Combining existing technologies in innovative new ways

Inertia through innovation: for a stable renewable energy supply

A key role for green hydrogen in the energy transition: how it takes shape in OranjeWind

35 megawatt battery system commissioned at Eemshaven

Blueprint

oranjewind

The OranjeWind technology report 2025

FOREWORD

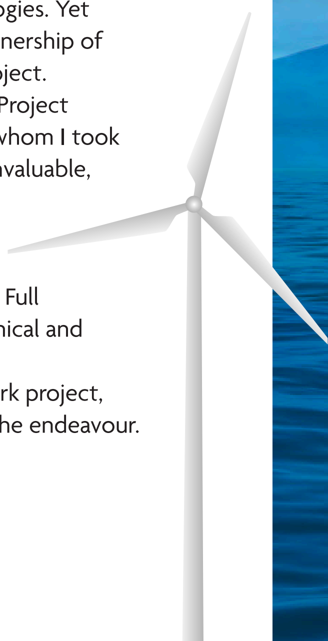
On behalf of the entire OranjeWind team, I am delighted to introduce the very first OranjeWind technology report. In it, we provide a comprehensive overview of the progress made since we won the bid for the OranjeWind offshore wind farm project in November 2022. I hope that this publication will convey a sense not only of the technical ambition of this extraordinary engineering project but also of the spirit of the team that will deliver it.

Conceived as a blueprint for the Dutch energy system of the future, the OranjeWind offshore wind farm project is a 50:50 joint venture between RWE and TotalEnergies. It is remarkable not just for its scale, with a targeted installed capacity of 795 megawatts – sufficient to meet the green electricity requirements of more than a million Dutch households annually – but also for its integrative approach, which combines a wide range of technologies to balance the realities of intermittent wind power on the one hand and flexible energy demand on the other.

Shaping the future of sustainable energy production
OranjeWind is the first system integration project in the Dutch market, and its successful completion will involve both partners delivering their allocated part of a sophisticated mix of integration solutions that includes batteries, e-boilers and electrolysers. The degree of knowledge-sharing and the combination of critical technologies make OranjeWind unique. With this partnership across technologies, we aim to provide learnings that will help shape the future of sustainable energy production in the Netherlands and beyond.
As Project Director, I am pleased to say that our project has got off to a very good start characterised by excellent teamwork across the board. Our team members from two different companies, based in a variety of locations, are already working together as a single team with a common purpose and identity. I would like to take this opportunity to thank my colleagues for the excellent spirit in which we have commenced: maintaining that spirit will see us through to a successful conclusion, whatever challenges we may encounter along the way.

Ownership of the outcome
And we will of course encounter challenges. The strong sea currents at the site, 53 kilometres off the Dutch coast, along with the nature of the seabed, present us with many challenges. So does the installation during the winter season, with its harsh weather conditions. So too does the sheer scope of the project, with its requirement for the deployment of so many interdependent and innovative technologies. Yet with committed leadership, thorough preparation, planning and co-ordination, and strong ownership of the outcome by all parties, I have no doubt that we will succeed in delivering a successful project.
On the subject of leadership, I would like to express my special thanks to my predecessor as Project Director, Frits Laugeman, with whom I had the pleasure of working for many years and from whom I took over in October 2024. Frits' efforts to make the OranjeWind concept a feasible reality were invaluable, and we will carefully build on them as we progress from planning to implementation.

Good progress
Offshore work will start in summer 2026, with the installation of the wind farm's foundations. Full commissioning is scheduled for 2027. At present, our focus is on solving a wide range of technical and logistical puzzles, and we are making good progress on many fronts.
I hope that the following pages will give a good impression of the many facets of this landmark project, and that it will convey some of the energy with which the OranjeWind team is approaching the endeavour.



Kind regards,

Matthias Esken | Project Director OranjeWind

Blueprint

The OranjeWind technology report 2025

The word 'blueprint' was first used in 1842 to describe a form of technical drawing invented by Sir John Herschel involving white lines on a blue background. It became an industry standard and before long acquired the metaphorical sense of any defining concept. The term looks back to the great engineering achievements of the 19th century. But it also looks forward: a blueprint describes something that will come into being.

Every newbuilt offshore wind farm generates enormous amounts of renewable power that is used for lighting, heating, transportation and many other applications. However, with the addition of each new offshore wind farm, it becomes increasingly difficult to match the power production with the demand for electricity. The consequences are widely seen today in the offshore wind sector. In times of peak wind power production, the demand falls short and electricity prices drop, resulting in difficult business cases for offshore wind farms.

OranjeWind is a blueprint for a new class of offshore wind farms based on unprecedented system integration. Our ambition is to show the world how future offshore wind farms can be economically and reliably integrated into our energy system.

We hope you will enjoy Blueprint – our blueprint for the energy transition

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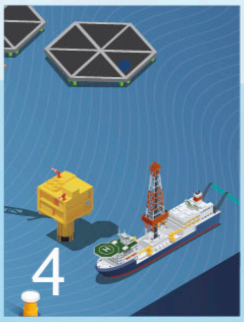


Effective management of inertia is a critical success factor for the energy transition.

Power-to-heat solutions can play an important role in shaping and optimizing the electricity consumption profile of the Netherlands.

The OranjeWind Project

The energy transition is in full swing, with more than half of Dutch electricity today coming from renewable sources. A key element in this mix is offshore wind, which has long since proven its viability as an alternative to carbon-based energy sources. However, the natural intermittency of wind energy presents challenges when it comes to integrating this valuable resource into the energy system.

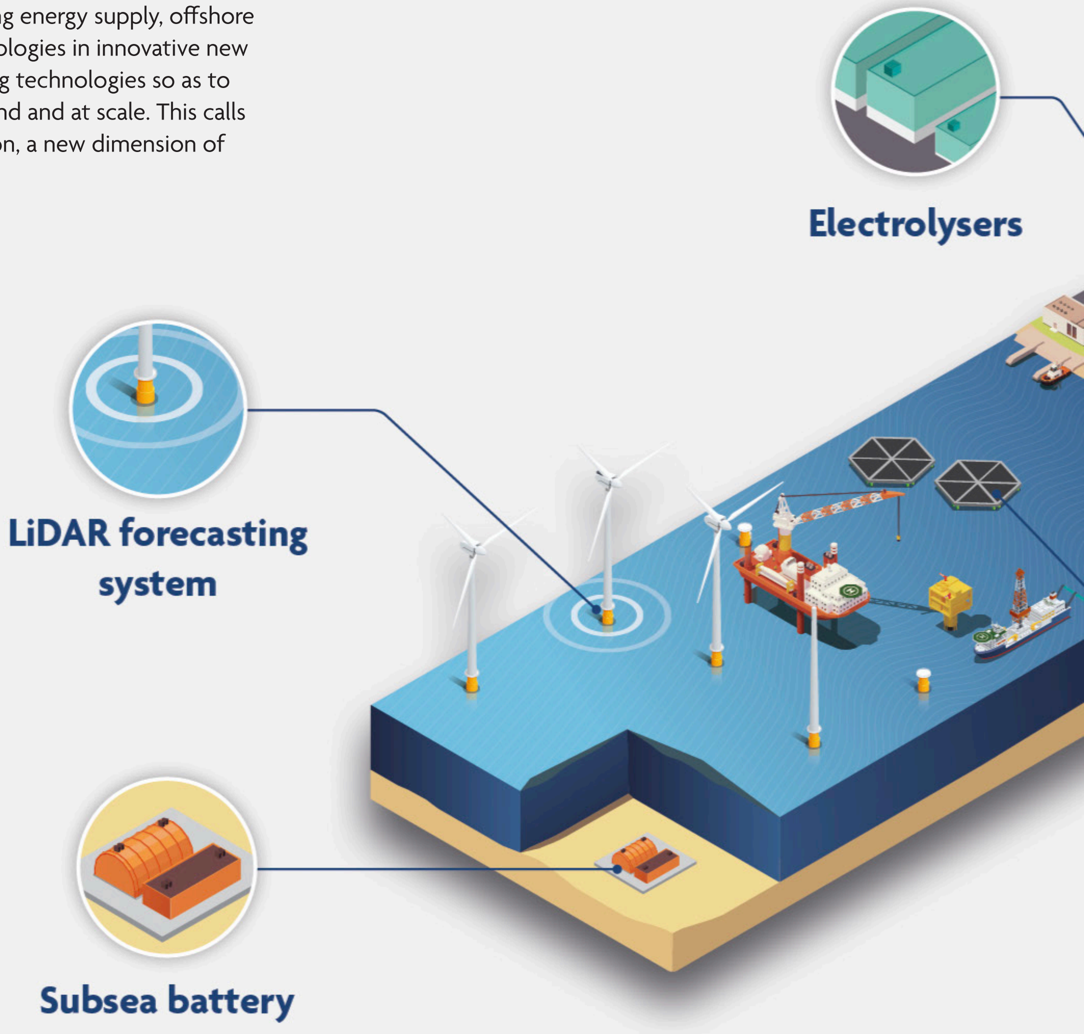
To solve the challenge of fluctuating energy supply, **offshore wind must combine existing technologies in innovative new ways**.

