5 Energy and resources from the ocean

> Today, industry and business are interested in a wide range of resources found in the ocean, including sand, crude oil and natural gas, while preparations are under way for the industrial exploitation of vast ore deposits in the deep sea. At the same time, governments and corporations are expanding the production of green electricity from the sea. Both of these developments will result in even more large-scale human interventions in the ocean environment.

Deep-sea mining – plans are taking shape

> The presence of valuable resources such as nickel, copper, cobalt and rare-earth metals in the ocean has been known for more than 140 years. So far, mining them was technologically scarcely possible and was unprofitable. However, climate action is causing demand for these metals and minerals to surge. The question arises whether they will continue to be mined only on land or can soon be extracted from the sea as well. Initial production tests have been carried out in the deep sea, but the environmental impacts have not yet been studied sufficiently.

Fundamental to technological progress

Mobile phones, internet and streaming TV have become as firmly embedded in our daily lives as electric vehicles, wind turbines and storage systems for the photovoltaic electricity generated in our homes. The increasing digitalization and electrification of our lives, however, has its price. To produce the necessary technology and expand the networks, large quantities of metals will be required, especially those of the rare earth group. Tungsten makes telephones vibrate, gallium and indium are necessary for light-emitting diode technology in lamps, semiconductors depend on silicon metal and hydrogen fuel cells require platinum-group metals.

Beside these, other mineral raw materials such as copper, nickel, cobalt, lithium and tellurium also have to be extracted from the earth using costly mining processes. As a rule, these activities are highly destructive to the environment, and in some countries the mining of raw materials also leads to corruption, war and the displacement of local inhabitants, and can have severe consequences for indigenous populations, especially when the mining is carried out in an unregulated or illegal manner.

These consequences loom even larger when we consider the fact that the demand for these metals and minerals can only increase with the various transformations in energy and transportation systems that result from our responses to climate change. Just two examples: It is now estimated that the European Union will require up to 18 times more lithium and five times more cobalt for the production of electric vehicles and energy storage in 2030 than was needed in 2020. According to the European Commission, the demand for rare-earth metals contained in the permanent magnets used for electric cars, digital technology and wind generators could increase tenfold by 2050. How to meet this mounting demand?

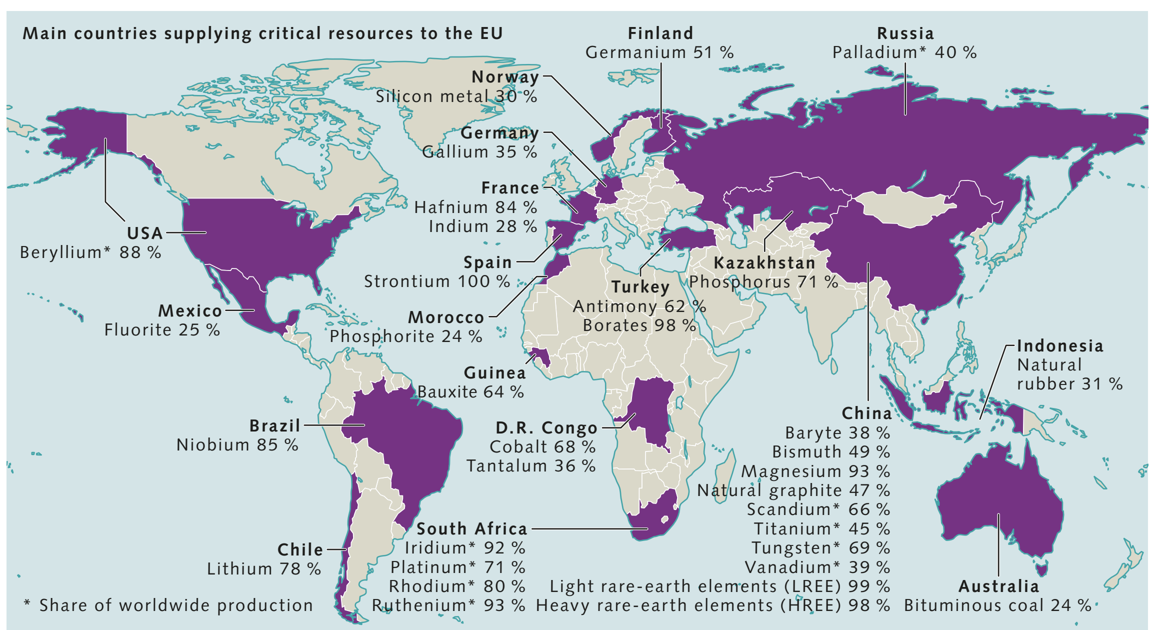
To date, there are only two areas on Earth where people have not yet engaged in commercial mining. One of these encompasses the entire Antarctic region, including all waters and land masses south of 60 degrees south latitude.

The Protocol on Environmental Protection to the Antarctic Treaty prohibits both the mining of mineral resources and the extraction of energy resources in this region. The latter include fossil materials such as coal, oil and natural gas. The second area as yet untouched by commercial mining is the bed of the deep sea. This can be defined as the bottom of the world's oceans at water depths greater than 200 metres.

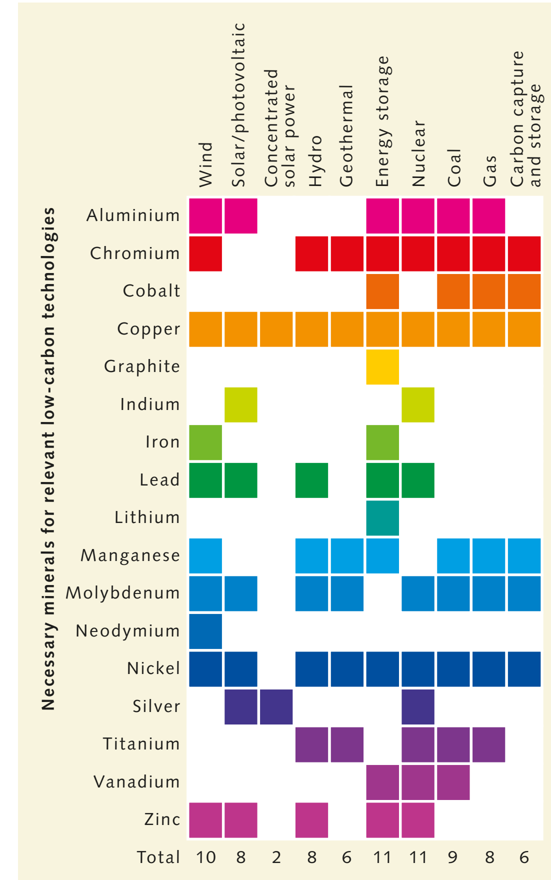
But the rising global demand for mineral resources is increasingly drawing the attention of the mining industry towards the oceans. There are a number of metals present in commercially promising quantities in the deep sea, including those of the rare earth group. Geologists distinguish three different kinds of potentially minable deep-sea ore deposits, each of which, unlike the deposits on land, contains a large variety of different metals. These three groups are manganese nodules, cobalt-rich ferromanganese crusts, and massive sulphides.

Manganese nodules

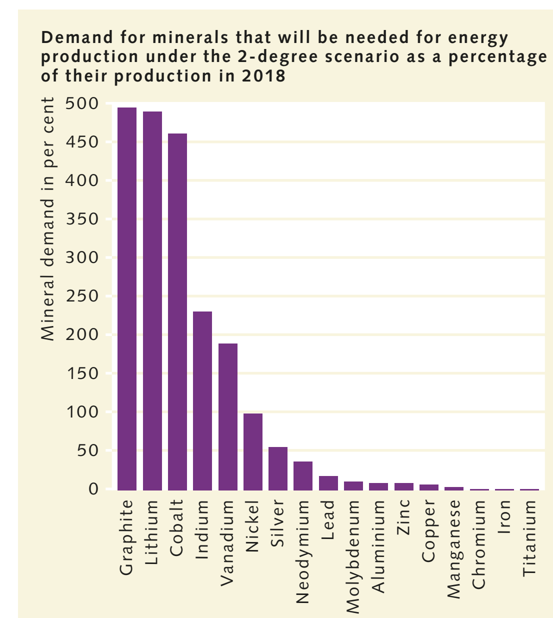
Manganese nodules are mineral bodies that are black-to-brown in colour, generally round with a diameter of one to 15 centimetres, and usually structured like an onion peel. They form primarily on the deep ocean floors covered by sediments (particle deposits) at water depths of 3500 to 6500 metres. Oxygen-rich deep water is necessary for their formation as well as a grain or nucleus, around which multiple layers of iron and manganese oxides are deposited over millions of years, along with minor and trace metals such as nickel, cobalt, copper, titanium, molybdenum and lithium.



5.1 > The European Union has to import many of the critical raw materials needed in Europe and relies on delivery of these from a few specific countries. There is an especially great dependency, for example, on China (99 per cent of all light rare-earth metals) and Turkey (98 per cent of the required borates).



5.2 > The global energy transition can only succeed if sufficient mineral raw materials are available. As many as eleven different metals are needed in the construction of wind turbines, photovoltaic systems and energy storage units.



5.3 > If mankind wants to limit global warming to two degrees Celsius by the year 2100, it will have to completely restructure its energy sector. According to the World Bank, the demand for products in the field of energy technology will increase significantly by 2050, especially for graphite, lithium, cobalt and indium.

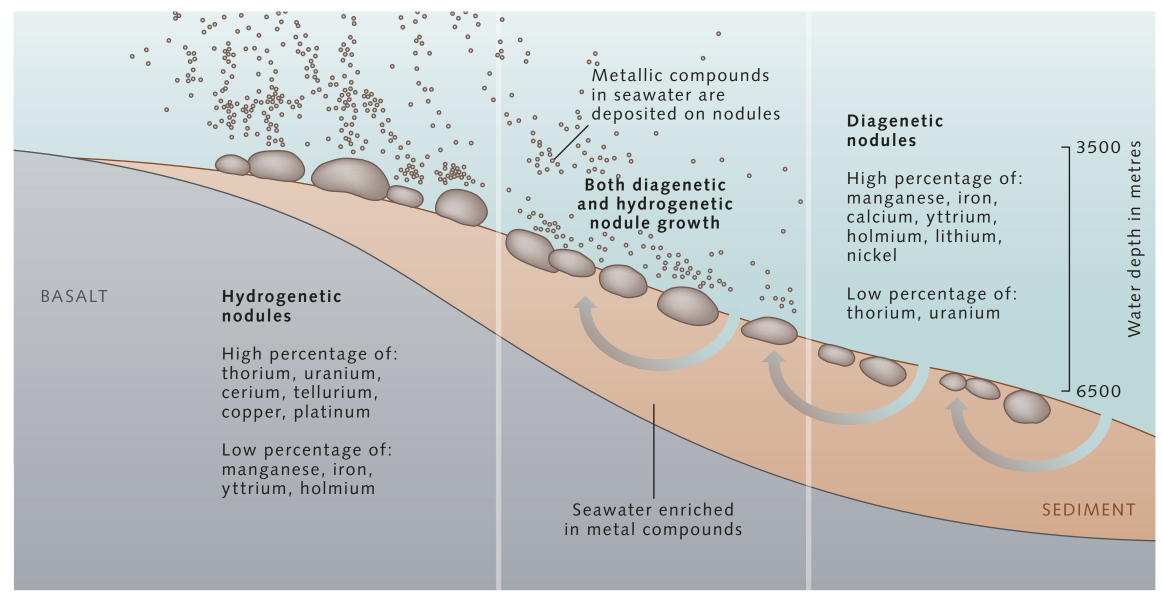
5.4 > Manganese nodules grow over time spans of millions of years by the precipitation of metals dissolved in the seawater or pore waters, forming in concentric layers around a nucleus. This gives them their spherical shape and onion-skin-like structure.

The nucleus is usually a piece of hard sediment or a nodule fragment, but may occasionally also be a fragment of basalt or other rock, or a piece of broken clam shell. Scientists have also found nodules that formed around a shark's tooth or the tiny inner-ear bones of a whale. The metals, on the other hand, are natural components dissolved in the seawater and the pore waters within the sediments, and are deposited onto the manganese nodules through diagenetic and hydrogenetic processes.

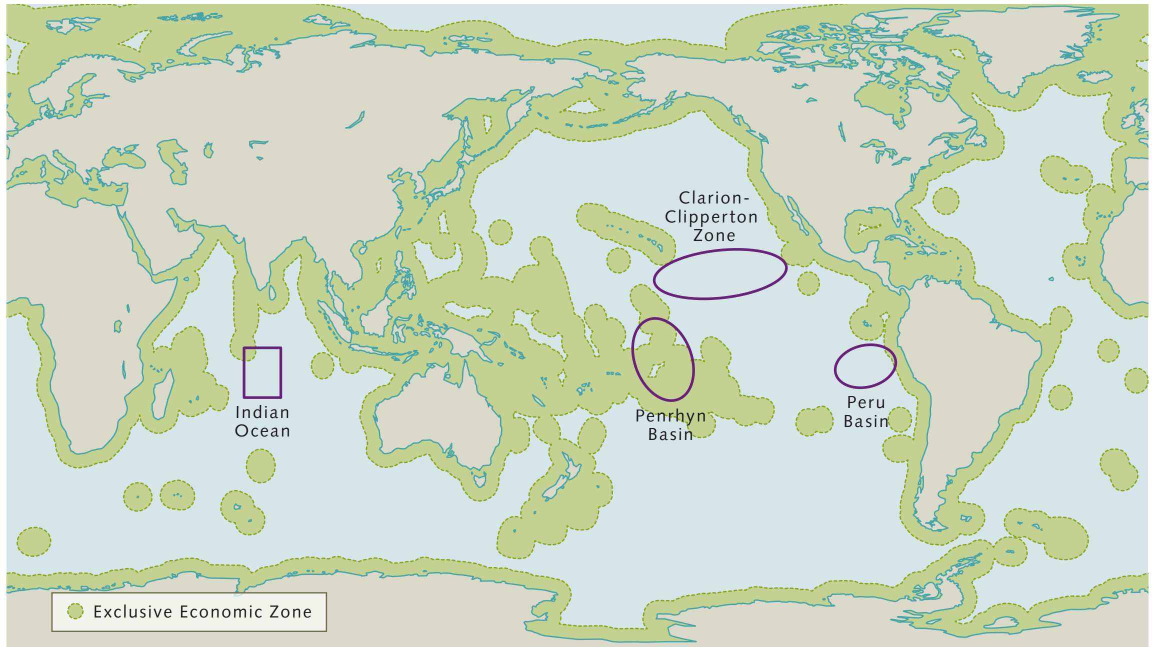
Diagenetic accretion occurs when metal oxides precipitate from the pore waters that circulate through the upper sediment layers of the seabed. Among other elements, these pore waters contain dissolved manganese, which diffuses upwards and trickles out of the sea floor due to differences in concentration. On contact with the oxygen-rich ocean water it is oxidized and manganese oxides precipitate. These accumulate in concentric spheres around the nucleus. Other metals dissolved in the pore waters, including copper and nickel, are also captured with the manganese oxide. These originate primarily from the microbial breakdown of organic material in the sea floor. They may also be released, however, through the dissolution of calcareous or silicate shells of dead plankton in the sediments. As a rule, manganese nodules extract more than 80 per cent of their metals from the pore waters. This constant supply of material allows them to grow, albeit no more than a few centimetres over a time period of a million years.

Hydrogenetic processes also contribute to the growth of most manganese nodules. These involve the precipitation of colloids (minute particles from one nanometre to one micrometre in size) of hydrated manganese and iron oxides directly from the seawater. Manganese nodules that are formed exclusively, or mostly, through hydrogenetic processes are found on the slopes or peaks of seamounts. Their composition is determined by the water chemistry and by biogeochemical processes between the seawater and the particles it contains. Nodules formed by hydrogenetic processes grow extremely slowly. Their diameter increases by only a few millimetres per million years. However, they accrete more cobalt and rare earth metals than the nodules of predominately diagenetic origin.

Manganese nodules are typically found lying detached on the sea floor, with usually between one-third and two-thirds of the nodule embedded in the sediment. In some areas there are only a few nodules per square metre of seabed, while other areas can have as many as 1000. The largest and economically most attractive occurrences are found in the manganese nodule belt of the Clarion-Clipperton Zone (CCZ). This is situated in the



5.5 > Manganese nodules grow in one way through the precipitation of metal oxides from the pore waters in marine sediments (diagenetic accumulation), and in another by the precipitation of manganese and iron oxides directly from the seawater (hydrogenetic accumulation). These two processes can occur simultaneously.



5.6 > The commercially most interesting occurrences of manganese nodules are found in the Clarion-Clipperton Zone of the North Pacific, the Peru Basin, the western Pacific Penrhyn Basin and the central Indian Ocean.

