

7 Marine minerals and energy



> Our appetite for energy and mineral resources seems insatiable. As land-based resources become increasingly scarce, those in the oceans are attracting greater interest. The fuels and ores in the deep sea are particularly tempting. But wind and wave power could also meet a proportion of our energy needs.



Fossil fuels

> Oil and natural gas are the key resources powering industrial societies. But deposits are dwindling and prices are rising. For this reason oil companies are turning their attention to resources which were previously thought too difficult and expensive to tap: the oil and gas deposits deep in the oceans. Already, more than a third of the oil and gas extracted worldwide comes from offshore sources.

Reliance on oil and gas

Without natural gas, oil and coal, our world would stand still. Scarcely a car, a train or a ship would be seen. Computers would shut down and the lights would go out in most offices. Today's industrial nations are almost entirely dependent on fossil fuels, and energy consumption around the world has risen by about 70 per cent over the past three decades. The International Energy Agency (IEA) in Paris estimates that consumption will increase by at least another 50 per cent by 2030. The greatest consumers are the USA, China and Russia, but here too the demand for energy will continue to escalate.

The growing demand and increasing prices can be expected to fuel interest in the oil and gas deposits buried deep in the oceans, previously considered too expensive to extract.

Formation and exploration of fossil fuels

Gas and oil form in the sea over a period of millions of years, as the remains of animals and plants sink to the ocean floor. Combined with particles flushed from the land, they are buried and compressed into layers of sediment several kilometres thick on the ocean floor. Aided by the Earth's pressure and temperature conditions, bacteria convert the biomass into precursor substances from which hydrocarbons are ultimately formed. These hydrocarbons can permeate certain layers of rock and sediment as they move up towards the surface, in a process called migration. In some cases they become trapped in impermeable layers of rock, which is where

the actual deposits are ultimately formed. Depending on the ambient conditions, oil or natural gas develops.

Today's sources of fossil fuels are between 15 and 600 million years old. During this period the continental plates shifted, transforming oceans into landmasses, with the result that mineral deposits can be found both on land and at sea. Oil and gas are usually found where vast layers of sediment cover the ocean floor.

These days seismic equipment is used to prospect for new reserves. This equipment generates sound waves which are reflected back from the layers of rock and sediment in the ground. From the sound waves geologists can estimate whether the layers could contain oil or natural gas. At sea the sound waves are generated by what is known as an airgun, which works with compressed air. The echoes reflected back are received via hydrophones on the ocean floor or the research vessel.

The future of oil lies in our oceans

Since industrial oil extraction began in the mid-19th century, 147 billion tonnes of oil have been pumped from reserves around the world – half of it during the past 20 years. In 2007 alone, oil consumption worldwide reached a total of about 3.9 billion tonnes. There is no doubt that extraction will soon be unable to keep pace with annually increasing needs. Experts anticipate that in the next 10 years so-called "peak oil" will be reached, the point at which the world's oil supplies go into irreversible decline.

Currently the conventional oil reserves – i.e. those which can be recovered easily and affordably using

today's technology – are estimated to be a good 157 billion tonnes. Of this amount, 26 per cent (41 billion tonnes) are to be found in offshore areas. In 2007 1.4 billion tonnes of oil, the equivalent of about 37 per cent of annual oil production, was derived from the ocean. The proportion of offshore production is therefore already relatively high. The most productive areas are currently the North Sea and the Gulf of Mexico, the Atlantic Ocean off Brazil and West Africa, the Arabian Gulf and the seas off South East Asia.

For some years now the trend has been towards drilling in deeper and deeper water. In 2007 oil was extracted from 157 fields at depths of more than 500 metres. In 2000 there were only 44 such fields. Of these, 91 per cent are situated in the so-called Golden Triangle in the Atlantic between the Gulf of Mexico, Brazil and West Africa. While the output of the relatively shallow waters of the North Sea (average depth 40 metres) will reduce in the coming years, production is likely to increase elsewhere, particularly in the Golden Triangle, off India, in the South China Sea and the Caspian Sea off Kazakhstan.

The deeper marine areas therefore harbour additional potential for the future. Experts estimate that the offshore trend will accelerate as oil becomes increasingly

scarce. The downside here is that extraction is complex and expensive. For instance, extraction from fields at great depths requires floating production and drilling vessels, or pumping stations permanently mounted on the ocean bed.

Offshore gas prospects

The consumption of natural gas is also steadily growing. In 2007 global consumption was a good 3 trillion cubic metres, about 520 billion cubic metres more than in 2001. As a comparison, the average German house-hold uses about 3500 cubic metres of gas each year. The greatest consumers of natural gas are the USA, which accounts for about a quarter of world gas consumption, followed by Russia, Iran, Japan and Germany.

Occurrences of natural gas are very unevenly distributed around the globe. As far as onshore deposits are concerned, almost three quarters of the world's reserves are concentrated in the Commonwealth of Independent States (CIS) and the Middle East. Offshore it is a slightly different story. The frontrunner is the Middle East, which harbours considerably more gas in the ocean floor than in its land-based reserves.

The South Pars/North Dome field located on the Iranian border with Qatar in the Persian Gulf is considered the world's largest reserve of natural gas, with an estimated 38 trillion cubic metres. This amount is phenomenal considering that the total reserves of natural gas worldwide are thought to be 183 trillion. Other potentially important offshore regions are the North Sea, the Gulf of Mexico, Australasia, Africa and the CIS states, along with the Golden Triangle where gas is also produced as a by-product of the oil industry.

The North Sea is still the most important gas-producing area, but it will be overtaken by other regions in the years to come. Extraction will pick up in the Middle East in the near future, as well as off India and Bangladesh, Indonesia and Malaysia.

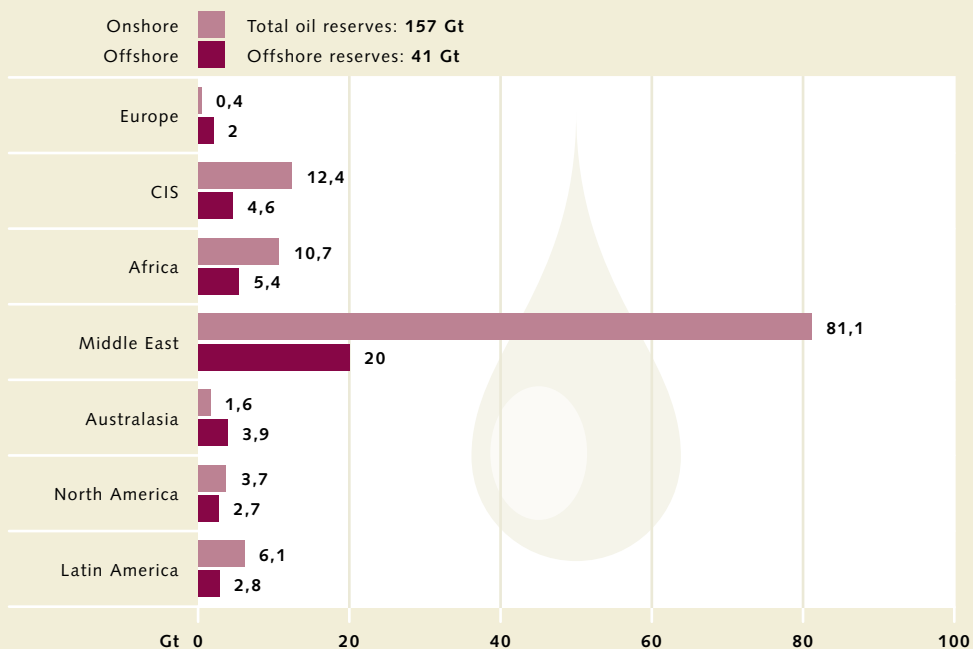
Offshore gas production of 65 trillion cubic metres currently accounts for a good third of the worldwide total, and this figure will continue to rise. Between 2001 and

