

Review

Offshore Geothermal Energy and Repurposing of Oil and Gas Platforms for Integrated Offshore Energy Systems: A Review

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Abstract

Offshore geothermal energy and the reuse of decommissioned oil and gas platforms are emerging as linked pathways for reducing the carbon intensity of marine energy supply while extending the value of mature offshore assets. This review examines offshore geothermal development from a full-chain perspective that connects resource assessment, platform and wellbore reuse, heat extraction, medium- and low-temperature conversion, multi-energy coupling, techno-economic evaluation and environmental risk management. The paper first clarifies the resource logic of offshore geothermal systems, especially sedimentary-basin resources that spatially overlap with mature petroleum provinces. It then analyzes two principal engineering routes: the reuse of existing offshore platforms as energy hubs and the reutilization of abandoned wells as open-loop or closed-loop heat-extraction systems. The review finds that platform and wellbore reuse can reduce drilling demand, shorten offshore construction cycles and lower life-cycle environmental burdens, but engineering feasibility remains constrained by wellbore integrity, thermal losses, corrosion and scaling, platform life extension, regulatory liability and the limited availability of field-scale demonstration data. Coupling geothermal energy with offshore wind power, hydrogen production, OTEC and desalination can improve system stability and equipment utilization; however, standardized assessment boundaries and comparable cost models are still insufficient. Future research should focus on resource-engineering-economic integrated assessment, standardized reuse packages, long-term offshore reliability databases, corrosion-resistant material systems, auditable TEA/LCA models and risk-based regulatory frameworks. This review provides a technical basis for offshore geothermal pilot projects and for the low-carbon transformation of offshore oil and gas infrastructure.

Keywords: offshore geothermal energy; platform reuse; abandoned oil and gas wells; wellbore heat exchanger; organic Rankine cycle; offshore integrated energy system; life-cycle assessment



Academic Editor: Alpaslan Atmanli

Received: 11 June 2026

Revised: 25 June 2026

Accepted: 29 June 2026

Published: 1 July 2026

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1. Introduction

The global energy transition is reshaping offshore energy infrastructure. Offshore oil and gas assets were originally designed for hydrocarbon extraction, but many mature fields are now approaching production decline or decommissioning. At the same time, marine energy demand is growing around platform electrification, offshore hydrogen production, subsea equipment, islands, ports, aquaculture and deep-sea industrial facilities. These two trends create a practical question: whether existing offshore platforms, wells and pipeline corridors can be transformed from fossil-energy assets into low-carbon energy nodes.

Santos et al. reviewed the reuse of abandoned oil and gas wells for geothermal energy and argued that the existing well stock represents a potentially valuable infrastructure base rather than only a decommissioning liability [1].

Offshore geothermal energy is attractive because it can provide stable heat or baseload power. Unlike offshore wind and solar resources, geothermal output is less dependent on weather and can therefore support continuous offshore loads, thermal management and auxiliary power. This stability is especially relevant for isolated offshore systems, where grid connection is limited and maintenance costs are high. Wiegner et al. examined offshore energy system integration in the North Sea and emphasized that offshore decarbonization should be understood as a cross-sector system problem involving energy carriers, infrastructure, governance and engineering constraints [2]. Their work provides a useful conceptual reference for reviewing offshore geothermal systems as part of broader integrated offshore energy networks.

In geothermal systems, heat stored in rocks and formation fluids is transferred to the surface either by producing geothermal fluid from a reservoir or by circulating a working fluid through a closed wellbore loop. For petroleum provinces, an oil and gas well generally consists of casing, cement, tubing, wellhead equipment and completion intervals designed for hydrocarbon production rather than long-term heat extraction. Santos et al. emphasized that repurposing oil and gas wells for geothermal use requires the existing well stock to be treated as both an infrastructure opportunity and an integrity-management challenge [1].

The reuse of offshore oil and gas infrastructure has an additional environmental rationale. Complete removal of platforms and well plugging can be expensive, technically difficult and ecologically disruptive. Reuse may reduce new steel fabrication, marine installation, drilling and transport activities, thereby lowering embodied emissions and improving circularity. Li et al. conducted a life-cycle assessment of repurposing abandoned oil and gas wells for geothermal power generation and found that reusing existing wells can reduce environmental burdens compared with drilling new geothermal wells, although the final performance depends strongly on well depth, flow rate and power conversion efficiency [3].

