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Lessons from the Offshore Oil and Gas Industry for Hydro-Pneumatic Subsea Energy Storage Concepts#

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ABSTRACT

In order to avoid catastrophic climate change, the world is currently involved in an ambitious energy transition. In this great transition, fossil-based fuels are to be replaced with intermittent renewable energy. Science will provide the "know-why" but the ultimate success will be dependent on combining this with the engineers "know-how". This paper aims to bring light to what capabilities the engineer discipline has with regards to subsea engineering with a focus on subsea structures so that the scientific community can make use of it when researching new subsea storage concepts. Novel ideas for design of subsea hydropneumatics energy storage concepts adapted from the oil and gas industry including a justification for them has been reviewed and presented in the paper. Although publications around subsea hydropneumatics energy storage solutions exists there are few, if any, related to design considerations.

Keywords: Subsea engineering, subsea energy storage, hydro-pneumatic energy storage, energy transition

NOMENCLATURE

Abbreviations	
CAES	Compressed Air Energy Storage
CAPEX	CAPital EXpenses
Condeep	Concrete deep-water structure
CTO	Configure To Order
ETO	Engineering To Order
NCS	Norwegian Continental Shelf
PHS	Pumped Hydro Storage
ROV	Remotely Operated Vehicle
WoW	Waiting on Weather
Symbols	
ϵ_{iso}	Energy Density [J/m^3]
CR	Compression ratio [-]
p_0	Initial pressure [bar]
p_{ocean}	Ocean pressure [bar]
p_{tank}	Tank pressure [bar]

1. INTRODUCTION

The need for energy storage with the introduction of intermittent renewable energy sources and scaling down of the fossil fuel based power supply is a well-known fact, this need will require significant investment in energy storage [1].

The energy storage of the future will aim to provide the world with affordable storage suitable for highly intermittent energy sources while making sure that the demands from the users, both industrial and residential, are met. But one should not forget the primary cause of the energy transition, to lower emissions and reduce the impact of climate change. Meeting all of these diverse requirements means that an array of different energy storage concepts is needed. No single concept can meet all the demands.

Pumped Hydro Storage is a mature energy storage technology and comprises the vast majority of existing storage capacity in the world[2]. The lack of suitable geographical locations is one of the drawbacks preventing further extension of PHS. Designing a PHS system for use subsea has been proposed in the scientific community for several years. Multiple initiatives have been made, notably: ORES [3], FLASC [4] and STENSEA [5] to name a few.

A subsea energy storage device needs to fulfill the requirements in the entire lifecycle of the product. This includes installation, operation and decommissioning while maintainability needs to be ensured throughout the operational lifetime. To date, the oil and gas industry is one of the few industries that has the know-how and experience of deepwater subsea operations. The oil and gas industry has since the 1970s planned, designed, installed operated, maintained and de-commissioned large complex subsea structures. The latest development within subsea oil and gas has been subsea processing where complex processing equipment has been marinized and placed subsea to reduce the need for expensive platforms and reduce the need for manned operations.

The aim of this paper is to highlight the experience of the subsea engineers in the oil and gas industry so that the scientific community can benefit from it. Early feedback to scientist is considered to provide more value than late feedback as it has a higher chance of positively influencing the research before changes become too costly. The first part of the paper will highlight some key features of a proposed subsea energy storage based on PHS principles while the second part will look into design considerations based on experience from the oil and gas industry.

2. SUBSEA ENERGY STORAGE

The ocean is a resource and humans have been making use of this resource throughout human history. From fishing to oil and gas extraction, the ocean provide a basis for low emission energy storage. It has already been mentioned that further expansion of PHS capacity is limited by the lack of suitable onshore locations, a subsea based PHS will open up more possibilities for further energy storage. The move towards increasing the amount of offshore floating wind means wind parks further away from land, a subsea energy storage designed for deep waters would mean that an energy storage can be installed near the wind turbines. The energy storage can act as an accumulator regulating the amount of power being exported to shore reducing the need for power cables designed for peak power. The possibility of storing energy offshore, also allows the building of offshore energy hubs used for distributing energy towards different users. Isolated islands or coastal areas could make use of a subsea energy storage to store energy in lack of suitable topography for onshore PHS.