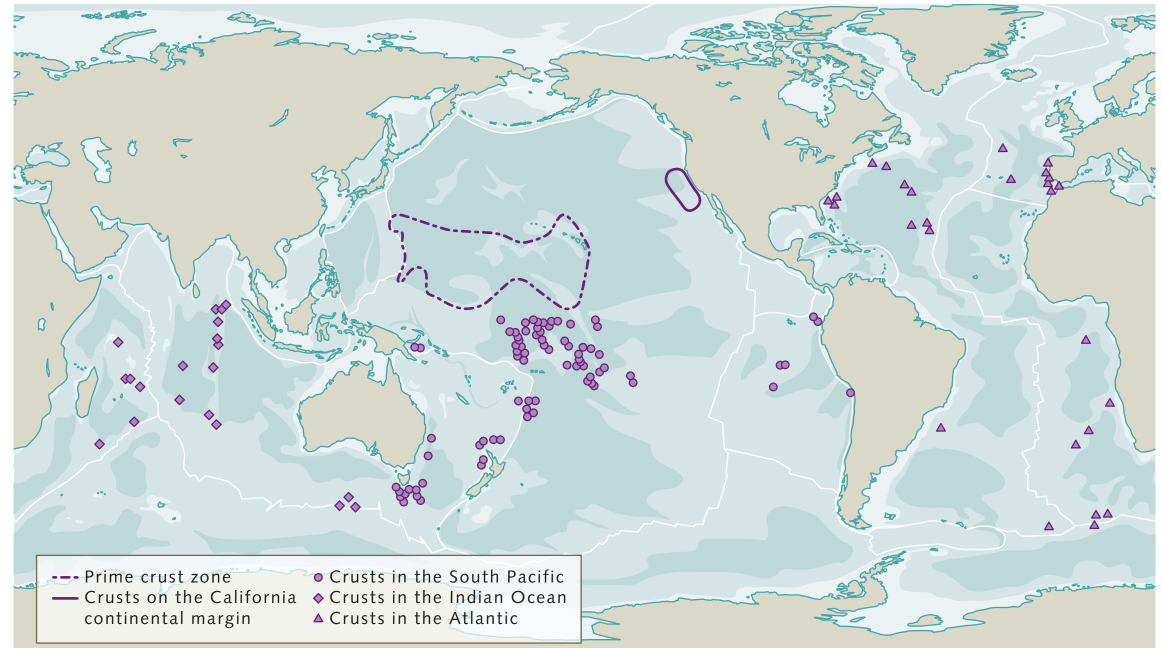
near-equatorial region of the North Pacific between Hawaii and Mexico. Other significant manganese nodule deposits are found in the Peru Basin (southeast Pacific), the Penrhyn Basin (western Pacific) and in the central Indian Ocean.

The manganese nodule belt of the Clarion-Clipperton Zone in the Pacific, with an area of around five million square kilometres (circa 5000 kilometres long and 1000 kilometres wide), is larger than the European Union. About three-fourths of this deep-sea area is characterized by a flat sea floor. Seamounts rise up throughout the remaining areas, some with heights of up to 1000 metres. On the deep-sea plains there are some areas where almost all of the nodules are large, ranging from four to 15 centimetres in diameter, and others where almost all the nodules are smaller than four centimetres. Smaller nodules cover around 85 per cent of the deep-sea plains in the Clarion-Clipperton Zone. Areas with larger nodules comprise about twelve per cent, and nodules are absent in the remaining three per cent of the areas. In areas especially rich in nodules, the clumps of ore are so dense that they commonly have a wet weight between 15 and 30 kilograms per square metre of seabed area. It is estimated that the Clarion-Clipperton Zone contains nodule deposits with a total wet weight of 25 to 40 billion tonnes.

These have attracted particular commercial interest because of their high contents of manganese (30 weight per cent), nickel (1.4 weight per cent), copper (1.1 weight per cent) and cobalt (0.2 weight per cent). These four metals are necessary, among other things, in the production of communication technology and electric cars and for steel refinement. Along with nickel and manganese, cobalt, which until now has primarily been mined in the Democratic Republic of the Congo, is also a particularly indispensable component of modern lithium batteries. Compared to all of the known deposits on land, the manganese nodules in the Clarion-Clipperton Zone alone contain around 3.4 to five times more cobalt, 1.8 to three times more nickel and 1.2 times more manganese. Moreover, the nodules also contain comparatively high proportions of titanium, molybdenum and lithium.

Cobalt-rich ferromanganese crusts

Cobalt-rich ferromanganese crusts are hard coatings of iron and manganese oxides that form on the slopes of



5.7 > Ferromanganese crusts are mainly found in marine regions with the oldest oceanic crust, where the ore deposits have had the most time to grow. This is the case in the western Pacific, for example.

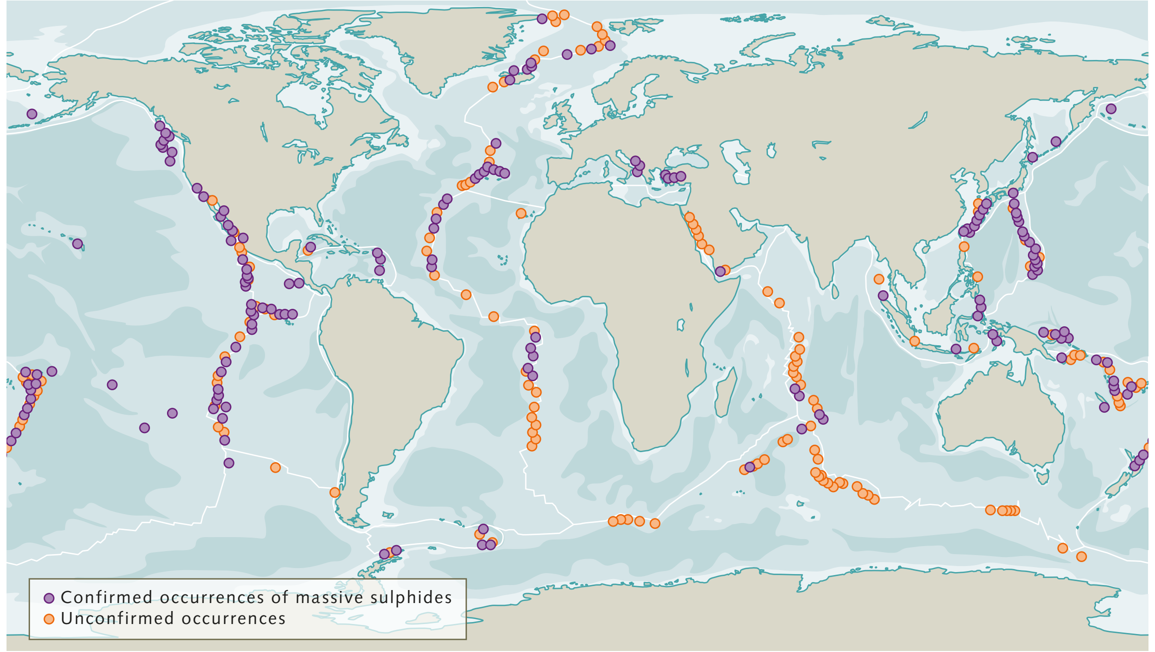
seamounts and, like hydrogenetic manganese nodules, obtain most of their metals from the surrounding seawater. Unlike in the flat deep-sea plains, no sediments are deposited on the slopes of the seamounts. Ocean currents wash away sinking particles rather quickly, so the ferromanganese crusts are only able to grow extremely slowly – about one to five millimetres per million years.

Various metals that are crucial for the production of modern energy supply, computer and communication systems are concentrated in the crusts. These include cobalt, titanium, molybdenum, zirconium, tellurium, bismuth, niobium, tungsten, rare earths and platinum. The rare metalloid tellurium, for example, is used both for cadmium-telluride alloys in thin-film photovoltaics and for bismuth-telluride alloys in computer chips.

Around two-thirds of the occurrences of cobalt-rich ferromanganese crusts that are considered significant for deep-sea mining are located in the Pacific Ocean, while 23 per cent are in the Atlantic and about eleven per cent in the Indian Ocean. Deposits in water depths from 800 to 2500 metres are considered to be commercially promising. The known crusts are generally three to six centimetres thick, in exceptional cases sometimes up to 26 centimetres, so experts calculate that they contain 60 to 120 kilograms of ore per square metre of slope surface. The total global quantity of cobalt-rich ferromanganese crusts is estimated at 40 billion tonnes, whereby only half of these could be profitably mined given the present state of knowledge. To date, however, much fewer than one-tenth of the known occurrences have been studied in detail.

Massive sulphides

Sea-floor massive sulphides are metal-sulphur compounds (metal sulphides) that form at hydrothermal vents on the sea floor, in water depths of 1600 to 4000 metres. These hydrothermal deposits are associated with volcanic structures and therefore occur primarily at tectonically weak points in the Earth's crust, for example, at mid-ocean ridges, at island arcs and in back-arc spreading zones. They form as a result of the circulation of seawater through the uppermost three kilometres of the oceanic crust. The seawater is heated by deep-lying heat sources (magma chambers) and transformed into a hot, acidic and highly concentrated solution that can dissolve metals from the volcanic rocks.



5.8 > Massive sulphides form at hydrothermal seeps, which only occur at tectonically weak points in the Earth's crust, for example at mid-ocean ridges, in back-arc spreading zones and at island arcs. As yet, however, only the occurrences at hydrothermal seeps that have cooled down are considered to be minable.

The hot hydrothermal solution eventually rises and seeps out of the sea floor at specific sites. When it comes into contact with the cold, oxygen-rich seawater, the dissolved metals are precipitated in the form of metal sulphides. These include, for example, pyrite, chalcopyrite and sphalerite.

As a result of the focused, upward flow of the hydrothermal solution at the hot seeps, spectacular chimney-like structures called "black smokers" are formed. These can reach heights of 20 or 30 metres, or even more. At some point, however, the chimneys become unstable and fall apart. Another chimney then begins to form and grows to a certain height until it also collapses. This continuous successive process results in the formation of metal sulphide mounds on the sea floor, which are subsequently further altered and consolidated by internal chemical reactions through the mixing of the hydrothermal solutions with penetrating seawater. These ore deposits can be several hundred metres in diameter and several tens of metres thick. In addition, the hydrothermal solutions can also precipitate their load of metals beneath the sea floor. This forms a zone of mineralization called a stockwork.

The sea-floor massive sulphides are the present-day counterparts to the fossil volcanic massive sulphide deposits on land. The latter are important sources of copper, zinc, lead, silver and gold. These same metals are found in the massive sulphide deposits on the sea floor. However, the current deposits in the sea contain additional minor and trace metals that are important for modern high-tech applications. These include cobalt, antimony, indium, selenium, tellurium, gallium, germanium, bismuth and molybdenum.

More than 630 active hydrothermal seeps with proven metal sulphide accumulation are now known to scientists. But hydrothermal fields always contain a combination of active and inactive areas. In this case, inactive means that no hydrothermal solutions are presently seeping out of the sea floor. For two reasons, only the inactive areas can be considered for possible mining of the massive sulphides. For one, it is assumed that there is less danger of the destruction of rare deep-sea ecosystems here than at active seeps. For another, in the active areas the high temperatures of several hundred degrees Celsius and strongly acidic solutions would probably damage the mining equipment in a very short time.

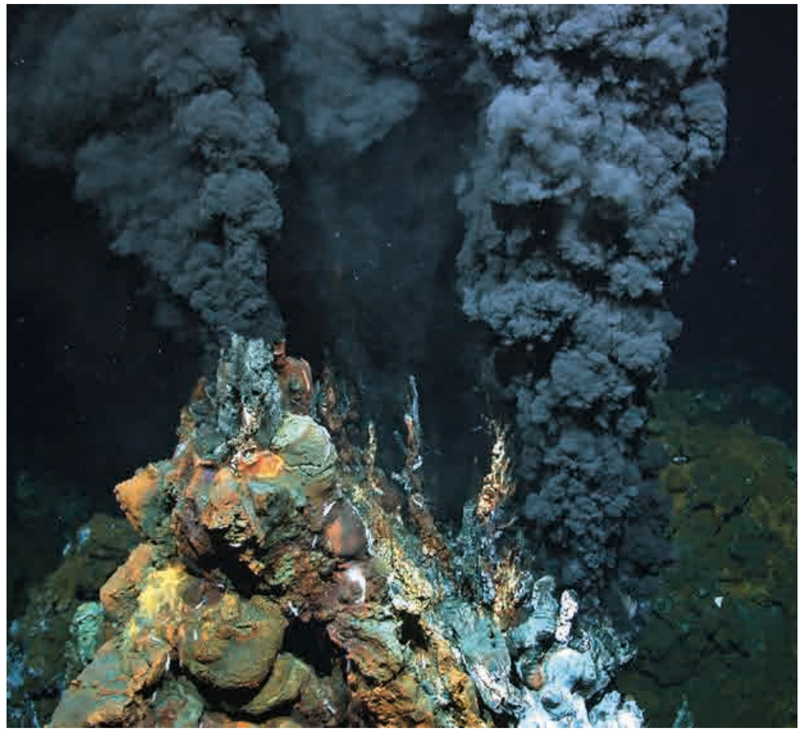
As yet, only a few completely inactive massive sulphide deposits are known. This is because inactive deposits are much more difficult to find than the active seeps. The latter can be located comparatively easily on the basis of their chemical signature and the particles that the escaping hydrothermal solutions produce in the surrounding seawater.

Guardian of the heritage of mankind

Around 81 per cent of all known manganese nodule fields, 46 per cent of the ferromanganese crusts and 58 per cent of massive sulphides are located in international waters, and therefore do not fall under the jurisdiction of any individual nations. Rather they belong to the common heritage of mankind, as Article 136 of the United Nations Convention on the Law of the Sea defines the sea floor outside of the Exclusive Economic Zone.

This heritage, which encompasses about 42 per cent of the Earth's surface, is managed by the International Seabed Authority (ISA), which has its headquarters in Kingston, Jamaica. It regulates and oversees all activities related to the commercial use of the international seabed and its subsurface. Furthermore, it is the obligation of the ISA to ensure the balance of interests between industrialized and developing countries as established in the Law of the Sea. Because no deep-sea mining is being carried out at an industrial scale as yet, its main tasks at present are to issue and oversee contracts for exploration of deep-sea deposits, to draft regulations for future mining, and constantly update the adopted statutory foundations. To date, 167 nations and the European Union have joined the ISA.

Applications for an exploration contract can be submitted by either states or private companies. As a prerequisite, however, the applicant has to pay a fee of USD 500,000 and the home state of the company, known as the "Sponsoring State", must support the application. In addition, the state must have adopted and implemented its own marine mining legislation, which it can use to verify compliance with the licensing obligations as well as the company's financial and technical capabilities at any time.



5.9 > Metal sulphides are precipitated where high-temperature hydrothermal solutions rise out of the sea floor and mix with cold, oxygen-rich seawater. They are deposited and, over time, form spectacular chimney-like structures called black smokers.

National regulations on marine mining may not be more permissive than the international regulations in this regard. The Sponsoring State is accountable for the activities of the contract partner it supports. In Germany, the State Authority for Mining, Energy and Geology (LBEG), headquartered in Hannover, is responsible for overseeing exploration activities.

Through its Federal Institute for Geosciences and Natural Resources (BGR), Germany itself holds exploration contracts for two areas in international waters. The first of these has been valid since 2006 for the exploration of manganese nodule deposits. The area involved consists of two tracts, both of which are located in the Clarion-Clipperton Zone in the Pacific Ocean. One tract lies in the central area of the manganese nodule belt, and the other is an area of about 60,000 square kilometres in the eastern part of the zone. Regarding the latter, around 20 per cent of the area may be considered minable for manganese nodules because only there is the seabed flat enough and the nodules present at a sufficient density to make mining worthwhile.

The second German exploration contract area encompasses a 10,000 square kilometre deep-sea region of the Central Indian Ridge and the Southeast Indian Ridge in the southwestern Indian Ocean, where abundant occurrences of sulphides are presumed to be present. Geologists of the BGR, together with deep-sea experts from other German research institutes, have been regularly carrying out expeditions to the contract area since 2015 in order to determine the extent of the deposits there as well as to study species diversity and evaluate the impacts of possible mining activity. In the German contract area they have now discovered twelve sulphide deposits with 30 active and 34 inactive sites (e.g., sulphide mounds with numerous chimneys). Based on chemical and physical investigations in the water column, evidence has been found for twelve additional deposits.

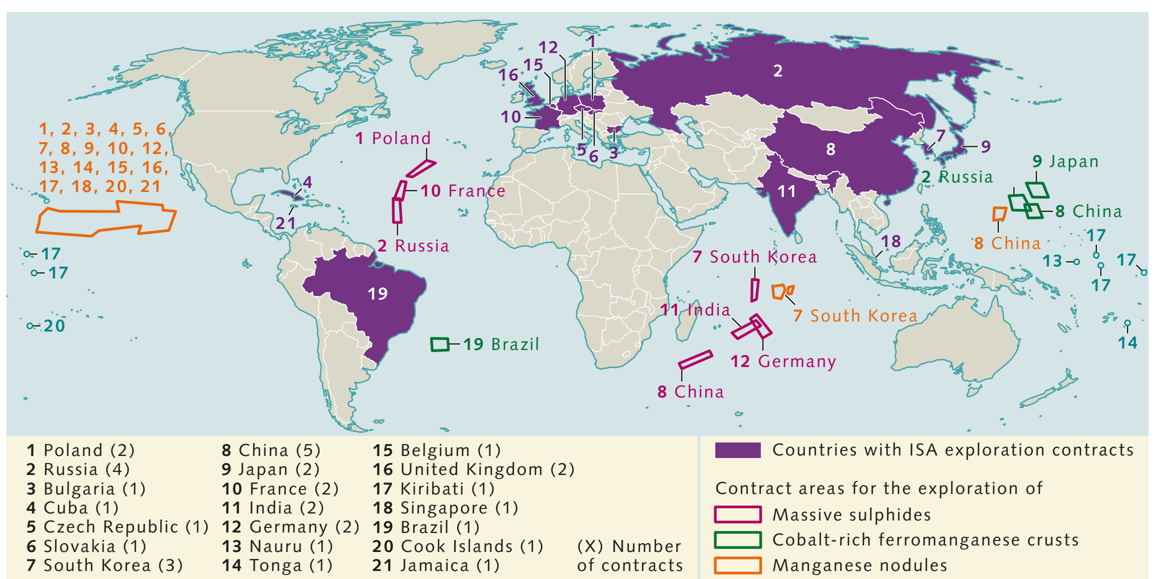
Plans are progressing

Since the year 2002 the International Seabed Authority has issued 31 contracts for exploration rights for mineral resources on the sea floor. There are 19 contracts for the exploration of manganese nodules with areas of around 75,000 square kilometres each, an area larger than the German state of Bavaria, five contracts for the exploration of ferromanganese crusts with areas of 3000 square kilometres each, and seven contracts for the exploration of massive sulphides in areas of 10,000 square kilometres each. With all of the contracted areas together, the ISA has so far authorized a sea-floor area of around 1.5 million square kilometres for the exploration of resources, an area as large as France, Spain and Germany combined.