Reserves and resources

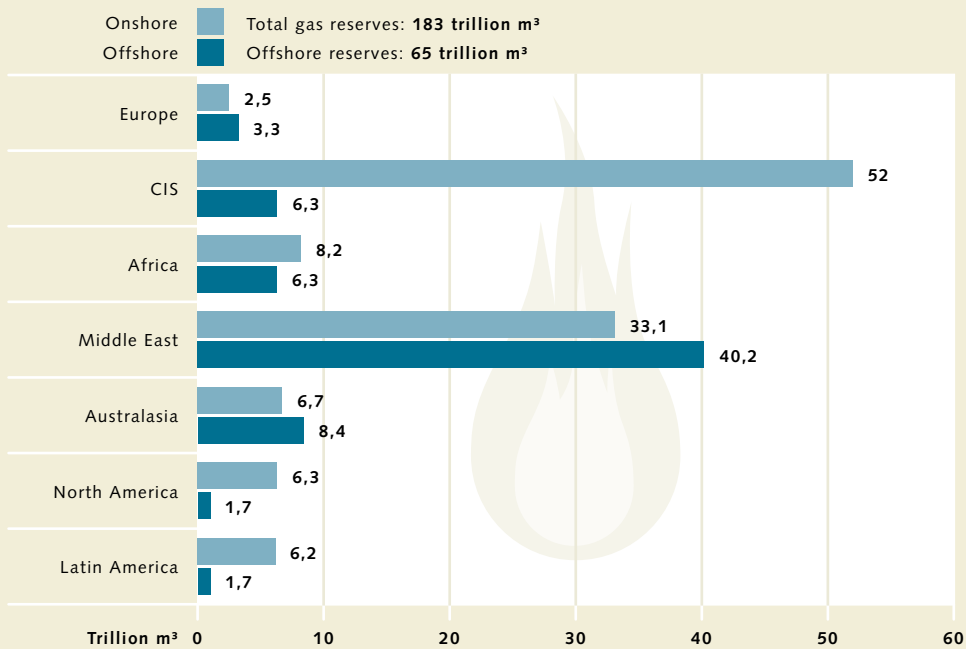
"Reserves" are mineral deposits which have been accurately measured and which can be extracted economically using current technology. In contrast, "resources" are mineral deposits which are geologically proven, but which are not currently feasible for economic extraction, and also those deposits which have not yet been ascertained with certainty, but which can reasonably be expected to occur based on the geological characteristics of the area.

	IEA (2008) USD per barrel	Petrobras (2008) USD per barrel
Middle East	3–14	7–19
CIS States	n.s.	15–35
Deep sea	32–65	23–45
Enhanced Oil Recovery	30–82	25–63
Arctic	32–100	25–50
Other regions	10–40	12–30

7.1 > Extraction costs of conventional oil by type and region according to IEA and Petrobras estimates (enhanced oil recovery = improved oil production in mature oil fields).



7.2 > Geographic distribution of conventional oil reserves 2007 onshore and offshore by region



7.3 > Geographic distribution of conventional natural gas reserves 2007 onshore and offshore by region

2007 it grew by just under 20 per cent, of which about a quarter each came from the North Sea and Australasia, and about 15 per cent from the Gulf of Mexico and the Middle East. As with oil, the trend is clear: offshore production is growing more strongly than onshore production. Drilling operations are also moving into greater water depths. The Cheyenne gas field in the Gulf of Mexico currently holds the record, producing from a depth of 2740 metres.

Getting gas across oceans:

Liquefied natural gas

Liquefied natural gas (LNG) plays a crucial role in humankind's conquest of the sea. It is cheaper to ship cooled and liquefied natural gas across the oceans in huge tankers than through pipelines. LNG already accounts for a quarter of today's global trade in gas. In future, natural gas is more likely to be moved by ship than overland through pipelines. On land it is cheaper to use pipelines of up to about 3000 kilometres in length than to liquefy the gas and transport it by sea. On the seabed, however, pipelines are uneconomical from the first metre onwards. Shipping the liquefied natural gas from the offshore extraction plant to the land is much more cost-effective.

An LNG plant liquefies natural gas by cooling it to about minus 160 degrees Celsius. This process consumes large amounts of energy and contributes significantly to the cost of the LNG transport chain. Nonetheless, it is clear that the LNG proportion of the natural gas trade will substantially increase in future. The market is expected to grow by 8 per cent annually over the next 15 years, and to expand more strongly than the pipeline gas trade. Several liquefaction facilities are already in operation.

Recently an LNG plant began operations in Norway, liquefying gas from the Barents Sea. First the natural gas is pumped from the "Snø-hvit" ("Snow White") gas field to dry land at Hammerfest where it is processed. The first LNG facilities will also soon be built directly over the gas fields off the West African coast. Tankers will be able to berth on the spot.

The Arctic region, a special case

As the Arctic sea ice melts as a result of climate change (Chapter 1), hopes are growing among Arctic nations of tapping the oil and natural gas deposits in the northern polar regions. Current scientific studies suggest that the area harbours substantial resource deposits. It is estimated that about 30 per cent of undiscovered gas and 13 per cent of undiscovered oil can be found in the marine areas north of the Arctic Circle. According to scientists, the considerable gas deposits are located mainly in Russian waters. In contrast, the relatively small quantities of oil are hardly likely to impact greatly on world oil production.

As yet, nobody can say whether or when extraction will begin in the Arctic, especially as various legal questions have yet to be clarified (see Chapter 10). Also, production is not yet viable in these undeveloped areas as prospecting will require complex and expensive operations using icebreakers.

The finite nature of oil and natural gas

What is certain is that the extraction of oil and natural gas from the world's oceans will increase in future. The technology is already well-established, but the costs involved are still much higher than for onshore or shallow water production. As the world's reserves of oil and gas run short and prices increase, however, hitherto unprofitable sources will become more economic to exploit. Offshore fields will be able to contribute significantly to meeting the future energy needs of our industrial society.

Nobody knows for certain how long the global reserves and resources of oil and gas will last – particularly as it is difficult to predict future consumption trends. For example, from today's perspective, resources of natural gas will probably be adequate to ensure supply well into the second half of this century. But if natural gas is used to power motor vehicles or generate electricity in power stations, the reserves could be exhausted much more quickly.

Marine minerals

> Natural gas and oil have been extracted from the seas for decades, but the ores and mineral deposits on the sea floor have attracted little interest. Yet as resource prices rise, so too does the appeal of ocean mining. The excavation of massive sulphides and manganese nodules is expected to begin within the next few years.

The sea floor – humankind's resource repository

The oceans hold a veritable treasure trove of valuable resources. Sand and gravel, oil and gas have been extracted from the sea for many years. In addition, minerals transported by erosion from the continents to the coastal areas are mined from the shallow **shelf** and beach areas. These include diamonds off the coasts of South Africa and Namibia as well as deposits of tin, titanium and gold along the shores of Africa, Asia and South America.

Efforts to expand ocean mining into deep-sea waters have recently begun. The major focus is on manganese nodules, which are usually located at depths below 4000 metres, gas hydrates (located between 350 and 5000 metres), and cobalt crusts along the flanks of under-sea mountain ranges (between 1000 and 3000 metres), as well as massive sulphides and the sulphide muds that form in areas of volcanic activity near the plate boundaries, at depths of 500 to 4000 metres.

Back in the early 1980s there was great commercial interest in manganese nodules and cobalt crusts. This initial euphoria over marine mining led to the International Seabed Authority (ISA) being established in Jamaica, and the United Nations Convention on the Law of the Sea (UNCLOS) being signed in 1982 – the “constitution for the seas”. Since entering into force in 1994, this major convention has formed the basis for signatories’ legal rights to use the marine resources on the sea floor outside national territorial waters (Chapter 10).

After that, however, the industrial countries lost interest in resources. For one thing, prices dropped –

making it no longer profitable to retrieve the accretions from the deep sea and utilize the metals they contained. Also, new onshore deposits were discovered, which were cheaper to exploit. The present resurgence of interest is due to the sharp increase in resource prices and attendant rise in profitability of the exploration business, and in particular to strong economic growth in countries like China and India which purchase large quantities of metal on world markets.