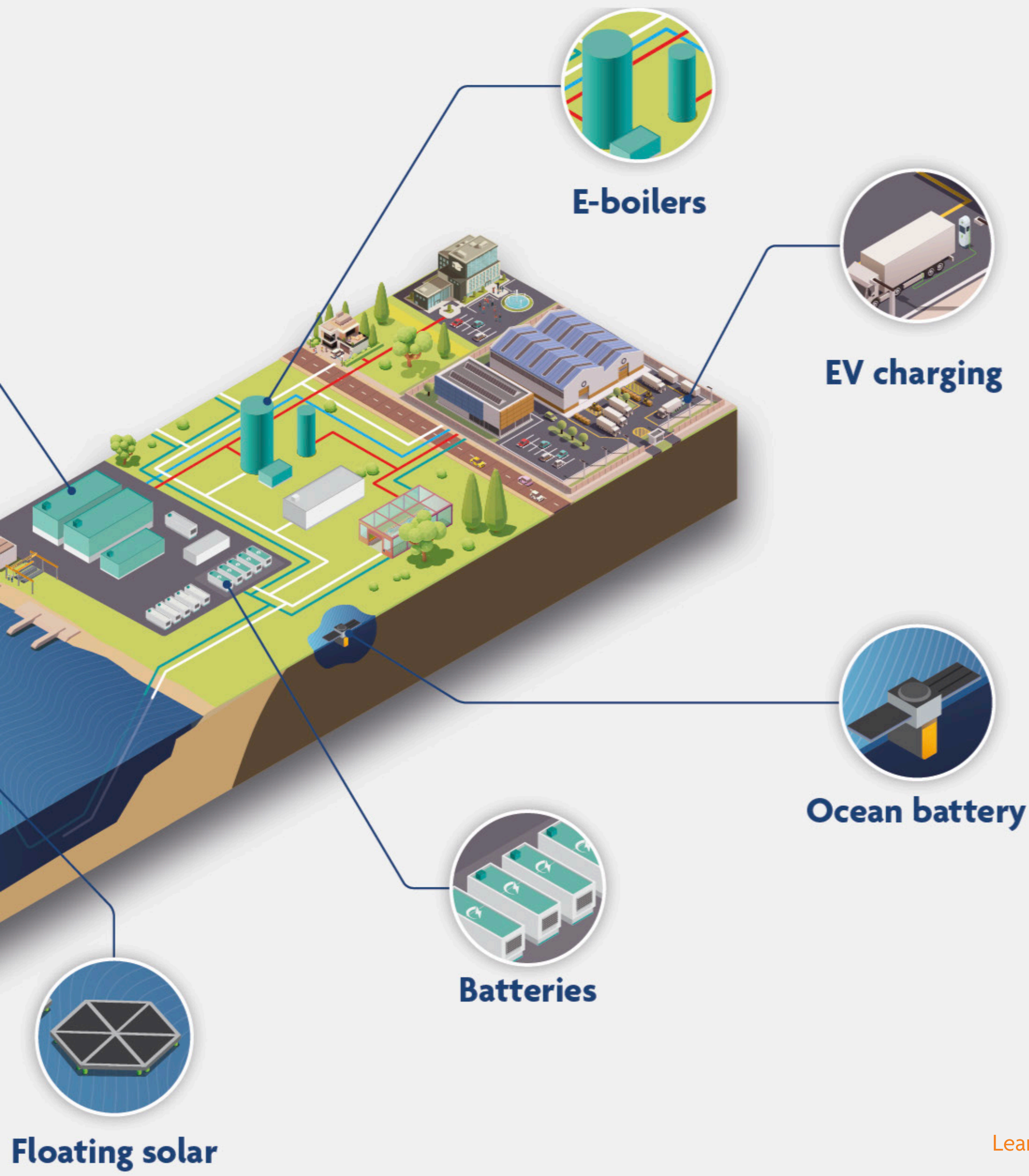
To solve the challenge of fluctuating energy supply, offshore wind must combine existing technologies in innovative new ways. It must also develop emerging technologies so as to supply energy to the grid on demand and at scale. This calls for a high level of system integration, a new dimension of renewable electricity production.

OranjeWind is therefore much more than just a large-scale project. It is a project based on an unprecedented level of system integration that aims to balance the intermittent production of wind energy and the requirements of the Dutch grid. It will enable us to store energy when there is high production and low demand, and to use stored energy when there is low production and high demand. This involves investing in a range of technologies - some of them proven, such as batteries, power-to-heat solutions and electric vehicles, and others still emerging, such as electrolysers.

Our endeavour also involves developing innovative approaches for testing new technologies, working closely with a wide range of highly specialized partners, initiating and conducting fundamental research, and sharing the knowledge acquired in the process with the wider world, to help accelerate the energy transition.

With OranjeWind, we are developing a blueprint for the Dutch energy system of the future.





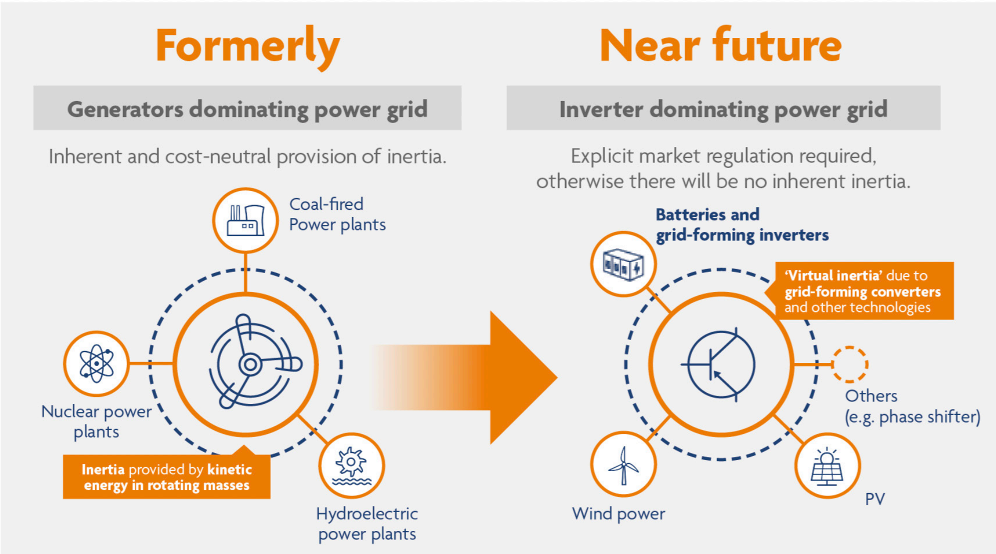
Learn more at **oranjewind.com**

The OranjeWind Inertia Battery

Making stable renewable energy supply a reality

The word ‘inertia’ is probably not the first thing that comes to mind when considering the energy transition. However, the effective management of inertia is a critical success factor in achieving stability of any form of energy supply. Rajiv Hotchandani, Battery Project Developer, explains the connection, and why it is so central to the OranjeWind project.