Each contract has a duration of 15 years and includes the option for multiple extensions of five years each time if the contracted party has been unable to complete the exploration work for reasons beyond its control (for example, due to a pandemic), or if the global economic situation precluded the mining of raw materials in the deep sea. Holders of an exploration licence also have preferential rights to subsequent mining and are allowed to test their technology for raw-material production in the deep sea. For this, however, they are required to have an environmental impact statement approved and recognized by the ISA Legal and Technical Commission.

Deep-sea mining technology

MANGANESE NODULES: To date there has been no mining of manganese nodules. But over the past ten years at least five different companies and government institutions have contributed to its technological advancement by testing initial prototypes for future mining tools, albeit at reduced size and weight scales. The Korean research institute KIOST, for example, has designed a collector for manganese nodules as well as a conveyor system for transporting the nodules to the sea surface, and has already tested both of these in water depths of 1200 and 1400 metres.



5.10 > Since 2002 the International Seabed Authority has issued 31 contracts for exploration of the sea floor for mineral resources. These comprise 19 contracts for the exploration of manganese nodules, five for ferromanganese crusts and seven for massive sulphides.

5.11 > *Patania II*, a caterpillar-like collector of manganese nodules made by the Belgian company DEME-GSR, is twelve metres long, 4.5 metres high, four metres wide and weighs 25 tonnes. The prototype was tested successfully in the spring of 2021 in the Clarion-Clipperton Zone at a water depth of 4500 metres.

A water depth of 4400 metres was achieved in 2017 with the basic chassis assembly of the manganese nodule collector *Patania I*, which was developed and successfully tested by the Belgian company DEME-GSR. The company has an exploration contract for the Clarion-Clipperton Zone. In September 2018 it publicly presented for the first time the *Patania II* collector, which had been upgraded with a manganese nodule collection system. An early deep-sea deployment of this prototype in the contract area (also at a water depth of 4400 metres) in 2019 failed due to technical problems with the cable connecting it to the ship. A second test in the spring of 2021, however, was successful, and was closely monitored by European researchers in order to gain information about the impacts of nodule mining on the marine environment and to evaluate the observation systems.

Both the Belgian and South Korean manganese nodule collectors are caterpillar-like vehicles in design, and both employ a hydraulic collection system to pick up the loose nodules lying on the sea floor. The Indian contract holder MoES, on the other hand, is adopting a mechanical concept for collecting the nodules, and is developing a mobile system with barbed shapes to rake up the nodules. After they are picked up, the nodules are cleaned, crushed and transferred to a vertical conveyor system. Depending on the design used, the nodules are then transported to a delivery platform at the water surface via a pneumatic process or by the use of a slurry. There they are dewatered and loaded onto bulk carriers for transport to shore.

COBALT-RICH FERROMANGANESE CRUSTS: For mining ferromanganese crusts, the China Merchants Industry Holdings (CMI) has developed a prototype that was successfully tested at a water depth of 1300 metres in the South China Sea. The machine not only proved its ability to move along the sea floor, but also to cut and crush ferromanganese crusts. Dislodging ferromanganese crusts from the subsurface of the sea floor is a technical challenge, because the crusts often replicate the form of the underlying bedrock surface. For example, if there are

5.12 > The now bankrupt Canadian company Nautilus Minerals developed three remote-controlled underwater vehicles for mining a massive sulphide deposit in the Bismarck Sea off Papua New Guinea: a shaper (auxiliary cutter, right), a bulk cutter (centre) and a collector (left).

boulders, rounded blocks and slabs of rock, or the flow structures of ancient lava beneath the crusts, the crusts will precisely follow those structures. As a result, mining machines could easily become stuck on very uneven grounds. The Chinese vehicle, however, appears to move in steps that compensate for the unevenness. For cutting and crushing the crusts, engineers rely on designs that employ either a high-pressure water jet or rotating roller bits like those used in mining coal.

MASSIVE SULPHIDES: The mining of massive sulphides will probably prove to be equally difficult, but initial progress is being made here as well. The now bankrupt Canadian company Nautilus Minerals, for example, developed a process for mining a massive sulphide deposit at a depth of 1600 metres in the Bismarck Sea off Papua New Guinea using three remote-controlled underwater vehicles, and even had the machines built. The fleet consists of a shaper to level the seabed, a bulk cutter (the main mining vehicle) and a collector.

However, experts doubt that all three of these vehicles can be deployed feasibly at one time. The area of the targeted ore deposit, with a diameter of a few hundred metres, is relatively small. Moreover, the deposit is cone-shaped. This means that its area decreases in size with increasing depth, which would severely limit the mobility of the mining machines. The specialists see a further obstacle in the presence of hard volcanic rocks in the vicinity of the massive sulphides, which would have to be removed. Nautilus Minerals wanted to use a roller-bit technology for this, but experts believe that this procedure would be very difficult. Nevertheless, the Japan Oil, Gas and Metals National Corporation (JOGMEC) is pursuing a similar approach. In 2017 the company carried out an initial successful mining test for sulphides in the Okinawa Trough in Japanese territorial waters. Plans for undersea mining in the Okinawa Trough foresee an annual production of 1.3 million tonnes of ore following additional multi-year development and testing phases.

A consortium of German companies comprising Harren & Partner, Combi Lift and Bauer is counting on a single piece of equipment to mine massive sulphides. Their designers are developing a vertical mining system that works on the same principle as diaphragm wall cutters, like those used for rectangular foundations in underground construction, but also in pipeline, harbour and canal construction. The vertical cutter consists of a steel frame with counter-rotating cutting-wheel drums on the underside. This kind of design has already been used successfully in the sea to mine diamonds at a water depth of 165 metres.

With this method, the need for removal of the associated volcanic rocks in projected sulphide mining could be largely avoided and more focus given to production of the ore. The technology would make it possible to cut several dozen metres deep into the massive sulphides at selected locations, thus leaving a very small footprint of only a few square metres at each site on the sea floor. Specialists would therefore expect a much smaller environmental impact. For example, there would be a minimal amount of drill cuttings or tailings released onto the sea floor. It would allow a more focussed mining of the ore on the sea floor without causing a significant suspension plume. Moreover, the installation of a vertical conveyor pipe would be eliminated, and with it the environmentally risky transport from the deep water to the surface. However, the earliest possible test-scale trials of a prototype of this device are planned for 2026 at a water depth of 2400 metres in the German contract area in the Indian Ocean.

Technical development not yet complete

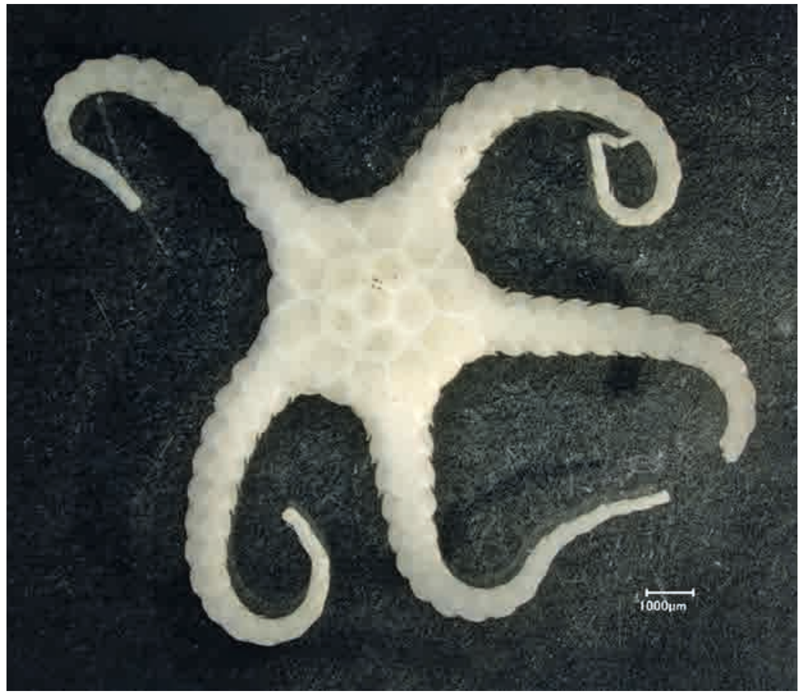
In theory, all of these technical mining concepts may sound comparatively straightforward and achievable, but in practice the technology has to overcome a myriad of challenges over the long term. These include, among other things, water pressures of 400 to 600 bars and ambient temperatures near the freezing point at the deep-sea floor, as well as corrosive salt water. In addition, the cutters, nodule collectors and conveyor systems would have to operate for long periods of time without maintenance because bringing them to the sea surface for repairs would involve considerable expense.

All of the test operations so far have been carried out with prototypes at a reduced scale. For production at an industrial scale, mining machines four to five times as large will have to be built and tested. Methods for the metallurgical processing of manganese nodules and crusts are also still in the early stages of development. For the first time in the world, a concept for the complete smelting and utilization of manganese nodules has been developed by scientists from Germany's Federal Institute for Geosciences and Natural Resources and RWTH Aachen University, and has already been tested successfully on an expanded laboratory scale. The project partners are presently working to convert the process to an industrial scale. The initial objective is to demonstrate the feasibility of virtually residue-free metallurgical processing and, secondly, they want to find out what a smelting plant would have to look like, and how expensive it would ultimately be to actually extract all the materials contained in the manganese nodules and process them into marketable intermediate products.

Present estimates suggest that the costs of preparation and processing of the nodules would probably make up about one-half to two-thirds of the total investment and operating costs of a deep-sea mining project. The investment costs would amount to around USD 1.5 billion, a sum that is on the order of that required for the development of land-based deposits. The operating costs are estimated at USD 160 to 400 million per year, which means that deep-sea mining is probably not economical today with the current world market prices for metals. The increasing demand for raw materials, however, should cause a long-term rise in prices. Due to these financial aspects and the technological uncertainties set out above, experts believe that it will take at least another five, but more likely ten years before marine mineral resources can be mined on a large scale for the first time. How realistic this assumption is remains to be seen.

Progress or dirty business?

The increasing technological feasibility of marine mining has rekindled the dispute over the desirability and sustainability of extracting ore deposits from the sea. Proponents argue that the resource requirements of humankind are increasing enormously as a result of the transition from fossil fuels to renewable energy (electricity storage, e-mobility). If states do not satisfy this demand, it will put their economic development and the prosperity of their populations at risk. In order to meet the demand for raw materials, the existing mining facilities on land would



5.13 > The brittle star *Amphiophiura bullata* is one of several new deep-sea species that researchers have discovered in the Clarion-Clipperton Zone in recent years. Genetic analyses have revealed that some of the previously unknown brittle stars belong to new ancestral lineages that have evolved in the deep sea over more than 70 million years.

have to be expanded or new mines opened. Either of these options would have immense environmental impacts. Supporters of deep-sea mining therefore point out that:

- For deep-sea mining it would not be necessary for forests to be cleared, groundwater levels to be lowered, or people to be resettled or displaced. Furthermore, there would be no need for costly infrastructures such as roads, power lines, buildings and dewatering systems;
- No large tailings piles would be generated because the ore deposits are directly accessible, and there would be no need to remove tonnes of overburden material;
- With deep-sea mining no pollutants or heavy metals would be released, a problem that often leads to severe environmental damage in the mining of ores on land;
- Deposits in the deep sea, such as manganese nodules, often contain three or more metals in economically viable quantities, so that a number of materials can retrieved from a single site. On land, different deposits have to be excavated for each individual metal;
- The mining of raw materials in the sea can only be carried out by machines. Compared to mining on land, there would thus be significantly less risk for mine workers. Child labour, which is especially common in developing countries, would not occur;
- Mining the marine deposits would help to diversify the currently increasingly concentrated sources of supply on the international commodity markets. For many metals, a large proportion of production comes from a single country, some from politically unstable or undemocratic states that use their market power for political leverage. Resources from the deep sea would mitigate dependency on these nations, because their extraction from international waters is subject to international law and thus to control by the international community.

Opponents of deep-sea mining are not at all convinced by these arguments. Firstly, they are concerned about the environmental impacts of extracting raw materials from the sea. Secondly, they criticize the role and the regulations of the International Seabed Authority and remain unconvinced that the income from the sale of humanity's mutual heritage would benefit people in the poorest developing countries.

Impacts on the marine environment

After 30 years of research, a lot has been learned about the possible consequences of deep-sea mining for species diversity and biological assemblages on the seabed, although researchers still do not completely understand the functioning of deep-sea ecosystems and their role in the many services provided by the sea. There are a plethora of mobile and sessile organisms living on and beneath the sea floor, including in those areas rich in manganese nodules. They range in size from nematodes, which are only a few tenths of a millimetre long and make up the largest share of species diversity, to sea cucumbers and metres-long fish. Sponges and deep-sea corals grow on the nodules and provide a source of food and protection for many other animals.

5.14 > The marine snail *Chrysomallon squamiferum* is the first deep-sea species to be added to the red list of endangered animal species because of impending mining operations. The snail lives at three hydrothermal vents east of Madagascar. Two of these are located in areas for which exploration contracts have already been issued.

5.15 > Octopuses are one of the many deep-sea inhabitants that are directly dependent on manganese nodules. They attach their eggs to sponges that grow on the manganese nodules.

Who lives where on the sea floor depends on the particular conditions at a given location. In the German contract area of the Clarion-Clipperton Zone, for example, the sedimentological and geochemical conditions on the seabed can change within a distance of less than 1000 metres. In addition, the expansive deep-sea plain is punctuated by seamounts and ridges. The associated biotic communities are adapted to the local conditions.

The diversity of life in the deep sea is much greater than was previously believed. In recent years, scientists have been able to identify and describe numerous species from the Clarion-Clipperton Zone. In addition, through the use of molecular genetic investigation techniques, they have also succeeded in obtaining an initial impression of the diversity of deep-sea organisms. This is so huge that it is often compared with the species diversity of rainforests. However, the population density of most of the individual species on the sea floor is low, which is why only an estimated ten per cent of the smallest organisms (meiofauna, benthic organisms from 0.32 to 1.0 millimetres in size) and 30 per cent of the mid-sized animals (macrofauna, body size from two to 20 millimetres) have been scientifically described so far.

On the other hand, the conditions that deep-sea inhabitants have adapted to, which are very inhospitable from a human point of view, are well known. Food is only sporadically available, the water pressure is immense, and temperatures are low. It is also pitch dark 24 hours a day. Most organisms feed on the few particles that sink down from the upper layers of the sea. The consequences of the paucity, and especially of the short-term availability of food following the sinking of plankton blooms at the surface, are that the animals grow slowly on the sea floor, reproduce very late in life, and under some circumstances have extremely long cycles of brooding.

In the period from 2007 to 2011, for example, US American scientists observed a female deep-sea octopus of the species *Graneledone boreopacifica* off the coast of California whose offspring hatched from the eggs after it had guarded its clutch for four and a half years. Soon thereafter, German deep-sea researchers were able to verify that deep-sea octopuses in the Peru Basin laid their eggs directly on manganese nodules. The animals had attached their eggs to sponges growing on the manganese nodules at a water depth of about 4000 metres.

In the eastern part of the Clarion-Clipperton Zone, other researchers have determined that around one of every two deep-sea inhabitants larger than two centimetres (megafauna) is dependent on manganese nodules because these present virtually the only firm substrate onto which sponges, corals and other sessile organisms can attach. If the nodules were to be removed by giant mining machines, there would no longer be a substrate for recolonization unless restoration measures were carried out to replace the nodules with other solid objects. European researchers are presently carrying out a series of experiments to test the feasibility of these kinds of measures.

Larger organisms are comparatively rare in the Clarion-Clipperton Zone. Researchers calculate just 0.5 animals per square metre of seabed area. The smallest animals, which live mainly within the sediment (microfauna, smaller than 0.3 millimetres), are much more abundant. With an average density of around 300,000 organisms per square metre, they represent the greatest proportion of animals by far. During mining, however, not only the nodules themselves would be removed, but also the upper ten centimetres of the seabed, along with all of the organisms living on it or in it. How long it would subsequently take for nature to recover from this massive intervention is poorly understood.

Using so-called disturbance and recolonization experiments, scientists have been able to show that interventions in deep-sea life result in long-lasting, but extremely variable changes in the abundance and species composition of animals. In 1989, in order to simulate manganese nodule mining, scientists ploughed up the deep-sea floor across an area of a few square kilometres in the Peru Basin with a harrow. They returned 26 years later to investigate the life in and on the ploughed seabed. They found that the traces of ploughing were still very visible. Surprisingly, the biogeochemical conditions in the sea floor had been altered to such an extent that even the microorganisms able to live there were still severely impacted and, according to predictions, would need at least another 50 years to even approach a state of full recovery.

An overview study from the Clarion-Clipperton Zone also concluded that, following an intervention, some of the species living in the sediment will return to the area relatively soon, meaning within a few months to years, and that their numbers even exceed the original abundance, while other species require decades to recover. Experts therefore contend that the resettlement of disturbed areas can take many generations. The composition of the biotic community on and in the seabed remains altered for decades after the event, although research results from one kind of area cannot be extrapolated – neither to other deep-sea regions nor to other types of marine mineral deposits (sulphides, crusts).

