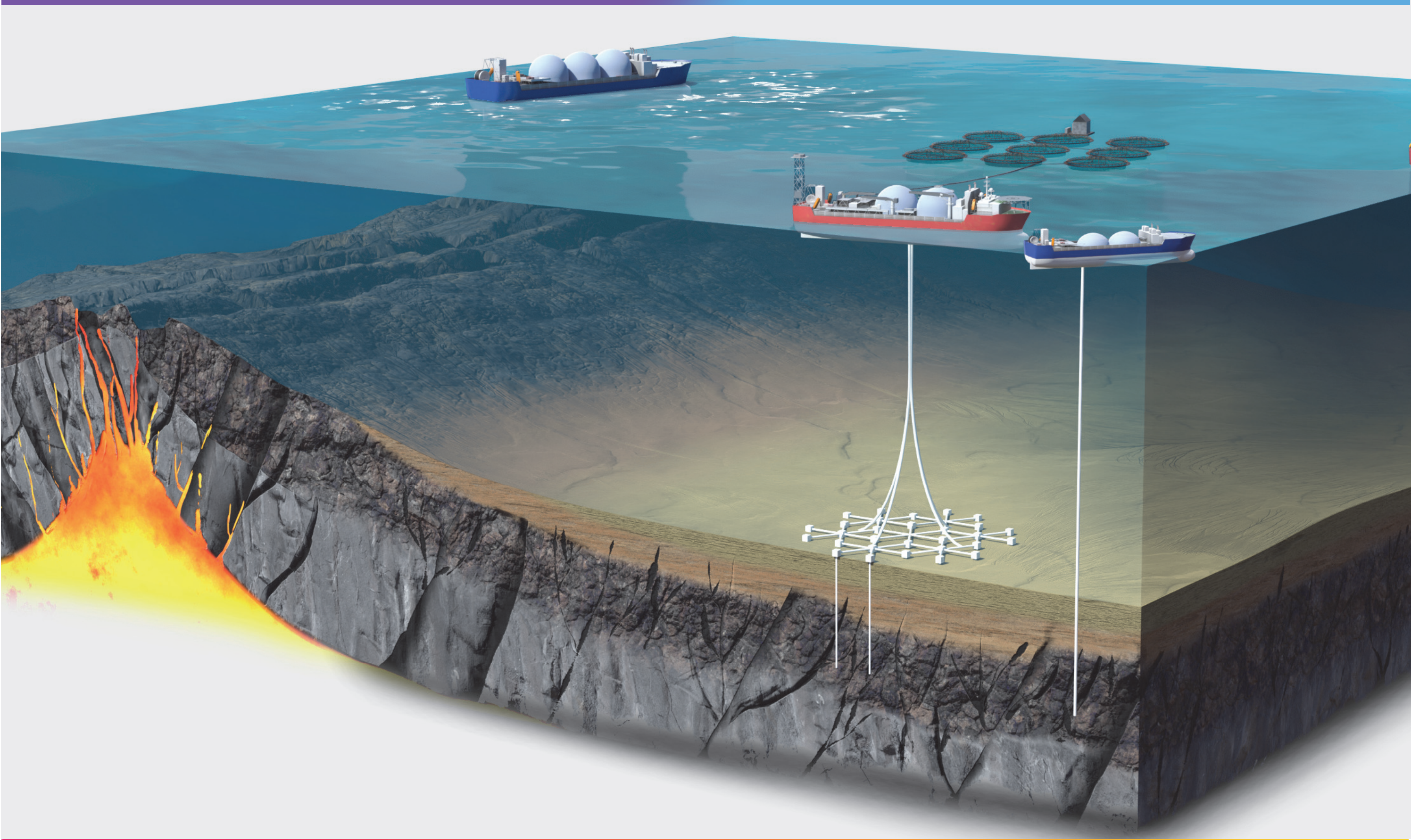

WHITE PAPER

OFFSHORE GEOTHERMAL:
A GREEN ENERGY RESOURCE OF GLOBAL SIGNIFICANCE AND ITS RESPONSIBLE DEVELOPMENT

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1 Purpose of this Document

This document intends to provide essential reference elements for framing this important topic and to draw the attention of geoscientists, companies, regulators, policymakers and society to the ideas, approaches and ethical perspectives that those involved in geothermal resource development will need to develop and use, in particular:

- A high-level summary of the marine geothermal system and co-production opportunities.
- An overview of where geothermal can be deployed.
- Best practices that will enable the responsible development of offshore geothermal.
- The economic, developmental and socio-economic growth opportunities that offshore geothermal can bring to developing nations.