China's offshore basins also provide a relevant geological and engineering context for this topic. Chen et al. assessed geothermal resources in the Huangliu Formation of the Yinggehai Basin using volumetric and Monte Carlo approaches, showing that offshore sedimentary basins can be evaluated through a combined resource and engineering lens [4]. The northern South China Sea contains hydrocarbon-bearing basins with extensive drilling data, platforms and subsea infrastructure, which makes it a natural testing ground for evaluating geothermal reuse of mature offshore assets. This does not mean that every platform can be converted into a geothermal facility, but it suggests that offshore geothermal assessment should start from the intersection of temperature, reservoir conditions, well integrity and platform accessibility.

Previous regional geological studies support this assessment logic. Yuan et al. identified a relatively uniform geothermal gradient and heat-flow characteristics in the Qiongdongnan and Pearl River Mouth basins of the South China Sea, providing an important basis for understanding geothermal conditions in northern South China Sea sedimentary basins [5]. Tang et al. further analyzed geothermal characteristics and hydrocarbon accumulation in northern marginal basins of the South China Sea, indicating that thermal regimes are closely related to basin evolution and petroleum system development [6]. Zuo et al. studied the geothermal regime and hydrocarbon kitchen evolution of the offshore Bohai Bay Basin and showed that heat-flow analysis can support both hydrocarbon exploration and future geothermal evaluation [7]. These studies are not offshore geothermal

engineering papers in a narrow sense, but they provide the geological foundation required to judge whether offshore geothermal systems can be technically meaningful.

A review of offshore geothermal energy should therefore not be limited to resource description. It needs to connect geology with engineering: whether the wellbore can be reused, whether the platform has sufficient structural margin, whether geothermal fluids will cause corrosion and scaling, whether the heat source can drive ORC or other binary cycles, and whether the output can be integrated with offshore wind, hydrogen production, desalination or OTEC.

This review systematically surveys peer-reviewed studies relevant to offshore geothermal resources, platform and wellbore reuse, offshore integrated energy systems, ORC conversion, corrosion and scaling, techno-economic assessment, life-cycle assessment and multi-energy coupling. Studies were selected according to their relevance to offshore engineering applications, methodological transparency, availability of quantitative or case-based evidence, and contribution to resource assessment, system design, performance evaluation or environmental analysis. This screening logic supports a synthesis of the literature from the perspectives of resources, engineering reuse, energy conversion, system integration, economics and environmental sustainability.

The novelty of this review lies in its explicit integration of three previously separated research streams: offshore sedimentary-basin geothermal resource assessment, abandoned offshore platform/wellbore reuse, and offshore multi-energy system coupling. Instead of treating offshore geothermal energy only as a subsurface resource, the review evaluates it as a deployable offshore energy subsystem that must satisfy resource, wellbore, platform, conversion, economic, environmental and regulatory conditions simultaneously.

The contributions of this review are threefold. First, it reorganizes offshore geothermal development around the chain of resources, engineering reuse, energy conversion, system integration and sustainability assessment. Second, it improves the explanatory value of figures by combining field photographs, resource-assessment maps, simulation/result figures and schematic diagrams. Third, it rewrites the literature discussion in a more review-oriented manner, emphasizing what each study investigated, proposed or demonstrated rather than simply attaching multiple references at the end of broad statements. The remainder of this paper is organized as follows. Section 2 reviews offshore geothermal resource types and assessment priorities. Section 3 discusses platform and wellbore reuse. Section 4 analyzes energy conversion and multi-energy coupling. Section 5 evaluates techno-economic and environmental performance. Section 6 summarizes research gaps and future directions.

2. Offshore Geothermal Resource Types and Assessment Framework

Offshore geothermal resources can be grouped according to geological setting, heat source, reservoir type and engineering accessibility. Moeck classified geothermal systems according to geological controls and play-type logic, which provides a useful basis for distinguishing plate-margin systems from sedimentary-basin systems [8]. Chen et al. evaluated the Huangliu Formation in the Yinggehai Basin and showed how offshore sedimentary basins can be assessed through geothermal-gradient, heat-flow and reservoir-temperature evidence [4]. Santos et al. reviewed abandoned-well reuse for geothermal energy and emphasized that existing wellbores can reduce drilling demand but require careful integrity screening [1]. For enhanced or engineered geothermal resources, Olasolo et al. reviewed EGS development and summarized reservoir stimulation and engineering uncertainties [9]. Lu provided a global review of EGS and highlighted the importance of reservoir creation, circulation control and heat-extraction sustainability [10]. This distinction is important for offshore platform reuse: the most technically convenient target is not necessarily the

hottest resource, but the resource that can be accessed through existing infrastructure with acceptable integrity, temperature and reservoir conditions.

Figure 1 provides direct regional evidence for offshore geothermal resource assessment in the Yinggehai Basin. Chen et al. [4] integrated drilling temperature data and heat-flow datasets to map the geothermal gradient and terrestrial heat flow of the basin. The maps show a relatively high geothermal-gradient and heat-flow background, with higher values mainly associated with the central depression, diapiric structures and fault zones.