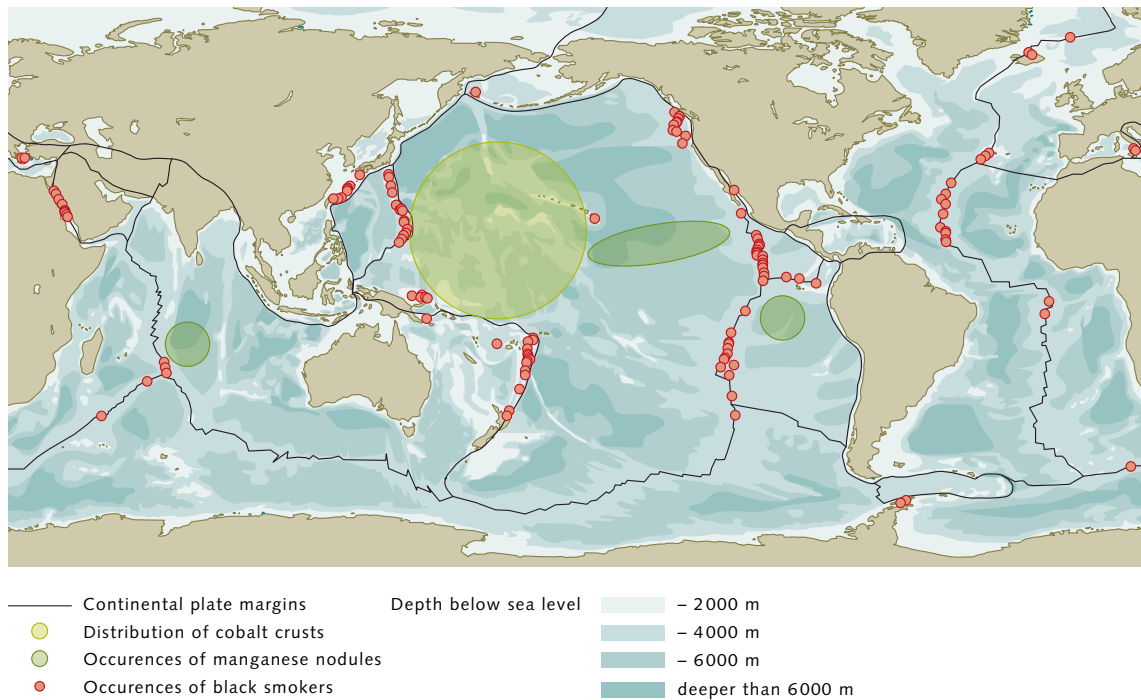
Even the latest economic crisis is not expected to slow this trend for long. The industrial and emerging countries’ geopolitical interests in safeguarding their supplies of resources also play a role. In light of the increasing demand for resources, those countries which have no reserves of their own are seeking to assert extraterritorial claims in the oceans.

Manganese nodules

Covering huge areas of the deep sea with masses of up to 75 kilograms per square metre, manganese nodules are lumps of minerals ranging in size from a potato to a head of lettuce. They are composed mainly of manganese, iron, silicates and hydroxides, and they grow around a crystalline nucleus at a rate of only about one to 3 millimetres per million years. The chemical elements are precipitated from seawater or originate in the pore waters of the underlying sediments. The greatest densities of nodules occur off the west coast of Mexico (in the Clarion-Clipperton Zone), in the Peru Basin, and the Indian Ocean. In the Clarion-Clipperton Zone the manganese nodules lie on the deep-sea sediments covering an area

Continental plates

The Earth's crust is made up of numerous continental plates that are in permanent motion. They move a few centimetres each year. This continental drift means that plates are veering away from each other in some places. At these plate boundaries the Earth's crust is splitting apart. Fresh magma is continuously being extruded from the fissures and, over time, it piles up on the ocean floor to form large undersea ridges.



7.4 > The sea floor contains extensive resources. They are concentrated in certain regions depending on how they were formed.

of at least 9 million square kilometres – an area the size of Europe. Their concentration in this area can probably be attributed to an increased input of manganese-rich minerals through the sediments released from the interior of the Earth at the **East Pacific Rise** by hydrothermal activity – that is, released from within the Earth by warm-water seeps on the sea floor and distributed over a large area by deep ocean currents.

Manganese nodules are composed primarily of manganese and iron. The elements of economic interest, including cobalt, copper and nickel, are present in lower concentrations and make up a total of around 3.0 per cent by weight. In addition there are traces of other significant elements such as platinum or tellurium that are important in industry for various high-tech products.

The actual mining process does not present any major technological problems because the nodules can be collected fairly easily from the surface of the sea floor. Excavation tests as early as 1978 were successful in transporting manganese nodules up to the sea surface. But

before large-scale mining of the nodules can be carried out there are still questions that need to be answered. For one, neither the density of nodule occurrence nor the variability of the metal content is accurately known. In addition, recent investigations show that the deep seabed is not as flat as it was thought to be 30 years ago. The presence of numerous volcanic elevations limits the size of the areas that can be mined.

Furthermore, the excavation of manganese nodules would considerably disturb parts of the seabed. The projected impact would affect about 120 square kilometres of ocean floor per year, an area the size of the city of Kiel. Huge amounts of sediment, water, and countless organisms would be dug up with the nodules, and the destruction of the deep-sea habitat would be substantial. It is not yet known how, or even whether, repopulation of the excavated areas would occur.

Since 2001 several permits have been issued to governmental institutions by the ISA to survey manganese fields. These are not for actual mining but for a detailed initial investigation of the potential mining areas. In



Cross-section view of a manganese nodule:
Over millions of years, minerals are deposited around a nucleus.

2006 Germany also secured the rights to a 150,000 square kilometre area – twice the size of Bavaria – for a period of 15 years. Last year, for the first time, industrial companies also submitted applications for the exploration of manganese nodule fields in the open sea in cooperation with developing countries (Kingdom of Tonga, Republic of Nauru).

Cobalt crusts

Cobalt crusts form at depths of 1000 to 3000 metres on the flanks of submarine volcanoes, and therefore usually occur in regions with high volcanic activity such as the territorial waters around the island states of the South Pacific. The crusts accumulate when manganese, iron and a wide array of trace metals dissolved in the water (cobalt, copper, nickel, and platinum) are deposited on the volcanic substrates.

Their growth rates are comparable to those of manganese nodules. The cobalt crusts also contain relatively small amounts of the economically important resources. Literally tonnes of raw material have to be excavated in order to obtain significant amounts of the metals. However, the content of cobalt (up to 2 per cent) and platinum (up to 0.0001 per cent) is somewhat higher than in manganese nodules. Extracting cobalt from the ocean is of particular interest because it is found on land in only a few countries (Congo, Zaire, Russia, Australia and China), some of which are politically unstable. Alternative marine prospects could reduce our dependence on supplies from these countries.

Technologically, the mining of cobalt crusts is much more complex than manganese nodules. For one, it is critical that only the crust is removed, and not the underlying volcanic rocks. In addition, the slopes of the volcanoes are very ragged and steep, which makes the use of excavation equipment more difficult. It is therefore not surprising that cobalt crust mining is only at the conceptual stage at present. Cobalt crust mining would also have a significant impact on the benthic organisms. It is therefore vital that prior environmental impact studies are carried out. In most cases monitoring by the Interna-

tional Seabed Authority (ISA) is not possible because many cobalt occurrences are located within the territorial waters of various countries.

