Arena Pro
Ocean Hyway Cluster

UWH
[Under Water Hydrogen]

Electrolysis production and hydrogen storage clusters as a factor in balancing energy systems

[a brief description of the concept]

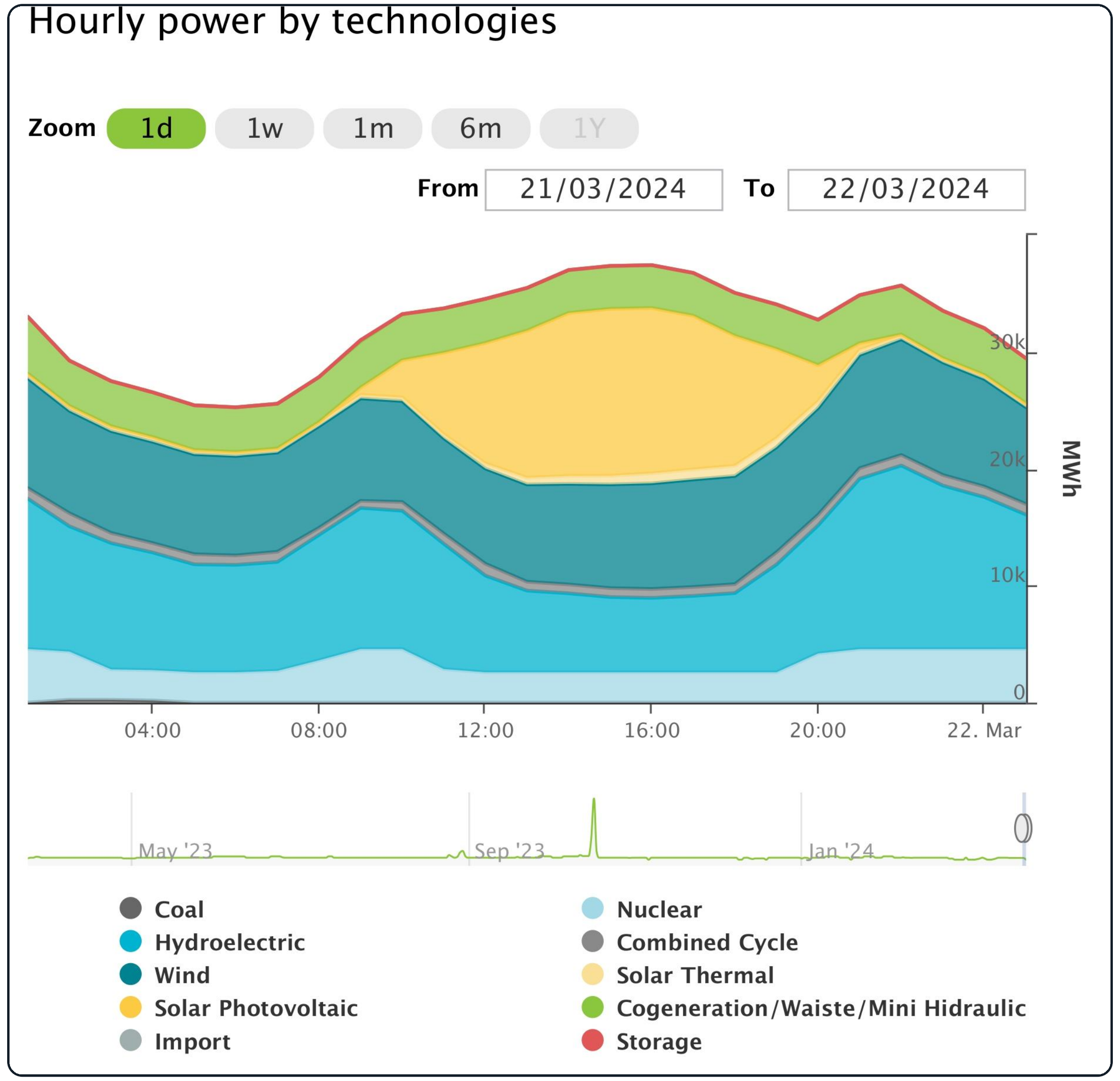
INTRODUCTION

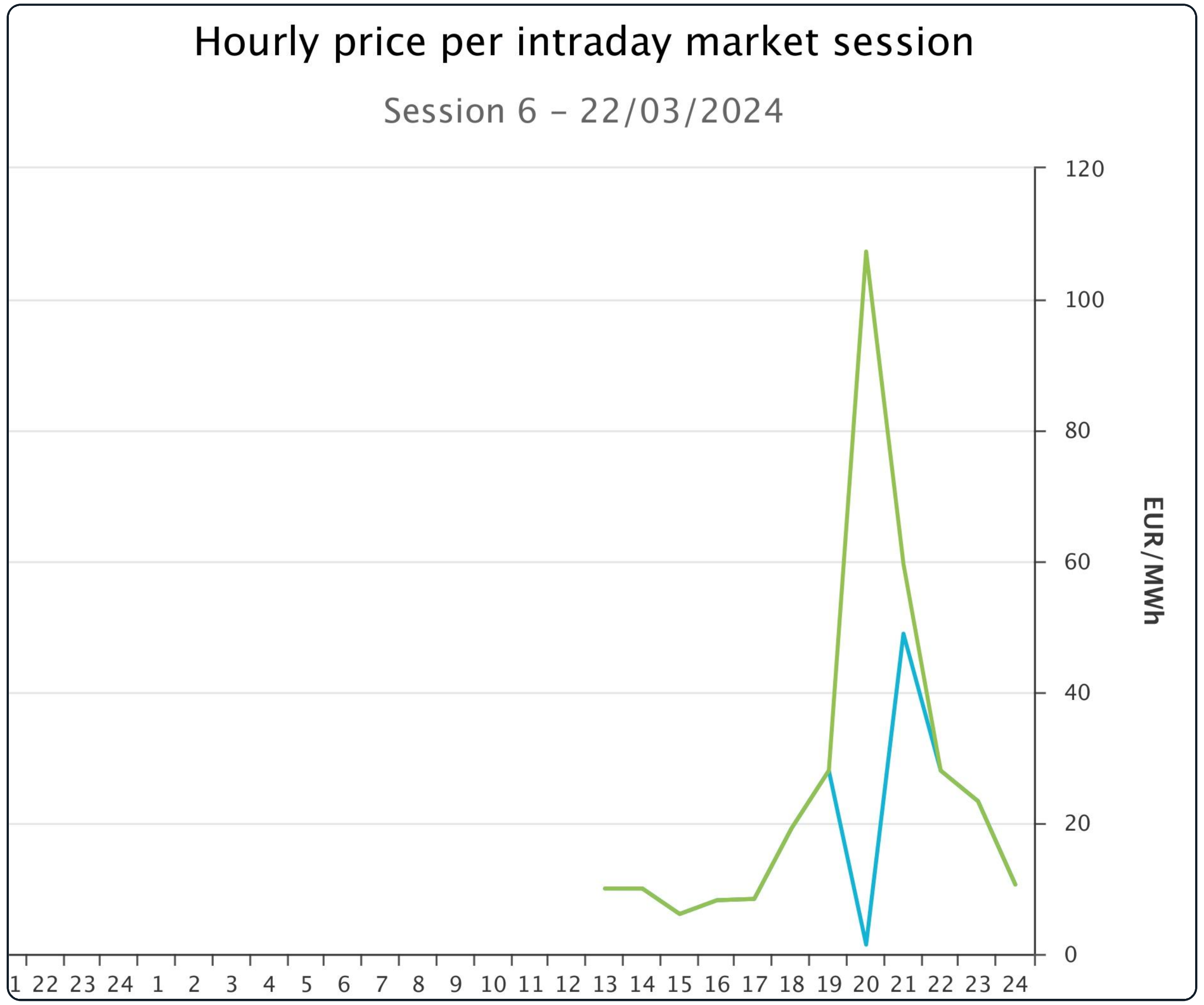
Currently, the commercially justified development of renewable generation and the commissioning of additional capacities is **complicated by the irregularity of generation.**