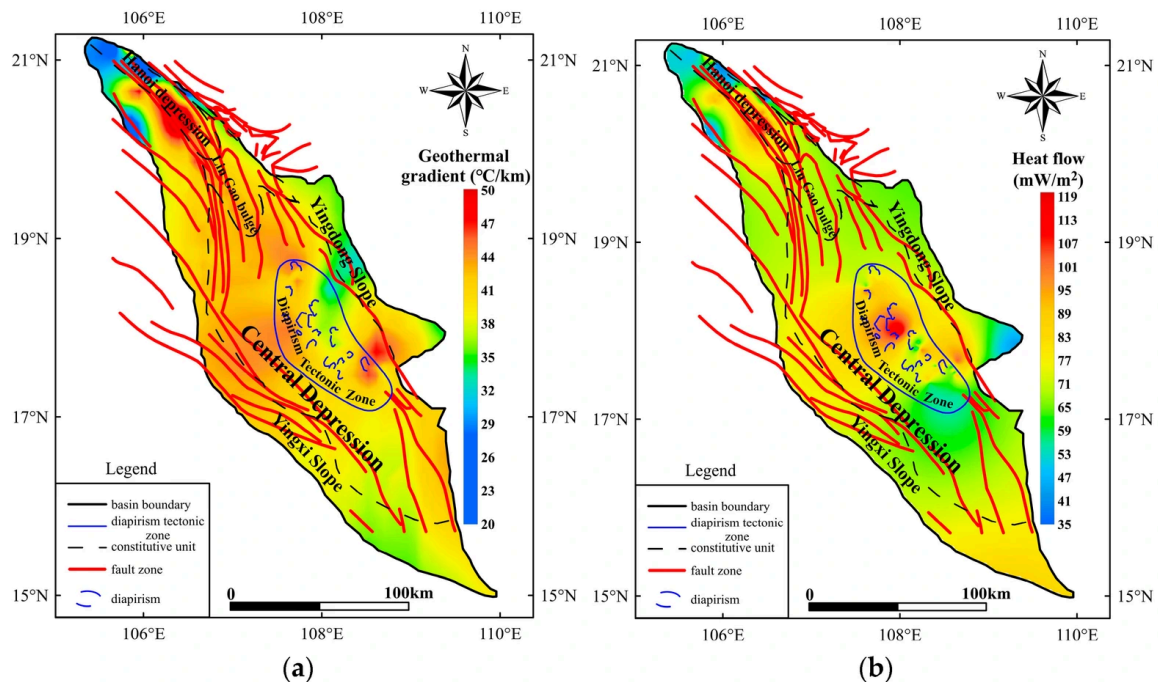


Figure 1. Geothermal field characteristics of the Yinggehai Basin: (a) geothermal gradient map; (b) terrestrial heat-flow map. Adapted from Chen et al. [4] under the CC BY 4.0 license.

Figure 2 adds the original temperature-measurement and correction basis used for the Yinggehai Basin assessment. The measured and corrected temperature–depth relationships show a clear conductive geothermal trend: the compiled borehole data cover depths of approximately 778.1–4154.5 m and formation temperatures of about 72.98–210.75 °C. These data explain how the regional geothermal-gradient and heat-flow maps were derived and why temperature–depth correction is necessary before offshore geothermal screening [4].

Figure 3 further connects the basin-scale geothermal field to the Huangliu Formation reservoir target. Chen et al. reported an average reservoir temperature of about 140.9 °C and an estimated total geothermal resource of approximately 2.75×10^{20} J for the Huangliu Formation, with Monte Carlo simulations indicating a maximum potential of about 3.10×10^{20} J [4]. The mapped top- and bottom-temperature distributions indicate that higher-temperature zones are concentrated around the central depression, diapiric structures and fault zones, which are also the areas most relevant to offshore geothermal screening and potential oil-and-gas infrastructure reuse.

Figure 4 provides a conceptual classification of the two geological settings most relevant to this review. It distinguishes plate-margin hydrothermal systems from intra-plate sedimentary-basin systems and helps explain why sedimentary basins with existing oil and gas infrastructure are especially relevant for platform reuse [8].