Rajiv, what is inertia and why is it important for the electricity grid?
The phenomenon of inertia itself is essentially about resistance to change. Electrical power is dynamic by nature. The frequency – the rate per second at which alternating current reverses direction and completes a cycle – is not intrinsically stable. When more power is needed while supply remains constant, the number of cycles per second decreases. It's like riding a bicycle and encountering a steep hill: your pedal speed will decrease. Similarly, when your bicycle chain breaks and the power demand disappears, your pedal speed increases a lot.



Inertia in the past and in the near future.

That's a very abstract explanation, but let's now put the principle in the context of an electricity grid. In an ideal world, the electricity would always flow at a standard frequency, with no highs or lows and no interruptions. The standard frequency in Europe is 50 Hz. All devices connected to the grid are designed to operate on this frequency. Therefore, deviating from this 50 Hz can result in damages and grid failures.

The frequency of the grid doesn't stay constant automatically, as demand for, and supply of, electricity will vary over time, depending on many factors such as the weather, the season, and the behaviour patterns of those using it. It's therefore a full-time task to keep the grid stable by actively resisting such sudden changes in frequency.

In conventional power stations, fuels such as natural gas and coal are burned to produce steam that powers a large turbine. The spinning mass of these turbines resists sudden changes in their rotating speed. Like any heavy moving object, the turbines want to continue at the same pace, even if external forces are telling them to slow down or speed up. The inertia within them therefore acts rather like a shock absorber on the grid, keeping them turning at the same rate and thereby helping to maintain a stable frequency within the network.

"The effective management of inertia is a critical success factor in achieving **stability of any form of energy supply**."

What if your power-generating system doesn't involve massive turbines, though?
That's exactly the challenge we face in the energy transition. Replacing conventional power plants with renewable sources of electricity such as wind and solar means phasing out the rotating mass of the turbines. This leads to a lack of inertia in the grid, a less stable frequency, and therefore a less reliable electricity supply. Nevertheless, inertia – that stabilising influence – has to be provided by some means.

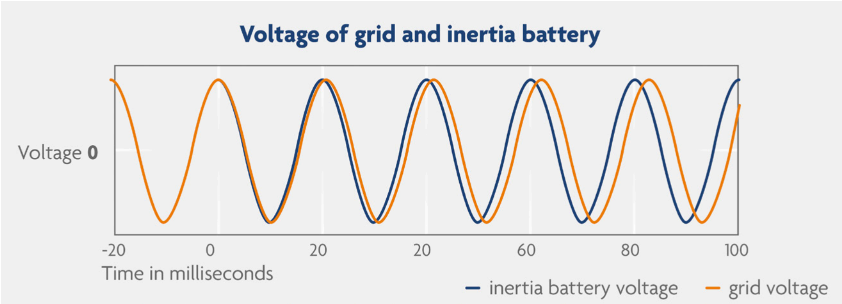
How is it done, then?
That's what this aspect of the OranjeWind Project is all about. We're developing an innovative technology, an ultra-fast battery storage system, designed to stabilise the grid.

Batteries are very different things from turbines...
They are, but we've found a way to provide batteries with inertia so that they can stabilise the grid in the same manner. We sometimes refer to this as 'synthetic' inertia.

How does that work?
Our battery storage system is powered by lithium iron phosphate (LFP) batteries housed in three shipping containers, and it has the ability to provide or absorb electricity within milliseconds, to meet the demands of the grid. While the batteries themselves are nothing special, the innovation lies in the highly reactive "grid-forming" inverters with which they are equipped, which can set their own voltage waveform and frequency and thus provide inertia by not "following" the grid.

Could we unpack that? Let's start with what inverters do.
Sure. Inverters play a very important role in renewable energy systems by making it possible to integrate the energy produced into the grid. The grid

Project team for the inertia battery.



Voltage of grid and inertia battery.

uses alternating current (AC) whereas renewable energy sources such as solar panels produce direct current (DC). Inverters transform the DC into AC so that electricity can be supplied compatible with the grid.

In the case of wind turbines, it's rather different. They produce AC, which they convert to DC with a rectifier, and then back to AC using an inverter. This is to ensure that the frequency and phase of the electricity is in line with the requirements of the grid.

And where does 'not following' the grid come into it?
Batteries, wind turbines and solar parks are usually provided with grid-following inverters - ones that follow the voltage signal of the grid. We often use the analogy of ducklings following a mother duck: where she leads, they follow. Without a mother duck, the ducklings start losing direction. By upgrading the software and hardware on the inverter so that it can make calculations and perform appropriate adjustments in milliseconds, we can provide virtual inertia. The inverter allows the battery to operate independently of fluctuations in the grid to which it is connected by establishing its own stable voltage and frequency. We thus have a grid-forming inverter rather than a grid-following one – that is to say, one that exerts a normative influence on the system in which it participates, our mother duck.

And this is particularly useful in the context of renewable energy?
It's absolutely essential. The intermittent character of renewable sources of electricity results in unpredictable sudden changes in supply. In a renewable energy system, our new inertia battery will be the first responder to

"Inverters play a very important role in renewable energy systems by making it possible **to integrate the energy produced into the grid**."

fix this deviation of scheduled power generation. It's therefore an important element in a suite of integrated solutions we're developing to create a reliable supply of renewable energy.

What's the current status of the inertia battery, Rajiv?
The battery has been constructed at our power plant in Moerdijk, in the province of North Brabant in the south of the Netherlands. It has an installed capacity of 7.5 megawatts (MW) and a storage capacity of 11 megawatt hours (MWh).

The battery was commissioned at the beginning of 2025 and is currently undergoing a two-year pilot phase, during which the provision of inertia will be tested and monitored. Based on the learnings from the pilot, the transmission system operator TenneT, one of our partners in the pilot, will further develop its technical requirements and the relevant grid compliance procedures.

This is the first time that a battery of this scale and type will be connected to a high-voltage grid. Together with TenneT, we want to learn how much inertia the battery can provide, and to assess the potential commercial value of this application. So the first thing we're doing is to run a series of simulation studies using different types of scenarios. The next will be to find out whether the battery can work in situations of system overload, and what effect this might have on the degradation of the batteries. We'll be combining the provision of inertia with different market services. This is done to test if virtual inertia can be delivered on top of other market services, providing extra commercial value.

Do you have any projections regarding that value?
It's too early to say, but certainly we see an important future market for this technology. As Europe moves to an increasingly renewable energy system with less spinning mass, the need for virtual inertia will only grow.

Thank you, Rajiv, and good luck with the next phase of the pilot!
Thank you!

System Integration: Green Hydrogen

Of all the system integration applications in the OranjeWind Project, the production of green hydrogen is the most ambitious and wide-ranging.

Green hydrogen – produced via electrolysis powered by renewable energy – has a key role to play in the energy transition. Laurent Ferry, Director for the Zeeland Hydrogen Project at TotalEnergies, and Janet Heida, Project Director Hydrogen at RWE, discuss the progress of plans to help make green hydrogen the new industrial standard in hydrogen production.

Laurent Ferry | Zeeland Hydrogen Project Director at TotalEnergies.