We can observe the processes of large companies exiting solar and wind generation projects, which are conditioned by the absence or non-provision of existing sales guarantees, as **the increase in the volume of unpredictable generation has reached maximum indicators** that can be processed within the existing networks.

INTRODUCTION

The most qualitative example can be the data of intraday spot electricity sales. Ignoring the seasonal generation fluctuations, nevertheless, **daily imbalances are evident,** which are mainly due to the low night-time consumption and the overproduction of solar during the day.



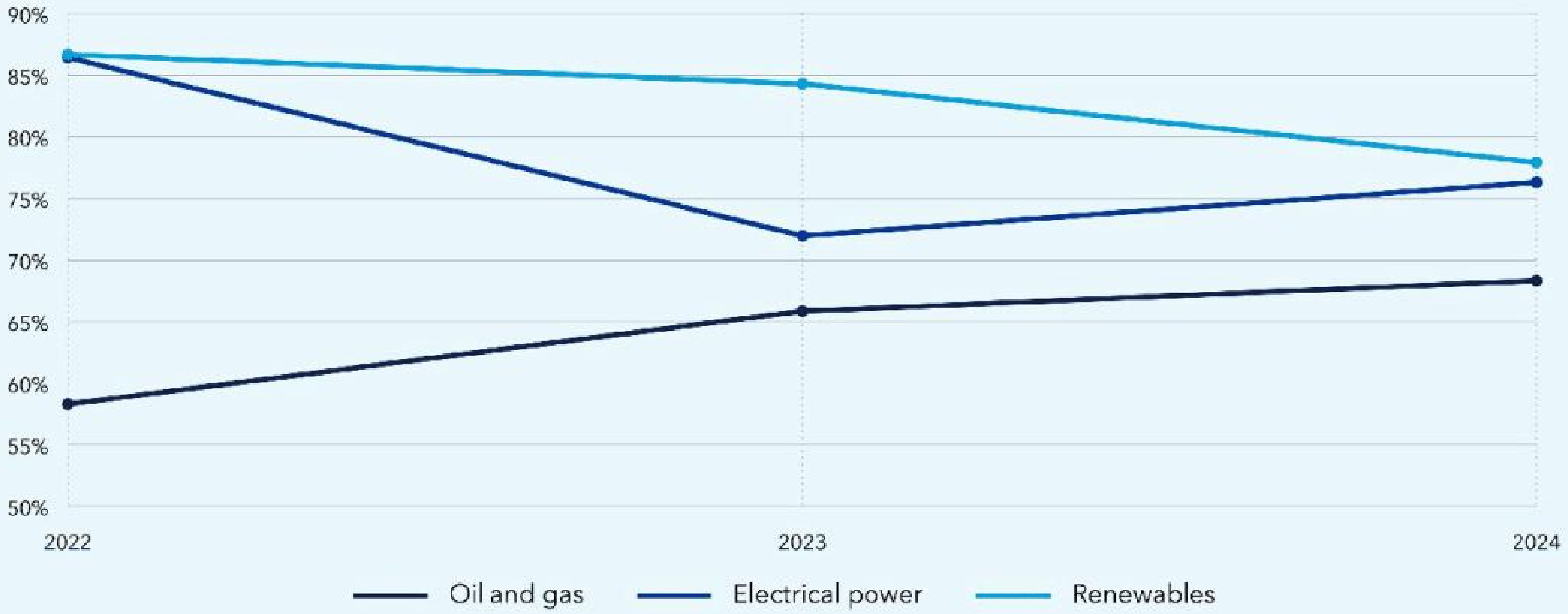


In the same way, **the imbalances of onshore and offshore wind energy,** which are subject to worse forecasting compared to solar generation, are intensified.

INTRODUCTION

FIGURE 1.1

Optimism for energy industry growth by sector



* Percentages show 'net optimism' – the sum of 'somewhat optimistic' or 'highly optimistic' about the growth prospects for (their part of) the energy industry in the year ahead.

According to the main report Energy Industry Insights 2024, which surveyed nearly 1300 senior professionals in the energy sector, there has been a **significant decrease in optimism regarding the growth prospects of renewable energy** (from 87% to 78%) during the period 2022-2024. In our view, this is partly due to the insufficient utilization rate of existing production capacities.

PROJECT CONCEPT

DD WAVE ENERGY LLC

The Gas Institute

Odesa National Technological University

Ukrainian State University of Chemical Technology

The **UWH project consists of several interconnected sub-projects** that, as a result of implementation, can ensure the commercialization of green hydrogen production under current market conditions, perceiving existing state support as a development accelerator.

DD WAVE ENERGY LLC —

initiator and coordinator of the Under Water Hydrogen project.

Under Water Desalination (UWD) —

the technology is being developed jointly by DDWE LLC with the Odessa National Technological University;

Under Water Electrolysis (UWE) —

the technology is being developed jointly by DDWE LLC with the Ukrainian State Chemical Technology Institute;

Under Water Storage (UWS) —

the technology has been developed jointly by DDWE LLC with the Gas Institute of the National Academy of Sciences of Ukraine.

Under Water Desalination (UWD)

The temperature of seawater at depths of around 500 meters is about 5-7 °C, depending on the location. The UWD project **involves desalinating seawater to the level of distilled water** using a freezing method followed by natural leaching of the salt content.