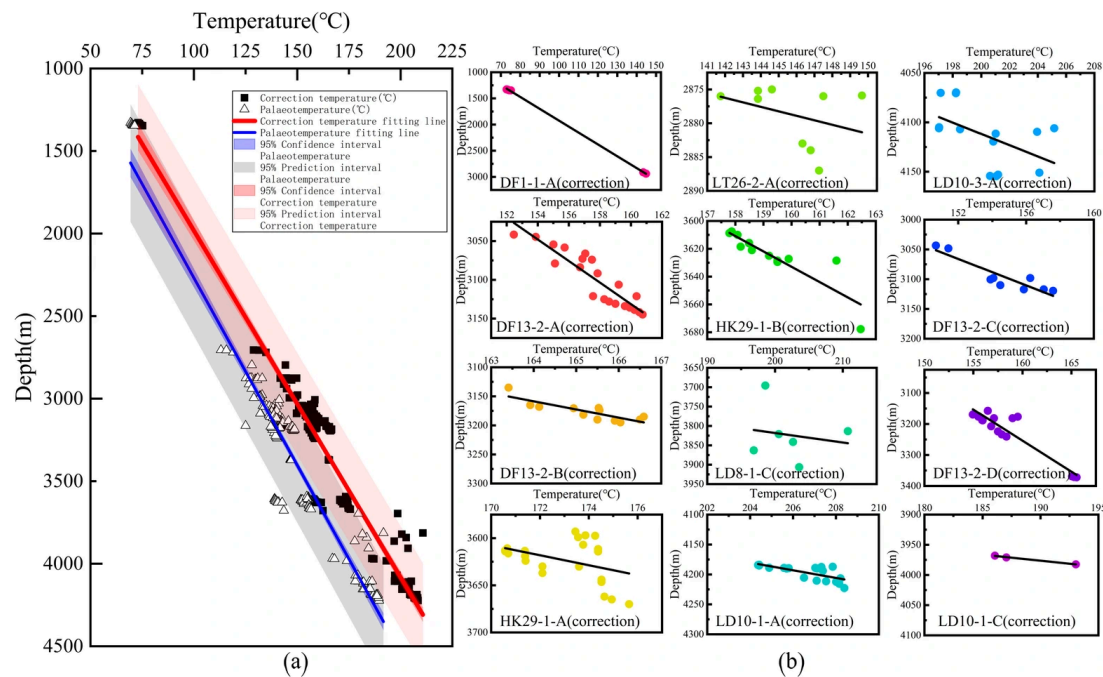


Figure 2. Temperature–depth relationships and corrected formation-temperature data for the Yinggehai Basin. Adapted from Chen et al. [4] under the CC BY 4.0 license. (a) The variation of measured and corrected temperature with depth in Yinggehai Basin; (b) the variation of corrected temperature with depth in each well.

Noorollahi et al. reviewed the potential of repurposing decommissioned offshore oil and gas platforms for renewable energy integration and showed that platform reuse must be evaluated in relation to asset condition, residual life, location and connection to nearby renewable resources. For offshore geothermal development, the same logic applies. Resource assessment should not stop at heat-flow mapping. It should include reservoir temperature, permeability, pressure, fluid chemistry, well condition, well depth, completion structure and the cost of offshore intervention.

Enhanced and engineered geothermal resources are treated in this review as longer-term offshore pathways rather than near-term platform-reuse targets. Olasolo et al. reviewed EGS development and summarized reservoir stimulation and technical uncertainty [9]. Lu provided a global review of EGS and emphasized reservoir creation, circulation control and heat-extraction sustainability [10].

Alirahmi et al. modelled renewable-integrated flexible production of energy and methane by reusing offshore oil and gas infrastructure, which supports the view that existing offshore assets can be evaluated as flexible energy hubs rather than single-purpose production facilities [11].

For sedimentary-basin geothermal resources, temperature is only one part of feasibility. A reservoir may have sufficient temperature but limited permeability, or it may require reinjection management that increases corrosion and scaling risk. Closed-loop wellbore heat exchangers reduce fluid-production risk but often have lower heat extraction rates. Therefore, an offshore geothermal resource should be defined as a developable system rather than as an isolated geological anomaly. A developable system is one in which heat, well access, platform space, conversion equipment, operation and maintenance, environmental controls and regulatory approval can be combined into a practical project.