Laurent, before we dive into the details of TotalEnergies' plans for green hydrogen, could you first explain a little about electrolysis itself, and how an electrolyser works?
Yes, of course. Electrolysis involves the use of direct electric current to bring about a chemical reaction that would not happen otherwise. In the case of hydrogen production, the electrolyser uses electricity to split demineralised water into hydrogen and oxygen.

The electrolyser consists of multiple cells with electrodes and an electrolyte. When electricity is applied, water molecules are split at the anode (the positive terminal) to produce oxygen and protons, while at the cathode (the negative terminal), protons combine with electrons to form hydrogen gas. The hydrogen produced is collected and compressed, and can be used for various applications such as fuel cells for mobility or for industrial processes. The oxygen produced is a by-product.

And what makes the hydrogen green?
That depends on the source of the electricity used. If the electrolyser uses renewable electricity, then the hydrogen is classed as green because it is produced without the production of the CO_2 emissions that are associated with the use of electricity generated using fossil fuel sources. Doing this at scale is what is so exciting about this project, for it has huge possibilities for the large-scale decarbonisation of current industrial processes.

What's the current state of TotalEnergies' planning on this front?
For our Zeeland Refinery, we plan to build what will be one of the largest electrolysers in Europe, which will enable the production of up to 30,000 tons of green hydrogen a year. The electrolyser will be supplied with renewable energy produced by OranjeWind.

And how will this green hydrogen be used?
In our refineries, we use hydrogen in the desulfurization process to reduce the sulphur content in fuels. This is essential for meeting environmental regulations and producing low-sulphur diesel and gasoline. TotalEnergies intends replacing this fossil-based grey hydrogen by green hydrogen. The green hydrogen from the new electrolyser will provide about a third of our hydrogen requirements and allow us to reduce our CO_2 emissions by up to 300,000 tons annually.

How does this fit within the wider context of TotalEnergies' overall decarbonisation strategy?
We have the ambition to completely decarbonize the hydrogen used in our European refineries by 2030. With a view to achieving this goal, in 2023 we launched a call for tenders for an annual production of 500,000 of green hydrogen. This will be a major step towards achieving our overall GHG reduction targets. Making such a huge transition in the coming years wouldn't be possible without the cooperation other industrial players. We've therefore entered into a 50:50 joint venture with Air Liquide to study, build and operate the electrolyser.

"For our Zeeland Refinery, we plan to build what will be **one of the largest electrolysers in Europe**, which will enable the production of up to 30,000 tons of green hydrogen a year."

Why was Air Liquide chosen as TotalEnergies' partner for this project?
We've had several successful cooperations with Air Liquide in the past two years involving the production of green hydrogen for industrial use and for mobility. Air Liquide was therefore the natural strategic partner to help us develop a green hydrogen plant of this scale. They've acquired extensive experience in designing and operating electrolysers in recent years. Joining forces enables us to be more efficient and to secure a reliable supply of green hydrogen for our refinery.

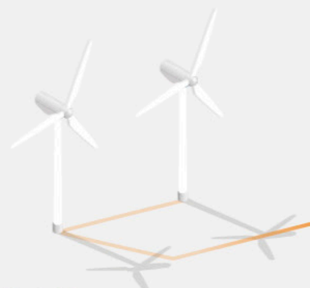
Can you tell us something about the electrolyser's design?
It's based on PEM technology. PEM stands for proton exchange membrane. In the electrolyser, the cathode and the anode are separated by a membrane which has the property to enable the movements of protons while blocking the passage of electrons so that the hydrogen is produced only at the cathode. It will be supplied by Siemens Energy, and it uses a modular design: one stack consists of multiple individual cells, each containing an anode, cathode, and a proton exchange membrane. Multiple stacks are combined into arrays. Our plant will have 14 arrays in total, to reach an overall capacity of 250 MW.

This is all still at the planning stage, however. When do you expect to take the final investment decision?
For the FID, we need to finalize our ongoing engineering studies and also to secure all the prerequisites, such as the necessary permits, the grid connection, and of course a solid business case. We're confident, however, that the FID will be taken in 2026.

Assuming the FID goes ahead, what obstacles do you envisage to the actual construction of the electrolyser?
I wouldn't speak in terms of obstacles, but naturally there are certain challenges to be overcome. One of these involves the issue of intermittency. Our production will have to be phased with the electricity production from the OranjeWind offshore wind farm. So our production will be full-load when there is a lot of wind and will have to be reduced or even stopped when there is no wind. While the refinery has a constant baseload hydrogen need, we must find ways to accommodate this intermittency in the green hydrogen supply. We're currently exploring various technical options, including a connection to the hydrogen backbone.

Another important factor here is the legislation on Renewable Fuels of Non-Biological Origin: the implementation of the European renewable directive in the Netherlands with regard to RFNBO is still under discussion and is not yet finalized.

A further challenge is the financial viability of the project, as we're facing an extremely high grid tariff that is specific to Netherlands. Nevertheless, we're confident that all these challenges can be successfully addressed and that the electrolyser will be built as planned.



See **press release** TotalEnergies

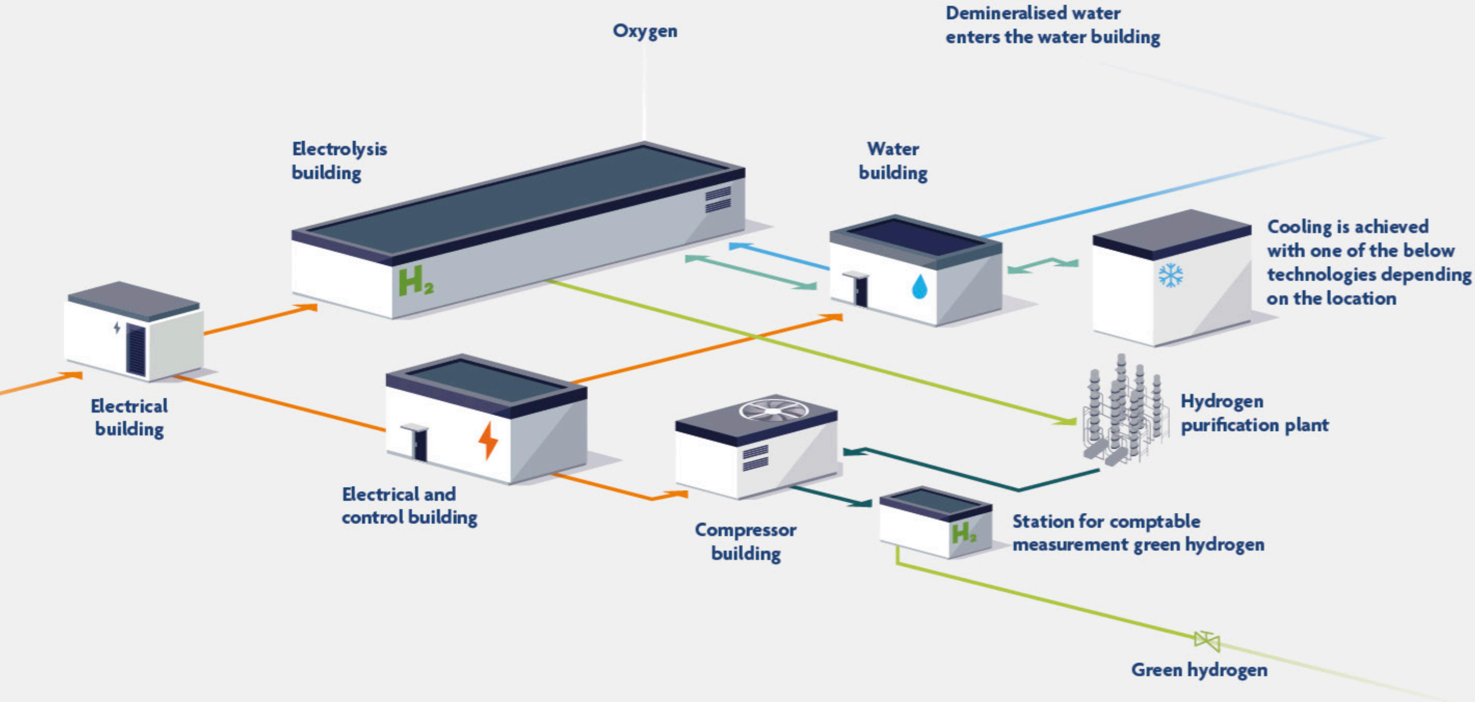
Janet Heida | Project Director Hydrogen at RWE

Janet, RWE is also exploring electrolyser technology within the framework of OranjeWind. How does this fit in with the overall system integration philosophy?