Simplified description of the UWD technology:

In a thermally insulated reactor filled with seawater, **bubbling of the water occurs with gas cooled to below 273 K (oxygen/air),** with the bottom of the reactor open for water access;

At the top of the reactor, there is a condenser from a refrigeration unit that intensifies the **ice melting process;**

A compressor for the cycle **creates minimal pressure sufficient to ensure gas delivery** through the evaporator at the bottom of the reactor;

The refrigeration unit **cools the cycle gas and facilitates accelerated ice melting;**

Desalinated water is pumped out continuously or intermittently **by a water pump.**

DESALINATION OF SEAWATER:

The formation of ice at the bottom of the reactor **causes it to float due to its lower density.** The lower density of the desalinated water keeps it at the top of the reactor, as the rate of thermal and salinity diffusion is significantly slower than the rate of ice melting at the top of the reactor.

The productivity of the unit depends on the density of the refrigerant gas and proportionally increases with operating depth *(at a depth of 500 meters, the density of oxygen is 70 kg/cubic meter).*
Considering two energetically equivalent phase transitions — the formation and melting of the same amount of ice in the system, the need to cool 1 cubic meter of water involves reducing the water temperature by about 6 degrees and is energetically estimated at 7 kWt.

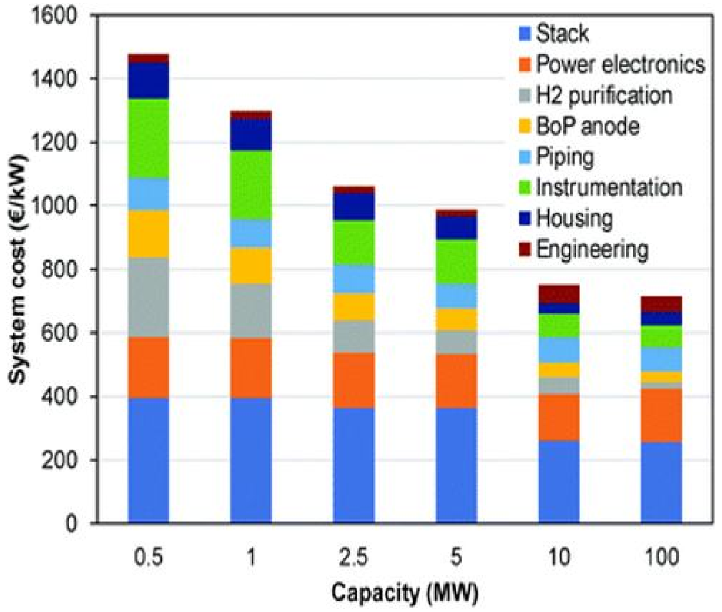
Due to the simplicity of the design and the minimum number of processes occurring, **the installation does not require significant capital investment or regular maintenance,** and it has virtually no environmental impact, provided that the compressor part is soundproofed.

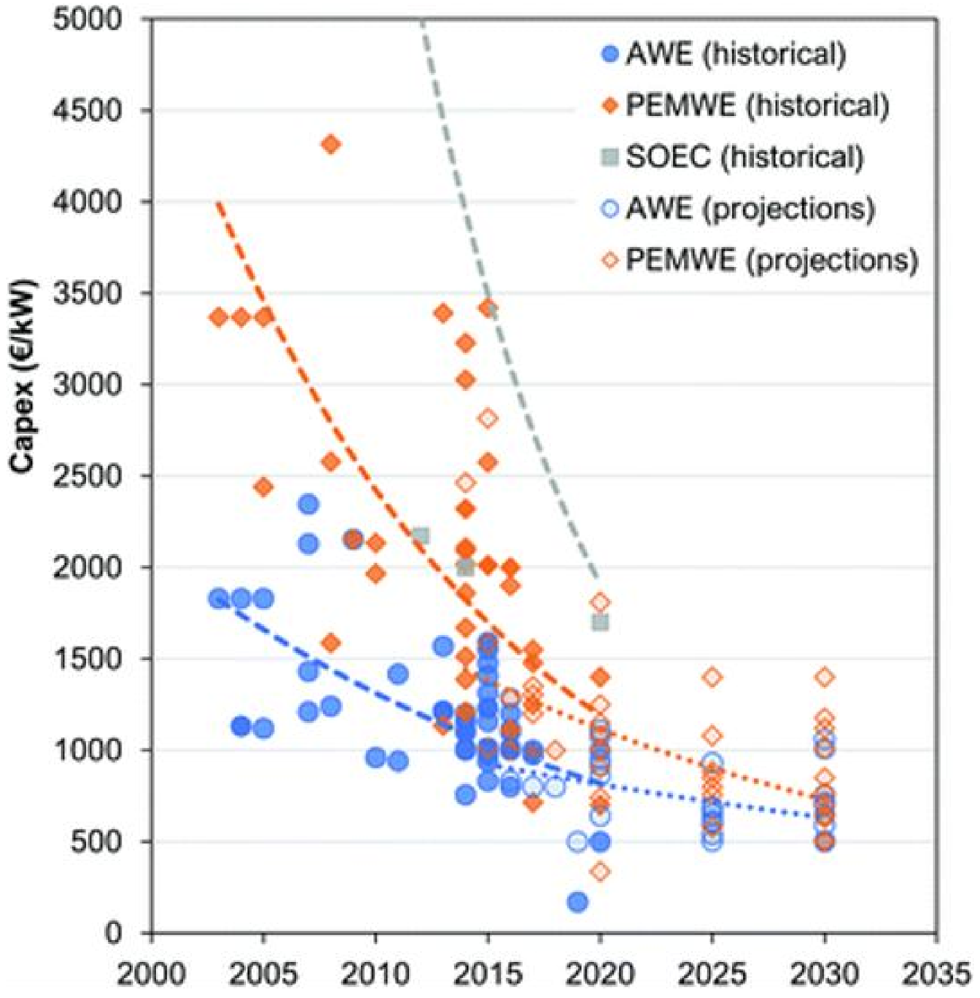
In laboratory conditions, water with a salinity level of 145 mg/liter was obtained from seawater, enabling the possibility of membrane-free electrolysis. Testing continues to refine the technology, with **an expected achievement of TRL4 by June 2024.**

CURRENT AND FORECAST DEVELOPMENT OF WATER ELECTROLYSIS TECHNOLOGIES

From our perspective, the key issue in the efficiency of green hydrogen production by electrolysis is not the electricity consumption for hydrogen production but rather the **significant material and capital intensity of electrolysis.**

According to IRENA data, the current and forecast characteristics of various types of electrolyzer production look approximately as follows:





Retrospectively, there is an **obvious process of reducing CAPEX** to a level of about 800 USD/kW for alkaline electrolyzers, but, unfortunately, further significant cost reduction is not anticipated.