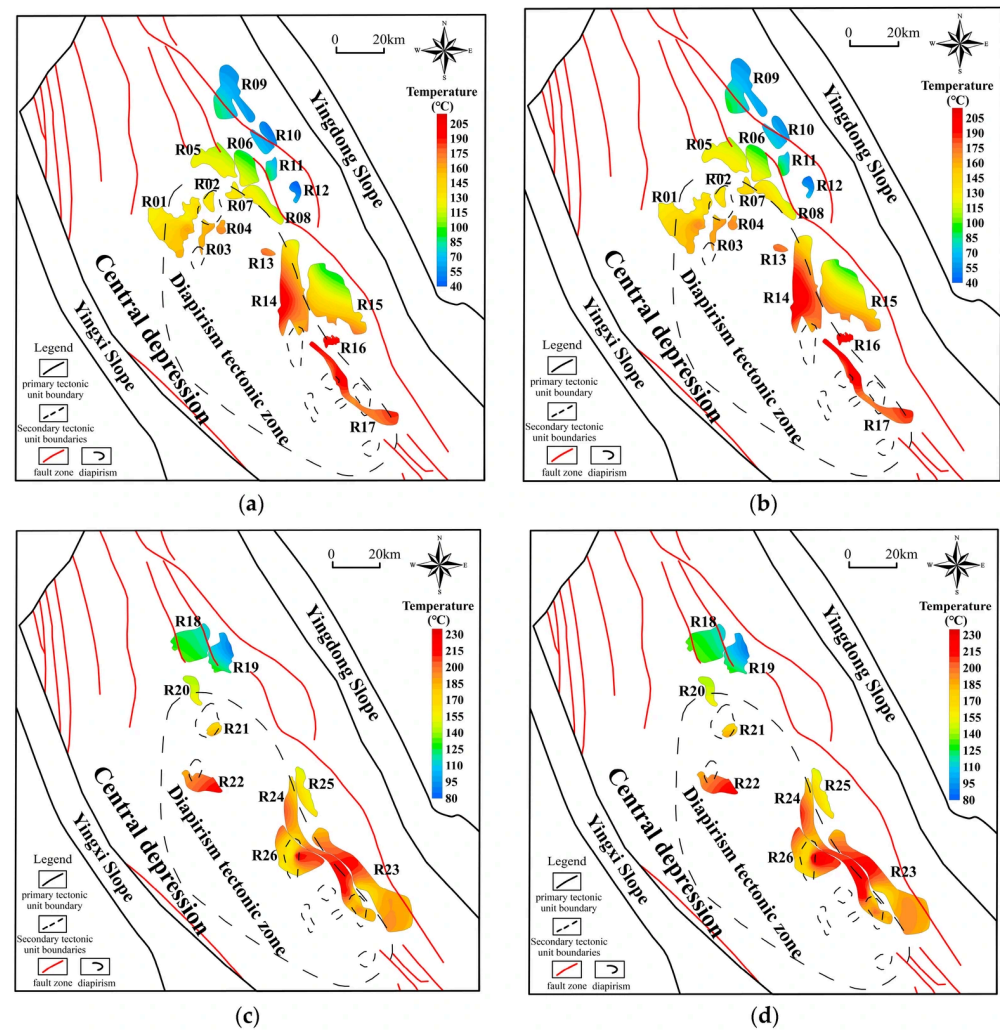


Figure 3. Temperature distribution at the top and bottom of Huangliu Formation geothermal reservoirs in the central depression of the Yinggehai Basin. Adapted from Chen et al. [4] under the CC BY 4.0 license. (a) Temperature at the top of the thermal reservoir in Member 1 of the Huangliu Formation; (b) temperature at the bottom of the thermal reservoir in Member 1 of the Huangliu Formation; (c) temperature at the top of the thermal reservoir in Member 2 of the Huangliu Formation; (d) temperature at the bottom of the thermal reservoir in Member 2 of the Huangliu Formation.

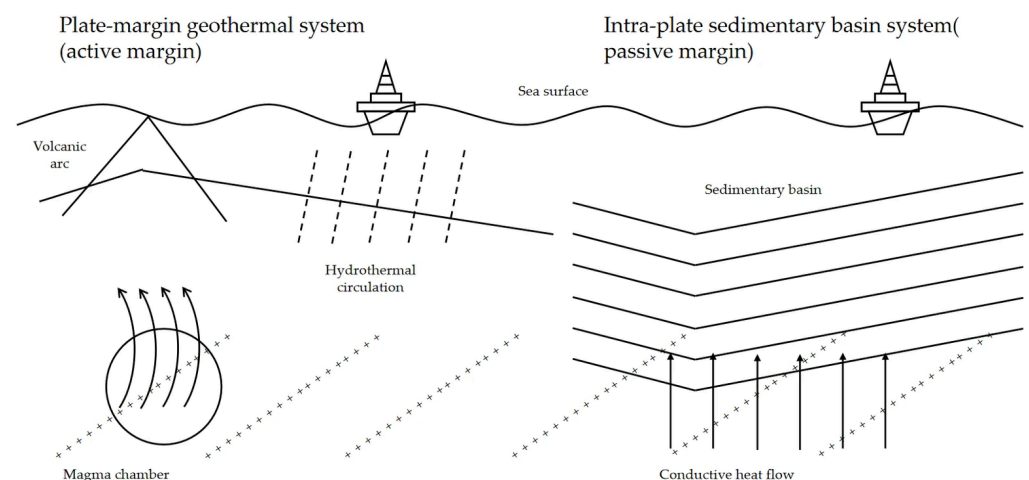


Figure 4. Conceptual classification of offshore geothermal resource types relevant to offshore platform reuse, based on the geothermal play-type framework discussed by Moeck [8].