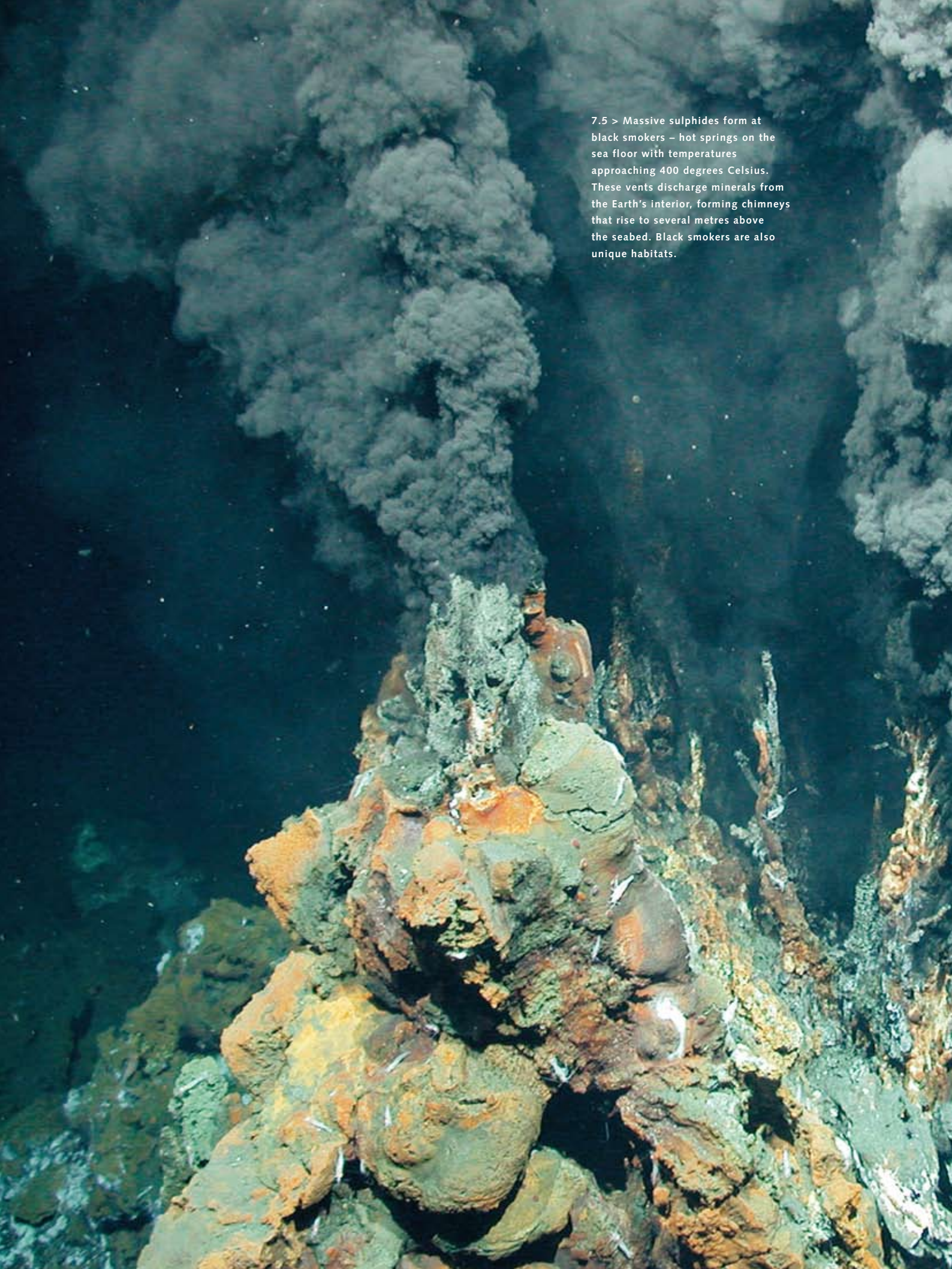
Massive sulphides

The third resource under discussion is a sulphur-rich ore that originates at “black smokers”. These occurrences of massive sulphides form at submarine plate boundaries, where an exchange of heat and elements occurs between rocks in the Earth’s crust and the ocean due to the interaction of volcanic activity with seawater.

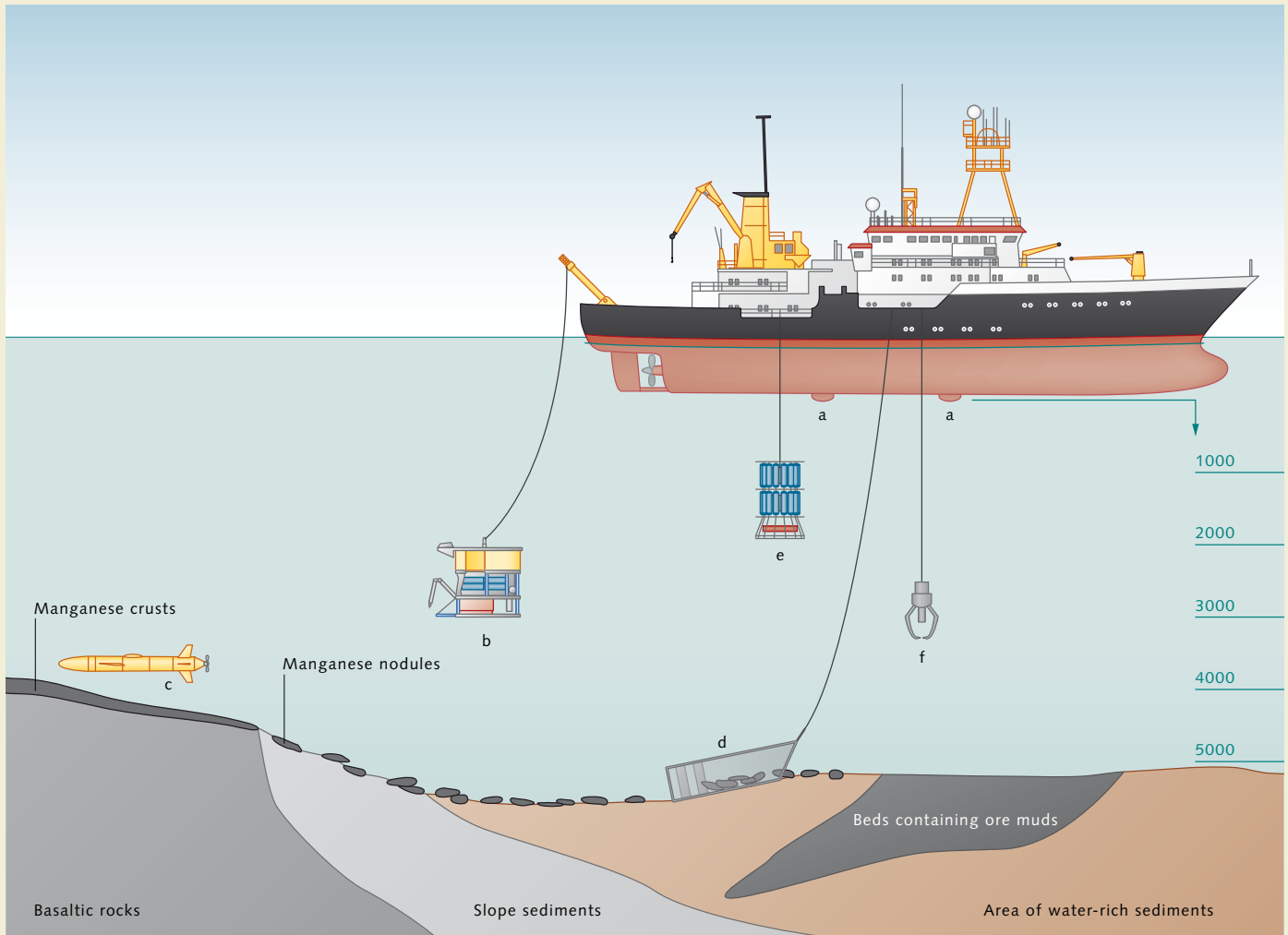
Cold seawater penetrates through cracks in the sea floor down to depths of several kilometres. Near heat sources such as magma chambers, the seawater is heated to temperatures exceeding 400 degrees Celsius. Upon warming, the water rises rapidly again and is extruded back into the sea. These hydrothermal solutions transport metals dissolved from the rocks and magma, which are then deposited on the sea floor and accumulate in layers. This is how the massive sulphides and the characteristic chimneys (“black smokers”) are produced.

These were first discovered in 1978 at the East Pacific Rise. For a long time it was thought that massive sulphides with mining potential were only formed on **mid-ocean ridges**, because the volcanic activity and heat production here are especially intense. But since then more than 200 occurrences worldwide have been identified. Experts even estimate that 500 to 1000 large occurrences may exist on the sea floor. But there are also great differences in size. Most occurrences are only a few metres in diameter and the amount of material present is negligible.

So far only a few massive sulphide occurrences which are of economic interest due to their size and composition are known. While the black smokers along the East Pacific Rise and in the central Atlantic produce sulphides comprising predominantly iron-rich sulphur compounds – which are not worth considering for deep-sea mining – the occurrences in the southwest Pacific contain greater amounts of copper, zinc and gold. They are also located in comparatively shallow water (less than

A photograph of a black smoker hydrothermal vent on the seafloor. The vent is a tall, conical structure made of dark, porous mineral deposits, primarily iron sulfide. It is surrounded by a dark, deep-sea environment. A large, billowing plume of dark, mineral-rich superheated water is being discharged from the top of the vent, rising into the water column. The plume has a dense, cauliflower-like texture. The seafloor around the vent is covered in dark, rocky material and some smaller, similar mineral structures. The lighting is focused on the vent, highlighting its texture and the color of the mineral deposits.

7.5 > Massive sulphides form at black smokers – hot springs on the sea floor with temperatures approaching 400 degrees Celsius. These vents discharge minerals from the Earth's interior, forming chimneys that rise to several metres above the seabed. Black smokers are also unique habitats.