2 Why This Matters

The IPCC AR6 Synthesis Report contains the stark warning that "the pace and scale of climate action are insufficient to tackle climate change" (IPCC 2023). Currently, the major options for future mitigation of energy emissions to 2030 cited by the IPCC are the continued expansion of wind and solar. Large potential reductions in emission of methane during exploitation and use of fossil fuels are also available, and carbon emissions can be captured and stored. Other energy sources that IPCC note could be expanded to 2030 without contributing directly to emissions include bioenergy with carbon capture and storage (BECCS), geothermal, hydropower and nuclear.

CGG has been investigating whether, in the longer term, the use of geothermal could be expanded significantly beyond our current technical and geographical horizons.

Geothermal provides the benefits of both heat and power and gives the opportunity to generate many cascading use opportunities. Geothermal energy is a proven baseload resource onshore, although current commercial developments are often localized and difficult to develop at scale because of the variable distribution of heat in the subsurface.

Hypothetically, an additional ideal green electrical energy resource with global impact would:

- Not add to atmospheric CO_2 – and ideally would sequester and actively draw down atmospheric CO_2.
- Not use more natural land – so it would be offshore.
- Be developed at scale and speed – under a single best-practice licensing regime that minimizes delays.
- Have a minimal environmental impact – independently monitored under a single protocol for consistency.
- Be capable of delivering reliable, steady power, and additional beneficial byproducts (such as green hydrogen or ammonia – according to local demand and global economics).
- Use tried and tested technologies – though potentially in novel combinations.
- Not use critical minerals – and use materials that are relatively easy to recycle, such as steel.
- Not use fresh water – and ideally would be a net producer of fresh water.
- Not negatively impact existing sea life – and ideally would enhance it, develop aquaculture and enhance the open water fishery.
- Be cost-effective.

Our research indicates that vast geothermal resources are present beneath the world's seas and oceans, and could provide an additional green energy solution that is close to the ideal scenario listed above. The rift systems, which provide some of the world's highest concentrations of geothermal power onshore, are much more extensive offshore, in both national and international waters.

Offshore geothermal for green energy and global development

We conclude that potentially substantial geothermal resources exist along the magmatically active and 65,000 sq.km-long ocean floor spreading centers which occur in all of the world's major oceans. We also identify major geothermal potential along the flooded rift systems that represent the landward continuation of the oceanic spreading centers, and additional geothermal potential in some seas formed where the Earth's crust is stretching.

The successful development of geothermal energy near volcanoes around the Indo-Pacific "Ring of Fire" has become well established as the geothermal industry has learned to master the geological complexity of the volcanic setting. We have learnt that each volcano is different in its magma types, geothermal fluid chemistry and subsurface "plumbing", whilst temperatures decrease rapidly away from each volcanic geothermal area.

In contrast, the ocean floor spreading centers offer a more continuous belt of subsurface heat because igneous or dilational tectonic processes, and resulting hydrothermal activity, occur along the full length of each spreading system. The magma types and temperatures are quite similar in most of the spreading systems, and the geothermal fluids are relatively consistent and chemically benign – because they are essentially modified seawater.

The world-class geothermal potential of oceanic spreading centers is already demonstrated in southern Iceland. Here, deposits from adjacent volcanoes have built up on top of submarine basalts of the North Atlantic Oceanic Ridge, allowing the underlying submarine geothermal system to be developed onshore. The experience gained from Iceland gives the world a “flying start” for developing similar submarine geothermal reservoirs offshore. Offshore geothermal power does not need to be transmitted by cable to shore: the power can be used to electrolyze the fresh water from turbine steam condensate to give transportable green hydrogen or ammonia.

Offshore, we have the added advantage of being able to undertake rapid geophysical mapping of the seabed and subsurface in order to design the most cost-effective pattern of drilling for geothermal energy. This means that the experience gained from early offshore geothermal drilling along the oceanic spreading centers can be rolled out rapidly along ocean spreading centers worldwide.