For practical deployment, the most relevant target locations are mature offshore petroleum provinces where medium- and low-temperature sedimentary-basin geothermal resources overlap with existing wells, platforms, pipelines and maintenance logistics. Chen et al. provided a resource-assessment case for the Huangliu Formation in the Yinggehai Basin [4]. Yuan et al. reported geothermal-gradient and heat-flow evidence for the Qiongdongnan and Pearl River Mouth basins [5]. Tang et al. linked thermal regimes in the northern South China Sea marginal basins with hydrocarbon accumulation [6]. Zuo et al. showed that heat-flow analysis in the offshore Bohai Bay Basin can inform both hydrocarbon and geothermal assessment [7]. These examples indicate that target screening should begin with petroleum provinces where public basin-scale thermal data, drilling information and infrastructure access can be integrated, while acknowledging that some well-level and platform-level data may remain commercially confidential.

Table 1 summarizes the offshore geothermal resource categories considered in this review by linking each category with representative settings, examples, assessment priorities and platform-reuse relevance. This structure extends the discussion beyond the Yinggehai Basin case and supports a more complete comparison of plate-margin systems, sedimentary-basin systems, abandoned-well-based resources and enhanced or engineered geothermal resources.

Table 1. Offshore geothermal resource types, representative examples and assessment priorities.

Resource Type	Representative Setting and Examples	Assessment Focus	Relevance to Platform Reuse
Plate-margin geothermal system	Volcanic arcs, rifts and high heat-flow margins. The play-type framework discussed by Moeck helps distinguish active-margin hydrothermal systems from sedimentary-basin systems [8].	Reservoir temperature, permeability, geohazards, reinjection feasibility and distance from offshore infrastructure.	High-temperature potential may be strong, but overlap with mature oil and gas platforms is often limited; reuse is case specific.
Intraplate sedimentary-basin system	Passive continental margins and hydrocarbon basins. Examples include the Yinggehai Basin [4], the Qiongdongnan and Pearl River Mouth basins [5], and the offshore Bohai Bay Basin [7].	Geothermal gradient, heat flow, reservoir continuity, reservoir temperature, well depth, permeability and data quality.	Strong overlap with wells, platforms and subsea pipelines; currently the most relevant resource type for offshore reuse screening.
Abandoned-well-based resource	Mature, late-life or abandoned oil and gas fields with accessible wellbores. Santos et al. reviewed geothermal reuse of abandoned wells [1].	Casing/cement integrity, pressure history, completion structure, diameter, thermal loss, workover need and leakage control.	Can reduce drilling demand and enable pilot-scale demonstration, but only where integrity testing and liability management are satisfactory.
Enhanced or engineered geothermal resource	Low-permeability formations requiring stimulation or engineered circulation. Olasolo et al. reviewed EGS development and technical uncertainties [9]. Lu provided a global review of EGS development [10].	Stimulation risk, induced seismicity, reservoir sustainability, heat-extraction lifetime, offshore monitoring and regulation.	Longer-term option with higher technical and environmental uncertainty; may be relevant after resource and integrity data improve.

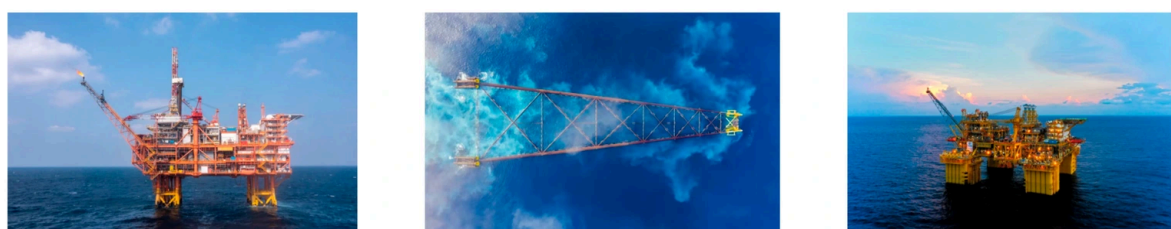
On this basis, target selection should be staged. Near-term offshore geothermal pilots are most likely to emerge in sedimentary basins where geothermal gradients, reservoir temperatures and existing oil-and-gas infrastructure overlap. Plate-margin systems may have stronger heat resources but weaker platform-reuse compatibility, while enhanced or engineered geothermal options require more stringent reservoir stimulation, monitoring and regulatory conditions.