In addition to the stripping of the top layer of the seabed, however, experts expect to see other kinds of environmental impacts from the mining methods that have been developed for manganese nodules. For one, there would be disturbances caused by the noise, the vibrations and the bright lights of the giant excavation machines. For another, as a result of the collection of manganese nodules and the processes for cleaning and transporting the ore, clouds of sediment or turbidity can be expected to form, mainly near the sea floor but also higher in the water column. Researchers expect that the hydraulic nodule collectors now being built will stir up 500 to 1000 tonnes of sediment from the sea floor per hour. This amount of material will be extremely problematic when it settles back onto the surface. Under natural conditions, sedimentation rates in the deep sea are only a few millimetres per 1000 years. But the agitation from nodule mining would cause a drastic increase in this rate.

From experiments and computer calculations it has been determined that 90 to 95 per cent of the sediment churned up by the mining machines would be redeposited quickly within a radius of up to ten kilometres. However, the newly formed sediment surface has a completely different structure and composition than the original sea floor, and thus no longer resembles the former natural habitat. The remaining particles are carried away by ocean currents and deposited outside of the mining area. Experts believe that industrial mining of the manganese nodules will lead to significantly higher sedimentation rates as far away as 20 or 30 kilometres.

The impacts that these turbulence clouds and sediment deposits will have on the biotic communities of the deep sea probably vary from species to species, and have not yet been thoroughly researched. Initial investigations indicate that microorganisms in the sediment can tolerate up to about one additional centimetre of cover by resuspended sediment. If this sediment layer is thicker, very few animals will survive. Sessile animals like sponges and corals, which live on the sea floor close to the mining area and filter the otherwise very clear bottom water to obtain food, will be covered by the masses of sinking sediment particles and have very low chances of survival. But octopuses, fish and the larvae of many other deep-sea species could also suffer under the clouds of sediment. In addition, scientists cannot rule out the possibility that the turbidity clouds caused by deep-sea mining could be detrimental to fisheries.

Basically, then, the bottom line for science is this: Because no deep-sea mining has yet been carried out at an industrial scale, and there is a lack of relevant accompanying studies, no dependable conclusions can be drawn regarding the true intensity and duration of the disruptive intervention, nor about its long-term consequences for the biotic communities of the deep sea. Therefore, the only option for regulatory bodies such as the International Seabed Authority is to introduce regulations at the outset that limit the consequences as far as possible. Minimizing large-scale consequences will require the development of low-impact equipment and careful and adaptive territorial planning for mining areas. The current level of knowledge, however, is not sufficient to allow effective protective measures to be taken. Many areas of the deep sea can be considered as still undiscovered. Furthermore, no one can say with certainty exactly what role the deepest layers of the ocean play in the many mass cycles of the sea, and thus ultimately for the Earth's climate processes.

The International Seabed Authority addresses this lack of knowledge by requiring compliance with the **precautionary principle** and the highest environmental standards, and by establishing regional environmental management plans. For the protection of species diversity in the Clarion-Clipperton Zone, it has also created nine protected areas on the sea floor of 160,000 square kilometres each, which constitute around 30 per cent of the total area. However, it has not yet been scientifically proven that their size, location and species diversity would be sufficient for the recolonization of potentially disturbed mining areas. For this reason, the Legal and Technical Commission of the ISA is now discussing whether an additional three or four protected areas should be established that encompass habitats previously not considered. In addition, international negotiations are being held to determine where appropriate protected zones should be established for all other areas of the high seas that are rich in resources, and what obligations these would carry for the contract holders. The primary goal is to create binding regulations for careful and adaptive territorial planning for deep-sea mining, and provide effective environmental protection measures on a regional level.

Criticism of the International Seabed Authority

Environmentalists, however, doubt that the International Seabed Authority can justly fulfil its diverse roles as contractor, mining facilitator, fee collector and top-level inspection and environmental protection body. The ISA bodies, but particularly its key organ, the Legal and Technical Commission, which is responsible for legal and science-technology questions, are very insufficiently funded and too understaffed in the field of environmental expertise to be able to properly carry out their tasks. Moreover, there are fundamental conflicts of interest within the agency resulting from the various requirements. For example, how can an agency be expected to effectively protect the environment when at the same time it is evaluated based on the extent to which it enables deep-sea mining?

The environmental organization Greenpeace accuses the ISA of issuing exploration contracts to various companies that are acting on behalf of only a few corporations from industrialized countries. The subsequent deep-sea mining in international waters would thus preferentially benefit these companies. The burden of the many risks associated with mining, on the other hand, would be carried mainly by the developing countries. For one reason, this is because they act as the Sponsoring States for private mining companies and, for another, because large ore deposits lie within their national waters. Although the ISA cannot make decisions about the mining of these, conceivable damages such as the collapse of ecosystems or the impacts on fisheries would mainly affect the coastal populations of these countries.

Other experts dispute Greenpeace, saying that there are currently no private investors in massive sulphides and ferromanganese crusts, and that about half of the manganese nodules are also state-held contracts involving both industrialized and developing countries. Companies that want to carry out mining in international waters also have to be insured against environmental damage and pay into an environmental compensation fund. With respect to the criticism of the ISA, it should be noted that the Authority itself calls upon all member states to send additional specialists to strengthen the Commission's environmental expertise.

These experts also praise the international cooperation within the ISA and the progress that the Seabed Authority has made in recent years. In July 2000 the legal foundations for prospecting and exploration of manganese nodules were adopted. This was followed in May 2010 by the regulations for massive sulphides and in July 2012 by those for ferromanganese crusts. Since July 2016 the ISA member states have been negotiating mining regulations that will become a component of the Mining Code, an overarching set of regulations for the exploration and industrial mining of mineral resources, which, in the view of many observers, offers the rare opportunity to establish science-based environmental protection measures prior to the actual mining activities.

The Mining Code regulates the formal aspects of proposal submission, protection of the environment through environmental impact statements, including environmental management and monitoring, as well as public involvement, occupational safety, monitoring of mining activities by inspectors, and the shutdown plans. In addition, the regulations shall spell out what fees and compensation payments the mining companies must pay to the ISA when they extract raw materials from international waters and privately profit from the common heritage of mankind. Directly related to this is the question of how the potential income could be fairly distributed to all countries. The Convention on the Law of the Sea contains an important clause that says raw material mining in the sea may not be detrimental to production on land. If one or more nations do incur a disadvantage due to deep-sea mining, perhaps because it causes a decline in raw-material prices or their ore deposits are no longer exploitable and the state loses income in the form of taxes, then according to the Law of the Sea they must be compensated by the ISA. How and by whom has also not yet been completely clarified.

Circular economy plus X – the better alternative

Only the future will tell whether industrial deep-sea mining will someday become a reality. Environmentalists demand a general ban and comprehensive protection of the deep-sea environment. The arguments of businesses and governments, on the other hand, are based on the rising demand for raw materials and the need to secure the supply of these and the jobs that depend on their respective industries.

Added to all of this, there is also the fear that individual resource-rich nations will gain excessive market power and use it to exert political leverage. One conceivable solution to this dilemma entails a combination of different strategies, based on the premise that the global economic system and consumer behaviour could be fundamentally altered and no longer based exclusively on growth and consumption.

To start with, this would require adoption of a sustainable circular economy. Among other things, this presupposes that:

- there are sufficient metals within the circular economy to meet demand;
- products undergo further development so that as little mineral resources as possible are used in their production;
- goods and products have high durability and a long lifetime;

In high demand – sand and gravel from the sea

While deep-sea mining remains a prospect for an uncertain future, many countries have been extracting sand and gravel from the sea for decades. These two loose aggregates are now among the most sought-after raw materials in the world. They are important not only for the production of concrete, glass, and electronic devices like computers, but also as fill sand at construction sites and in harbours, for coastal protection through beach replenishment, and for land reclamation. From 1960 to 2017, for example, the coastal city-state of Singapore was expanded by more than 130 square kilometres by means of sand filling, and an additional 56 square kilometres are planned by the year 2030. Over the past 20 years, the city-state has imported around 517 million tonnes of sand and gravel for this purpose, making it the world's largest importer of sand.

"Sand" is a collective term for mineral raw materials with a diameter from 0.063 to two millimetres, regardless of the minerals that the individual grains are composed of. Gravel is coarser and can contain material with grain sizes up to 63 millimetres. Most sand originates as the product of natural erosion of rocks on land. But an important portion is also contributed by glaciers, whose ice masses slice along mountain slopes like a planer, and by streams and rivers, which, almost unnoticed, eat into the landscape and wash away large quantities of sand. It usually takes tens of thousands of years before a boulder is reduced to the size of sand and is deposited on the banks of a river or in the sea. But sand is also generated directly in the sea. Parrotfish, for example, eat corals and eventually excrete the indigestible remains of the coral skeleton as sand. An adult may produce as much as 90 kilograms of coral sand each year in this way. Added to this are the many snail and clam shells that are ground up by currents, waves and wind.

All of the sand generated in these ways, however, is insufficient by far to cover the sand demands of humankind. In the year 2014, experts at the United Nations Environment Programme (UNEP) estimated that between 32 and 50 billion tonnes of sand and gravel are processed worldwide every year. If this level of consumption continues, which is probable considering the growing world population and increasing urbanization, the natural resources on land, in rivers, and in the sea will be exhausted in less than 30 years. The prices for these two raw materials are already rising considerably, currently at a rate of five to ten per cent annually in Germany.

The quantity of sand and gravel being removed from the world's oceans is difficult to estimate because the data are not recorded in a central location, and sand deposits in many rivers and coastal areas are excavated illegally. In many places, experts actually refer to a sand mafia. The business is growing because of the enormous increase in demand for the material, especially in economically emerging regions such as China, India and Africa, where there is a great deal of new construction. For example, cement is necessary for the production of concrete. Six to seven tonnes of sand and gravel have to be added to one tonne of cement, which is mixed with water and aggregates to produce concrete. As a result of the global construction boom, the amount of concrete produced every year is enough to build a wall around the Earth at the equator that is 27 metres high and 27 metres thick. Calculating the amount of sand and gravel needed for this, the enormous magnitude of raw-material consumption becomes obvious.

For large construction projects, even desert nations like the United Arab Emirates have to import sand or recover it from the sea, as their local dune or desert sand is not suitable for the production of concrete. This is because the sand grains in the desert have been too thoroughly rounded. Their surface is too smooth and their size too uniform for the cement and other components to effectively adhere to them. The sand grains from rivers or the sea, by contrast, are more angular and have a rougher surface. This is perfect for use as construction sand.

In Great Britain, around every fifth tonne of sand or gravel currently processed as concrete in England and Wales comes from the coastal waters of the island nation. Nevertheless, in 2018 the country held only second place on the list of Europe's largest marine sand producers. According to the International Council for the Exploration of the Sea (ICES), which provides scientific advice for the North Atlantic, the Netherlands topped the list with a production quantity of around 24.6 million cubic metres. Depending on the grain size, this is equivalent to a total weight of 30 to 40 million tonnes. Around half of this was used for land reclamation on the North Sea coast and on the Dutch islands. This is needed to replace the volumes of sand that are washed away every year by the autumn and winter storms on the North Sea. In 2018 in Europe, a total of around 54.13 million cubic metres of sand and gravel were removed from the sea.

Marine sand and gravel are generally only used when there are no appropriate deposits on land. The mining of sand and gravel in the sea is generally more expensive than on land, which is why, from a global perspective, deposits on land or in rivers are usually preferred. The impacts on the affected environments are enormous. River beds are deepened, which increases the current speed, causing bank areas to be washed away and bridge pilings to be undercut. When coastal sandbanks are removed, the land areas behind them lose their most effective wave barriers. As a consequence, flooding, coastal erosion and storm damage increase. Through uncontrolled sand extraction from the sea, Indonesia has already lost 24 islands.

Biological studies have also proven that sand production is very detrimental to life on the sea floor. In the North Atlantic alone, more than 48 fish species are dependent on sandy bottom conditions for their spawning areas, including some popular food fishes such as herring. Although the impacts are relatively local, the damage can be very severe when the mined sand or gravel area is the only one around and dependent species lose their only possible habitat. Production contracts should therefore not be issued until a thorough assessment has been carried out. Areas that have been intensively used for sand extraction require an average of five to ten years before they are completely recolonized. Depending on the local environmental conditions (sea swell and sediment motion) and the water depths that are excavated, however, the recovery phase can also take decades.

If dredging is carried out for a short period of time or only once, the original conditions may return within two to four years in an ideal situation. In this case, the biotic communities that are more accustomed to fast currents or strong tides will recover fastest. Species that live in quieter water conditions will generally require longer. If especially deep holes are created by the extraction of sand, and finer material is subsequently deposited there, it may even result in the development of completely new biotic communities.

For these reasons, scientists recommend clear guidelines for the mining of sand and gravel in the sea. These include moratoriums on production in regions and at times when important fish species are spawning, regular shifting of the areas of extraction so that the bottom communities have a greater chance of recovering, and maintaining refuges. These lie between the areas of extraction and can serve as retreats for the impacted bottom dwellers.

In addition, for the mining of marine sands a compromise must be found between minimization of the area exploited and duration of the recovery phase. When sand is extracted from a single location, creating a deep hole, less total area is impacted, but a longer time is required for the hole to fill naturally and recolonization to occur. If the area of mining is expanded, and only the upper layer of the seabed is scraped off, a larger area is affected but the recovery time is shorter, at least in shallow water depths. In deeper water the seabed requires longer to recover from any kind of disturbance because the water masses do not transport and redeposit as much sediment as they do in shallow-water areas.

5.16 > Off the Dutch island of Ameland a suction dredger extracts sand from the bottom of the North Sea to be used in widening the island's beach.

5.17 > These pictures show two of the coral atolls in the South China Sea that China has transformed into islands using sand replenishment. Both the Fiery Cross Reef (above) and the Subi Reef have served as military stations since 2017. The atolls have been largely destroyed as habitats for corals and associated reef dwellers.

- all end-of-life devices and the materials they contain are recycled and reused.

Circular systems not only preserve the environment, they also have economic advantages. Through the recycling of metallic waste and scrap, the amounts of raw materials extracted by mining would be reduced and a great deal of energy saved in production. The mountains of waste would stop growing. Furthermore, many metals can be recovered with no loss in quality.

Worldwide today, recovery rates for materials such as iron, zinc, copper, gold and silver already reach 50 to 90 per cent. With many other metals there is great potential to improve recovery rates. However, it is also a fact that electronic products and their resulting scrap continue to become more complex, which makes the recycling of individual materials more difficult and in some cases no longer economical. Furthermore, a circular economy can only function if the amount of materials recovered is sufficient to cover worldwide demand.

Experts believe, however, that, in view of rapid population growth and increasing technological transformation around the world, the need will remain for metallic raw materials to be extracted from natural deposits in the future. On the other hand, the supply situation could be improved by a more thorough development of deposits.

Given this background, a few years ago the European Commission contracted scientists to determine the amounts of valuable minerals and metals that might still be present in the tailings of former mines or strip mines, and how they could be extracted in future.

Their results indicated that the probability of finding raw materials such as chromium, niobium or vanadium in the tailings piles is great, particularly because land-based mining in the past has always concentrated on the production of only one or two resources. However, it must be considered that some effort would be required to recover the metals and minerals that were previously not recognized as important. Methods by which various materials are all extracted at the same time are the most sensible, even though these kinds of processes are generally very energy-intensive.

Other researchers are searching for ways to directly extract dissolved metals from sea water. For example, there is an estimated 180 billion tonnes of lithium stored in the ocean. But the actual concentration of this metal in sea water is only 0.2 parts per million. In order to extract this very minor amount, scientists employ specially coated electrodes, which they repeatedly subject to an electric current. As a reaction to the electric current, the lithium ions migrate out of the water into the electrode. This method works in an experimental setting, but it is still far from being applicable on an industrial scale.

For this reason, in 2017, a number of German scientists posed the question of whether it would be conceivable to search for ore deposits in the subsurface of the shallow, near-coastal shelves before undertaking deep-sea mining, which is technically more complex and fraught with serious consequences. The seabed of the continental shelf is merely an extension of the continent, which could mean that metal or mineral deposits occurring on land near the coasts also extend out onto the sea floor. These near-coastal resources could probably be extracted comparatively easily, and with significantly less risk, than the ore deposits in the deep sea.

For example, geologists have predicted the presence of large gold deposits off the west coast of Africa, nickel deposits in the Arctic Ocean and lead-zinc deposits in the Gulf of Mexico and Mediterranean Sea. In many of these regions resource extraction would not be a new concept. In several shelf seas, oil and natural gas have been produced for more than 70 years. In other coastal areas, sand and gravel are being extracted, albeit with serious consequences for the sensitive coastal marine ecosystems.

This means that as long as demand continues to rise and truly sustainable alternatives are lacking, the extraction of mineral resources will always be a matter of balancing interests, posing the question of how the benefits compare to the somewhat unforeseeable consequences to the environment and people. The international community is now, for the first time, faced with the decision of whether industrial mining should actually take place in the international deep sea.