Many of these resources lie in international waters and will be regulated by the UN Convention of the Law of the Sea (UNCLOS) and its regulatory body, the International Seabed Authority (ISA), so exploration, research, development and manufacturing opportunities can be shared across the globe, for the benefit of humankind. Countries with ridge segments under national jurisdiction will benefit from knowledge-sharing and technological developments. The prospects presented will help low- to middle-income countries achieve sustained levels of economic productivity with a stream of diverse and inclusive work opportunities with proper regulations and training programs:

- Immediate- to long-term job opportunities will include research and environmental monitoring roles.
- Medium-term job opportunities will include supply boat and helicopter support for exploration and initial development activities, followed by construction-based roles as offshore development designs become standardized and suitable for modular construction in coastal or island states.
- Long-term job opportunities include production and environmental monitoring, maintenance and operations support.

These are all critical roles which would be required through the multi-decade project life of each offshore geothermal development.

Offshore geothermal ways forward

Evidently, the nature of each geothermal development will depend on the temperatures and flow rates of the geothermal fluids, geographical location and climate, global and local economic drivers, plus the interests of the stakeholders in each development. The diversity of potential offshore geothermal resources and economic applications offers a real and urgent incentive for developed and developing nations to collaborate. That collaboration should aim to ensure a fair distribution of benefits, and to protect waters internationally through multi-facetted capacity building and sharing of a diverse suite of marine technologies.

CGG has a published patent application for a novel combination of geological, geophysical and engineering technologies to help explore and develop these resources (CGG, 2022). Our motivation for obtaining the patent is to ensure that there will be no patent “blockers” delaying rapid development of these resources. CGG patent licenses will be available at a reasonable cost to companies from developed countries and at an easily affordable cost to underdeveloped countries in their own exclusive economic zones or when participating in projects in areas administered by the International Seabed Authority (ISA).

It is important to consider the UN sustainability goals for offshore geothermal developments because they provide a framework for achieving development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The UN Sustainable Development Goals (UNDP 2023) address a broad range of environmental, social, and economic issues. The diversity and magnitude of opportunities presented by offshore geothermal resources has the potential to contribute significantly to the achievement of many of the SDGs, particularly those related to clean energy, climate action, responsible consumption and production, and partnerships for sustainable development.

Since many of these geothermal resources lie in international waters administered by the ISA, the scientific research, exploration, environmental baseline surveys, future production and economic activity in the ISA areas could be developed in ways that maximize the benefits to developing nations, whilst at the same time supplying large-scale multi-component green resources of benefit to humankind.

3 Offshore Geothermal Resources and a Framework for their Responsible Development

These notes represent a selection of the issues that will need to be addressed in the future by specific guidelines for sustainable offshore geothermal development in order to develop relevant laws and international best practice.

The widespread submarine rift systems of less than 10 million years old, which formed at oceanic spreading centers, back-arc rifts, island arcs and in areas of thinning of continental crust, offer some of the best potential for development of offshore geothermal power. We recognize that within these areas there are scientifically significant sites that need to be studied before any geothermal development.

Based on discoveries and research to date, active submarine vents occur at a spacing of 1 to 5 per 100km length of an ocean ridge system. Recognizing that our knowledge of these systems is far from complete, environmental baseline studies need to continue at pace in order to identify those vents which should be excluded from development on the basis of their special biology, chemistry and physics.

Active vents discovered in the process of exploring for offshore geothermal resources should be subject to the same environmental study and, if applicable, exclusion zone criteria. The size of exclusion zones around active vents would need to be defined after consultation with the scientific community, and then embodied by the ISA in a standard licensing agreement.

Protocols will need to be in place as part of the exploration license to ensure it is in the exploration company's interests to document these new vent locations. Future scientific research on the new vents will, in the long term, benefit the offshore geothermal industry by improving our understanding of how these geothermal systems work – thereby helping to improve exploration targeting and reducing costs.

Some submarine brine pools are sites of leakage of fluids from the deep subsurface, carrying implications for temperatures at depth, and all are extremely important sites for wildlife and for existing and future research across the fields of biology, chemistry and physics. Discovery disclosure and protection protocols designed for active geothermal vents should therefore also apply to these types of brine pools.