2.1 Subsea Energy Storage Concept

Although different version exists, a subsea PHS proposed by the authors is based on placing a gas-filled tank on the seabed with an initial internal pressure of p_0. The pressure outside the tank is the ocean pressure p_{ocean} (constant). This pressure difference can be utilized to create a flow of water into the tank. While water is flowing into the tank the gas inside the tank will be compressed increasing the pressure in the tank, p_{tank}, until it is equal to the ocean pressure p_{ocean}. Electrical energy can be generated by running this flow through a turbine. Charging of the tank is done by pumping water out of the tank thereby reducing the pressure in the tank restoring the pressure difference.

2.2 Properties of subsea energy storage

The theoretical energy density of a concept described in 2.1 can be calculated using the following formula:

$$\epsilon_{iso} = p_0\big((CR - 1) - \ln(CR)\big) \qquad (1)$$

Where CR is the compression ratio, i.e. the pressure before and after water has been filled into the tank. For a tank placed at the seabed on a depth of 1000m with an initial pressure in the tank of p_0 =1bar (CR=100) this would mean an energy density of about 2600Wh/m^3. This is in the upper regions of onshore PSH and in the region of CAES [6]. Although some energy is lost in the compression of the gas high energy densities can be achieved especially at higher CR. Higher CR equals higher waterdepths.

Studies performed by the authors on the flow into the tank show that it is possible to achieve relatively stable flows of water into the tank at CR>50. The normalized flow is relatively stable up until around 80% of the volume is occupied by water at these higher compression ratios, see Fig. 1. This stable flow ensures that turbines can be designed for a certain flow rather than having a highly variable flow. This is another reason why deepwater installations are preferred.

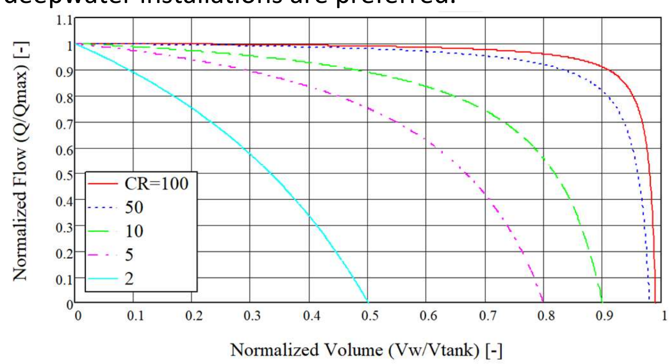

Fig. 1 Normalized flow into the tank as a function of water volume (Vw) and total volume of tank (Vtank)

3. DESIGN CONSIDERATIONS

There are several design considerations that need to be taken into account for subsea equipment. The subsea environment presents designers with a new type of environment that requires different thinking. The first that comes to mind is the water pressure and the second the corrosive environment at sea. Some parameters can even be noted as an advantage such as the (nearly) constant temperature and the heat capacity of water creating a heatsink.

However, there is more to it. To name a few:

- Structural design
- Modularity
- Installation
- Trawl protection

It is easy to think of the seabed as a calm place but in fact there is a lot of activity at the seabed requiring careful considerations for a successful product.

3.1 Structural design

In the 1970:s there was a need for large offshore plattforms on the NCS. Based on previous experience with on-shore large scale concrete structures, a new design was proposed, the Condeep (Concrete deep-water structure). Between 1975 and 1995, 14 of these large structures where built. The largest, Troll A, was installed in 1995. It is situated on a waterdepth at 300m and it has a concrete volume of 245 000m^3 [7]. Although the Condeep is not something that was designed for the energy transition it does show the benefits of concrete as a building material for subsea use, the majority of the plattforms are still in use today.

The installation cost and design complexities mean that most subsea structures tend to be CAPEX intensive projects. Therefore, subsea energy storage devices needs to be large scale to make up for the CAPEX.

A lot of developments have been made with regards to concrete since the design of the Condeep plattforms, these developments together with advances in composites could provide significant cost savings needed for moving from the high profit margin oil and gas industry towards the energy transition. Work done in the oil and gas industry shows the increase in cost when using steel, the traditional building block of oil and gas components, as opposed to composites [8]. Significant cost savings can be made by utilizing composite materials especially with regards to deep water operations, see Fig. 2.