Freshwater reserves in the seabed

In the past, it was only in arid regions that freshwater was viewed as a precious asset. Now, however, the lakes, rivers, springs and wells in many of the Earth's coastal regions are also drying up. The reasons for this are many and varied. In some places it is raining less as a result of climate change. In others the precipitation is no longer regularly spaced through time, but occurs episodically as heavy rain events. During these extreme precipitation events most of the water runs off the surface because the soil cannot absorb it fast enough. At the same time, human demands upon freshwater resources are increasing because more people are moving to the coastal regions or taking their vacations there, while farmers are watering larger areas. In some places, the inland surface waters and groundwater reservoirs are being senselessly polluted, for example through over-fertilization or the excessive application of pesticides. In response to the increasingly frequent and severe water shortages, researchers have long been searching for new freshwater reservoirs. Their explorations have become strongly concentrated on areas beneath the sea. It has been known for a number of years that untapped groundwater reserves exist below the sea floor near the coasts, and that this is presumably the case on all the continents. Most of the offshore reservoirs of this kind discovered so far are on the east coast of the USA, the northwest coast of Europe and the west coast of Australia. It is estimated that all of the known reservoirs beneath the sea together store around one million cubic kilometres of freshwater. This amount would theoretically be enough to fill the Black Sea twice or, to give a more practical example, to supply the population of Germany with drinking water for more than 192,000 years.

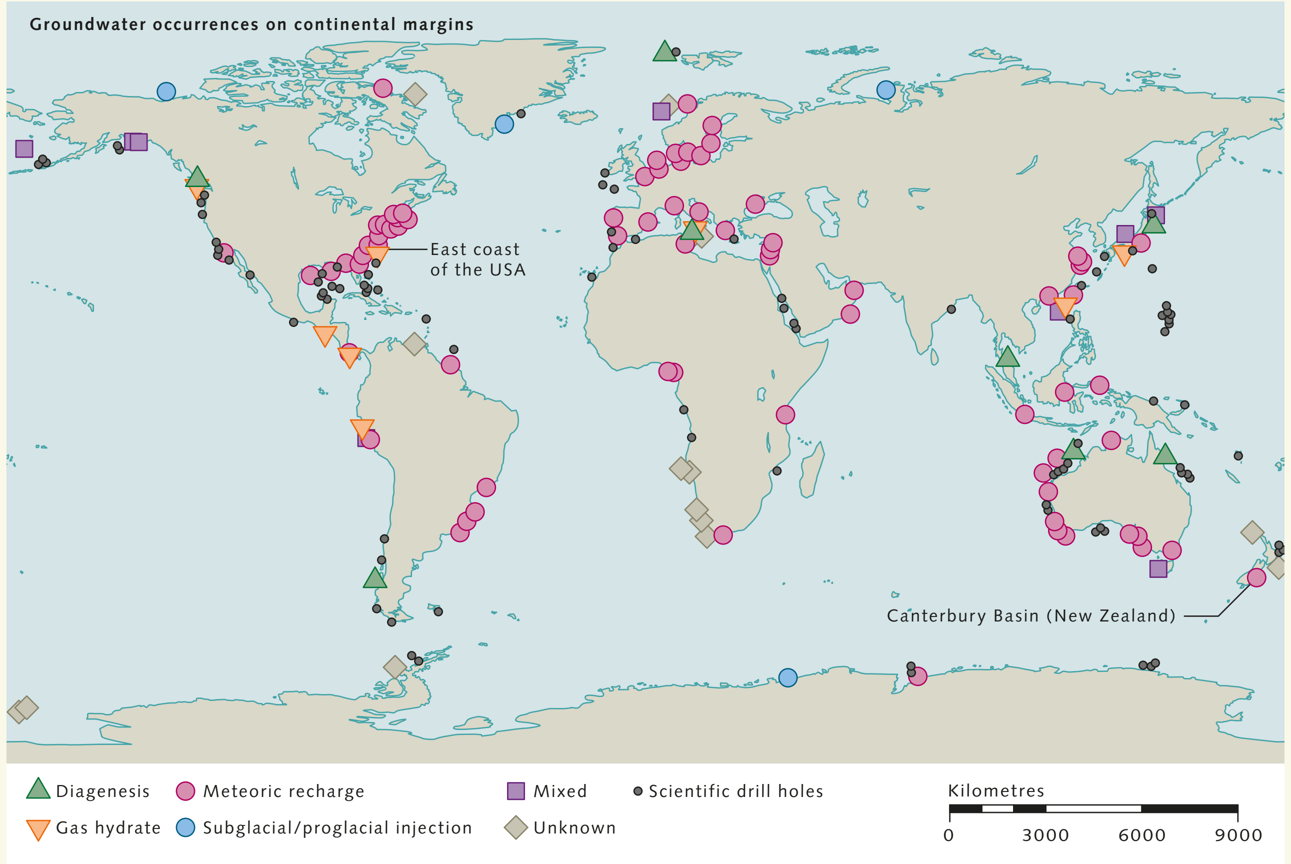
Occurrences of groundwater below the sea can originate in different ways. Experts currently distinguish between five fundamentally different formation processes. Some reservoirs are formed by the natural breakdown of gas hydrates in the sea floor, during which low-salinity water is released. In other places, water accumulates in the subsurface as a result of physical and chemical processes during the induration of sediments. Geologists refer to this kind of rock formation process as diagenesis. Occurrences in coastal regions previously covered by glaciers can be attributed to meltwater from the former large ice masses penetrating into the sea floor and collecting there (subglacial/proglacial injection). Some known offshore reservoirs are also fed from the land, for example by precipitation on land percolating downward and then being carried underground toward the sea by deep-lying rock layers (meteoric recharge 1).

Most of the groundwater reservoirs found under the sea, however, originated during past cold intervals, such as the last glacial period around 20,000 years ago. During that period the ice sheets in the Arctic and Antarctic regions grew. Due to the great amount of water that was thus bound in the ice sheets, the global sea level dropped by more than 100 metres compared to today. As a result, the shallow coastal waters around the world retreated and the shelf areas of the continental margins dried up. When it rained or snowed on these areas, the water percolated into the soil and collected in hard, porous limestones, where it was stored in a manner similar to being absorbed by a sponge. This process is known as meteoric recharge 2. At the end of the glacial period, as sea level began to rise again, the shelf areas were flooded once more. Since then, the groundwater reservoirs have been located underwater beyond the coasts, and have become especially interesting for countries with limited water resources such as South Africa, Mexico, New Zealand and Malta.

In the waters of Malta, studies led by German scientists have revealed that the water-bearing limestones in the region lie around 400 metres below the sea floor. Off the New Zealand coast of Canterbury (eastern part of the southern island), by contrast, the researchers only had to drill 20 metres into the sea floor to find freshwater-bearing rocks. This is one of the shallowest groundwater reservoirs in the world. It extends to as far as 60 kilometres from the coastline, and is thought to hold up to 200 cubic kilometres of water. By comparison, Germany's largest inland lake, Lake Constance, holds 48 cubic kilometres of water. The volume of groundwater discovered off the coast of New Zealand is around four times as large.

Researchers have been able to obtain such detailed knowledge of the freshwater systems beneath the sea recently through a combination of various geophysical and geochemical research methods. With the help of marine electromagnetics, they can measure electrical resistivity below the seabed. Using these measurements, it is possible to determine whether the rocks in the subsurface have saltwater or freshwater stored in their pores. Saltwater is an excellent conductor, while freshwater has three times the electrical resistance.

In order to determine the salinity of the pore water with a great degree of accuracy and, furthermore, to estimate the volume of the groundwater, the geologists then combine the electromagnetic data with seismic profiles of the sea floor layers. This integration is essentially a statistical-mathematical process that links numerical models with machine learning algorithms. The method puts scientists in a position to characterize and map offshore freshwater systems in extraordinary detail. Strictly speaking, this research field is actually a bit more mathematics than geology and hydrology.



5.18 > Groundwater reservoirs have now been discovered in the coastal areas of all continents. They are formed by the breakdown of gas hydrates, by the consolidation of sediments (diagenesis), through the input of glacial meltwater, and by rainwater input from the land, but most commonly by the formation of groundwater reservoirs during past glacial periods.

The ocean as energy source – potential and expectations

> The ocean is being promoted as a component of the energy transition. The principal advocates for this include large oil corporations. They are investing in the expansion of offshore wind energy and developing concepts for storing carbon dioxide beneath the sea floor. These technologies provide a ray of hope in efforts to shift away from coal, oil and natural gas. But for the ocean, this development means that many of its regions will be even more intensively and permanently exploited by humans in the future.

A new era in the energy sector

Energy makes our lives much easier. In the form of electricity, it runs machines, trains and increasing numbers of automobiles. It allows real-time communication around the globe with pictures, and lights up apartments and entire cities after the sun has sunk below the horizon. In the form of heat, energy can melt ice and iron ore, and it keeps our homes cosy and warm when it is cold outside. Released by burning fuel in motors, it allows traffic to move and airplanes to fly.

Due to expansion of the world's population, with growing numbers of people owning heaters, home electrical connections and automobiles, and with ever widening fields of their daily lives being electrified, there is also a rapid growth in global primary energy consumption. Experts define this term as the total amount of energy required to supply the global economy. Up to now this need has been mainly produced by burning fossil fuels. In Germany, for example, roughly 80 per cent of the energy used in the year 2018 came from coal, natural gas and petroleum products.

Looking at the production of electric current alone, two-thirds of the electricity used globally is still generated by burning fossil fuels. The greenhouse gas emissions of the energy and traffic sectors are correspondingly high. More than one-quarter of the oil and gas burned is produced from the sea.

However, the energy sector is facing a radical transformation in two areas. The present power grids have to be expanded, modernized and intelligently managed in order to address the growing needs. At the same time, renewable energy sources such as wind, sun, biomass and hydropower are to replace conventional ones. Here, the ocean will also play a key role: for one, as a location for giant wind farms, and for another as a driver of wave energy converters and water-current power plants. There is also some discussion as to whether depleted natural-gas reservoirs beneath the seabed might be a suitable place to store carbon dioxide that has been captured from industrial operations and subsequently liquefied. At any rate, the storage potential would be enormous, and it is presently of great interest to a number of oil- and gas-producing companies.

Deep and ultra-deep water
The term "deep water" originated during the time when offshore drilling platforms still stood on the sea floor. It referred to the maximum water depth at which this kind of bottom support was possible. But the number assigned to this depth increased with advancing technology. While a water depth of 300 metres was considered to be "deep water" in the 1990s, today the term indicates a depth of more than 500 metres. When resource experts speak of "ultra-deep water", on the other hand, they are talking about water depths greater than 1500 metres.

Oil and natural gas production in the sea

Many of the Earth's oil and natural gas deposits are located beneath the sea. Formed over millions of years, the first of these to be drilled were in the Santa Barbara Channel off the coast of the US state of California at the end of the 19th century, although they were still within sight of the coast at that time. But shallow waters and close proximity to land ceased to be basic requirements more than 70 years ago. Due to improved exploration, drilling and production methods, oil and natural gas can now be retrieved from reservoirs in water depths greater than 3000 metres and more than 160 kilometres from the coast. However, the areas of deep-water and ultra-deep-water production are limited to the shelf seas on the continental margins. The deep-sea regions, which by far make up the largest part of the marine area, are underlain by oceanic crust, and have a very low or non-existent potential for the presence of oil or natural gas.

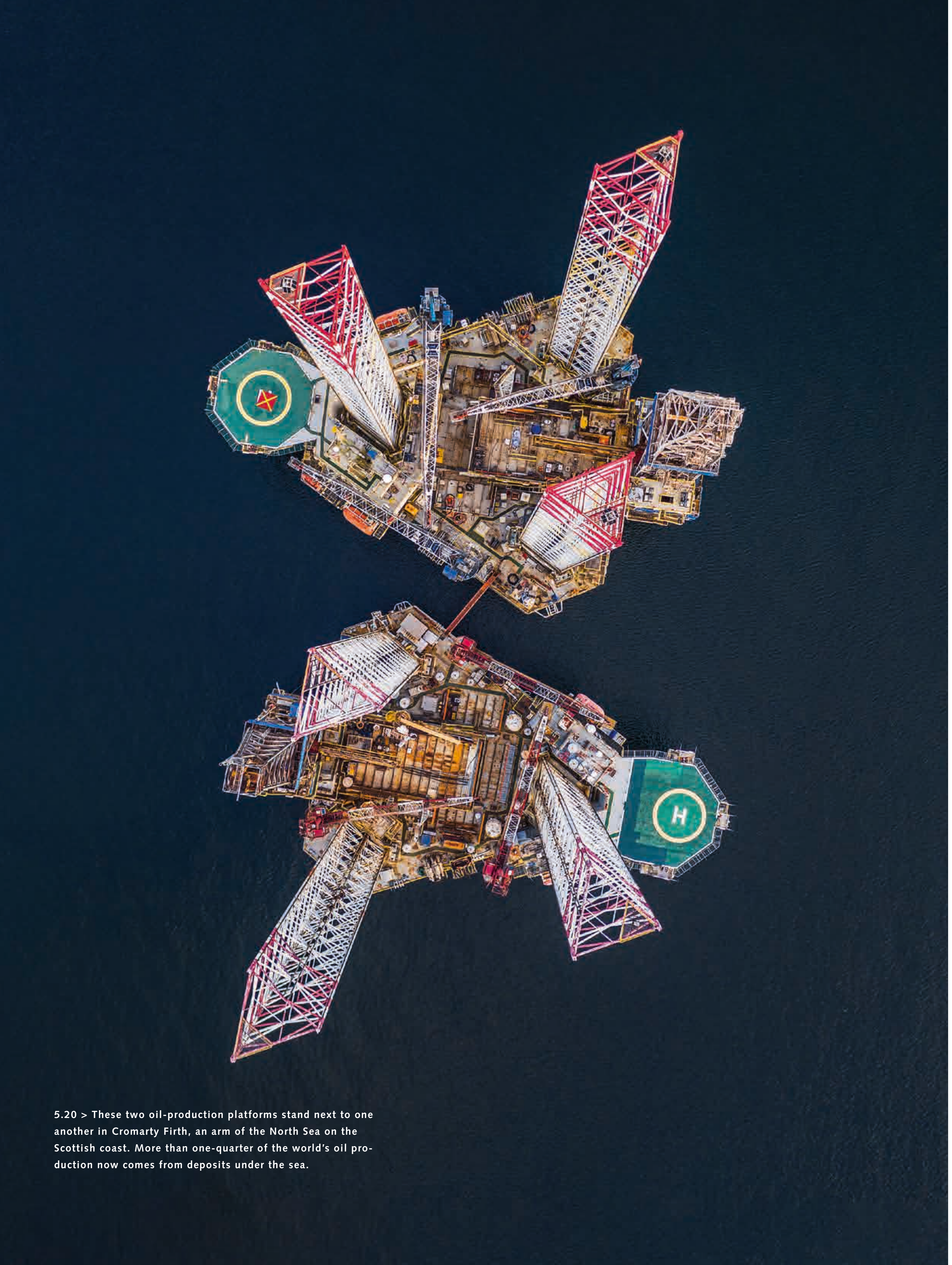
Drilling beneath the sea has now also achieved extreme depths. The deepest oil wells in the Gulf of Mexico, for example, extend for more than 6000 metres into the sea floor, and there are platforms whose drilling equipment could theoretically penetrate up to 11,400 metres below the bed under favourable conditions.

5.19 > A supply ship of the Norwegian energy company Equinor delivers technical equipment for oil production to the *Johan-Castberg* oil field in the Arctic. When the deposit in the Barents Sea goes into production it will be Norway's northernmost oil field.

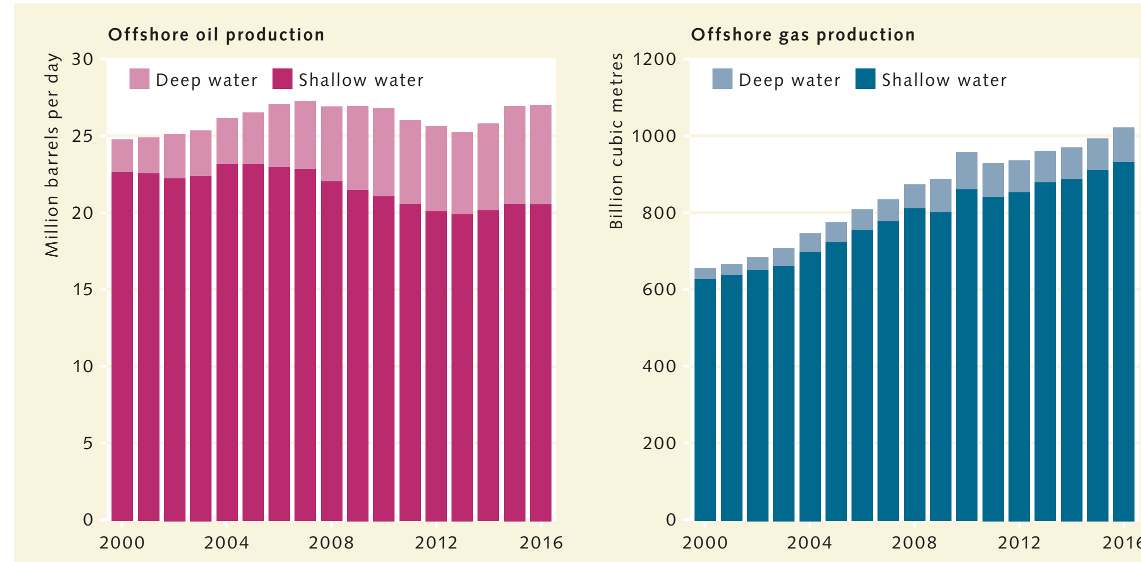
Technological advances have also allowed oil companies to expand their operations into areas where extreme weather or environmental conditions previously prevented production. In 2016, for example, the two Norwegian energy companies Vår Energi AS and Equinor (formerly Statoil) erected the *Goliat* drilling and production platform in the Arctic Barents Sea, thus developing the world's northernmost oil field to date. Development of another deposit, even further to the north, is already underway. Production in the *Johan-Castberg* oil field is projected to begin in 2023.

