy Vestas sugests the follwing targets:

1. Keep Capex and Opex signficantly below competeting battery technolgies – aim to be 30% below the expecetd Lithium-Ion prices in 2030
    a. UPHS is a new storge technolgy and in its characteristics seems to have more in common with traditional Pumped Hydro rather than batteries. Pumped Hydro storage has a price point that is below half of that for Lithium-Ion which is the argument for setting an aggressive target for the CAPEX and OPEX price points
    b. Based on the current bloomberg predictions for the price point for Lithium ion in 2030 the UPHS techocligy should target a goal of 110 kEUR/MWh installed.
2. Focus on impooving the technical capabilaities
    a. Flexibilit is key in the energystsystem of the future and therfor it is vitale that the UPHS technology is continued to be developed in that direction.
    b. Focus on increasing the efficiancy - aim for >80% to compete with regular PHS
    c. Focus on the ability to hold enegry for long periods of time with out losses
    d. Focus on investigating degradation – degradation is the single largest risk a storage operator has to deal with, and being a new technology this will cost a discount on the price for comemrcial operators.
    e. Focus on ramprates and the speed at hich the flow can be reversed – aim for 30% of nominal power increase or reduction within 7,5 seconds to fulfill the FCR-D requriemnts in th e nordics.

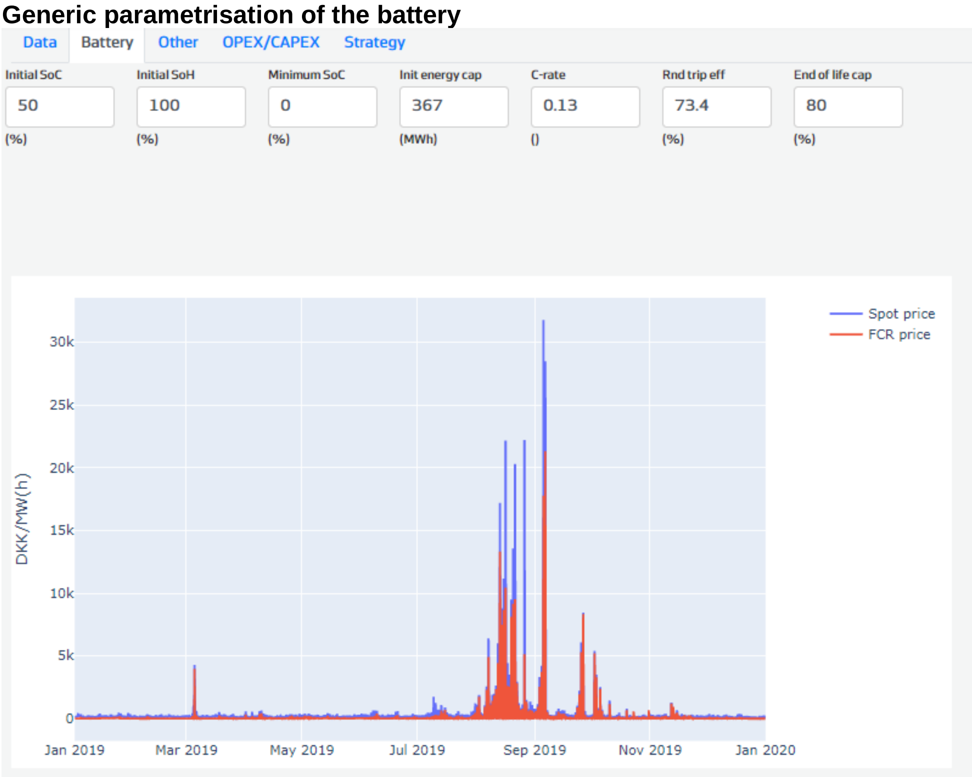
[1] Lazards-levelized-cost-of-storage-version-70-vf.pdf https://www.lazard.com/media/451882/lazards-levelized-cost-of-storage-version-70-vf.pdf

Appendix

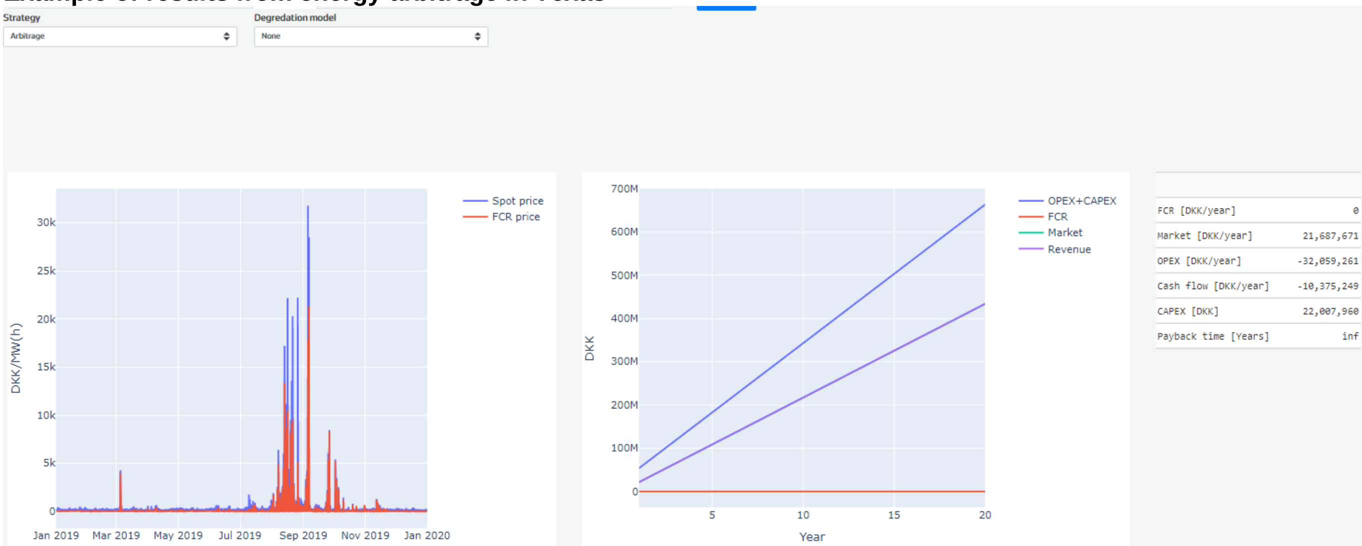
Input data where region and year of analysis can be chosen



Generic parametrisation of the battery



Example of results from energy arbitrage in Texas



Example of results from frequency reserves in Texas