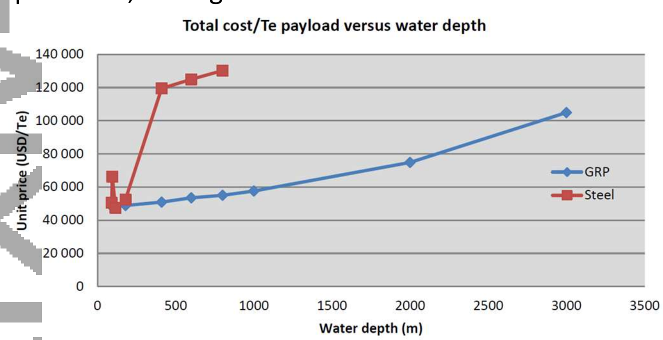

Fig. 2 Total cost per payload when using steel and composites as material for structures [8]

3.2 Modularity

The oil and gas industry has tried to shift the focus from an "Engineering To Order" (ETO) culture towards a "Configure To Order" (CTO) approach. Traditionally an offshore oilfield was discovered and the needs from that particular oil field would dictate the requirement which ended up as design requirements. The designwork would start after the requirements where decided. In the shift towards CTO a lot of the equipment would be predesigned so that each unit could be modified to suit the particular need. Note that this is different from standardizing to a point where one size fits all. The subsea environment differs between each location and project to such a degree that a one size fits all is not cost effective even in the high margin oil and gas industry. A CTO process would also reap the benefits when it comes to interchangeable parts etc. that could ensure reliable operations. Using a modular approach to design an array of different configurations will be critical moving forward, work towards this is already under way in the Oil and gas industry, see Fig. 3.

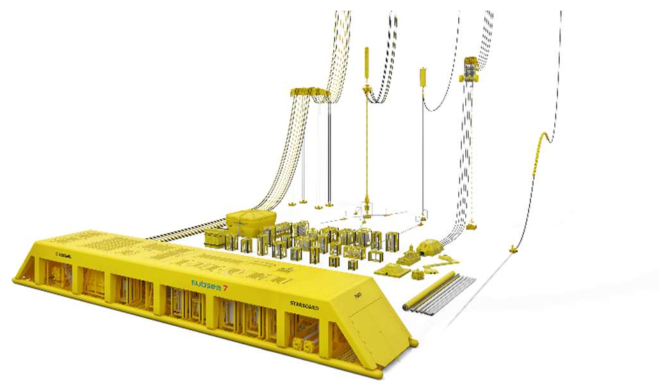

Fig. 3 Modularity to reinforce reliability [8]

Again, experience from oil and gas can give an important idea of the difficulties. Lessons learned from the Åsgård subsea gas compression project show that the need for interchangeability was the main technical challenge in fabrication due to the building tolerances [9]. In order to achieve series production of components for energy storage the lessons learned needs to be reviewed and the design revised to overcome these issues.

Any subsea structure with complex integrated units be they mechanical or electrical needs to be designed so that divers, ROVs and even autonomous inspection vehicles can inspect and perform maintenance as required. The introduction of digital twins has required more sensors and higher bandwidth communication between subsea unit and operations, here it is necessary to thoroughly evaluate the need for information and the reliability required vs the cost and increased complexity.

3.3 Towing vs lifting

Traditionally most subsea installations related to oil and gas has been through the use of crane vessels. The structure would be built on land and a special installation vessel would lift it onboard for transit to the desired location where it again would be lifted and lowered to the seabed. As development of new processing equipment has progressed, equipment that was typically installed on platforms has been moved subsea. Both because there are certain advantages of processing close to the source reducing the need of transporting materials that are not wanted but also because space on platforms is scarce and expensive. With larger units to be installed this means that the crane capacities of the installation vessels needed to increase. With the increased complexity of the units being installed subsea comes the need for reliability and the possibility of installation in adverse weather. Experience from the Åsgård compression project found that the biggest challenge with respect to installation was to ensure that installation could be done in rough sea states requiring a purposely designed handling system on the vessel [9]. Such a custom-made design also prevents the use of other vessels without this system to perform installation.

In addition, any unit that is to be designed for installation by lifting needs to be designed for the loads encountered during the actual lifting operation. Loads from lifting operations can be entirely different from the loads seen during operation and this adds additional requirements. Typically, oil and gas structures have a design life of 20-30 years depending on the type of structure. With installation taking in the area of days to weeks the actual installation is only a fraction of the total design life. This means that any reinforcement of the structure to be installed will only be used during a fraction of its lifetime.

There are several ways of mitigating the effects of poor weather conditions and lifting requirements. Active heave compensation limit the effects of movement, larger cranes reduces the utilization factor during lifting and larger vessels are not as sensitive to the motion of the ocean. However larger vessels mean increased costs, a vessel designed for the largest installations might not be cost effective for smaller installations.