7.6 > A wide variety of instruments is used to explore the sea floor in the search for resources.

- a. A depth profile of the sea floor is produced using an echo sounder.
- b. Remotely-operated vehicles (ROVs) are equipped with cameras and grabbing arms. These are used to produce images of the sea floor and collect rock samples.
- c. Autonomous underwater vehicles (AUVs) can dive down to the sea floor. They are equipped with echo sounders and various measurement sensors, and return to the ship after a deployment of about 20 hours.
- d. Large samples are collected by a dredge towed behind the ship as it can hold more material than a grab sampler.
- e. Multirosettes are used to take water samples at different depths and to measure physical and chemical parameters.
- f. Individual bottom samples, including small boulders, can be collected by grab samplers deployed directly from the ship. These instruments are equipped with cameras to facilitate underwater orientation.

2000 metres) and lie within the exclusive economic zones of nations near them (Chapter 10), which makes the possible mining more technologically and politically feasible. This is because a country can decide for itself with respect to the mining of marine resources within its own exclusive economic zone. The deep sea floor outside these sovereignty limits, however, is overseen by the International Seabed Authority (ISA; Chapter 10).

Present mining scenarios primarily envision the exploitation of cooled, inactive massive sulphide occurrences that are only sparsely populated by living organisms. Active black smokers are rejected for the time being because most of them contain only comparatively minor amounts of resources. Furthermore, because of the nutrient rich waters rising from below, they provide an important habitat for numerous, and in part, endemic organisms.

The largest known sulphide occurrence is located in the Red Sea, where tectonic forces are pulling Africa and the Arabian Peninsula apart. Here, the sulphides are not associated with black smokers, but appear in the form of iron-rich ore muds with high contents of copper, zinc and gold. This occurrence, at a water depth of about 2000 metres, was discovered in the 1960s. Because of its muddy consistency, it appears that these deposits will not prove problematic to mine, and this was successfully tested in the 1980s.

Of the three sea floor resources discussed here, massive sulphides are the least abundant in terms of total volume, but they are of particular interest because of their high resource content. Some mining companies have already obtained exploration licences in national waters, and are advancing the technology for prospecting and extraction. In May 2010 the ISA even has granted one exploration licence in the Indian Ocean to China. So far only permits for research have been granted for the deep sea.

In the near future the mining of copper and gold from massive sulphides is likely to commence off the coasts of Papua New Guinea and New Zealand. Mining operations had been planned to start this year, but due to the present economic recession, major metal and mining

companies have experienced a decline in turnover in spite of the relatively high prices of gold, and the projects were postponed at short notice. But a recovery of the metal market is expected for the future. The companies will therefore soon be able to proceed with their plans.

The future of marine mining

Of the three resource types waiting to be extracted from the deep sea, the mining of massive sulphides in the exclusive economic zones (200 nautical miles) of west Pacific nations (Papua New Guinea) seems to be most feasible at present. Despite the latest economic crisis, production could start in the next few years. Because of their relatively high content of valuable metals, the mining of massive sulphides may be profitable for some companies. But the metal content of the global massive sulphides is lower than that of the ore deposits on land. It is therefore unlikely that the marine mining of massive sulphides will have a significant impact on the global resource supply.

Manganese nodules and cobalt crusts present quite different prospects. The amounts of copper, cobalt and nickel they contain could without doubt rival the occurrences on land. In fact, the total cobalt is significantly more than in all the known deposits on land. About 70,000 tonnes of cobalt are presently mined on land each year and the worldwide supply is estimated at about 15 million tonnes. By comparison, a total of about 1000 million tonnes of cobalt is estimated to be contained in the marine manganese nodules and cobalt crusts.

In spite of these immense resources, sea floor mining will only be able to compete with the substantial deposits presently available on land if there is sufficient demand and metal prices are correspondingly high. Furthermore, the excavation technology has yet to be developed.

The serious technological difficulties in separating the crusts from the substrate, combined with the problems presented by the uneven sea floor surface, further reduce the economic potential of the cobalt crusts for the present. Therefore, it seems that marine mining of cobalt crusts should not be anticipated any time soon.

Methane hydrates

> Until 10 years ago, hardly anyone had heard of methane hydrates. But now these chemical compounds in the sea floor are mooted to be an energy source of the future. The amount of hydrate-bound u far exceeds the reserves in conventional deposits. However, methane hydrates are not only a potential energy source; they also pose a considerable climate risk.

Breeding ground for methane hydrates: The sea floor

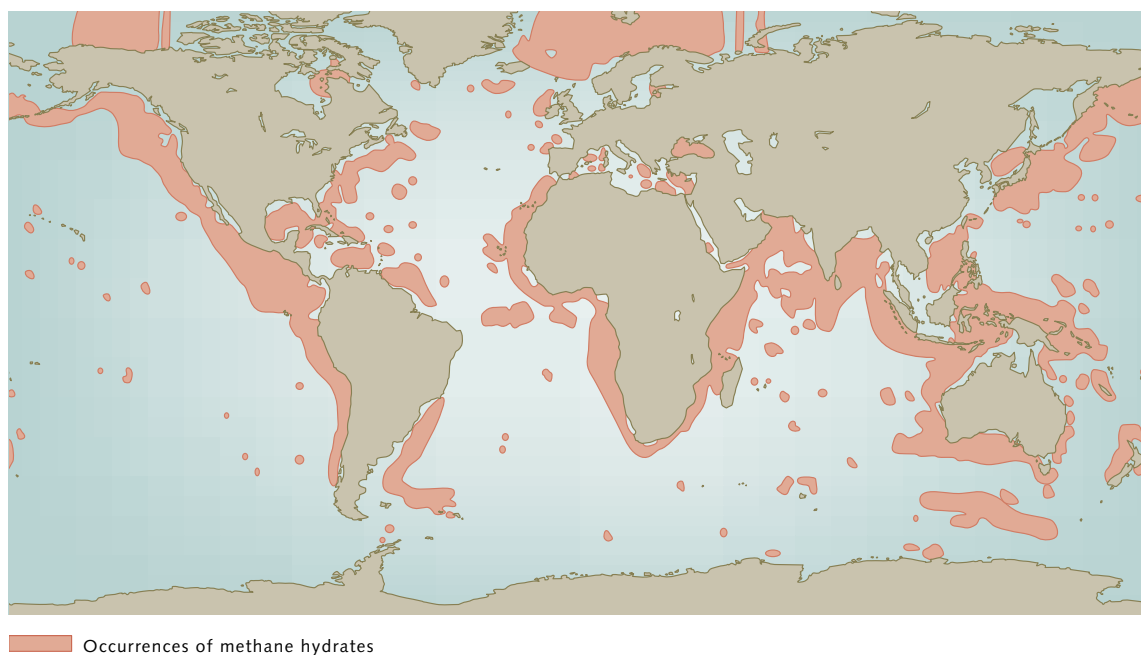
Methane hydrates are white, ice-like solids that consist of methane and water. The methane molecules are enclosed in microscopic cages composed of water molecules. Methane gas is primarily formed by microorganisms that live in the deep sediment layers and slowly convert organic substances to methane. These organic materials are the remains of **plankton** that lived in the ocean long ago, sank to the ocean floor, and were finally incorporated into the sediments.

Methane hydrates are only stable under pressures in excess of 35 bar and at low temperatures. The sea floor is thus an ideal location for their formation: the bottom waters of the oceans and the deep seabed are almost uniformly cold, with temperatures from 0 to 4 degrees Celsius. In addition, below a water depth of about 350 metres, the pressure is sufficient to stabilize the hydrates. But with increasing depth into the thick sediment layers on the sea floor the temperatures begin to rise again because of the proximity to the Earth's interior. In sediment depths greater than about 1 kilometre the temperatures rise to over 30 degrees Celsius, so that no methane hydrates can be deposited. This, however, is where the methane formation is especially vigorous. First, small methane gas bubbles are produced deep within the sediment. These then rise and are transformed to methane hydrates in the cooler pore waters near the sea floor. So the methane is formed in the deep warm sediment horizons and is converted and consolidated as methane hydrate in the cold upper sediment layers. No

methane hydrates are found in marginal seas and shelf areas because the pressure at the sea floor is not sufficient to stabilize the hydrates. At the bottom of the expansive ocean basins, on the other hand, where the pressure is great enough, scarcely any hydrates are found because there is insufficient organic matter embedded in the deep-sea sediments. The reason for this is that in the open sea the water is comparatively nutrient poor, so that little biomass is produced to sink to the sea floor. Methane hydrates therefore occur mainly near the continental margins at water depths between 350 and 5000 metres. For one reason, enough organic material is deposited in the sediments there, and for another, the temperature and pressure conditions are favourable for methane to be converted to methane hydrates.