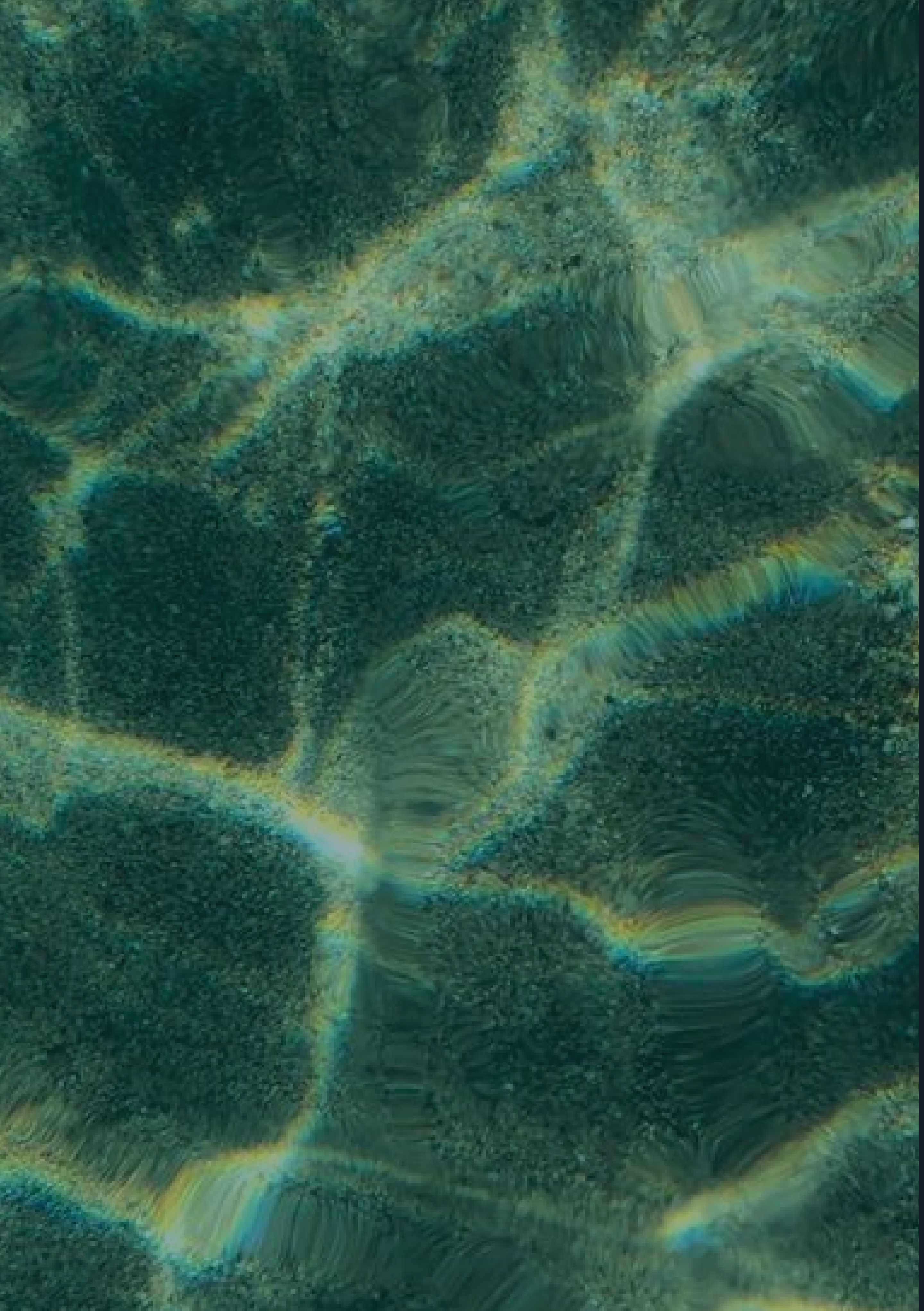
Also, it is **critically important to assess the cost ratio** of the electrolysis unit itself and the supporting infrastructure.

Under Water Electrolysis (UWE)

The undersea alkaline non-diaphragm electrolysis technology being developed by DD WAVE ENERGY LLC offers the possibility of significantly reducing the CAPEX of the process to a level below 100 USD/kW, below are the IRENA data regarding the current state of technology, goals for 2050 compared with the forecast indicators of UWE:

INDICATOR	*IRENA DATA 2022*	*IRENA FORECAST 2050*	*UWE DATA*
Nominal current density	0,2–0,8 A cm^{-2}	>2 A cm^{-2}	>2 A cm^{-2}
Voltage range (limits)	1,4–3 B	<1,7 B	<1,7 B
Operating Temperature	70–90 °C	>90 °C	**capability >250 °C**
Cell pressure	<30 bar	>70 bar	**>50 bar**
Load range	15–100%	5–300%	5–300%
H_2 purity	99,9–99,9998%	>99,9999%	>99,9999%
Efficiency by voltage (LHV)	50–68%	>70%	>70%
Electrical efficiency (stack)	47–66 kWh kgH_2	<42 kWh kgH_2	**<40 kWh kgH_2**
Electrical efficiency (system)	50–78 kWh kgH_2	<45 kWh kgH_2	**<41 kWh kgH_2**
Lifetime (stack)	60 000 hours	100 000 hours	100 000 hours
Stack block size	1 MW	10 MW	**100 MW**
Electrode area	10 000–30 000 cm^2	30 000 cm^2	**30 000 cm^2 (3*1 m)**
Cold start (to nominal load)	<50 min.	<30 min.	**<1 min.**
CAPEX (stack) not less than 1 MW	270 USD kW^{-1}	<100 USD kW^{-1}	**<100 USD kW**
CAPEX (system) not less than 10 MW	500–1000 USD kW^{-1}	<200 USD kW^{-1}	CAPEX of the stack