Our starting-point is of course different from that of TotalEnergies, in that TotalEnergies can offtake the green hydrogen produced within the framework of OranjeWind for use in its own refineries. At RWE, we can't do that, but we're nevertheless committed to increasing the provision of green hydrogen at scale as a fundamental building-block of the energy transition. Our goal is to become net-zero by 2040. Our position in offshore wind is already very strong, and green hydrogen can significantly strengthen that value chain.

What plans do you have in place at the moment?
We're planning to construct an electrolyser to deliver 100 MW of renewable hydrogen production near our Magnum Power Station in Eemshaven. If construction goes

Electrolysers using electricity from OranjeWind provide green hydrogen, reducing CO_2 emissions for industrial companies or refineries. (This is an example. It can be different for each project.)



ahead, the electrolyser will support our ambitions to make the Eemshaven region a sustainable energy hub and will make a significant contribution to improving the sustainability profile of Dutch industry. One of the beauties of green hydrogen production is that if it can be achieved at sufficient scale, excess qualities of hydrogen can be stored for long periods and converted back into electricity. Hydrogen can be stored for months, whereas electricity can only be stored for about 24 hours, via the use of batteries.

What's the current status of the project?
The necessary environmental and building permits for the electrolyser have been secured, which is the essential first step. Some of the boundary conditions include the overall development of the green hydrogen market in the Netherlands and specifically the national hydrogen backbone.

We're also working on the realisation of a 50 MW electrolyser at our nearby Eems Power Station. Both projects are subject to final investment decisions, which are dependent on these wider developments. The potential of this technology is enormous. For the present, the key thing is that we are very well positioned to serve the market as this becomes properly established.

Can you say something about the technical design of these electrolysers?
It's too early to say, I'm afraid. We'll be working together with technically and financially mature partners in the field of electrolyser construction, but our philosophy is technology-neutral at this stage.

"**Our goal is to become net zero by 2040.** Our position in offshore wind is already very strong, and green hydrogen can significantly strengthen that value chain."

See **press release** RWE

The OranjeWind Knowledge Programme

Bas Jansen | Programme Manager OranjeWind Knowledge

There are many firsts in the OranjeWind Project. One of particular note is the OranjeWind Knowledge Programme. Our aim is not just to create an ordinary wind farm; it is to create a wind farm that will actively accelerate the transition to a sustainable energy system by balancing the dynamics of offshore electricity production and onshore demand.

To do this, we need to learn about a future energy system that has not yet been built. The knowledge and insights that we develop will accelerate the roll-out of offshore wind, thereby paving the way to a sustainable energy system. A fundamental aspect of our approach is to share all of this knowledge with the world. This level of transparency has never existed before in the context of any other offshore wind farm – which makes it all the more exciting.

OranjeWind Knowledge

Research, communication and dissemination

Generating knowledge

- Collecting in-house expertise
- Learning from OranjeWind
- Facilitating research
- Stimulating innovations

Sharing knowledge

- Initiating and joining learning communities
- Hosting on-site demonstrations and events
- Developing workshops, webinars and teaching material
- Contributing to the education of the future workforce
- Publishing in scientific journals and at conferences

"**We need to learn** about a system that has not yet been built."

There are two sides to this programme: generating knowledge, and sharing it with the public. Knowledge is generated through the PhD research programme, whereby data and insights from the project are collected and innovation is stimulated. The research has already started even before offshore construction begins, and six OranjeWind PhD candidates are currently exploring different aspects of system integration in offshore wind in the North Sea.

In addition to the OranjeWind research project itself, two other research projects are supported by OranjeWind: the DEFLAME project and the OESTER project. DEFLAME focuses on the electrification of industry and OESTER on offshore energy storage.

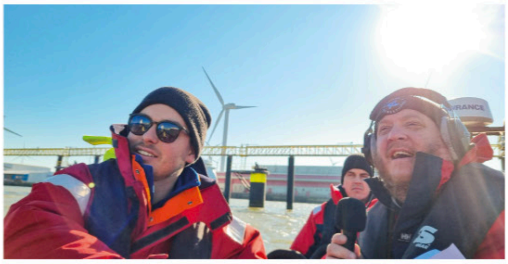
Once the wind farm, its flexible demand assets and the off- and onshore innovations become operational, a great quantity of collected data and insights will be made freely available via our public knowledge sharing platform. During the project, we keep pushing innovations that can play a role in matching supply and demand in a sustainable energy system.

To make sure that the knowledge generated is widely used, we are creating a knowledge network by joining learning communities, reaching out to teachers, involving our suppliers, and developing workshops, podcasts and masterclasses. Besides this, we will also organise an annual OranjeWind Symposium.

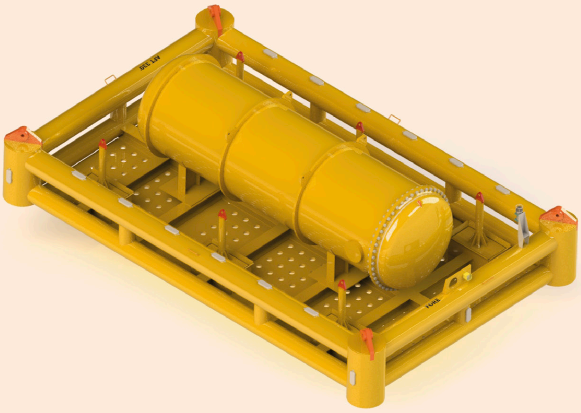
"The energy transition is far **too big to keep all the knowledge to ourselves**."

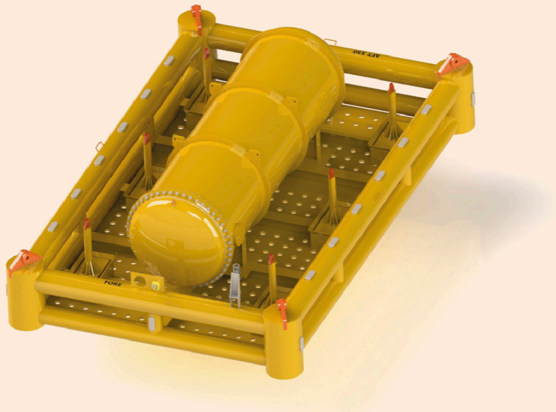
In due course, we will publish advisory reports for policy-makers and industrial partners on how to improve the design, construction and operations of offshore wind farms and flexible electricity demand assets for optimal integration in a future energy system.

The energy transition is far too important to keep all the knowledge we generate to ourselves. It is good to see that the key players in offshore wind are starting to recognise that the energy transition is a joint effort in which the exchange of knowledge is essential. I am proud that the OranjeWind Knowledge programme is leading that change.



OranjeWind Knowledge initiatives across the Netherlands.





New frontiers in energy storage

Subsea Battery Pilot

Partnership in pursuit of innovation is at the heart of the OranjeWind concept – which is why RWE regularly makes use of innovation competitions to uncover groundbreaking approaches to the challenge of integrating offshore wind into the energy grid.

A winner of one such competition is the Scottish company Verlume, which develops offshore subsea battery systems with integrated intelligent energy management.