Another option is to use towing instead of lifting. Towing the equipment to its location offshore has been done for many years. With towing, the mass of the object is offset by buoyancy modules. Using a submerged towing technique does not only mean that larger units can be installed but it also reduced sensitivity to weather, see Fig. 4.

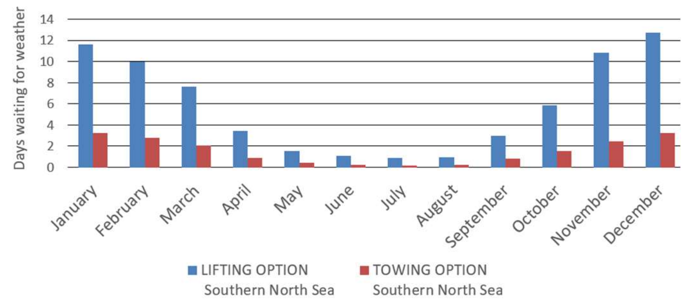

Fig. 4 Data on waiting for weather in the southern North sea [8]

An added benefit of towing is that mass is less of a constrain than using lifting, the crane capacity is the direct constrain on the mass of the object to be installed. With mass being less of a concern, larger masses can be installed meaning that entire processing factories can be installed in one go without having to disconnect individual processing units and installing them individually before connecting them subsea and performing testing. Towing mans that everything can be tested on land and then towed to location, installed and operated without the need for disconnections.

3.4 Trawl protection

As mentioned, the ocean has been and continues to be an important resource for the world. Among other things the oceans provide humanity with food, fish is an important source of nutrition. Todays sophisticated fishing methods include trawling, using trawl doors and clump weights to optimize catching of fish. The mass of these components can be over 5tonnes and with trawl speeds of 1-2m/s an impact of a trawl door on subsea equipment can be significant. In the NCS, NORSOK-U001 [10] has been one of the standards when it comes to defining loads for trawl protection. By understanding the trawling and using known design principles it is possible to lower the loads and hence design requirements of subsea structures. Designing for full loads as specified in NORSOK is a cost-driver in the oil and gas industry. Tests performed by the authors on subsea oil and gas structures in cooperation with SINTEF showed that it was possible to reduce the design loads by 50% [11].

Not only can scaled testing give an idea about the loads encountered during trawl impact but it can also provide valuable insight into duration and possible excitation of eigenfrequencies of the structure. Lastly, tests also provide an overview of design parameters not critical to impact loads which is also very important to understand.

Fig. 5 Trawlnet impacting a subsea structure, scaled laboratory test performed at SINTEF Energy Trondheim [11]

3.5 Results

- For an energy storage concept based on using pressure difference in subsea tank at seabed to generate a flow, deep waters will ensure high energy density and a stable flow throughout the filling of the tank.
- Lessons learned from Condeep structures can be used to design large scale concrete structures for subsea PHS both in terms of cost and expected lifetime.
- Moving from an ETO to a CTO philosophy can make sure that the products can be produced in larger series and used in different configurations which in the end results in cost savings.
- Results from studies show that designing an offshore structure to be towed instead of lifted could potentially have a huge impact on installation costs.
- Experience from interaction between subsea structures and fishing gear show that correct design can lower loads by around 50%

4. DISCUSSION

The results show that the oil and gas industry has made significant progress. Installation of the first Condeep platforms built in the 70's has proven that long lifetime subsea concrete structures can be designed and operated in harsh conditions. The work done by the oil and gas industry to move from an ETO to a CTO based process should be included in the scope, previous experience shows that ETO leads to costly designs and the need for specialized equipment.

Design for installation through towing can provide significant cost savings by reduced dependency of heavy lift vessels and reduced design requirements.

Testing and experience shows that proper design can reduce the design loads from interaction of fishing gear while making sure that fishing activities are not excluded from the locations where subsea installations are made.

5. CONCLUSIONS

The ocean, a significant resource throughout human history, can become a critical part in the energy transition. It can provide renewable energy in terms of floating solar and wind power as well as the location for low emission subsea PHS.

In terms of design of subsea structures both for installation and operation/maintenance the experience from the oil and gas industry might provide critical in terms of not re-inventing the wheel when the world shifts from fossil fuels to renewables. Considering the lessons learned and implementation of the novel designs presented in this paper at an early point when developing subsea PHS will reduce the risk of costly make overs of over-constrained designs.

Significant modifications will be needed in order to adapt any successful designs from the oil and gas industry towards the energy transition but it would be a waste not to acknowledge the significant developments made be the oil and gas industry in the last 50 years.

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