3. Engineering Practice of Platform and Wellbore Reuse

3.1. Platform Reuse and Field-Image Interpretation

The reuse of offshore platforms requires both physical and institutional feasibility. Physically, a platform must have sufficient structural integrity, deck space, load-bearing margin, corrosion protection and access for installation and maintenance. Institutionally, the asset must have clear ownership, life-extension certification, environmental responsibility and decommissioning arrangements. Contreras Lopez et al. reviewed maintenance strategies for long-life structures and showed that inspection, structural health monitoring and condition-based maintenance are important means to support safe life extension and sustainability assessment [12]. This finding is relevant to offshore platform reuse because a repurposed platform must be evaluated through residual-life evidence rather than through design life alone.

Representative offshore platforms differ in deck space, wellhead access, jacket and foundation condition, module complexity and safety zoning (Figure 5). These physical constraints determine whether an existing asset can accommodate geothermal heat-extraction equipment, ORC modules, pumps, electrical systems or auxiliary low-carbon facilities.



(a) Enping 15-1 production platform.

(b) Haiji-2 offshore platform structure.

(c) Shenhai-1 platform.

Figure 5. Representative offshore platform assets relevant to geothermal or integrated-energy retrofit: (a) conventional production platform and deck space; (b) offshore jacket/foundation structure requiring residual-life assessment; (c) deepwater platform module layout and safety zoning. The photographs are used to illustrate reuse constraints and do not represent existing geothermal projects.

The engineering feasibility of platform reuse depends on the difference between original design conditions and new operating conditions. Oil and gas platforms were designed for hydrocarbon production loads, drilling or workover operations, accommodation, processing equipment and safety systems. A geothermal reuse project may reduce hydrocarbon-processing load but add heat conversion equipment, working-fluid loops, pumping units, cooling systems, storage batteries, electrolyzers or desalination units. Therefore, reuse is not simply an administrative decision to keep the platform in place; it requires structural recalculation, fatigue assessment, hazardous-area classification, fire and explosion safety review and maintainability analysis.

Amaechi et al. summarized asset-management issues for offshore facilities and emphasized that ageing structures require systematic inspection, risk ranking and life-extension planning rather than one-time visual judgement [13]. This point is particularly important for geothermal reuse because the expected project life may extend beyond the original oil and gas production plan. If the geothermal system is expected to operate for 20 years, the

platform must have a certified residual life that covers both normal operation and extreme environmental conditions.

3.2. Wellbore Reuse Heat Extraction Modes

Wellbore reuse is one of the most direct routes for offshore geothermal development because drilling is one of the largest cost components in geothermal projects. An existing well may already provide access to a hot formation, and its location near an offshore platform may reduce installation and logistics costs. Zhang et al. analyzed an offshore floating wind-geothermal integrated energy system for hydrogen production and showed that geothermal heat can become part of an offshore renewable energy configuration when heat extraction and conversion are matched with downstream energy demand [14].

Figure 6 illustrates the conceptual conversion from a conventional offshore oil and gas well to a geothermal reuse well. It highlights the reuse of casing, cement and perforated intervals, and the need to verify wellbore integrity before geothermal operation [1].