Balancing supply and demand

Without reliable, large-scale energy storage solutions, renewable energy production means intermittent energy production, which is associated with a host of technical and economic challenges. The search is therefore on for new ways of balancing supply and demand. Batteries have a key role to play here, and Verlume is developing a subsea lithium-ion battery as part of the mix of technologies that will make up OranjeWind's unique system integration solution.

One of the advantages of subsea operation is that the seawater offers natural cooling for the battery. Installation at the OranjeWind site, however, presents considerable challenges, due to the North Sea's highly dynamic character, involving relatively shallow water, high wave interaction, and significant movement of the seabed.

Piloting

A pilot project currently in progress is exploring these challenges using a small-scale battery with a capacity of 500 kWh and an output of 250 kW. The pilot is exploring every aspect of this innovation, including how to install and operate the battery, how to integrate it into a wind farm and how its exterior responds to long-term immersion in the sea. Experience so far indicates, however, that this technology could be better suited to seas with a rocky seabed, where the logistics of installation are less challenging.

Despite this caveat, the potential expansion of this technology is also under review. There might be a case for positioning the battery within the wind turbine monopile to maintain the advantages of immersion but isolating the system from the dynamic environment (seabed & sea). This case is currently being investigated as part of project OESTER. Undersea batteries might also be used for charging and discharging of Autonomous Underwater Vehicles. AUV's can play an important role in the installation, maintenance and monitoring of wind farms, although this is not within the current scope of the OranjeWind project.

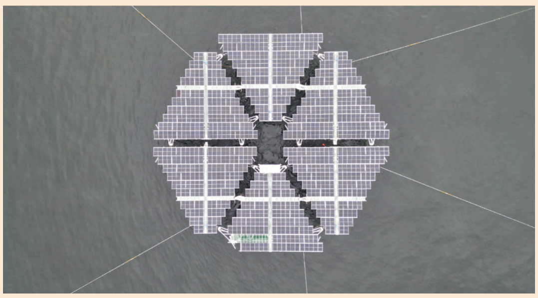
Latest Project Learnings

Floating solar and the challenge of the North Sea

With its shallow depth, strong currents, high winds, waves of up to eight metres, winter fogs and density of maritime traffic, the North Sea is a highly challenging environment for locating energy infrastructure. Some solutions are well suited to these harsh conditions; others, less so.

An important aspect of the initial phase of the OranjeWind Project has been to investigate the viability of floating solar installations as part of a broader mix of renewable energy technologies offshore.

Complementary technologies
From a purely spatial point of view, the production of solar energy at sea using floating installations has much to recommend it. The installations take up no valuable space on dry land and can be situated between offshore wind turbines, where maritime traffic is strictly forbidden for reasons of safety. Moreover, the power production profiles of wind and solar are complimentary due to the prevalence of more powerful winds in the winter and more sunshine in the summer. There is thus an attractive argument for adding solar panels to a wind farm to help stabilise its output. This combination has, however, only been piloted on a small scale to date, and many technical challenges remain to be overcome in order to achieve the desired stability of output.



The Merganser pilot project in the North Sea.

Pilot project
Floating solar farms have been successfully installed and operated in inland waters. To test the viability of this concept in the rough conditions of the North Sea, a pilot offshore solar installation named Merganser was positioned off the coast of Scheveningen in the Dutch North Sea in July 2024. Merganser was designed to move with the winds and tides of the sea. The installation was intended to serve as a stepping stone towards scale-up of the technology. Multiple summer storms have provided an opportunity to test and validate elements of the design, but have also highlighted areas for further technology developments especially in relation to the mechanism connecting the platforms together. The structure was towed back to shore and analysis is still ongoing on further technology development and validation.

Another challenge facing offshore floating solar is how to connect the floating installation to the electricity grid by means of a cable that can cope with the installation's movements. The suitability of such a cable has not been demonstrated for offshore solar energy production in the North Sea and hence this element of the OranjeWind Project is currently being investigated further.

A new application of a tried and tested technology

Sub-surface energy storage

While certain energy storage solutions being explored within OranjeWind are radically innovative, others involve the application of tried and tested technologies – applied in new ways, however. This is the case with sub-surface pumped hydro storage.

Pumped hydro storage
The pumped hydro storage (PHS) system currently being developed by our partner company Ocean Grazer uses the principles of hydroelectric power to store energy and release it to the grid when required.

PHS is a technology that is more than a century old: it was first used in Schaffhausen, Switzerland, in 1907. The PHS system comprises two water reservoirs which are positioned at different heights and connected with each other. When demand for electricity is low, excess generation capacity is used to pump water from the lower to the upper reservoir. When demand for electricity increases, water is released back to the lower reservoir through a turbine. The gravitation potential energy of the water is thereby turned into the required electricity.

PHS under water
PHS is the most widespread form of large-scale energy storage today. Traditionally, however, it has been located on land. In the OranjeWind Project, we are exploring the possibility of applying the principles of PHS under water.

Imagine the seabed as the plateau for the upper reservoir. Water is stored in a flexible 'bladder' that can be opened to permit water to flow in and out of it. The lower reservoir is created by drilling a shaft from the seabed down into the earth's crust. The lowest point of the shaft equates to the level of the lower reservoir on land. At the bottom of the undersea shaft, a turbine is installed.

When excess electricity – generated by the wind farm – is available, water is pumped up the shaft and into the bladder. When, conversely, electricity is required by the grid, water in the bladder is released to shoot down the shaft, where it powers the turbine and generates electricity.

Onshore pilot
Within the OranjeWind Project, the concept is being developed by our partner Ocean Grazer as the 'AquaVault'. The AquaVault will be piloted at a sand-mining lake in Sellingen (Groningen, Netherlands). The pilot will take place onshore in order to rigorously test the concept's functionality and minimise potential risks before it is trialled at sea.

Enhanced wind forecasting for more accurate energy management

LiDAR

One well-established technology undergoing deployment within the OranjeWind Project is LiDAR. Short for 'light detection and ranging', LiDAR determines distances and velocities by means of laser light.

In its simplest form, the concept was first developed by the Irish physicist Edward Hutchinson Synge in 1930. It was first commercialised by the Hughes Aircraft Company, an American aerospace and defence contractor, in 1961. Today, LiDAR finds applications in areas as diverse as mapping and surveying, atmospheric physics, archaeology, and forestry, as well as in self-driving cars and emergency response planning.

Within the context of OranjeWind, LiDAR offers the possibility of more accurate ways of short-term wind speed and power forecasting, with a view to helping optimise the wind farm's energy output and thereby increase the efficiency of energy trading. Using LiDAR is more costly than using statistical methods and weather models, so a cost-benefit analysis forms part of this project.

Benefits of using LiDARs

Large weather models and statistical methods are commonly used to forecast the energy output of wind farms. The addition of local wind speed information can be used to improve the forecast, in particular for sudden changes in wind speed, also known as wind ramps. Scanning LiDAR devices offer the benefit of not only measuring at the wind farm itself but also in its surroundings with high temporal and spatial resolution. The University of Oldenburg / ForWind has developed such a LiDAR-based forecasting method within an R&D project.

Current LiDAR systems, which can be flexibly installed on the access platforms of offshore wind farms, offer a forecast horizon of approximately 15 minutes. An innovative, extra-long-range version called the XXL-LiDAR has the potential to double this figure. If successfully trialled during the pilot phase, the XXL-LiDAR will be fully integrated into OranjeWind. Soon after the commencement of operations in 2027, wind field information will be used in combination with live operational data to forecast wind ramps and sudden changes in turbine power.