The environmental impact of geothermal development will be very different from that of seabed mineral mining. Offshore geothermal development has a very small footprint area, with economic success dependent on drilling the smallest possible number of boreholes to obtain the geothermal water temperatures and flow rates required for energy production. The fact that reducing costs and minimizing environmental impact are economic drivers of geothermal development means that there is natural co-alignment with pillars of the framework that should be documented for the responsible development of geothermal resources.

Acknowledgement and respect of cultural heritage and traditional knowledge of local communities and indigenous groups who can provide key information in potential offshore geothermal areas will be honored and integrated. For example, indigenous knowledge of long-term changes in fisheries and the distribution of migratory species might help inform the design of geothermal developments.

By adhering to the law and to international best practices, the responsible development of marine geothermal resources will prioritize environmental protection and the health and safety of all involved. In ISA-administered areas, the benefits and opportunities will be shared fairly and equitably, so that there will be active engagement to involve parties from developing and landlocked nations in the development of marine geothermal resources.

We hope that the criteria established in ISA-administered areas would, where appropriate for national priorities and interests, also be applied in national waters.

4 Best Practice

Offshore geothermal resource development is a new field and the practical implementation of responsible exploration and development outlined below will require considerable thought and agile learnings from practical experience. The types of social and environmental issues raised by offshore geothermal are quite different from those related to geothermal activities on land, and the long-term impact of offshore geothermal resource development deserves to be carefully discussed and scientifically approached. The commentary provided below is designed for ISA-administered areas (hereafter referred to as 'Area'). It references some of the best practice procedures stated in the draft High Seas Treaty (United Nations, 2023):

1) Identify and engage all relevant actors and stakeholders, including authorities, indigenous and local communities, employees, contractors and non-government organizations. Maximize contribution to sustainable development, manage and mitigate environmental risks and impacts, better understand and meet the expectations and needs of

society and the political situation, assess social impacts and opportunities, conduct social baseline studies, ensure good governance and maintain high standards of ethics.

2) Location and project-appropriate environmental impact reports will be required to be lodged and approved by the relevant authority before any offshore activity commences. The assessment must look at the cumulative impacts of the proposed activity over time and consider the protection of migratory species across their entire migratory route. Companies and governments participating in these exercises will be required to publish all relevant information and any finished reports through a public mechanism.
3) As part of the public mechanism, companies that wish to conduct activities offshore to advance research, exploration or development for offshore geothermal will have to adhere to the minimum details of submission as stated in the High Seas Treaty in order to ensure transparency.
4) Every effort must be made to ensure that the initial offshore geothermal wells are a success. Early success will attract investment. Early failure will delay investment – a delay that the world cannot afford given the rate of climate change and the slowness of national remediation actions.
    a. In order to progress at the speed and scale required to make a meaningful impact on delivering sustainable energy at affordable cost, all existing information needs to be readily available. All existing and new data sets will need to be held in agreed project-friendly data structures, with duplicate data sets stored in several secure but public data repositories.
    b. This will ensure that gaps in existing data coverage can be accurately identified, enabling new work programmes to be designed efficiently and without duplication.
    c. In addition, since offshore geothermal wells are expensive to drill, it is vital that no offshore geothermal well is drilled unsuccessfully owing to a critical piece of information not being available to the exploration operation.
    d. Emphasis on transparency will require that all companies wishing to research or develop offshore geothermal will have to adhere to the minimum details of submission as stated in the High Seas Treaty.
5) Existing information in this context is defined to include (but not be limited to):
    a. Public, readily available data.
    b. Data held by companies, institutions and individuals in sites which are theoretically public but currently difficult to access.
    c. Information held in national data repositories with limited-access policies.
    d. Confidential information held by companies, institutions and individuals.
6) Companies, institutions or individuals contributing bona fide confidential information for offshore geothermal use should be given appropriate credit for their contributions, whilst entities or individuals found to have withheld public information should not be allowed to benefit from offshore geothermal activities in exploration or development.
7) In order to encourage the acquisition of technical and scientific data of all types, no entity should be allowed to insure against risk – in other words, the geological, engineering and environmental uncertainties will be managed by the acquisition of relevant data and by taking appropriate action, not by risk insurance.
8) In order to encourage the rapid acquisition of new data for exploration purposes, each data type would have a period of exclusivity of up to 24 months from the start of the data acquisition programme for that data type.
9) In order to encourage the rapid acquisition of new data for development and production purposes, each data type would have a period of exclusivity of up to 12 months from the start of the data acquisition programme for that data type.
10) Particular credit will be given to data acquisition programmes that are not only fit for the immediate purpose but are of sufficient quality to provide long-term cost effectiveness for offshore geothermal as a whole.
11) Many of the elements of the existing ISA legislation covering seabed mining activity could be readily adapted to offshore geothermal. However, the legislation and licencing would benefit from the addition of some protocols from onshore geothermal and offshore petroleum activities.
12) Onshore geothermal developments have for many decades been designed to handle the fluid temperatures and fluid chemistries likely to be targeted by offshore geothermal – so it would be beneficial to add relevant best practices from the onshore geothermal industry into the ISA legislation for offshore geothermal.
13) Offshore petroleum developments for oil and gas have for many decades been designed to handle fluid pressures far in excess of those to likely be targeted by offshore geothermal, and the industry also has experience of insulating tubing in deep water to minimise heat loss – it would therefore be beneficial to add relevant best practice from the offshore petroleum industry into the ISA legislation for offshore geothermal.
14) The oil and gas industry is looking at repurposing some of its offshore infrastructure. The lessons learned through that repurposing exercise will be useful in helping design, from the outset, offshore geothermal infrastructure with repurposing within the circular economy in mind.
15) This move away from an extract-manufacture-use-discard model to one embracing the recycle, reuse, and remanufacture concepts of a circular economy, will create new opportunities.