Greenhouse gas formation

Vast amounts of methane hydrate are buried in sediment deposits on the continental slopes. The total global amount of methane carbon bound up in these hydrate deposits is in the order of 1000 to 5000 gigatonnes – i.e. about 100 to 500 times more carbon than is released annually into the atmosphere by the burning of fossil fuels (coal, oil and gas). At low temperatures the methane hydrates on the sea floor are stable, but if the water and the sea floor become warmer, then the hydrates can break down. Because microorganisms then oxidize the resulting methane gas to form the greenhouse gas carbon dioxide (CO₂), methane hydrates have recently become a topic of intense discussion within the context of climate change. Methane, which itself acts as a strong green-



7.7 > It is known that methane hydrates are present throughout the world's oceans, primarily on the continental margins. Estimates of the total amounts of the deposits, however, are still very inexact.

house gas, does not escape directly out of the sea as methane because it is transformed into CO_2 . But the formation and release of carbon dioxide are considerable. An additional problem is that the oxygen in seawater is consumed through the formation of carbon dioxide (Chapter 2).

In 2008 British and German researchers discovered gas seeps at a depth of 350 metres on the continental slope off Spitsbergen that are probably fed by melting hydrates. Long-term measurements of the water temperatures off Spitsbergen indicate that the bottom-water masses and thus also the slope sediments have significantly warmed in recent decades. Models also predict that the sea floor in Arctic areas will continue to heat up in the coming decades and centuries due to climate change. Scientists therefore fear that large quantities of methane hydrate will melt there in the future, releasing increased amounts of CO_2 into the ocean and the atmosphere. The oxygen content of the seawater will decrease accordingly.

Furthermore, the CO_2 released not only contributes to further global warming, it also leads to acidification of

the oceans (Chapter 2). Examples from the geological past support this scenario. Based on geological records it can be assumed that hydrates have broken down on a large scale numerous times in the Earth's history, leading to extreme global warming and massive extinctions of organisms on the sea floor. Further investigations are necessary to determine the scale at which changes in the climate and oceans will accelerate in the future due to the release of methane gas at the sea floor.

A future energy source?

Although the immense methane hydrate occurrences represent a risk to the climate, they are also a potential energy source. The amount of natural gas bound up in the hydrates far exceeds the natural gas reserves in conventional deposits. Natural gas fed into the supply lines from conventional sources already consists of more than 95 per cent methane. Until now, mining hydrates in the ocean has been considered an expensive process. As resource prices rise, however, these reserves are becoming more attractive to the offshore industry.

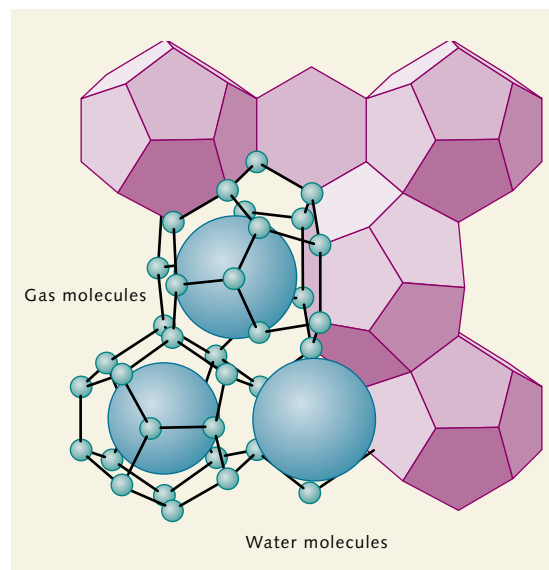


7.8 > Methane hydrates occur worldwide. This ice-like block with a honeycomb structure was obtained from the sea floor during a research expedition off the coast of Oregon.

Many scientists estimate that mining the hydrates could be economically feasible at an oil price of about 50 to 60 US dollars per barrel. This implies that production would already be profitable today. Great efforts are presently being made to develop hydrate deposits, particularly in the territorial waters of Japan, China, India, South Korea and Taiwan.

Carbon dioxide storage in the ocean

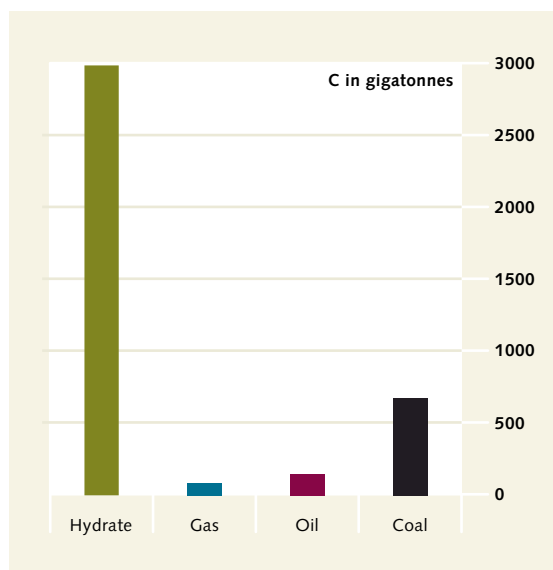
At the same time, new technologies are being developed in Germany that may be useful for exploring and extracting the hydrates. The basic idea is very simple: the methane (CH_4) is harvested from the hydrates by replacing it with CO_2 . Laboratory studies show that this is possible in theory because liquid carbon dioxide reacts spontaneously with methane hydrate. If this concept could become economically viable, it would be a win-win situation, because the gas exchange in the hydrates would be attractive both from a financial and a climate perspective.



7.9 > In methane hydrates, the methane gas molecules are tightly enclosed in cages composed of water molecules. Increasing temperatures render the cages unstable, the gas escapes.

Natural gas is a relatively clean fossil fuel. CO_2 emissions from gas-fired power plants are about 50 per cent lower than from conventional coal-fired plants. But even the emissions from modern gas-fired systems can be reduced considerably when CCS technology (carbon capture and storage) is installed. By this method the CO_2 is isolated directly at the power plant and is stored in underground geological formations.

Another option would be to inject the CO_2 into the marine methane hydrates; by this method, not only would methane gas be obtained, but the carbon dioxide would also be securely captured. Onshore, CO_2 is stored as a supercritical fluid that is mobile and chemically very aggressive. Some experts are concerned that underground storage reservoirs could therefore start to leak after a time. If, instead, carbon dioxide is stored as a hydrate within the cold deep sea floor, it would be much safer, because CO_2 hydrates are considerably more thermally stable than methane hydrates. Even warming of the sea floor would not destabilize them. But this approach also involves ecological risk. During hydrate



7.10 > The amount of carbon stored in methane hydrates at the sea floor (C in gigatonnes) far exceeds that stored in oil, gas and coal.



7.11 > A group of marine scientists on the deck of a research vessel ignite methane gas released from a degrading hydrate block.

excavation the methane could escape unchecked into the seawater. To eliminate this risk, only the very deep hydrate occurrences that are covered by fine-grained sediment layers at least 100 metres thick should be developed. This is the only way to enable the methane gas to be retrieved safely through a borehole without the possibility of its escaping into the environment.

In addition, care must be taken to ensure that the formation pressure is not increased by more than 10 bar during retrieval of the gas, as the sediment layers could otherwise break open and allow large amounts of methane to escape.

Is there a future for methane mining?

So far the necessary mining technology has only been tested under laboratory conditions. Many years of development work are still needed to be able to reliably evaluate the potentials and risks and to realize mining on an industrial scale. The extraction of natural gas from methane hydrates onshore was successfully tested for

the first time in 2008 by Japanese and Canadian scientists. In northern regions, methane hydrates lie hundreds of metres beneath the permafrost sediments. It is cold enough and the pressure is sufficient for hydrates to form there too. In contrast to the deposits in the sea floor, however, these hydrate occurrences are easy to access and therefore suitable for production tests. The tests showed that it is possible to produce natural gas by breaking down methane hydrates through the introduction of heat or the release of pressure.