Oil and natural-gas production in the sea is very time-intensive, and also particularly cost-intensive. It can take up to ten years from the discovery of an offshore oil reservoir in ultra-deep water until the sale of the first barrel of oil. The costs for geological surveys and all of the necessary drilling and production technology typically total in the billions. The decision by a company to develop an offshore field or not is therefore not based on the current oil price, but with a view to projected price trends in the future. For this reason also, the levels of offshore production are not so closely tied to current price developments as are the amounts produced from deposits on land.

According to the International Energy Agency (IEA), the volumes of oil and gas produced from beneath the sea make up more than one-quarter of the total global production. There are now around 6500 offshore oil and gas production facilities in operation worldwide. The principal locations are the waters of the Near East, Brazil, the North Sea, the Gulf of Mexico, the Niger Delta and the Caspian Sea. While the amount of offshore oil production remained relatively stable at 26 to 27 million barrels a day from 2000 to 2018, gas production during the same time period increased by 50 per cent, to more than 1000 billion cubic metres. Another new development is that some operational steps, such as the liquefaction of natural gas, are



5.20 > These two oil-production platforms stand next to one another in Cromarty Firth, an arm of the North Sea on the Scottish coast. More than one-quarter of the world's oil production now comes from deposits under the sea.



5.21 > Since the year 2000, the amounts of fossil-fuel resources produced from the sea have been increasing, a trend that can largely be attributed to the rise in natural gas production. This takes place primarily in shallow waters. Oil, on the other hand, is increasingly being produced in deep water.

no longer carried out on land, but increasingly on special ships while still at sea.

In this setting, the search for new oil and gas reservoirs in the oceans is a continuing process. Over the past two decades, the largest deposits have been discovered in water depths greater than 400 metres. Altogether, these make up around half of all the oil and gas deposits discovered during the period from 2008 to 2018 worldwide. Considering the new reservoirs individually, it is clear that only a few of them can produce oil. More than half of the newly discovered occurrences are classified as natural gas fields.

In spite of all the new discoveries, many plans for offshore development were put on temporary hold following the *Deepwater Horizon* disaster in the year 2010 and the collapse of oil prices in 2014. During the same period, between 2013 and 2016, the number of active production platforms fell from 320 to around 220. One reason for this decrease was the enormous expansion of hydraulic fracking on land, especially in the USA. Fracking involves the deep injection of liquids at very high pressure, which produces cracks in the dense shale and petroleum source rocks. The shale gas and oil trapped in the rocks can then be extracted, and the entire procedure is much less expensive than offshore drilling.

The growing competition from fracking and the resulting price war forced adjustments in the offshore industry. Only highly promising drilling projects are now being carried out, and generally with much more efficient planning. The platform designs have been simplified, largely standardized, and in some cases even decreased in size. At the same time, the worldwide surplus of offshore equipment and services is contributing to a decline in operating costs. Whereas oil production facilities in Norwegian waters or in the Gulf of Mexico previously only made a profit when the market price for oil was above a threshold of USD 60 to 80 per barrel (159 litre capacity), modern facilities can now operate profitably at a price of USD 25 to 40 per barrel.

At present, companies are striving to further reduce costs by digitalizing certain processes of offshore production. They know that the reservoir for the next project will likely lie in even deeper waters or be further from the coast. It will therefore present the operator with more new challenges, be they technological, logistical or financial – whereby unexpected discoveries cannot be ruled out in coastal waters that have been sparsely explored so far. In 2018, experts from the USA compiled the following list of significant scientific and technological hurdles for the industry:

Methane hydrates – the price ultimately decides

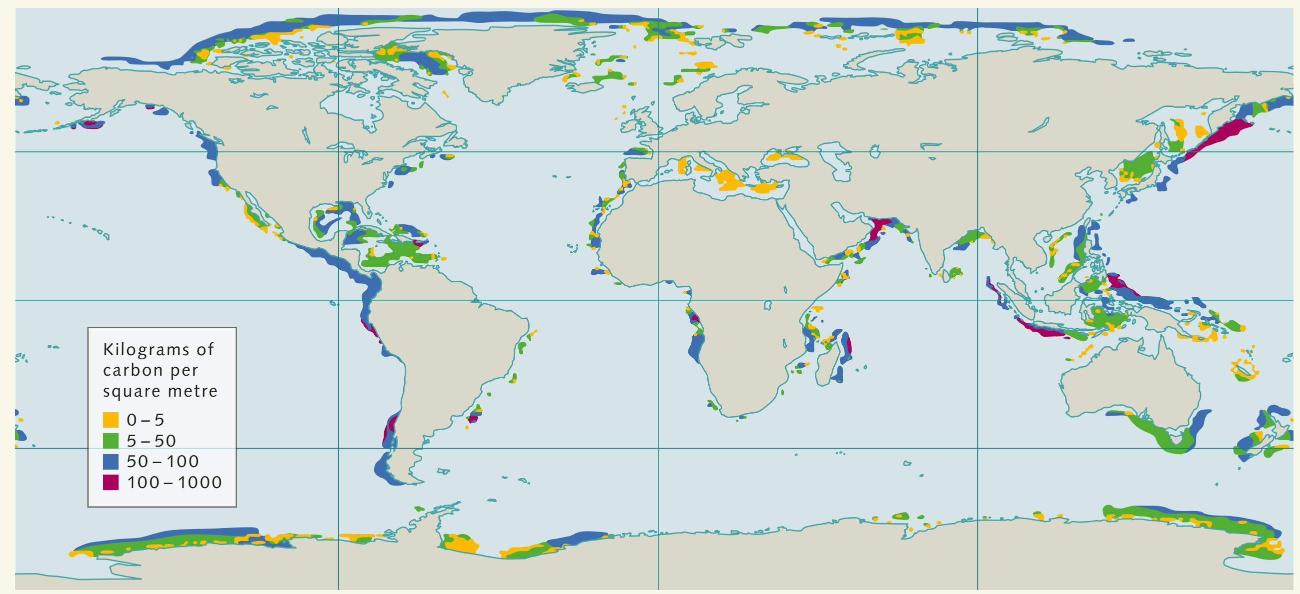
Natural gas in the sea floor occurs not only in the gas phase but also, and presumably much more abundantly, as gas hydrates, which are in solid form. Gas hydrates are composed mostly of frozen water molecules that form a solid crystal lattice. At first glance they therefore look just like ice. But unlike ice, there are one or more gases trapped within the crystal lattice of a gas hydrate. In many cases this gas is methane, but also nitrogen, carbon dioxide, hydrogen sulphide, ethane or propane may be present.

Gas hydrates therefore represent a highly concentrated form of natural gases. Roughly 160 to 180 cubic metres of methane gas can be obtained from one cubic metre of methane hydrate, which is why methane hydrates have been seen as an attractive potential energy resource for decades. Scientific studies suggest that there are between 100 and 1000 trillion cubic metres of methane gas in the form of hydrates in the sea floors of the shelf seas and continental margins. This amount would theoretically be sufficient to cover the current gas consumption of the world (2019: 4.088 trillion cubic metres) for at least another 24 years.

Realistically, however, only a comparatively small proportion of these deposits could actually be recovered because gas hydrates only form on the continental margins at water depths greater than around 300 metres. The reasons for this are twofold: For one, only on the continental margins does organic material settle from the upper water layers onto the bottom in sufficient amounts for microbes living in the sea floor to break it down and produce methane on a large scale. For another, only below a water depth of 300 metres is the pressure high enough that the gases generated in the sediments can combine with pore waters to form hydrates that remain stable. If the temperature on the sea floor changes or if the pressure decreases, the crystal lattice of the water molecules will break down and the trapped gases will escape. This physical process is known as dissociation, and it explains why it is possible to set fire to methane hydrates. The fire from a match first melts the ice and then ignites the escaping gas.

The extraction of methane hydrates has been technically possible for some time now. Japanese, US and European researchers have already developed and field-tested working methods. Their test results, however, were somewhat sobering. Compared to traditional natural gas production, it took far too much time for the drilled gas hydrates at depth to dissociate and for the escaping gas to rise through the pipeline. Considering the high investment costs projected by the tests, many experts concluded that industrial production is uneconomical. Nevertheless, Japan and China in particular are continuing to look at the development of new mining methods. If less expensive methods can be developed, Japan, for example, would be able to exploit the gas-hydrate deposits in its territorial waters and reduce its dependence on imported liquified natural gas. The experts working on it, however, have not yet achieved a decisive breakthrough. With the current world market prices for natural gas, extracting methane hydrates today would still be a losing proposition.

5.22 > When methane hydrates are brought up from the sea floor, they break down at atmospheric pressure. The methane released can then be easily ignited.



5.23 > Methane hydrates occur worldwide, especially on the continental slopes. The largest deposits are presumed to lie off Peru and the Arabian Peninsula. The figure illustrates only those hydrates in which the methane was produced by microorganisms. It does not include methane in the deeper sediment layers generated by the chemical transformation of biomass.

Looking through thick salt layers

In some regions, like the Gulf of Mexico and off the coast of Brazil, for example, oil deposits are present in the rock strata beneath thick layers of salt. However, these salt deposits, which can be up to two kilometres thick, are practically impossible to penetrate using conventional seismic methods. New analysis techniques and high-performance computers are needed that can analyse large numbers of geological datasets. Another problem is that salt dissolves when it comes into contact with drilling fluids. In some situations, it can even damage the drilling equipment or the borehole. Drilling through salt layers will therefore require new technology that is especially designed for salt.

Heat- and pressure-tolerant drilling technology

Conventional drilling equipment can be used at temperatures of up to around 175 degrees Celsius. In drilling for especially deep-lying deposits in the future, however, the ambient temperatures could be as high as 260 degrees Celsius. It would be hot enough in the borehole to bake a pizza. These temperature conditions would be destructive to many of the sensors and electrical components that are typically installed in the drilling system. For these kinds of operations, a drilling technology that is especially heat-tolerant, and that can withstand pressures 2000 times greater than the atmospheric pressure at the Earth's surface will be required.

New installation and observation systems

Companies are increasingly foregoing the use of floating platforms for producing oil and natural gas in deeper waters. This can be achieved instead by the installation of a subsea wellhead on the sea floor. Oil or gas flows from this through a pipeline directly to the shore. However, subsea systems still need to be monitored. This requires remotely controlled monitoring technology such as autonomous underwater vehicles with sensors and cameras that can examine the production systems for leaks or weak spots.

Storm-proof production facilities

Hurricanes are a growing safety issue because they are becoming stronger, particularly in the Gulf of Mexico. Oil and gas production facilities in storm-prone regions around the world have to be able to reliably withstand these weather extremes. The use of advanced technology or the installation of remotely operated underwater systems is therefore essential.

Another challenge is posed by production equipment that has been in use for decades. According to the IEA, around 2500 to 3000 oil or natural gas production systems will become obsolete by the year 2040. Many of these are steel platforms in shallow water. However, much more complex facilities in the deep sea are currently being added to these. The most environmentally friendly way to dispose of these would be to completely dismantle the systems and scrap them on land. But it is now conceivable that other solutions may be found such as using them as locations or foundations for offshore wind turbines in some situations.

The sea floor as a repository for carbon dioxide

The idea of using oil or gas platforms at the end of their service as sites for producing electricity from wind power, however, is just the beginning. With the advance of global warming and increasing pressure for action, governments and industry are intensively discussing whether it would be possible to store carbon dioxide in depleted oil or natural gas reservoirs beneath the sea to help prevent further warming of the Earth.

The idea of carbon capture and storage (CCS) is by no means a new notion. A number of concepts and approaches have been under consideration for several decades. But it has simply been much cheaper for industry to release greenhouse gases directly into the atmosphere than to capture them at great expense and store them underground.

One of two exceptions is provided by the oil industry itself. Particularly in the USA, oil companies sometimes inject carbon dioxide into partially depleted oil reservoirs in order to increase the pressure on the remaining oil and force it towards the production site.

As an added effect, the carbon dioxide improves the flow properties of the oil so that it can be produced faster. In this kind of oil production, known as Enhanced Oil Recovery (EOR), a portion of the injected carbon dioxide remains below the surface and is thus permanently stored. At present, however, only 30 per cent of the injected carbon dioxide comes from industrial capture projects. The rest, like the oil itself, comes from the subsurface.

Norway has gone a step further. As early as 1996, the country had already transformed one of its former marine natural gas fields into a carbon dioxide repository. As part of the *Sleipner* project in the North Sea, carbon dioxide that rises directly at the site of natural gas production is captured, liquified and then sequestered at a depth of 880 to 1100 metres below the sea floor. The responsible Norwegian oil company, Equinor (formerly Statoil), has also been operating under the same concept in the *Snøhvit* field in the southern Barents Sea since 2007. With these two CCS projects, the company now injects around 1.7 million tonnes of carbon dioxide into the sea floor each year. This amount is approximately equal to the emissions produced by a small coal power plant. But that is only the beginning.

According to its own reports, the company is now participating in more than 40 CCS projects and is developing concepts by which carbon dioxide can be separated during industrial production on land, liquified, and ultimately transported by ship or through pipelines to injection stations at sea. One of these is *Northern Lights*, a large Norwegian project that plans to capture carbon dioxide produced in cement production and waste incineration in the greater Oslo area and transport it by ship to the CCS terminal in Øygarden on the west coast of Norway. From there, it will be pumped through a 110-kilometre-long pipeline to an offshore temporary storage station south of the *Troll* natural gas field in the North Sea, where the liquified carbon dioxide will ultimately be injected to a depth of 2500 metres below the seabed. All of the necessary technological systems should be in operation by 2024.

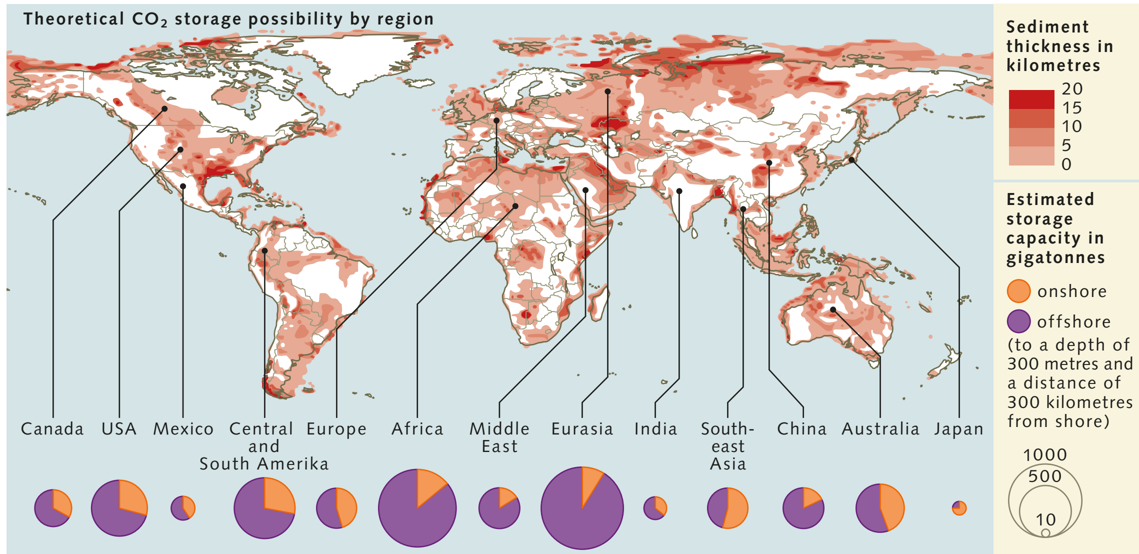
A group of companies in the Netherlands has similar plans. A depleted gas reservoir off Rotterdam (*Porthos* project) will serve as a carbon dioxide repository to store a portion of the 28 million tonnes of carbon dioxide released annually by the city's port and adjacent industrial area. The project plan estimates that two to five million tonnes of carbon dioxide can be injected into the *Porthos* reservoir annually. It remains to be seen, however, whether the emission-producing companies will actually follow through on their statements of intent and participate in the expensive process of carbon dioxide storage.

The cost of capturing one tonne of carbon dioxide at a cement plant, transporting it out to sea and injecting it into the sea floor is roughly estimated to be more than 50 Euros. CCS projects will not be economically viable until the cost for carbon dioxide emission exceeds the costs of capture and storage. For this to occur, however, the taxes on emissions will have to increase as drastically as the prices for the emission certificates. According to the World Bank, in 2019 companies paid between one and 19 US dollars for every tonne of carbon dioxide released, whereby more than half of the emissions were taxed at less than ten US dollars.

To date, initiators of CCS projects in Europe have been primarily focussing on the North Sea. This is partially due to the number of large industrial companies located in the coastal region, but also because of the ideal geological conditions beneath the floor of the North Sea. In order to store liquified carbon dioxide in the subsurface, a thick sandstone formation with abundant large pores between the individual sand grains is required, so that the carbon dioxide can easily disperse through the pore spaces. Overlying this sandstone formation, however, there must also be a layer of fine-grained clayey rock to seal it off and prevent the carbon dioxide from rising into the shallower layers of the sea floor.

After injection, the liquified carbon dioxide spreads through the porous region and slowly begins to dissolve in the pore waters of the sandstone formation. This process alone takes several hundred years. The dissolved carbon dioxide may eventually react with the surrounding rocks. It can dissolve them and form new rocks (limestone and other carbonates) in which the carbon dioxide is then per-

5.24 > In the *Sleipner* gas field in the North Sea, carbon dioxide that rises to the sea surface during the production of natural gas is captured directly on site, liquified, and then injected at a depth of 880 to 1100 metres back into the seabed.