16) An additional focus on modular construction to help drive down costs will be possible because of the scalability of offshore geothermal developments, and modularisation will make it easier for coastal and island nations to participate in the manufacturing processes.
17) Whilst it is possible that some oil and gas industry materials and structures can be directly repurposed for the new offshore geothermal industry, adequate inspection and permitting safeguards will need to be in place to ensure that such materials and structures will indeed be fit for the new purpose throughout the long lifetime of a geothermal development.
18) Given the longevity of most geothermal developments, operation and environmental monitoring will be a vital part of the licence agreement. Publication of the monitoring results will be required to help ensure the integrity of the operation and will also provide a long time-series of new scientific data in under-sampled parts of the world's oceans.

5 Blue Economy and Growth Opportunities

Offshore geothermal development in the Area administered by the ISA offers significant opportunities for all members to collaborate. Well developed, well managed geothermal resources can support the movement towards sustainable development and attaining the targets set under the Paris Agreement and the United Nations Sustainable Development Goals (SDG's). By adhering to the High Seas Treaty and international law, offshore geothermal presents a fair and equitable opportunity for all nations.

The offshore geothermal system can ensure access to an affordable, reliable, sustainable baseload energy that can be utilised for a number of processes that generate additional commodities and revenue streams outside the realms of just heat and power. These co-developed processes have the cascading potential to support many SDG's.

Offshore geothermal resource development, viewed holistically, brings together a number of technologies that requires a diverse network of expertise and engineering capacity. This demand will therefore deliver increased job opportunities including scientific roles, engineering expertise and operational support. Specific training programs for people from developing nations will equitably distribute opportunities.

Although there are a number of suitable technologies available to deploy and harness the benefits of offshore geothermal presently, there are several opportunities associated with technological progress and innovation to further develop this resource.

The "Blue Economy", from green shipping technology to ocean mapping solutions, contributing to better protection and responsible management of marine resources, should significantly stimulate demand for a range of sectors and expertise. Consequently, there is significant scope for new business entities to enter the offshore geothermal space. The direct effect would be rapid growth in the sector and a need to expand human and technological resource capacities.

With the focus on partnerships to achieve the UN sustainability goals, wealthier nations that have supported the High Seas Treaty have pledged to support developing nations to protect international waters through capacity building and the development and transfer of marine technology.

Offshore geothermal can offer multiple routes to commercialization, and hence a diverse range of job opportunities within this immediate to long-term, sustainable employment framework. The following illustrate the diversity of potential developments that may apply in different techno-commercial and research settings:

Fresh water

In addition to generating green electric power, many offshore geothermal developments will deliver large volumes of fresh water by condensing steam from the turbines, which, if close to shore, could be used directly for agriculture or, with minimal processing, would be suitable for drinking.