The retrieval of methane by replacement with carbon dioxide will now be tested onshore. A Norwegian-American consortium is set to carry out a production test in Alaska. The first offshore attempts are then planned for 2012 to 2014 on the continental slope off Japan. How and when methane hydrates are finally mined in the future depends on the results of these field investigations. And of course the development of world market prices for natural gas and **carbon dioxide emission rights** are also pivotal to any decisions to begin offshore mining on a major scale.

Renewable energies

> Until now, the expansion of renewable energies, such as wind and solar power, has mainly taken place onshore. The energy in the oceans has remained largely untapped. But things are changing. The production of environmentally friendly energy from the oceans is now being promoted worldwide. Expectations are high. It is hoped that wind, waves and ocean currents will meet a substantial share of the world's electricity needs.

An unretrieved treasure trove

The oceans are teeming with energy. Tidal forces move immense masses of water. Strong winds build up mighty waves. Almost 90 per cent of global wind energy is contained in the turbulence above the world's oceans. Wind, waves and currents together contain 300 times more energy than humans are currently consuming. For a long time, this abundance went untapped. In recent years, however, we have begun to harness this energy. The first offshore wind farms were built. Hundreds of power plants have been and are being built to convert ocean current and wave energy to electricity. The key renewable marine energies are:

- Wind energy;
- Wave energy;
- Tidal energy;
- Ocean current energy;
- Energy derived from temperature differences at various ocean depths (ocean thermal energy conversion – OTEC);
- Energy derived from the different salt content of freshwater and saltwater (osmotic power).

In theory, these energy resources could easily meet the energy needs of the entire human race. However, only a proportion of their potential can be utilized: many marine regions such as the deep sea are virtually impossible to develop, and the costs of cabling the power to the grid would be prohibitive.

Many of the potential locations in coastal areas can be ruled out because they are either reserved for the fishing industry, reserved for shipping, or they are protected

areas. All the same, these renewable energies could still meet a significant share of the world's energy needs in future.

Offshore wind

Wind energy is currently at the most advanced stage of development, and the signs are extremely promising. Experts estimate that offshore wind power alone could in future supply about 5000 terawatt-hours (TWh) of electricity a year worldwide – approximately a third of the world's current annual electricity consumption of about 15,500 terawatt-hours (1 terawatt-hour = 1 trillion watts). It is anticipated that offshore wind energy plants (WEPs) alone in Europe will supply about 340 terawatt-hours a year by 2015.

About 40 offshore wind energy projects have so far been implemented worldwide, most of them in the United Kingdom, Denmark, the Netherlands and Sweden. Two trends are clear. One, that the facilities are getting bigger all the time, and two, that we are constantly venturing into deeper waters, which will allow the construction of wind farms over far greater areas. Whereas at the beginning of this century we were building in coastal areas at depths of 2 to 6 metres, wind turbine towers are now anchored to the ocean floor at depths of more than 40 metres.

Floating offshore concepts are also being developed for even deeper waters. The world's first floating wind energy plant was recently constructed off the coast of Norway by a Norwegian-German consortium. Backed by the experience of hundreds of thousands of onshore WEPs,

wind energy has become a mature technology. The high wind speeds and harsh environmental conditions at sea, however, mean that some technological improvements are required, a fact borne out by the problems encountered by the first large-scale wind farm in Denmark. For this reason only twelve wind turbines from different manufacturers were initially built and tested at Germany's first offshore wind farm "Alpha Ventus". Located in the North Sea about 40 kilometres off the island of Borkum, the farm was sponsored by the German Federal Ministry of Economics.

Offshore plant is still considerably more expensive to construct than onshore due to the challenging foundation work and complicated connection to the power grid. Nonetheless, according to experts, offshore wind energy, supported by feed-in payments and support measures, will continue to grow substantially in the coming years.

Wave energy

The global technical potential of wave energy is estimated at 11,400 TWh per year. Its sustainable generating potential of 1,700 TWh per year equates to about 10 per cent of global energy needs. There are various different concepts for generating power from wave energy, most of which can be classified in three basic types:

- The "Oscillating Water Column" principle:
Wave action causes water to move up and down in an air-filled chamber. The air is displaced and forced through a turbine which generates electricity. Pilot plants of this type were set up in recent years in Portugal, Scotland and Japan.
- The "Oscillating Bodies" principle:
Facilities of this type use the motion of ocean waves to generate electricity. They include semi-submerged generators on which a float on a fixed counterbearing moves either sideways or up and down. Other systems consist of flexible mounted components that move against each other, putting hydraulic oil under pressure. The oil in turn drives a turbine. Recently, the British "Pelamis" system, a type of sea snake composed of several segments that float on the water's surface,

The right location for green power

In future, before energy systems can be built in the sea, environment impact assessments must be made to determine how the technology will affect the marine environment. Many suitable locations are likely to be ruled out on environmental grounds. Experts therefore differentiate between the technical potential of an energy technology and its sustainable potential. The technical potential includes all the plant locations which are theoretically feasible. The sustainable potential looks at environmental factors, such as the damage a tidal power plant may cause to stretches of river, thus eliminating some locations. The sustainable potential is accordingly lower than the technical potential. Experts are calling for marine spatial planning for ocean-based renewable technologies to be simplified. Until now, separate approval processes have applied to wind energy and wave energy facilities respectively. To shorten decision-making processes, it would make sense to incorporate several energy production technologies in spatial planning at the same time, rather than individual wind farms, thereby designating areas for renewable marine power generation as a whole. This would make it much easier to combine different technologies in a single marine area – for instance, wind turbine towers which also incorporate ocean current plants.

created quite a stir. Pelamis, the world's first wave energy system, was established off the coast of Portugal in 2008 and is connected to the power grid by an undersea cable. Similar farms are planned in Spain and Portugal.

- The "Overtopping" principle:
Similar to a dam, overtopping devices have a reservoir that is filled by incoming waves to levels above the surrounding ocean. The energy of the water falling back to the ocean is used to drive a turbine. Prototypes of both floating and fixed systems have already been installed in Denmark and Norway.

Tidal energy

Tidal power plants work in a similar way to power plants at a reservoir – except that the water masses do not flow downhill but are moved back and forth with tidal flows. Unlike other forms of ocean energy, tidal energy has been utilized commercially for some time. The La Rance tidal power station began operations in 1966 at St. Malo on the Atlantic coast in northern France, where the La

Rance River flows into the sea. At high tide the water flows upstream through the large turbines of the power station, and at low tide it flows downstream again. The 240 megawatt (MW) power station (1 megawatt = 1 million watts) has a similar output to a gas-fired power station. Similar facilities have been constructed in Canada, China and Russia over the past 20 years, although these are considerably smaller. A 260 MW tidal power station integrated in an existing dam is scheduled to come on-stream in South Korea this year.

The United Kingdom has been planning to construct a major tidal power station at the estuary of the River Severn between England and Wales for some time. The location could supply enough energy to meet 7 per cent of the United Kingdom's entire power needs. However, critics fear that the construction of the dams could devastate vital nature reserves and bird sanctuaries. The environmental damage could be substantial. For this reason alternative concepts and locations are now being discussed.

Ocean current energy

Ocean current energy can also be harnessed using submerged rotors which are driven by the motion of the water. It has been estimated that ocean current power stations and tidal power plants together could harness several 100 terawatt-hours of electricity per year worldwide.

For some time now tests have been carried out on some rotor concepts, such as the Seaflow system, the prototype of which commenced operations off the English coast in 2003. Its successor, SeaGen, is now rotating in the Strangford Narrows off the Irish coast. Under this concept two rotors are mounted on the tower of the plant. This increases the electricity yield and balances out the high construction and start-up costs.

Such ocean facilities face much harsher stresses from currents and wave movements than wind turbines, for example, and for this reason extensive endurance testing is called for. Nonetheless, the SeaGen technology is closely based on the wind turbine model. The blade angle and

rotational speed can be adjusted to suit the prevailing current. Other concepts focus on fixed, non-adjustable systems.

Energy derived from temperature differences

Ocean thermal energy conversion (OTEC) utilizes the temperature difference between warm surface water and cold deep water to generate power. In order to drive the steam cycle in an OTEC power station, the temperature difference must be at least 20 degrees Celsius. The technology is therefore more suited to warmer marine regions. The warm water is used to evaporate a liquid which boils at low temperatures, producing steam which drives a turbine. Cold seawater (4 to 6 degrees) is then pumped up from a depth of several 100 metres and used to cool and condense the steam back to liquid form.