***UWE data highlighted laboratory and forecast data.**

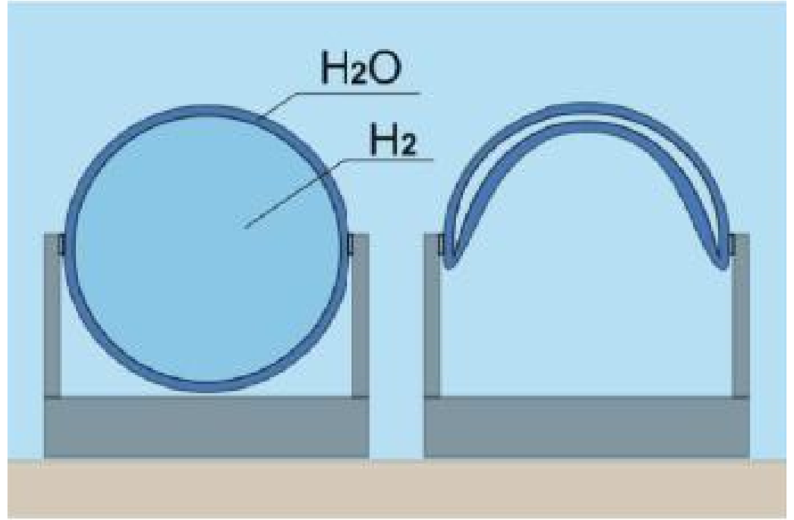


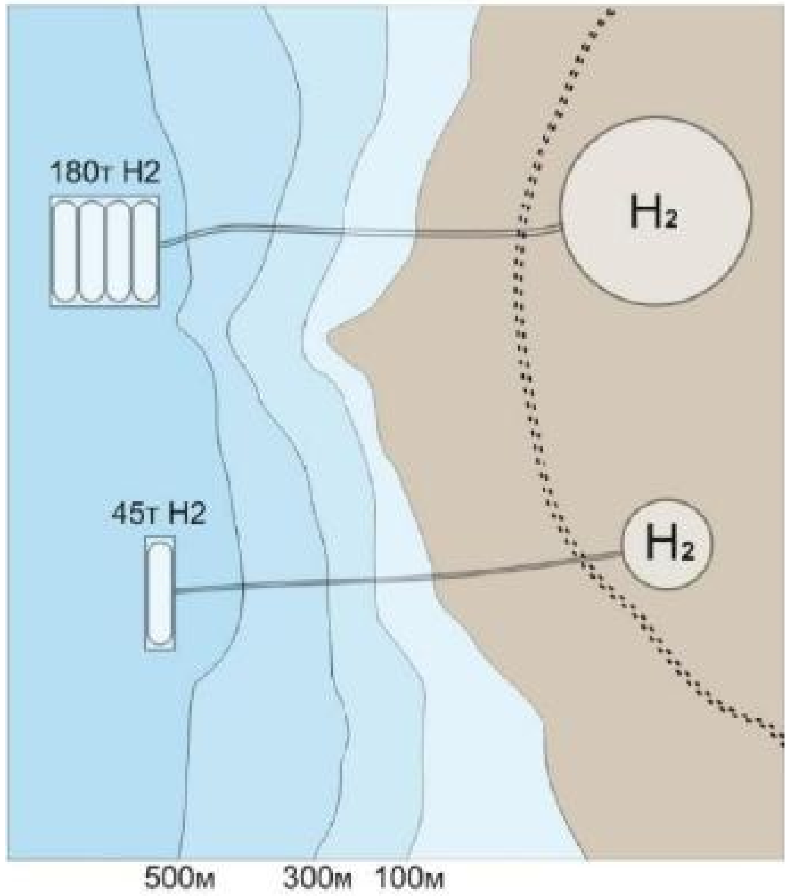
The **practical implementation of UWE allows eliminating from the construction of the alkaline electrolyzer all components except for the electrolysis block,** assembled without diaphragms while maintaining the electrolyte circulation system, as a result of which, according to our calculations, the capital costs per kW can be reduced to less than 100 USD/kW, which will provide the opportunity for periodic use of the electrolysis block, for electricity consumption during peak demand drops. Upon exiting, the compressed hydrogen-oxygen mixture undergoes cryoseparation into hydrogen and oxygen, with oxygen being used as a cryoagent.

Currently, **laboratory tests of non-diaphragm electrolysis are being conducted** with the aim of maximizing the production of the hydrogen-oxygen mixture by depolarizing the electrodes and increasing the electrolyte's conductivity.

THE EXPECTED TIME TO REACH AN OPTIMIZED TECHNOLOGY TRL4 — JUNE 2024.

Under Water Storage (UWS)





The lack of established solutions for delivering hydrogen to potential consumers is also **hindered by high costs and significant losses during storage.** In 2023, the European Commission aims to achieve the following key efficiency indicators for onshore storage of compressed hydrogen by 2030: *storage volume — 20 tons; capital costs — 600 euros/kg.*

The barrier properties of water for compressed hydrogen allow the use of soft double-layer containers **located at depths under hydrostatic pressure of water** for storage. Technically, exceeding the frydrost pressure a tate co resoreing de ta equiped with ballast, can retain significant volumes of compressed hydrogen in close proximity to the coastal consumer. Discarded floating vessels can be used as ballast, filling them with **additional mass.**

The quantity and pressure of compressed hydrogen are subject to **planning depending on available depths and required consumption volumes in a specific cluster,** with appropriate scalability considered.

According to preliminary estimates, **one storage unit can retain 45 tons of compressed hydrogen,** with capital costs of *less than 10 euros per 1 kg of hydrogen,* excluding the cost of pipeline and onshore infrastructure. The gradual integration of storage and consumption clusters can be achieved through the reconstruction of existing or the establishment of new pipeline infrastructure.

CURRENT LEVEL OF TECHNOLOGY DEVELOPMENT — TRL3
ACHIEVEMENT OF TRL6 IS PLANNED FOR 2024.

COMPREHENSIVE TECHNOLOGY DESCRIPTION

The technology is quite versatile for application depending on the set goals and can be designed in a specific location considering the availability of an energy connection source of appropriate power, the remoteness of working depths from the coastline, as well as the method of consuming the produced hydrogen.

As an example, below is shown the ***approximate configuration of the project when located at a depth of 500 meters:***

EQUIPMENT	PERFORMANCE	NOTES
AC power cable, high-pressure pipe	240 cu. m. mixture/hour at P-50 bar	
Thermally insulated electrolyzer block	50 MWt	
Desalination unit	10 cu. m.	
Hydrogen-oxygen mixture storage tank, 8 hours	400 MWt	17.5 MT H_2, V mixture-5841 cu. m.
Gas mixture cryo separation station	729 kg H_2/hour	
Finished product shipping infrastructure	17,5 MT H_2/day	

**it should be noted that the CAPEX of storage capacity decreases depending on the depth of immersion, but costs for communication infrastructure may increase.*

DEPTH FACTOR: FEASIBILITY

The oil and gas industry mastered depths ranging from 500 to 1000 meters about 20 years ago. Using **remotely operated vehicles (ROVs), an operator can perform monitoring tasks** to determine the location, provide servicing, and perform other operations related to submerged equipment. Given the placement of the underwater part of the project by controlled immersion, the necessary deep-water operations involve mooring for submerging or lifting equipment, connecting them with flexible pipeline structures to the surface part, and attaching additional capacities if cluster development is required.