Green hydrogen and green ammonia

In remote settings, the freshwater from condensing steam could be electrolyzed to produce green hydrogen. The geothermal electric power could also be used to convert the hydrogen to green ammonia, for use as fuel for shipping or for use in nitrate fertilizer.

In some geothermal developments, more fresh water may be delivered than can be converted to hydrogen or ammonia from the available geothermal electricity – this means that options such as utilizing floating wind farms or floating solar arrays to electrolyze the water might be adopted according to the geographic setting and economic drivers.

Potential for enhanced fisheries and atmospheric CO_2 draw-down

Fertilization of ocean waters by geothermal fluids occurs from numerous seabed vents at ocean spreading centers and according to Shine et al., 2021 locally may fertilize the surface waters, giving organic productivity "hot spots" in the open ocean which are regularly visited by marine mammals and fish stocks.

Thus, the spent geothermal brines may offer potential for localized fertilization that mimics natural processes. This could occur initially in an enclosed, controlled system during pilot research phases and potentially later in the open ocean. The enhanced fishery could initially take the form of aquaculture development adjacent to the geothermal power plant in a controlled system, and if successful, later extended to enhance the open water fishery. The process of leveraging naturally nutrient-rich seawater into enclosed systems for carbon sequestration is already being implemented. However, given the negative results of use of artificial fertilizers in the open ocean, extensive research into the environmental, biological and fisheries implications of ocean fertilization by geothermal brines would be required.

If the research results were positive, this could be particularly beneficial in the low-productivity ocean "deserts" that occur above many of the world's oceanic spreading centers. If necessary, the oxygen by-product from hydrogen production could be used to create well-oxygenated fertilized ocean waters. The increased primary productivity that could accompany successful fisheries could help draw down atmospheric CO_2 and offer opportunities for biodiversity enhancement, sustainable fish food production and the supply of valuable metabolites such as pigments.

If the fisheries enhancement model proved unattractive, the geothermal brines would be re-injected into permeable rocks deep below the ocean floor. Subsurface re-injection of brines is a well-established practice in onshore geothermal.

Minerals and mineralization

Our initial research into the amounts of minerals that could be extracted directly from the geothermal brines over the lifetime of an offshore geothermal field suggests that these may not be commercial, but the wide spectrum of elements available, advances in extraction technologies and the changing minerals market, means this could be important in future.

In Iceland, innovative research is being conducted on CO_2 sequestration and storage by carbonate mineralization in subsurface basaltic rocks. We do not currently know whether this additional green benefit would be viable for offshore geothermal.

Infrastructure

In order to maintain demand and support marine geothermal development, new infrastructure both offshore and onshore will be required. Onshore infrastructure developments can include storage and distribution centers for the produced commodities, laboratory facilities, improved transport networks and support service hubs.

Some of the new resource support requirements are not tied to the geography closest to the geothermal resource, so research, development and manufacturing opportunities can be shared across the globe. The involvement of the ISA will ensure that opportunities from international waters and the Area are shared with people in less economically developed areas. For example, during an offshore development this can be achieved through a number of strategies:

- Collaborating with local organizations and stakeholders can help ensure that opportunities are shared with people in less economically developed areas. They can help identify individuals and communities needing employment and training opportunities and help facilitate their participation in the project.
- Providing training and capacity-building programs can help people in low- to middle-income areas acquire the skills and knowledge needed to participate in the offshore energy development project. This can include programs that focus on technical skills, project management and leadership development.
- Providing development opportunities for existing geothermal facilities in developing countries (e.g., Eastern Africa).
- Developing a targeted hiring policy can ensure that job opportunities are equitably shared. This can include a requirement that targeted communities fill a certain percentage of jobs or that contractors and subcontractors hire from targeted areas.

The prospects presented will help low- to middle-income countries achieve sustained levels of economic productivity with a stream of diverse and inclusive work opportunities.

The requirements for good-standard, well trained personnel will be necessary for the success of offshore geothermal. These training opportunities would be inclusive and target all social demographics. Some of the learnings and training can be transferred to onshore applications, enabling people to share and implement their knowledge amongst their communities.