Pilot at Amrumbank West

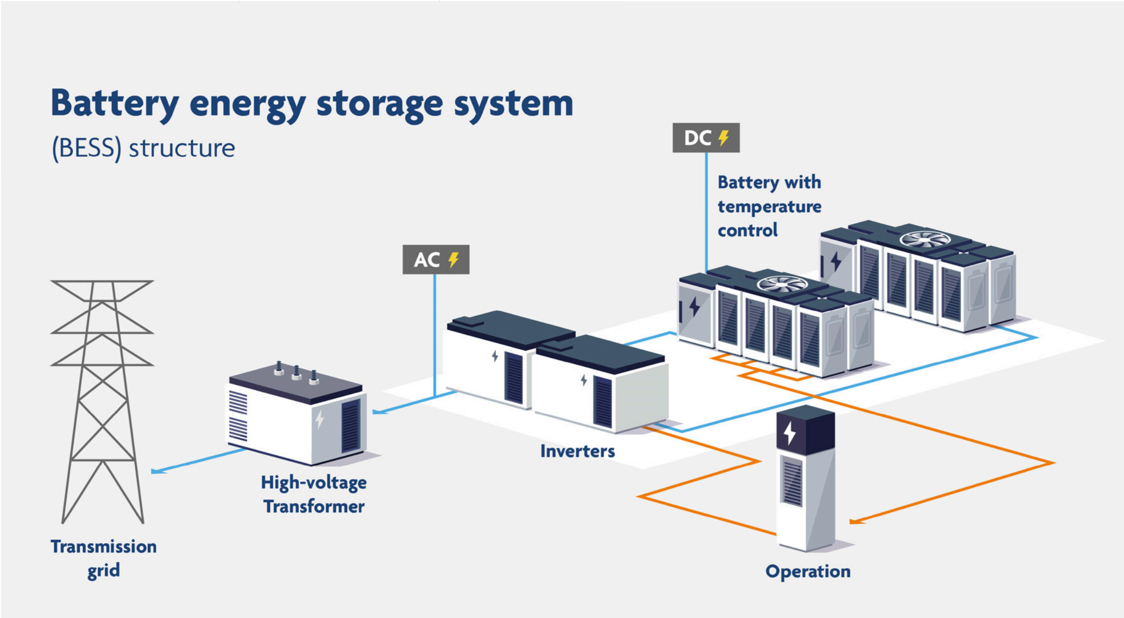
LiDAR data from a pilot at RWE's Amrumbank West offshore wind farm, some 35 km north of the island of Heligoland, is currently being processed in real time to produce a first system demonstration over a longer period.

Project Milestone

RWE's first large-scale battery on Dutch grid

The first commissioning of a new asset class is always a significant milestone. On 13 March 2025, we switched on our large-scale battery storage system in Eemshaven, the Netherlands.

The installation is the first large-scale battery to be connected to the high-voltage transmission grid in the Netherlands. It therefore represents a symbolic stepping-stone on the journey to the sustainable energy system of the future, allowing excess renewable energy to be stored efficiently so that it can be released to the grid when required, ensuring a match between supply and demand. Batteries play a key role in guaranteeing this match in a sustainable energy system, by displacing the production or consumption of power by several hours. Onshore storage of energy is therefore a central element in the system integration of the OranjeWind Project.



Basic structure of a battery energy storage system.

Switching on the large-scale battery energy storage system in Eemshaven.

The installation is **the first large-scale battery to be connected** to the high-voltage transmission grid in the Netherlands.

The 35-megawatt (MW) battery has a storage capacity of 41 megawatt hours (MWh). Running on lithium iron phosphate (LFP) lithium-ion batteries and equipped with state-of-the-art fire safety technology, it will help balance the production of renewable electricity and the demands of the Dutch grid by storing excess energy during off-peak periods and releasing it to the grid during peak demand times. Furthermore, the battery operates as primary reserve to stabilize the frequency of the power grid.

A new generation of technologies

One can also perceive symbolism in the location of the new battery. Eemshaven represents the transition towards a new energy system in miniature. The battery installation is the frontrunner in a series of local developments that increase the sustainability of the energy supply – such as carbon capture, renewable hydrogen production, and fuel conversion from coal to biomass. Fittingly, the battery has been constructed in such a fashion that it operates in an environmentally neutral way: thanks to its sound-proofed walls, neither its air conditioning system nor its inverters emit any additional noise to the outside world, and it produces no other emissions of any kind.

Batteries can be expected to play an **increasingly prominent role** in the energy transition.

Economies of scale

Batteries can be expected to play an increasingly prominent role in the energy transition, and this can be seen in the development of battery sizes. While the Eemshaven battery was considered large during its initial development, the size of installations is increasing rapidly. In Germany, RWE is currently building battery parks with a total installed capacity of around 600 megawatts (MW) and a storage capacity of 1.2 gigawatt hours on the site of its Westfalen power plant in Hamm (North Rhine-Westphalia). This trend towards ever-larger batteries delivers valuable economies of scale, ensuring reliability of supply at lower cost.

The realisation of the Eemshaven battery forms an important milestone in the OranjeWind project. Together with the inertia battery currently undergoing a two-year pilot phase in Moerdijk, battery technology is fundamental to the system integration approach on which the OranjeWind project is based.

Power-to-Heat: E-boilers and heat pumps

Power-to-heat solutions – e-boilers and heat pumps – can play an important role in shaping and optimizing the electricity consumption profile of the Netherlands.

E-boiler in Eemshaven
Industrial boilers take the chemical energy of some form of fuel and use it to heat water in order to produce steam. Traditional boilers run on fossil fuels such as coal, oil and natural gas. Transitioning to a system whereby heat demand is met by electricity results in a growing demand for electricity that fits perfectly with the production profile of wind turbines and solar panels.

Within the context of OranjeWind, we are building a 34 MW e-boiler at our power plant in Eemshaven. The e-boiler, which is planned for commissioning in the fourth quarter of 2025, will replace the diesel-fuelled boilers currently in use. It will deliver the significant environmental benefit of avoiding the emissions of nitric oxide, nitrogen dioxide and carbon dioxide produced by diesel-fuelled boilers.

Collaboration with Ennatuurlijk
Ennatuurlijk is currently constructing two 60MW e-boilers at their premises in Geertruidenberg, North Brabant.

For Rached Dekker, Director Customer Relations & Operations at Ennatuurlijk, working with RWE was a logical step: *"RWE and Ennatuurlijk have developed renewable heat production assets helping us to secure the integrity of our heating network for the years to come while at the same time ensuring that relevant sustainability targets are met,"* he explains. *"At Ennatuurlijk, we have the necessary expertise regarding heat offtake patterns and requirements, while RWE has the requisite know-how regarding industrial-scale asset development and energy markets. Combining the expertise allows Ennatuurlijk to develop an offering that is both competitive and sustainable for the 50,000 households who rely on Ennatuurlijk for heating."*

In addition, RWE is investigating the possibility of developing a 17 MW aqua thermal heat pump for district heating at RWE's Amer power plant, with the river Amer serving as a sustainable heat source. Ennatuurlijk will purchase the heat for their customers.

Inside the technologies

An **e-boiler** converts electricity into heat by means of electrodes positioned directly in a half-filled, pressurised vessel of water. The electric current ionizes the water and turns it into steam. This is different from the process in traditional boilers, whereby electrical current flowing through a metal coil or heating element causes the metal to heat up due to its resistance. This heat is then transferred to the water, causing it to boil.

Industrial e-boilers have a temperature range of approximately 190°C up to as much as 400°C, although a superheater is required to attain these levels.

Heat pumps, which use technology also deployed in refrigerators and air conditioning units, are fundamentally different from e-boilers in that they do not generate heat but simply *transfer* it. They are therefore much more energy-efficient than e-boilers. Heat pumps take a heat source (air, for instance, or water, both of which contain a certain amount of heat, even at relatively cool temperatures), amplify it, and move it to where it is needed. This is done using a compressor, which moves a refrigerant through a refrigeration cycle, and a heat exchanger, which extracts heat from the source. Current models are some 3-5 times more energy-efficient than electric or gas boilers.