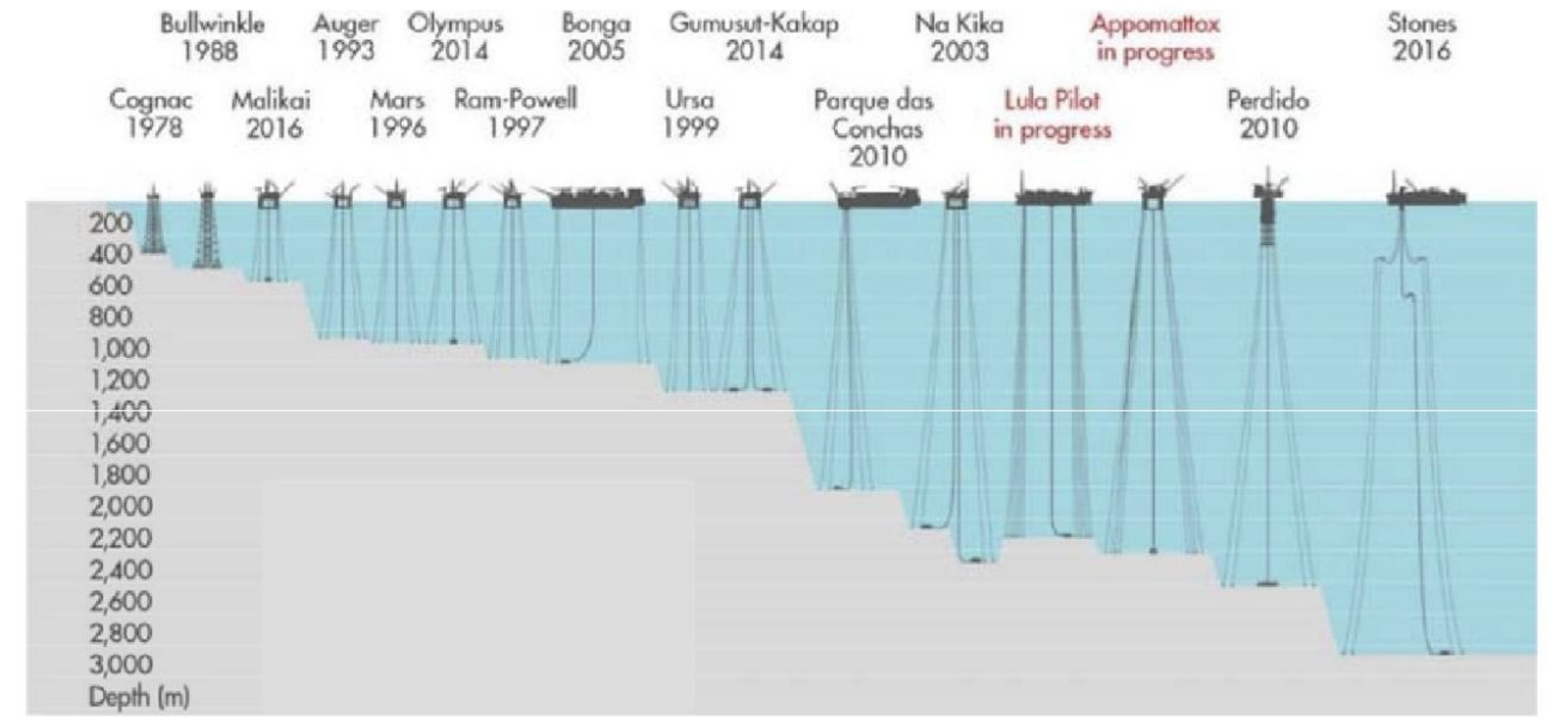


рис. *тенденция выхода нефтегазовой отрасли на глубокий шельф*

Considering the features of the equipment that facilitates the desalination cycle, **electrolysis, and energy storage, deep-water operations are essentially one-time tasks** during the initial installation and potential scaling of capacities. The functioning of the deep-water equipment is designed for a long-term autonomous operation mode, which is maintained by monitoring and measuring instruments.

DEPTH FACTOR: NECESSITY

A common factor for all equipment used at depth is **minimal material intensity.** Technological processes related to the state of gases in compressed form during desalination, electrolysis, and storage are facilitated by the hydrostatic pressure of water at the corresponding depth, eliminating the need for additional capital-intensive expenditures on their structures.

! ***Scaling is also a common factor:*** *adding necessary capacities to the existing system based on the operator's needs.*

FOR DESALINATION:

— a critical factor is the **density of oxygen as a refrigerant.** The gas density achieved at operational depth accelerates the necessary heat exchange processes, thereby reducing CAPEX and minimizing the diffusion processes between saline and desalinated water layers.

DEPTH FACTOR: NECESSITY

FOR ELECTROLYSIS:

— formation of a gas mixture during electrolysis **under pressure corresponding to the operational depth;**

— production of a **gas mixture** that, after dehydration, can be stored for the necessary time in a flexible container under operational pressure;

— harnessing the internal energy of the gas mixture, considering the molar mass of oxygen, which facilitates **further cryogenic separation processes;**

— conducting electrolysis under pressure **at higher temperatures;**

— gaining additional opportunities **to reduce depolarization phenomena on electrodes** and increase the conductivity of the electrolyte.

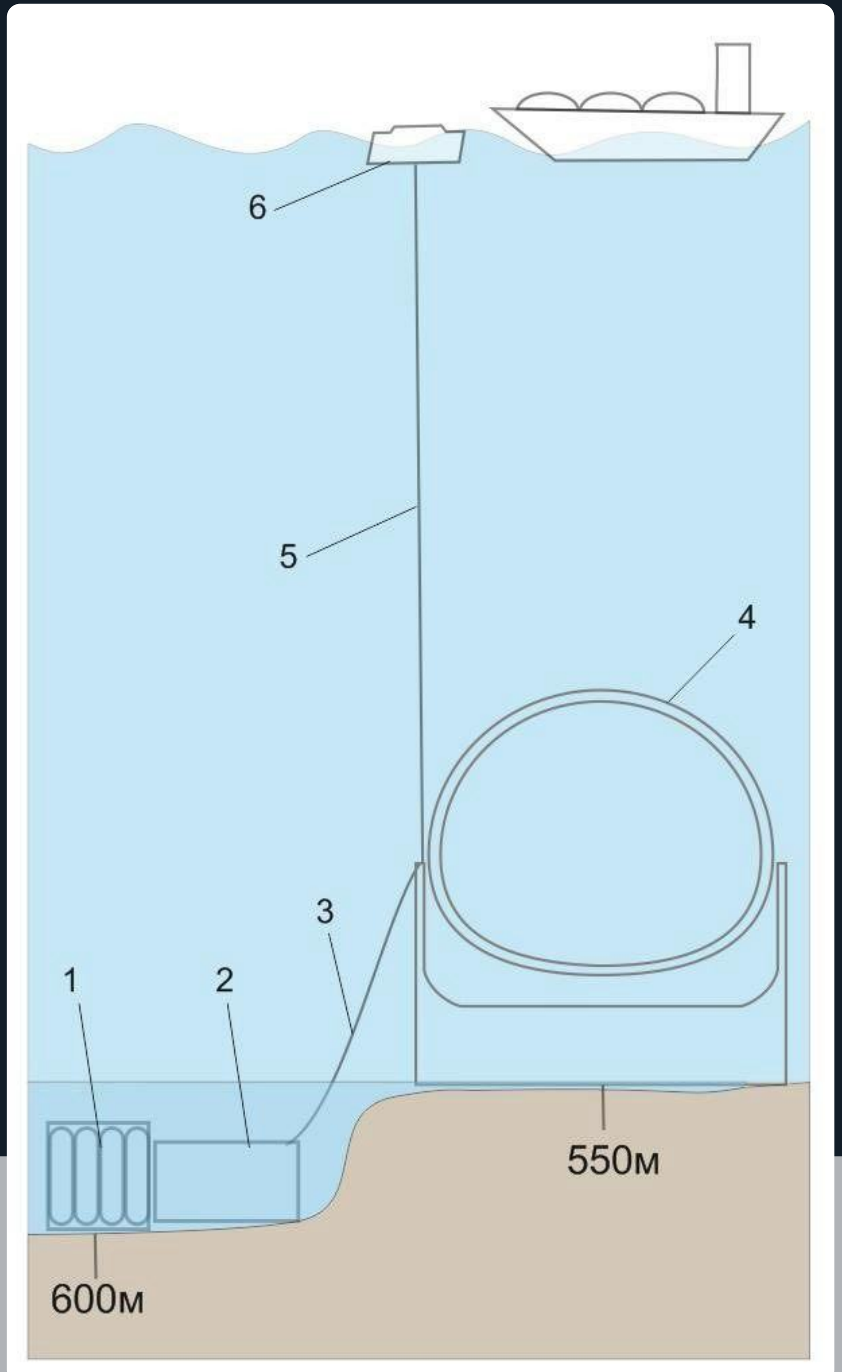
FOR STORAGE AND GENERATION OF GREEN HYDROGEN:

— proportional dependency of the incurred costs **on the depth of hydrogen/hydrogen mix storage;**

— **maximum quality of pure hydrogen** generation due to the cryogenic separation of the mixture;

— systematically **regulated hydrogen supply** depending on demand.

DEPTH FACTOR: VERSATILITY



The diagram shows a ***location-independent complex of equipment*** *consisting of:*

1. a desalinator;
2. an electrolysis unit;

3, 5 a pipeline for supplying the gas mixture;

4. a gas mixture storage with ballast;
6. a cryogenic separation and shipping station.

It is envisioned that compressed and cooled hydrogen, following cryogenic separation, will be pumped into container blocks with subsequent regasification using the ambient temperature to reach planned pressure in the tanks.

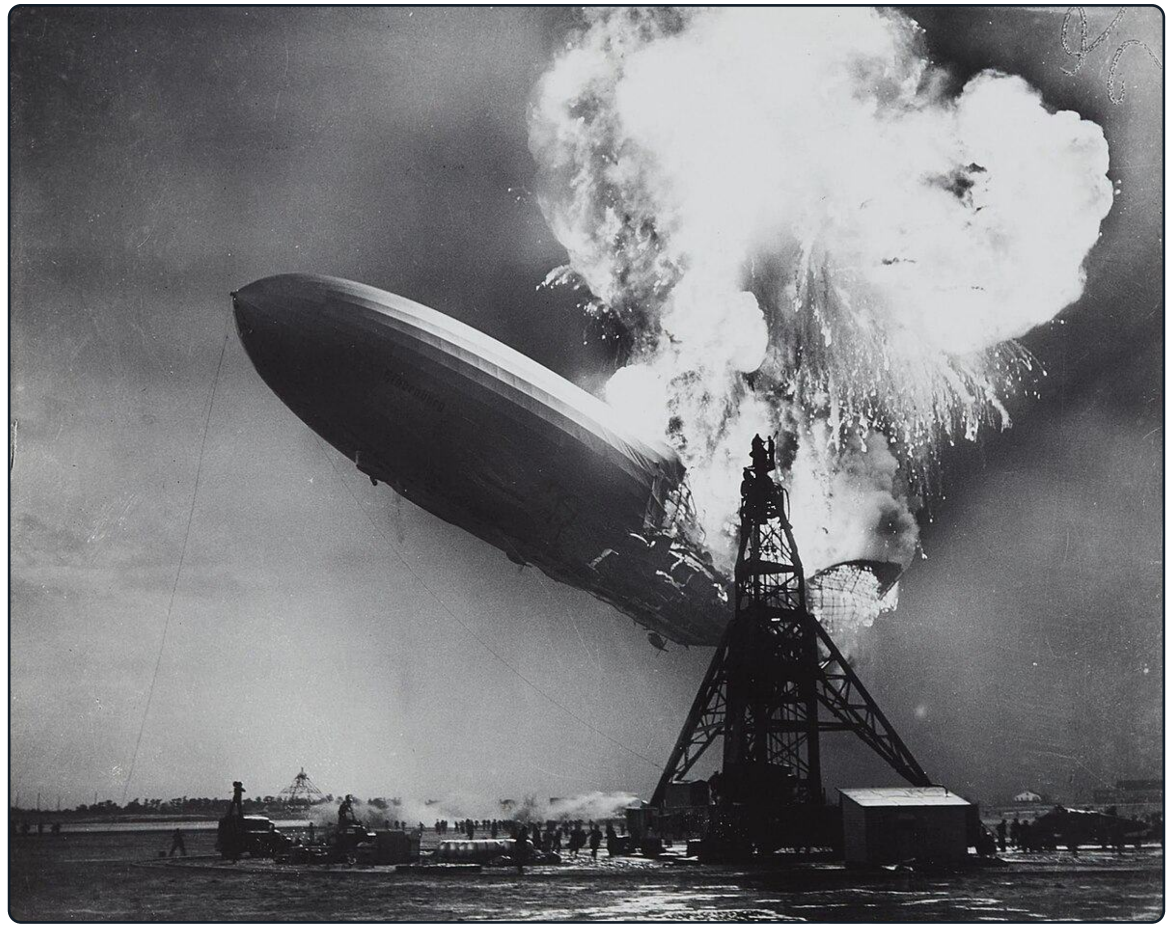
In this case, the placement location depends only on proximity to a power system connection via an electricity supply cable.

If the coast is near an acceptable operational depth and there is a constant local demand for hydrogen, the cryogenic separation and shipping station can be situated onshore.

Given the current level of technology development for hydrogen consumption and transportation as an energy resource, as well as the conditions for its bunkering in various states, we propose considering a simplified model for the generation of green hydrogen.

The technology for delivering compressed hydrogen has evolved through the use of specialized containers, similar to standard containers, for transportation by sea, road, or rail.

SAFETY AND ENVIRONMENTAL IMPACT



The most famous disaster associated with the use of hydrogen is the Hindenburg airship catastrophe on May 6, 1937, in New Jersey, USA, notably documented through numerous photographs.

Nevertheless, the use of hydrogen as an energy resource significantly increases the potential for disasters due to the properties of the gas, primarily because of the incomparable current need and range of use. There is an undeniable necessity for the **maximum possible application of safety regulations** during the production, transportation, and final use of hydrogen.

We believe that in this context, Underwater Hydrogen Warehouses **(UWH) clearly meet the highest safety requirements.**

The underwater production and storage of hydrogen technologically eliminate the contact of the gas with any possible electrical discharge, and the possibility of unpredictable environmental impacts, human factors, or acts of deliberate sabotage **is virtually nil** due to the practical inaccessibility of the production and storage facilities to external influences.