5.25 > The greatest amounts of carbon dioxide could be stored onshore because the geological conditions are best there. Nevertheless, storage beneath the sea floor is being considered in many places, in part because the possible adverse consequences would be less severe than in inhabited regions on land.

manently fixed. Experts refer to this process as chemical neutralization of the greenhouse gas. It takes many millennia for this process to occur.

Reservoir rocks suitable for CCS are commonly located on the shelves and in marginal seas like the North Sea. The storage capacity of these alone is so large that they could contain an estimated 150 billion tonnes of carbon dioxide, which is roughly three times the annual total emissions from pre-corona times (2019: 42.3 billion tonnes of CO_2). Worldwide, there are at least 794 geological basins on land and in the sea where it would be theoretically possible to store carbon dioxide underground. Their combined storage capacity has been estimated at about 8000 to 55,000 billion tonnes of carbon dioxide. Of this capacity, 2000 to 13,000 billion tonnes are located in marine regions, whereby this calculation only takes into account the coastal waters (up to 300 kilometres offshore, maximum water depth 300 metres), and the polar seas are also not included.

Nevertheless, even large-scale CCS projects would not be enough alone to curb anthropogenic carbon dioxide emissions sufficiently to achieve the Paris climate goal of limiting global warming to significantly less than two degrees Celsius. For this, a much broader spectrum of measures for reducing carbon dioxide concentrations in the atmosphere will be required. However, experts at the International Energy Agency say that CCS will still play a key role as an interim solution. This process should principally be implemented in the industrial sectors where carbon dioxide emissions are currently considered to be unavoidable, such as in the manufacture of cement, steel production, production of chemicals, generation of electricity in biomass or coal-driven power plants, and in oil and natural-gas production and refinement.

According to calculations by the International Energy Agency, existing power plants and industrial facilities could be equipped with capture technology at a scale that allows around 600 billion tonnes of carbon dioxide to be captured globally within the next 50 years. That is equal to 17 times the current amount of total emissions from the industrial sector. The total quantity of captured carbon dioxide would not have to be stored underground. Some of it could also be used for the production of synthetic fuels. Raw-material experts also argue that inexpensive hydrogen could be produced from natural gas with the help of CCS. This could then be employed as a low-emission fuel or energy source for new applications in transportation, heavy industry or in buildings.

Finally, projects for underground storage of carbon dioxide could also be considered where the carbon

dioxide is extracted directly from the atmosphere and subsequently liquified, a process known as direct air capture. This procedure is currently very energy-intensive and thus still too expensive. But for the long term, experts believe that unavoidable emissions will have to be offset by some degree of direct capture of carbon dioxide from the atmosphere. Otherwise, the goal of zero emissions will be no more than wishful thinking.

When comparing the advantages and disadvantages of storing carbon dioxide on land with storage options in the sea, the sub-seabed seems to be the lower-risk option because, as yet, there are virtually no infrastructures there that could be exposed to potentially serious damage. For example, if the sea floor is subjected to minor vibrations caused by the dispersion of carbon dioxide in the subsurface, the event would presumably cause very little disturbance to the biological communities on the sea floor. But on land these could cause damage to houses or roads. In addition, CCS projects on land could potentially affect the aquifers in the vicinity. These could be at risk of salinization, or acidification in some circumstances, and this could also be accompanied by the dissolution of toxic heavy metals from surrounding rocks. In the sea, such effects on possible groundwater reservoirs would be insignificant as long as these are not being used or planned as sources for drinking water.

The situation would be similar if carbon dioxide were to escape unintentionally from the subsurface. On land the greenhouse gas would be released directly into the atmosphere; but in the sea the escaping carbon dioxide would dissolve rapidly in the water, adding to its acidification. A large leakage experiment by European marine researchers in the Scottish North Sea suggested that this acidification is very localized, and only affects an area of ten to 20 metres around the site of seeping. If the site is in an area with noticeable currents or tides, the acidified water is diluted and its immediate detrimental effects on the marine animal and plant world are limited.

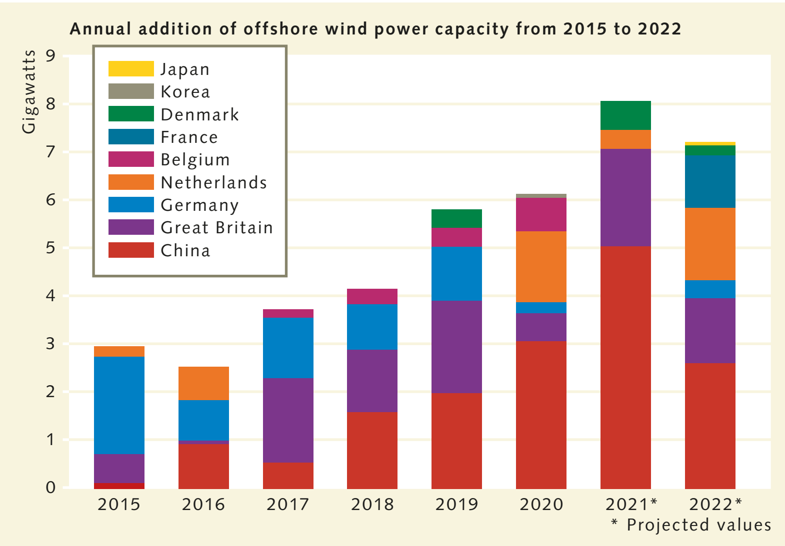
The leakage experiment has also helped to determine what kinds of technology will need to be employed to reliably and inexpensively monitor storage reservoirs of carbon dioxide in the sub-seabed over extended time periods. The operators of the two Norwegian CCS facilities in the sea perform regular seismic investigations of the subsurface. From the sea-floor profiles generated, the scientists can determine which rock layers the liquid carbon dioxide has penetrated. According to the experts, an observation network of geophones and passively listening robotic systems would be a beneficial addition to this. The geophones could be distributed on the sea floor and record the sounds of pressure-compensating motions, cracks or quakes in the subsurface. The robots would have the same function but, unlike the geophones, they would be mobile. They could thus move along the sea floor above the reservoir and check for signs of weakness, vibrations or leaks.

It is a well-known fact that the sea floor of the North Sea is perforated by around 20,000 drill holes. Added to this, there are naturally occurring cracks, fissures and vents. The subsurface is therefore as porous as a sieve. Methane is already escaping from the sea floor through around 4000 of the drill holes. Injecting carbon dioxide into the sub-ground near these holes would only induce additional leakage. Therefore, for the North Sea at least, it will not be a simple task to find potential reservoirs for carbon dioxide that satisfy all of the requirements. These are:

- located close enough to the coast to avoid high transport costs;
- located in a marine region where carbon dioxide storage is legally allowed;
- having reservoir rocks and an overlying caprock layer intact over a large geographic area;
- not already being used or planned for other purposes, such as shipping lanes, conservation areas or sites of future wind parks.

In the case of the North Sea, this does not leave very much suitable marine area. This situation has prompted the German government to initiate a national research project to study the possibilities and legal framework for CCS projects in German territorial waters. The experts

Terawatt-hours
One terawatt is equal to 1000 gigawatts, or one million megawatts. All three units express the power output that, in the case of a wind turbine, for example, specifies the maximum amount of energy that the unit can feed into the grid at a given instant in time. Tera-, giga- and megawatt-hours, on the other hand, are expressions of how much energy the wind turbine produces in one hour. These, therefore, address the question of how much current has actually flowed within one hour, rather than the peak output.



5.26 > The offshore wind sector is growing, but at very different rates in various regions of the world. The greatest annual growth in capacity during the period from 2015 to 2020 was seen in countries like Great Britain, China, Germany and the Netherlands.

began work in August 2021. A summary of their findings is expected in 2024.

However, whether the large-scale storage of carbon dioxide in the seabed will ultimately become a reality for Germany, Europe and areas beyond is, and will remain, primarily an economic decision. If the levies for greenhouse gas emissions do not continue to increase, industries will have absolutely no incentive to invest in and press forward with expensive CCS projects.

Promising sector — offshore wind power

An analysis by the International Energy Agency sounds promising: If wind turbines were to be actually built in all of the near-coastal marine areas that are suitable for their construction, and connected to the electricity grid, these offshore wind parks could generate a total of around 36,000 terawatt-hours of electricity per year.

This would be enough to supply the entire economy and all the world's households with power from a renewable source at least until the year 2040, and maybe beyond if electricity consumption doesn't continue to increase, which is not a realistic expectation. For comparison, in the year 2019, total global electricity consumption was 23,000 terawatt-hours. Roughly 0.3 per cent of this amount came from offshore wind turbines.

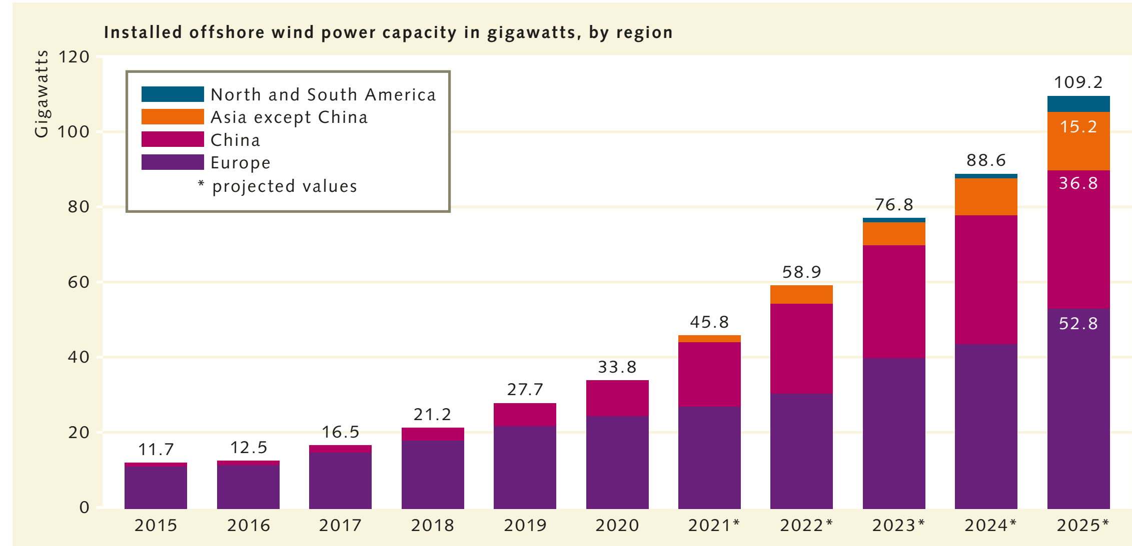
The urgency for producing electricity from renewable energy sources is growing every day. The reasons for this include more than just the steady advance of climate change. There is also the general increase in electrification of all aspects our lives and economies, including the transportation sector, heat supply and the growing need for cooling.

More than two-thirds of the electricity required for air conditioners, heating, robots, machines, e-mobility, computers and mobile telephones, however, presently comes from coal and gas power plants, although green electricity from renewable sources has become much cheaper. At the end of 2018, its share was 26 per cent of the electricity produced worldwide. If humankind is to meet the Paris climate target, it has less than 30 years to not only turn this ratio around, but to completely eliminate the generation of electricity and heat from fossil fuels by the year 2050.

Offshore wind turbines will play an important role in achieving this goal for four reasons. Firstly, they have the great advantage over onshore turbines that the wind at sea is generally stronger and more consistent. It can therefore generate more electricity for longer periods of time. Secondly, in many areas there is much less resistance from the population to offshore wind parks than to those on land. Construction projects thus have a greater chance of being approved. Thirdly, of all known technologies for generating electricity from renewable sources, offshore wind energy has the greatest potential for expansion.

And, finally, offshore wind farms can be constructed near small islands (small land areas that depend on imported fossil fuels) or in remote coastal regions (poor supply lines for fossil fuels) and thus significantly contribute to the energy needs of previously undersupplied areas with sufficient inexpensive and clean electricity, one of the 17 Sustainable Development Goals (SDGs) of the United Nations.

Because of the current state of affairs and the increasing societal pressure to act, the rate of expansion in offshore wind energy has risen significantly in recent years – driven primarily by investments from major oil-



5.27 > Worldwide, coastal states are investing massively in the expansion of offshore wind energy. If all of the projects presently planned are carried out, offshore wind parks with a total capacity of around 110 gigawatts will be connected to the electricity grids by 2025.

producing companies. During the period from 2010 to 2019, the offshore wind energy market grew by around 30 per cent per year, from three gigawatts of installed total capacity in 2010 to 29 gigawatts by the end of 2019. By that time, more than 5500 offshore wind turbines worldwide were connected to the electricity grid.

According to the International Energy Agency, another 150 offshore wind farm projects are expected to be completed by 2024, so that by the following year, one in five kilowatt-hours of wind energy will come from an offshore wind turbine.

The growing number of wind turbines in the German North Sea set a new record in 2020. According to the grid operator Tennet, with a combined capacity of 6679 megawatts, the turbines delivered a total of 22.76 terawatt-hours of electricity over the course of the year – an unprecedented yield. This is enough to supply around seven million households with green energy for one year.

The technology and expertise for the construction and operation of offshore wind turbines was developed primarily in Germany, Great Britain and Denmark. In 2019, Germany and the United Kingdom led the ranks of the largest offshore wind energy producers. However, China is presently making the largest investments in the construction of new offshore wind parks.

Larger wind turbines, lower electricity prices

The newest generation of offshore wind generators is equipped with larger turbines and many other improved technical functions that use the wind as efficiently as possible. For example, in 2023, when the first phase of the new *Dogger Bank* wind farm in the North Sea begins operation off the coast of Yorkshire, England, each of the 13-megawatt turbines will produce enough electricity with a single complete rotation of its rotor (blade length: 107 metres) to supply an English household with energy for two days.

In addition, new wind farms like *Dogger Bank* will be built at greater distances from the coast (100 kilometres and more), because the wind conditions are better further offshore. Because foundations on the sea floor are more expensive and technically difficult in deeper water, wind farm operators are now advancing the development of floating platforms like those used in offshore oil production. There are already 13 test sites globally, including in France, Portugal, Japan, South Korea and Scotland. Their initial performance results are promising. According to the Scottish operators, their five floating wind turbines produce more electricity than comparable facilities with fixed foundations. Experts therefore believe that floating wind farms could soon go into serial production.

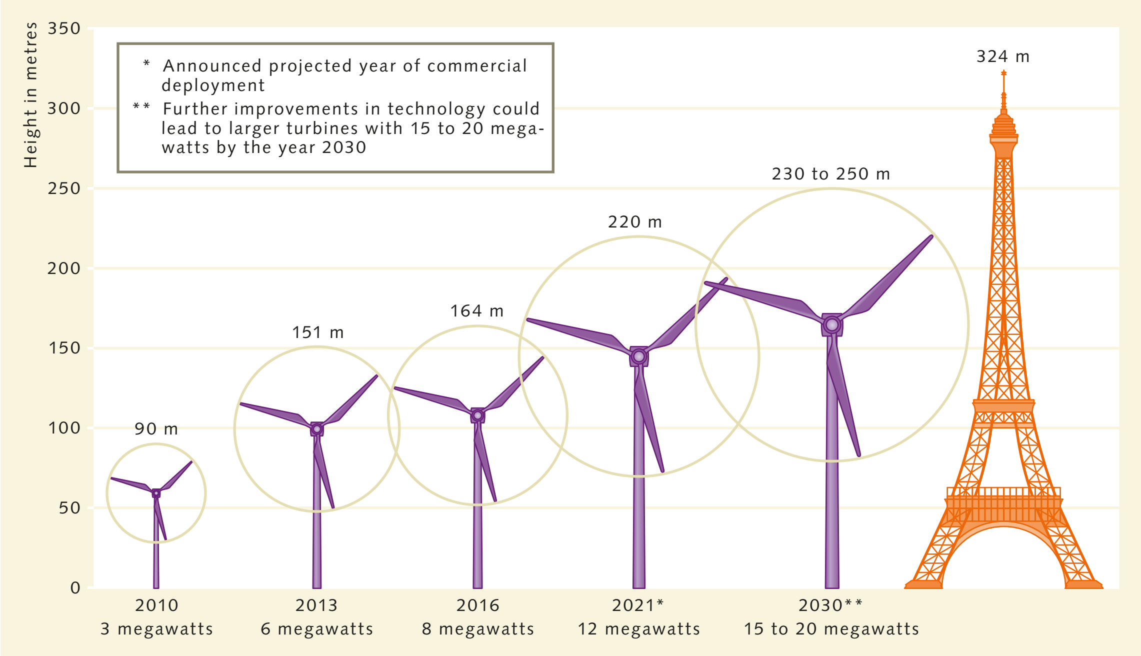
Due to numerous technological improvements, modern offshore wind turbines can now achieve a capacity factor of 40 to 50 per cent, and thus generate electricity with the same efficiency as many coal- or gas-fuelled power plants, even though the wind does not blow constantly. Offshore wind turbines are also more efficient than those on land, and have twice the capacity factor of photovoltaic systems. An additional advantage is that, unlike photovoltaic cells, offshore wind parks also generate electricity at night and under almost all weather conditions. In Europe, the USA and China, offshore wind parks produce particularly large amounts of electricity during the winter months. In India, the largest quantities of electricity are generated during monsoon periods.

Capacity factor
The capacity factor of a wind turbine is defined as the proportion of its maximum power output that it has generated within one year. The maximum value is the amount of energy that would have been generated if optimal wind conditions had prevailed throughout the entire year.

Calculations by the International Energy Agency suggest that the cost of constructing and operating offshore wind-energy facilities will drop by more than 40 per cent by the year 2030, so that green wind electricity from the sea will soon be cheaper to produce than electricity from coal and natural gas. It will also probably be able eventually to compete strongly with onshore solar and wind generation. The IEA experts are therefore predicting huge growth for offshore wind power. By the year 2040 the amount of energy generated in this manner is to increase by a factor of fifteen. The European Union alone wants to install facilities with a total capacity of 300 gigawatts by 2050.