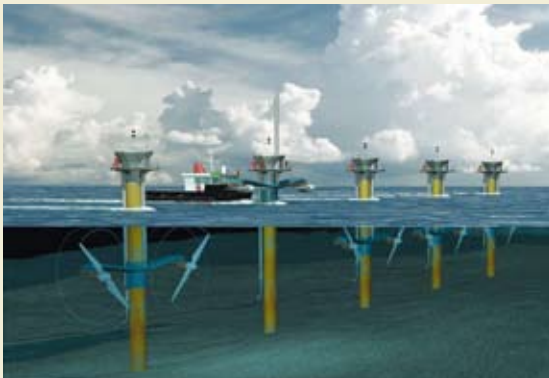
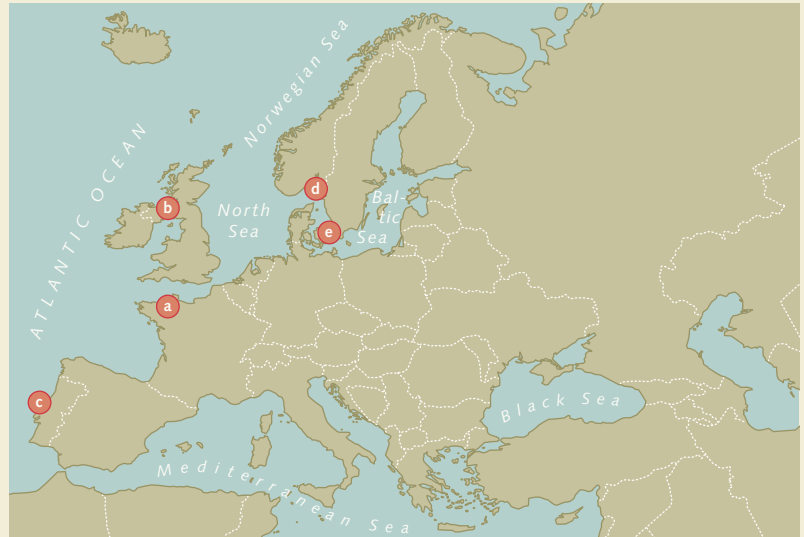
Until now the cost of OTEC technology has been considered prohibitive, requiring pipelines of several 100 metres in length and powerful pumping systems. The US government supported OTEC development and initial testing in the mid 1970s, but withdrew its funding in the early 1980s. Interest in the technology has recently been rekindled, however. An American-Taiwanese consortium is now planning to construct a 10 MW facility in Hawaii. Furthermore, public institutions and businesses in France have launched the IPANEMA initiative, which aims to promote both ocean-based renewable energies and OTEC technology. It is estimated that OTEC has the potential to harness several 1000 TWh of electric power each year. Unlike wind and wave energy, this form of electricity production is not subject to fluctuating weather conditions.

Energy derived from the different salt content of freshwater and saltwater

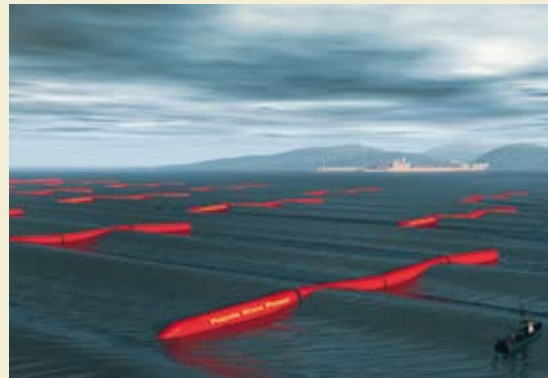
The osmotic power plant is an entirely new way of generating energy. It exploits the osmotic pressure which builds up between freshwater and saltwater when they are pumped into a double chamber and separated by a special semi-permeable membrane. The technology is



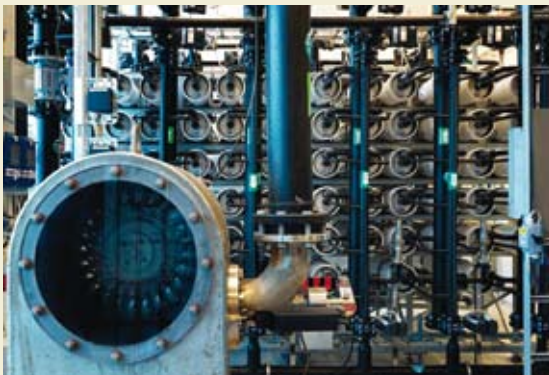
7.12 a > Power plants designed to harness ocean energy are already operating at several sites in Europe. The oldest is La Rance tidal power station near St. Malo in France, which was built in the 1960s. For many years it was the largest of its kind, with an output of 240 megawatts.



7.12 b > Tidal energy can be converted to electricity by underwater rotors, as at the SeaGen plant off the coast of Northern Ireland in Strangford Lough. One facility has already been constructed which feeds electricity into the grid onshore. Others will follow.



7.12 c > The Pelamis wave energy transformer floats on the ocean like a giant sea snake. It consists of several segments which move against each other and build up hydraulic pressure. This in turn drives a turbine. A new Pelamis generation is currently under construction.



7.12 d > The world's first osmotic power plant on the Oslo Fjord in Norway derives energy from the differences in salt concentration between saltwater and freshwater. A thin membrane separates the water masses, building up pressure which drives a turbine.



7.12 e > Offshore wind turbines produce electricity in many places around the world. One of the largest offshore wind farms, consisting of 48 turbines, is located in the Baltic Sea between Denmark and Sweden. A transformer station has been constructed here to feed power into the Swedish grid.

7.13 > Wind turbines are normally erected at a maximum water depth of 45 metres; otherwise, the cost of the towers is prohibitive. One alternative is to anchor floating turbines to the sea bed with holding cables. The first prototypes are currently being tested.



still in its infancy. In 2009, however, members of a Norwegian syndicate constructed the world's first osmotic power station on the Oslo Fjord. The plant is designed principally to develop this technology, at present generating only a few kilowatts of electricity. However, the sustainable global production capacity of osmotic power could in future amount to 2000 TWh annually.

Government support for the energy systems of the future

There is no doubt that major advances have been made in developing technologies to harness renewable energy from the oceans. Although many technologies show commercial promise, however, virtually all of them

depend on subsidies because they are driven by small, young businesses. Apart from the technological and economic risk, one difficulty is to achieve project sizes which would make such investment viable. Subsidies for these technologies are therefore essential. Various nations offer such programmes. The US Department of Energy and the European Union are already investing several 100 million euros in their development. The complex approval procedures for plants and grid connections also need to be simplified. In Germany the approval of offshore wind plant is entirely in the hands of the Federal Maritime and Hydrographic Agency, but in the USA plant operators must battle their way through various agencies and approval processes. Relaxing the rules would be of great benefit.

CONCLUSION

Pressure on the ocean floor is growing

For centuries the oceans provided a single resource – food. Only during the past few decades have technologies been developed which can extract more from them – for instance drilling technology to extract oil and gas. Until now drilling has been in relatively shallow waters, but companies are now penetrating greater depths. It is a complex and expensive process, but is becoming more feasible as land-based reserves become scarce and prices rise. The same applies to the metal reserves which are embedded in manganese nodules, cobalt deposits, massive sulphides and ore slurry in the sea. As metal prices rise, mining from the depths will become more attractive – although this will only apply to valuable metals such as copper, nickel and gold. As yet, however, no mining technology is gentle on the environment.

With respect to methane hydrate, it is unclear to what extent it is possible to mine the ocean floor without harming people or the environment. Also,

virtually no technology exists for the purpose. Many basic principles must first be clarified, such as whether laboratory results can be applied to mining practice. If it were possible to extract methane and at the same time safely store carbon dioxide from the burning of oil and gas, harnessing methane from the ocean bed might even prove to be a climate protection option.

The most sustainable system of marine energy production in terms of climate protection is probably from the ocean currents, waves and wind. In most cases there is considerable need for research into the impact of energy systems on the marine environment. Some technologies are ready for operation, while others are still in the pilot phase. Some nations have reduced the bureaucratic hurdles that planners and developers face. Before facilities can be utilized on a large scale, however, countries must decide whether and how they wish to promote ocean energy, because without initial governmental support none of the current technologies can be established in the medium term.

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