- UWH impacts the local marine environment by temporarily increasing the salinity of the seawater at the desalination site to approximately twice the normal level due to the extraction of freshwater. This effect is localized and monitored.
- UWH reduces the use of freshwater for hydrogen electrolysis production depending on the project development phase. This contributes to a more sustainable approach in regions where freshwater is scarce or conservation is prioritized.

OPEX OF THE PROJECT

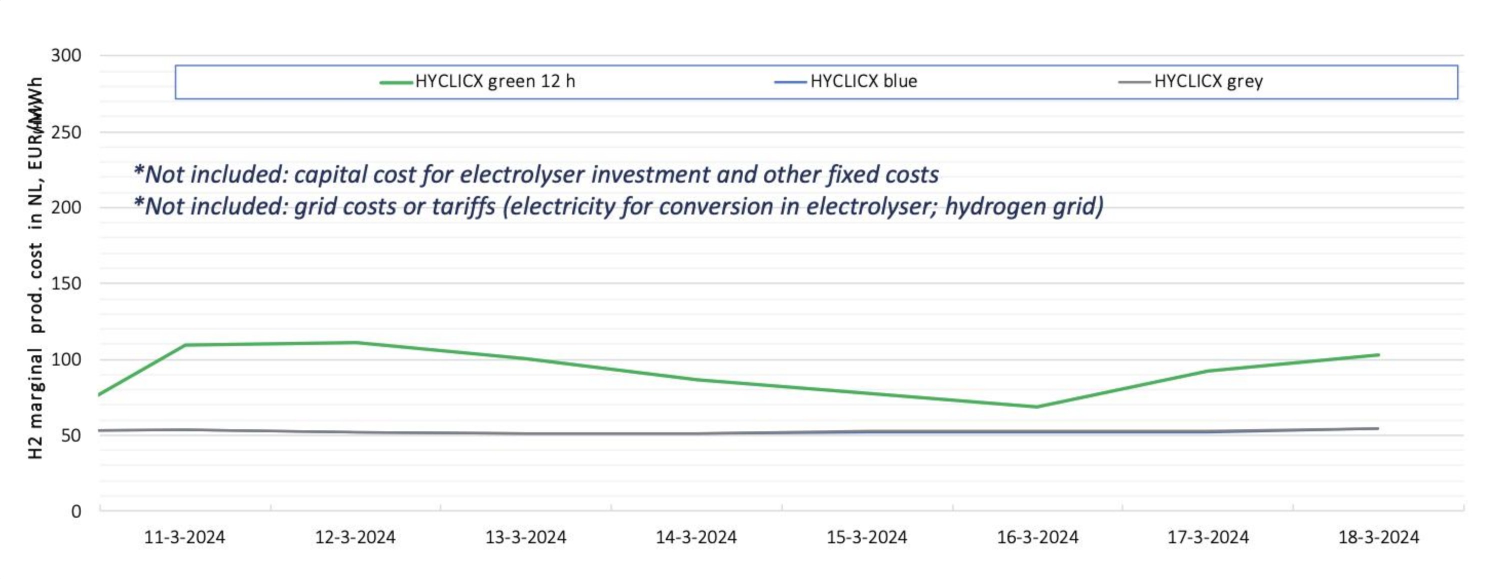
The daily imbalance between electricity production and consumption inhibits the development of unregulated renewable energy, primarily due to the lack of guaranteed consumption during the night period and due to the low consumption plateau during solar energy generation.

The low investment CAPEX provided by UWE technology allows for the operation of the following data:

ELECTRICITY, EUR/ MWH MWH	OPEX H2, EUR/KG	OPEX H2, EUR/MT	OPEX GREEN H2, EUR/MWH
1	0,05	47	1,57
5	0,24	235	7,83
10	0,47	470	15,65
20	0,94	940	31,30
30	1,41	1410	46,95


Day-ahead Market Price

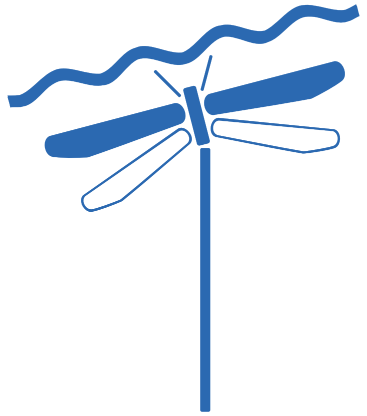
From 19/03/2024 To 26/03/2024


*Not included: capital cost for electrolyser investment and other fixed costs

*Not included: grid costs or tariffs (electricity for conversion in electrolyser; hydrogen grid)

CONCLUSIONS AND ACTIONS [1/3]

- commercial interest in the development of renewable energy remains high but is constrained by a number of objective circumstances, primarily the inability to maximize profits from both existing and planned complexes;
- UWH offers the opportunity to accumulate excess generation capacity in the short to medium term for the production of green hydrogen in any location near the sea;
- UWH provides a versatile technology for storing energy from renewable sources into hydrogen, which can be demanded by both electricity producers and potential hydrogen consumers;
- The impact of the technology can be applied to existing projects with the aim of optimizing their functionality, as well as to planned capacities;



A KEY FEATURE OF UWH

IS ITS UNIVERSAL COMMERCIAL APPLICABILITY

Regardless of the status of the energy producer or hydrogen consumer, each has the opportunity **to implement a UWH project to optimize existing needs,** ensuring a vested interest in commercialization.

CONCLUSIONS AND ACTIONS [1/3]

DESPITE THE MILITARY ACTIONS IN OUR COUNTRY, WE CONTINUE TO WORK ON DEVELOPING OUR PROJECT:

○ due to the military actions, work on creating a desalination plant intended for the PLOCAN platform (Spain, Canary Islands) became impossible, but we are starting anew;

○ we have successfully completed experiments on creating a water barrier layer to contain compressed hydrogen with the Gas Institute of the National Academy of Sciences of Ukraine. We are currently preparing a continuously operating model for storing compressed hydrogen in a flexible container under natural hydrostatic pressure, planned for early June 2024, and are also seeking a legal location for its placement;

○ we continue our experimental work with institutes in Ukraine to complete ongoing experiments, but we anticipate that our opportunities for advancing the project will be exhausted by the summer of 2024, reaching TRL4;

CONCLUSIONS AND ACTIONS [1/3]

DESPITE THE MILITARY ACTIONS IN OUR COUNTRY, WE CONTINUE TO WORK ON DEVELOPING OUR PROJECT:

- we are interested in collaboration with companies - consumers of technology - to create a universal preliminary financial and technological model of UWH that can be applied;
- we are interested in cooperation with companies manufacturing equipment that are interested in the project;
- we are interested in cooperation with specialized engineering companies that can provide a full and detailed calculation of the project;
- as an interim result, we can consider the creation of a working group consisting of several interested companies that will develop a universal technological and financial model of UWH, considering the necessary indicators of energy consumption, its storage volume, and the speed of hydrogen bunkering.

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