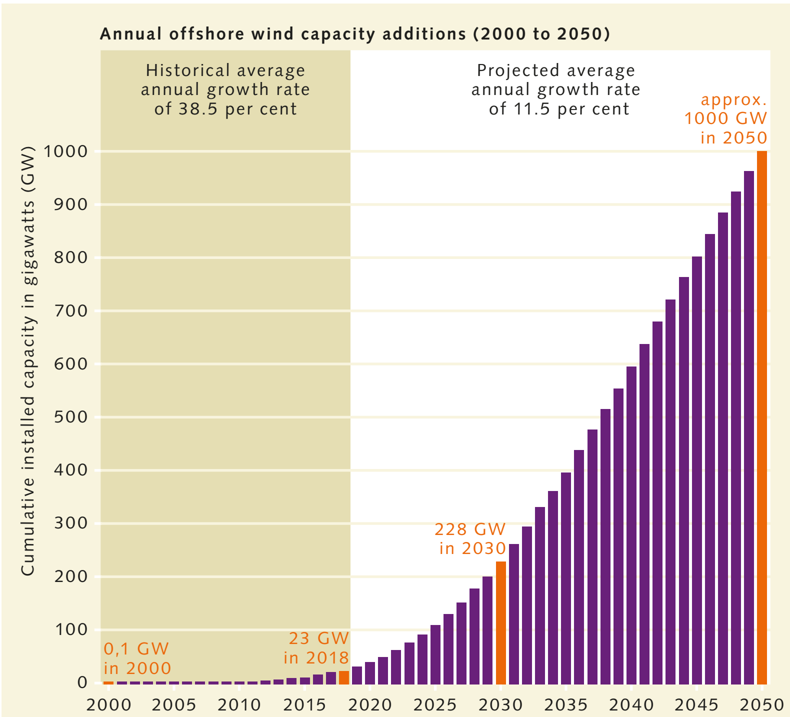
Because of the falling prices for wind energy from the sea, it is also being increasingly considered as an energy source for the production of green, or low-emission, hydrogen. This will be crucial for a number of uses that require a shift to low-emission energy sources, including the decarbonization of industry, transportation and heat supply. Just as one example, the output of a one-gigawatt offshore wind farm with present technology could produce enough hydrogen to heat around 250,000 homes. In January, 2021, the German government commissioned a large research project (H2Mare) to investigate the possibilities for producing green hydrogen and its by-products such as methane, ammonia and methanol directly at sea with the help of offshore wind turbines, and thus keep the costs of hydrogen production down.

However, this is no reason for euphoria. In order to achieve the climate and sustainability goals of the inter-



5.28 > Advances in technology make it possible. Modern offshore wind turbines are becoming larger and taller. Each new turbine, with its long rotor blades, catches more wind than its predecessors. The result is that electricity from wind energy can be generated in greater amounts and, above all, less expensively.

5.29 > The European Union is focussing strongly on green offshore wind energy. Member states aim to install facilities with a total capacity of 300 gigawatts by 2050.



5.30 > The Paris climate goal can only be achieved if humankind transforms its energy sector to renewable forms of energy. For this to be successful, calculations indicate that the offshore wind sector needs to be expanded to a total capacity of around 1000 gigawatts by the year 2050.

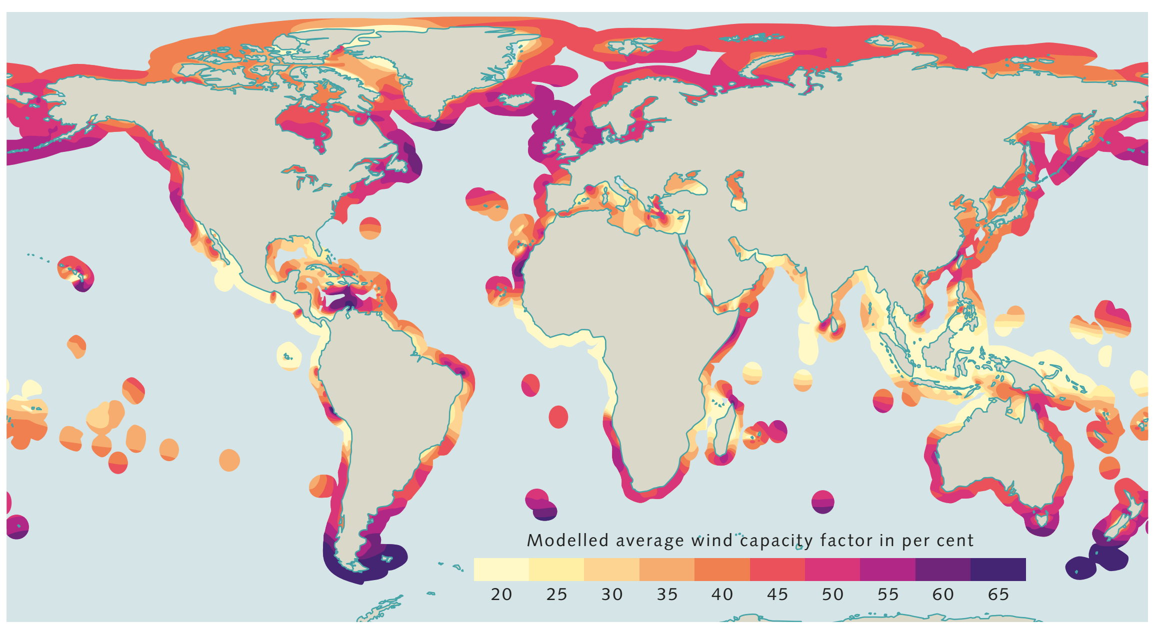
national community, the expansion of offshore wind farms will have to proceed twice as fast as it has been so far. For this to happen, the following are necessary:

- the explicit political will and a relevant offshore energy strategy,
- a clear legal framework,
- large investments, and
- progress in competitiveness, research and technology development.

Policymakers must lead the way

For a long time, the construction of offshore wind farms has been a national concern. But as the wind farms become larger and the sites shift further from shore, there is an increasing need for cooperation among multiple countries. This is necessary for the purpose of regional spatial planning, as well as for addressing the question of which grid the green electricity should be delivered to. An explicit commitment by every coastal state to advance the expansion of offshore wind energy and to cooperate with others in large-scale projects is therefore crucial.

Such an expression of intent is manifested by the formulation of national or joint offshore wind strategies by individual states or communities of states. These set the various expansion goals, characterize development trajectories and outline research, technology development and knowledge transfer approaches. This establishes a setting for companies and investors that is reliable over the long term. The European Commission, for instance, published its strategy to harness the potential of offshore renewable energy in November 2020.



5.31 > In the temperate and higher latitudes the winds blow stronger and more steadily, so wind capacity factors would be significantly greater than in the tropics.

A fundamental component of the EU strategy is its commitment to a systematic and transnational planning of all activities on and in the sea (spatial planning), by which a significantly larger number of areas and sites are designated for the installation of bottom-fixed or floating wind farms that do not interfere with other kinds of usage such as fisheries, shipping and tourism. Furthermore, the European Commission recommends that the EU member states use best-practice examples to guide them in their planning, especially successful pilot projects that allow multiple use of the wind farms or the areas occupied by them, such as combining them with fish, shellfish or algae cultivation in aquaculture farms.

Moreover, it is important to include everyone affected by offshore wind power in a dialogue from the beginning. According to the European Commission, offshore energy technology can only be truly sustainable and thus viable for the future if it does not have a negative impact on the environment and does not endanger economic, social and territorial cohesion in the affected region.

A uniform legal framework

The rapid expansion of offshore wind energy requires planning and legal certainty for all participants, as well as clearly laid out and transparent approval procedures. Among other things, this implies:

- uniform procedures for evaluating and minimizing possible environmental impacts (especially underwater noise, damage to bird and marine mammal habitats, electromagnetic fields around sea-floor cables);
- uniform standards, regulations and approval procedures for the planning and construction of offshore wind farms;
- uniform regulations for connecting the offshore wind farms to the mainland and efficient transmission of current into the grid;
- uniform standards and regulations for the operation and maintenance of offshore wind power facilities, as well as for protection of the safety and health of all workers.

High investments

The construction of offshore wind turbines consumes a lot of money. In 2018, building a wind farm with a nominal capacity of one gigawatt would have required an investment of USD four billion. Since then, however, construction costs have been dropping and investments in offshore wind farms have been growing. In 2020 they rose drastically by 56 per cent compared to the previous year, ultimately reaching a total of USD 50 billion. The European Union estimates the cost of targeted power expansion to a total capacity of 300 gigawatts to be up to 800 billion Euros.

A large proportion of that money will be used to expand the electrical grid and trans-border connection lines because without them the green wind power cannot be distributed over a wide area. States bordering on the North Sea are also planning to combine several offshore wind farms in clusters or hybrid projects whose connection networks can supply multiple countries with electricity simultaneously.

Competitiveness, research and technological advances

Lowering the costs of green electricity from offshore wind farms will require efficient and competitive supply lines for all the necessary components and services. Furthermore, supply of all the metals required for construction of the wind turbines (especially the rare earth metals) needs to be guaranteed far into the future. There must also be progress in research and technology. The following questions, for example, still need to be addressed:

- In a large wind farm, how do the individual turbines need to be arranged in order to make optimal use of the wind without interfering with one another?
- How do large wind farms influence each other, and how do they affect the local weather?

Green hydrogen
Hydrogen is a colourless gas. Depending on its origin, however, it is named by various colours. Grey hydrogen is obtained from fossil fuel by the splitting of natural gas. Carbon dioxide is also produced in this process and released into the atmosphere. With blue hydrogen, the carbon dioxide produced is captured and stored, and thus does not enter the atmosphere. Green hydrogen is produced by the electrolysis of water using electricity from renewable sources. This process is carbon dioxide free.

Energy from the sea – technologies promoted by the European Union

Offshore wind turbines are not the only kind of technology that can be used to obtain green energy from the sea. There is a wide range of other types of emission-free energy technology in this category that are at various stages of development, but which, in the long term, certainly have potential applications at the local, regional or even global levels. In its offshore energy strategy, the European Commission is considering the following technologies for marine energy:

Power plants driven by currents and tides

Electricity plants powered by water currents and tides are presently among the most technologically advanced concepts for the production of energy from the sea. They use the motions of water-mass flow from tides or other natural marine currents to produce electricity.

For tidal power plants of the dam-construction type, marine basins are separated from the open sea by a dyke. Large ducts with turbines are installed in the dykes, through which the rising or falling water flows. Electricity is produced each time this happens. The principle works in both directions, but requires especially high tidal ranges that are found only on a few coasts of the world. Because the damming of bays and estuaries is very costly and has extensive environmental impacts, only a few dam-type tidal power plants have been constructed. These include a 240-megawatt plant in France and a 254-megawatt facility in South Korea.

The construction of more power plants of this type is unlikely. Experts are now focussing on marine current power plants, in which large rotor turbines attached to a mast or cable are positioned in the current. Modern current turbines are similar to the rotors of wind turbines and can now produce up to 1.5 megawatts of power. The largest marine current power plant in the world to date is the *MeyGen* project in northern Scotland. Its first four underwater rotors officially started operation in April 2018 and now reliably and predictably generate electricity for 2600 households. Other water-current power plants are presently under construction; the total global installed capacity is to surpass the one-gigawatt mark by the year 2025. Theoretically, however, many times more than that would be possible. Experts believe that as much as 1200 terawatts could be generated with current and tidal power plants. At present, however, the costs for this type of electricity generation are still too high.

Wave power plants

Up to 29,500 terawatt-hours per year could theoretically be generated using wave-energy power plants, with the greatest potential in the high-wind regions of the temperate latitudes in both hemispheres (30 to 60 degrees latitude). A few technologies have been trialled, but so far none of them have been fully convincing. Experimental systems have typically consisted of a device floating on the surface of the sea that is anchored to the sea floor and produces electricity by rising and falling with the waves. Pilot systems now installed worldwide have a total capacity of 2.5 megawatts. As the technology advances, however, experts believe that wave energy capacity will soon increase to 100 megawatts or more. The European Union aims to expand its wave, current and tidal power capacity to 40 gigawatts by the year 2050.

Floating photovoltaic

The idea of installing photovoltaic modules on the water is not new, and it is already being practised on dammed reservoirs and dredged lakes. The time-tested solar technology is now being progressively adapted to the sea. In February 2018 a Dutch consortium installed a pilot system with a capacity of 8.5 kilowatts on the North Sea and is planning to expand this to 100 megawatts. But South Korea is already a step ahead. The country is constructing a vast floating offshore photovoltaic plant with a total capacity of 2.1 gigawatts off the southwest coast of the Korean peninsula. According to press reports, the first phase of this plant, built at a total cost of USD 3.96 billion, should be connected to the grid by 2022, and the second phase three years later. India, Thailand, Vietnam, Singapore and the Seychelles are also pushing their own pilot projects in this field. The European Commission acknowledges the promising potential of the technology for coastal and near-coastal areas, but also stresses that existing marine applications are still predominately in the research or demonstration phase.

Biofuels from algae

Technical solutions for producing biodiesel, biogas and bioethanol from large algae are also in the early stages of development. The European Commission has judged the potential to be very promising, and expects individual technologies to be ready for the market by the year 2030.

5.32 > One of the fastest marine currents of Scotland drives the underwater rotors of the MeyGen power plant. In the first phase, the operating company installed four turbines on the sea floor, which have been supplying around 2600 households with electricity since August 2018. Further turbines will be added.

- How should electric grids be built and managed to be able to feed in large amounts of electricity from different wind farms under high wind conditions, to distribute and, if necessary, store it, so that the current is always available when and where it is needed by industries and households?

The substantial expansion of wind energy also presents a great challenge to marine researchers in determining the short- and long-term environmental impacts of the intensive and large-scale use of wind offshore. It has long been known that the noise generated during construction work creates high levels of stress for marine organisms. But how, for example, is the wind-driven mixing of the surface waters and the consequent oxygen and nutrient exchange with deeper water layers affected when large numbers of wind turbines impede the flow of air on the sea surface to some extent? Would this result in decreased algal growth and ultimately lower biomass production? This kind of chain reaction is theoretically conceivable, but scientists will have to investigate it more thoroughly to determine whether it occurs in the real world.

What is certain, however, is that with the growth of the offshore wind energy branch new jobs are being created. In the EU today 62,000 people already work in this sector. According to calculations by the International Renewable Energy Agency (IRENA), by the year 2030 the wind energy branch, including both onshore and offshore, will employ up to 3.74 million people worldwide. By 2050 the number of workers could increase to more than six million. Offshore wind farms not only provide a vital contribution to transforming our energy supply to electricity from renewable sources, they also represent a key sector in the sustainable marine economy. Without offshore wind power, sustainable development in the world and comprehensive decarbonization of our economy would be inconceivable today.

5.33 > Photovoltaic arrays so far have been primarily located in shallow bays where they are protected from wind and waves. This installation in the Chinese coastal city of Zhangzhou is one example.

Conclusion

Our oceans – full of energy

Humankind is facing a huge task. If limiting global warming to less than two degrees Celsius is to succeed, the energy supply of the world, including transportation and heating, must be converted to low-emission or emission-free technology. According to our present knowledge, such a transformation is absolutely impossible without the world ocean. The world's oceans must be exploited for two processes simultaneously – almost certainly as a direct source of energy, and likely also as a source of raw materials.

Regarding the idea of energy production from the sea, mankind is now at a fork in the road. New oil and gas deposits are still being developed offshore. These new reservoirs mostly lie at greater depths than before, and at greater distances from the coasts. While the global production of oil from the sea is high but fairly static, natural gas production is steadily increasing. More than a quarter of global fossil resource production now comes from the sea.

At the same time, the primary investors in large offshore wind farms are oil producing companies. The wind farms are also being built at increasing distances from the coasts to take advantage of better wind conditions on the open sea. Technological advances have helped to build modern wind turbines much larger than their predecessors, and thus able to produce much more power. As a consequence, the prices for green offshore wind power are falling and demand is growing.

Because of the high potential of offshore wind energy, its production is one of the most important pillars of national and international strategies for sustainable energy production. Other systems, such as wave and current power plants, offshore photovoltaic arrays, or biofuels from algae are all still in the developmental stages. But, over the long term, these too must be employed to meet the increasing electricity requirements of modern societies.

However, the expansion of renewable offshore energy, as well as the distribution and storage of electric power, can only succeed if the necessary power plants, power lines and battery systems are installed. These require increasing amounts of raw materials, whose extraction on land destroys habitats for mankind and animals on a large scale. The mining of large raw-material deposits in the ocean, especially in the deep sea, which contain a greater variety of metals and minerals than the deposits on land, would be a conceivable alternative. Our knowledge of these deep-sea occurrences has grown significantly over the past 20 years. The International Seabed Authority (ISA) with headquarters in Kingston, Jamaica, has awarded 31 contracts for exploring the sea floor for mineral raw materials since the year 2002. Preliminary designs in mining technology have been tested on site. These were accompanied by extensive expert investigations of the environmental consequences of possible deep-sea mining and the development of monitoring systems. The ISA is presently drafting and negotiating a set of rules for deep-sea mining in international waters. This could commence, according to experts, within five to ten years.

Environmentalists are calling for a general ban on mining in the seas. They point out that in view of the tense situation regarding resource supply, developing further natural resource deposits is not a solution. Instead, the enormous consumption of resources must be reduced to a minimum. This, however, would require a fundamental restructuring of the consumption-based economic system and significant changes in the behaviour of each individual consumer.