Companies which plan to undertake activities in international waters will need to carry out environmental impact reports and assessments with the relevant authorities. A drive in terms of technology innovation in monitoring for a marine geothermal project life cycle does not only bring business opportunities, it also has the potential for crossover linkages with other marine sectors.

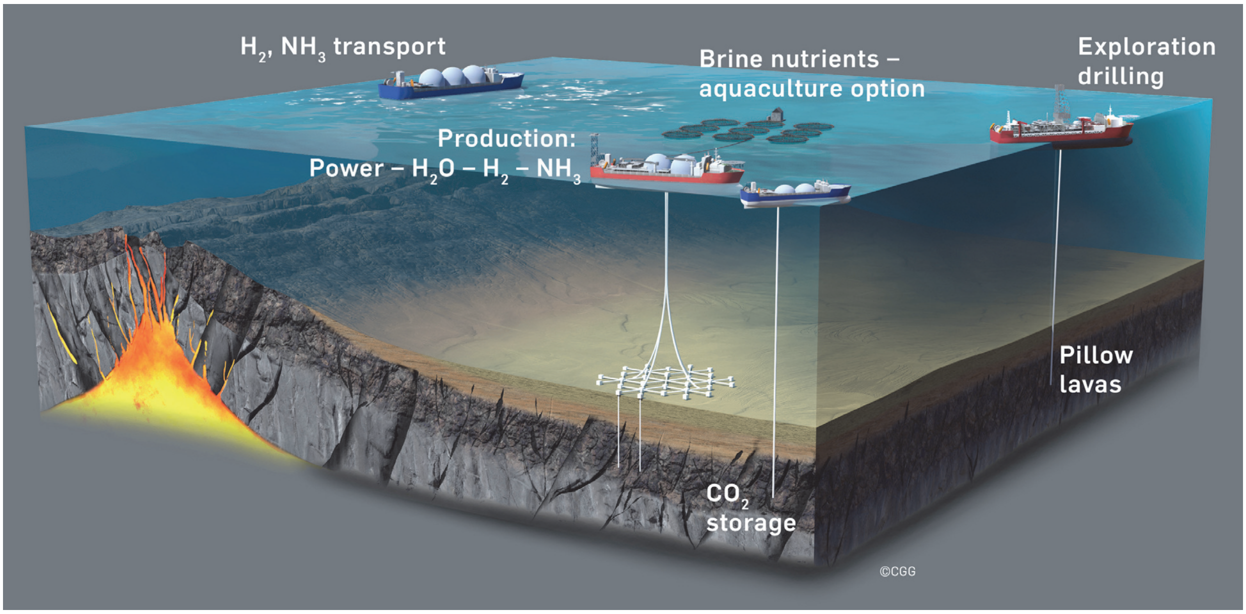
Compulsory, long-term data acquisition through environmental monitoring, system impacts, and production analysis will help drive further research into marine and offshore energy sciences. There are numerous opportunities to build research capacity in low- to middle-income countries and provide the basis for evidence-based tools for decision-makers.

The additional data and economic resources from fair and equitable sharing of the benefits from offshore geothermal will assist decision-makers in their global aims to enhance marine conservation and promote the sustainable use of ocean-based resources in order to help mitigate future challenges the oceans may face.

6 Concluding Remarks

Most countries are committed under the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement to reducing their carbon emissions to net zero. Emission achievements will be reviewed in the First Global Stocktake, but currently these are insufficient to reduce global CO_2 levels in line with decarbonization targets.

A huge coordinated international effort is required and a global green energy resource with the potential to be developed at scale and speed must be identified. CGG's research concludes that offshore geothermal has the potential to be a major contributor to achieving the targets set out in the Paris Agreement. Through our offshore geothermal patent and multi-decadal subsurface data, experience, diverse expertise, and high-performance technology, we will be poised to help countries and companies develop a series of pilot offshore geothermal projects and to support acceleration of the marine environmental research that will be needed to accompany development of the resulting resources.



Schematic showing offshore geothermal resource exploration and development adjacent to sea floor spreading centers generating baseload power, fresh H_2O, green H_2 and NH_3 with the potential for CO_2 storage and controlled ocean fertilization (image © CGG).

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