Industrial heat pumps deliver heat in the range of 90°C to 100°C. Some heat pumps can also work in reverse, transforming heat into cold during the summer months.

EV Charging? Yes, but at scale!

As the share of renewable, and hence fluctuating, electricity production grows, balancing supply and demand across the Dutch electricity grid becomes an increasingly critical challenge. Storing energy and managing electricity demand can offer some relief here. In their nature as 'batteries on wheels', EVs (electrical vehicles) present a distinct set of energy needs – and of commercial opportunities, too. With an eye to the potential of large-scale EV-charging, RWE is therefore working with partners to further develop smart charging as part as OranjeWind's system integration commitment.

Compelling perspectives
When the energy production profile of a wind farm is at its peak and there is a surplus of power, the offtake has to increase in order to keep the wind turbines on. Charging EVs could function as ideal demand sink here. The concept is simple, although realizing it at scale involves challenges. If EV owners can be incentivised to charge their vehicles during peak production hours, this will automatically help balance supply and demand. This could be done by planning charging sessions in advance – for instance, when EV owners know they will not be needing their vehicles for some time. Besides the reliability of this approach, EV owners could also benefit from the relatively low price of the electricity produced during hours of peak renewable power production.

In their nature as 'batteries on wheels', EVs **present a distinct set of energy needs** – and of commercial opportunities, too.

The potential of commercial vehicles
The logic does not stop at private cars, but continues with commercial vehicles such as semi-trucks. Commercial vehicles are equipped with large batteries, up to ten times larger than the batteries of passenger vehicles. They consume up to ten times more energy per kilometre, and drive up to ten times more kilometres per vehicle per year. They also need to be charged with up to five times more power.

Above and beyond these orders of magnitude, commercial vehicles show patterns for driving and charging that are far more plannable than is the case with passenger vehicles. While the sizeable demand forms a burden to the grid (demanding up to 1 GW of additional charging power before 2030) the characteristics form an excellent opportunity for flexible demand solutions. Importantly, large fleet owners offer a single point of contact to integrate the potential of their fleets.

This vision will eventually become reality, although there are many obstacles to overcome before this market is fully developed. However, this technology can support the decarbonization of road transport while providing much needed demand flexibility for a renewable energy system.

AFTERWORD

Although not a single monopile of the future OranjeWind complex has been installed as we write this first technology report, this game-changing offshore wind farm is a vivid reality in the minds of everyone who is working to create it.

As we progress to installation of the foundations next year, and subsequently introduce the project's unique mix of green energy production and usage, we will be doing much more than constructing a power plant: we will be helping to change the way the world produces, stores, trades and uses energy. This is a bold ambition. It is also an uncompromising commitment.

Growing Green
OranjeWind, RWE's first offshore wind farm in the Netherlands, is part of the "Growing Green" investment and growth strategy launched in 2021 – a strategy that is transforming our company by transforming the way we serve the world. We have already halved our CO_2 emissions from electricity generation since 2018, and we will phase out coal-fired power generation by 2030, with the aim of achieving net zero by 2040. Bold and challenging as OranjeWind is, it is just one part of an even bolder and more exciting picture of a commercially viable, technologically reliable and fully sustainable energy transition.

Stakeholder collaboration
It is a privilege to be involved in a project that is a model not just of engineering excellence but also of stakeholder collaboration. My colleagues and I at RWE are deeply appreciative of the strong and close collaboration we enjoy with our counterparts at TotalEnergies. We are extremely grateful for the Dutch government's confidence in our ability to bring this ambitious and complex project to a successful conclusion. A special word of thanks is due to RVO, the Netherlands Enterprise Agency, and to KGG, the Dutch Ministry of Climate and Green Growth, for their constructive co-operation and guidance. And we are excited by the productive relationships that are being developed through all dimensions within and around the project – between colleagues, with suppliers, and with academic institutions.

"We will be helping to **change the way the world produces**, stores, trades and uses energy."

OranjeWind is about producing energy in new ways, and that starts with producing the right energy between people. Thanks to #TeamRWE for everything that has been achieved so far, and here's to the crucial next steps in 2026!

Marinus Tabak | Chief Operating Officer RWE Generation SE and Country Chair for the Netherlands

AFTERWORD

Just like for RWE, OranjeWind is TotalEnergies' first offshore wind farm in the Netherlands. Our 50% stake in this system-integrated project marks a significant milestone in TotalEnergies' multi-energy strategy and our commitment to achieve net zero in 2050, together with society.

This annual Technology Report is to inform our stakeholders about the innovations and learnings that emerge from this remarkable project. As partners working in a relationship of close trust and mutual respect, RWE and TotalEnergies will both gain valuable insights to help shape our future endeavours and reinforce the positions of our respective companies as leaders in renewable energy.

System integration

By seamlessly integrating a unique combination of energy systems, we can increase efficiency, reduce emissions, and contribute to a sustainable future. This holistic approach ensures that the renewable energy source – wind power – is effectively utilized alongside other energy forms, creating a balanced and resilient energy landscape. System integration is the key to unlocking the full potential of our multi-energy strategy and achieving our sustainability goals.

> "This annual technology report is to inform our stakeholders about **the innovations and learnings** that emerge from this remarkable project."

One such example is our collaboration with Air Liquide for the deployment of electrolysers in the Netherlands. This partnership aims to produce green hydrogen by utilising energy of OranjeWind, thus contributing to the decarbonisation of Zeeland Refinery in flushing and fostering a sustainable energy transition.

Acknowledgements

I would like to extend my heartfelt thanks to all who have contributed to this inspiring technology report. Your dedication and expertise have been instrumental in sharing knowledge and driving innovation.

Special thanks go to Laurent Ferry, Director for our Zeeland Hydrogen Project, for his insightful explanation of the importance of electrolysis, and how it works. Also, to our secondees working for OranjeWind, who bring our extended offshore expertise in gas into this project. Additionally, I would like to express my gratitude to our partners, RWE and Air Liquide, and to other stakeholders, for their unwavering support and collaboration. Together, we are paving the way for a sustainable energy future with OranjeWind as a blueprint.

Robert Joore | Country Chair for TotalEnergies in the Netherlands oranjewind

RWE

RWE is leading the way to a clean energy world. With its investment and growth strategy Growing Green, RWE is contributing significantly to the success of the energy transition and the decarbonisation of the energy system. Around 20,000 employees work for the company in almost 30 countries worldwide. RWE is already one of the leading companies in the field of renewable energy. RWE is investing billions of euros in expanding its generation portfolio, in particular in offshore and onshore wind, solar energy and batteries. It is perfectly complemented by its global energy trading business. RWE is decarbonising its business in line with the 1.5-degree reduction pathway and will phase out coal by 2030. RWE will be net zero by 2040. Fully in line with the company's purpose – Our energy for a sustainable life.

TotalEnergies

TotalEnergies and electricity

As part of its ambition to get to net zero by 2050, TotalEnergies is building a world class cost-competitive portfolio combining renewables (solar, onshore and offshore wind) and flexible assets (CCGT, storage) to deliver clean firm power to its customers. As of early 2025, TotalEnergies' gross renewable electricity generation installed capacity had reached 28 GW. TotalEnergies will continue to expand this business to reach 35 GW in 2025 and more than 100 TWh of net electricity production by 2030.

About TotalEnergies

TotalEnergies is a global integrated energy company that produces and markets energies: oil and biofuels, natural gas, biogas and low-carbon hydrogen, renewables and electricity. Our more than 100,000 employees are committed to provide as many people as possible with energy that is more reliable, more affordable and more sustainable. Active in about 120 countries, TotalEnergies places sustainability at the heart of its strategy, its projects and its operations.

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