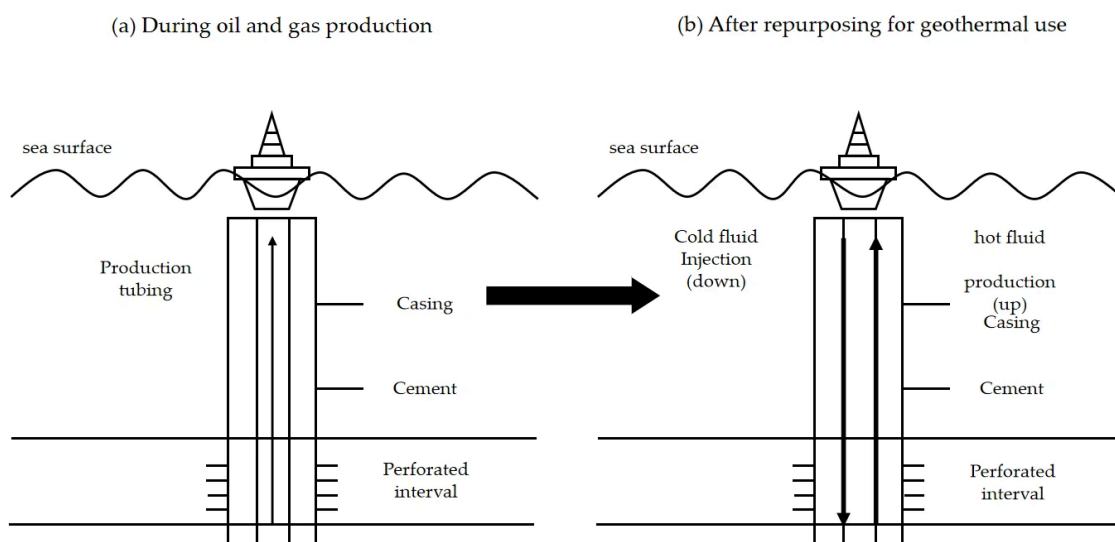


Figure 6. Conceptual illustration of repurposing abandoned offshore oil and gas wells for geothermal use [1].

Open-loop co-production and closed-loop wellbore heat exchanger systems are the two principal wellbore-based routes. In an open-loop system, formation fluid is produced to the surface, heat is extracted through a heat exchanger or power cycle, and the cooled fluid is reinjected. This route may provide higher thermal output, but it depends strongly on permeability, reservoir pressure, reinjection performance and brine chemistry. In a closed-loop WBHX system, the working fluid circulates within the wellbore and exchanges heat through the casing or internal heat exchanger without directly producing formation fluids. The closed-loop route reduces leakage and brine-disposal risks, but its heat output is often limited by the heat-transfer area, well depth, casing condition, flow rate and thermal insulation.

Figure 7 further compares the open-loop and closed-loop heat-extraction routes. The open-loop pathway depends on produced formation fluid and reinjection, whereas the closed-loop WBHX pathway circulates a working fluid without direct production of geothermal brine [1].

Zhao et al. conducted performance analysis and multi-objective optimization of an offshore renewable-energy-powered integrated energy supply system, demonstrating that offshore system design must coordinate resource availability, conversion devices and load

demand rather than optimize a single component in isolation [15]. This insight is directly relevant to wellbore reuse because the best heat-extraction mode depends not only on geothermal temperature but also on the downstream system. A platform that only requires heat for local thermal management may tolerate lower heat output than a platform that expects baseload electricity or hydrogen production. To further clarify the engineering differences among these heat-extraction routes, Figure 8 summarizes three representative wellbore-based configurations, including open-loop co-production, coaxial closed-loop WBHX and U-tube closed-loop WBHX.

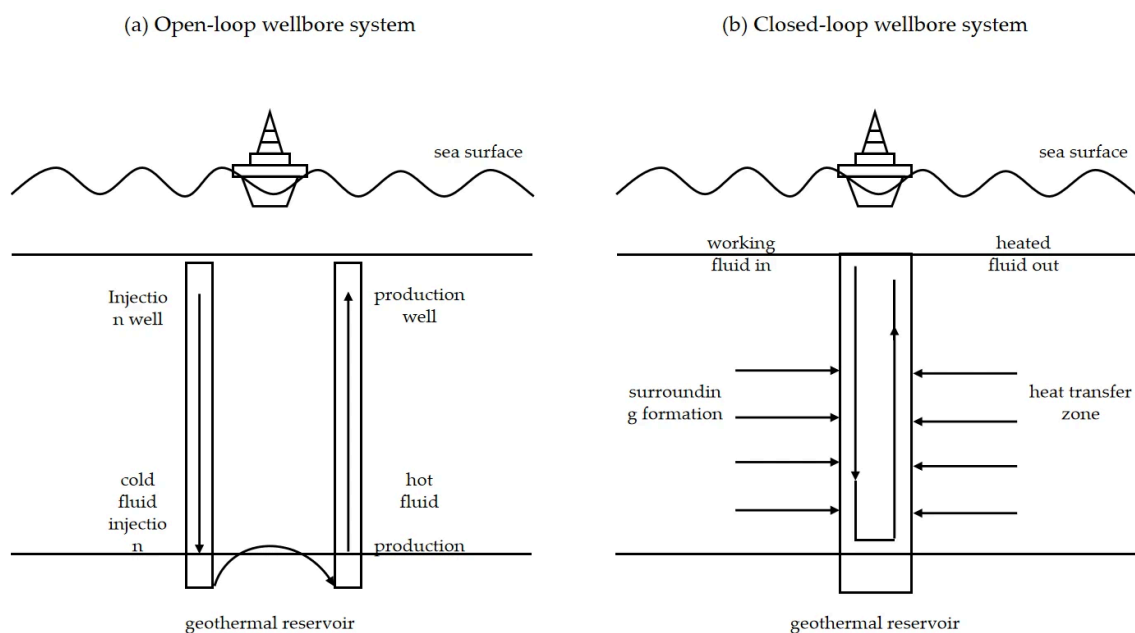


Figure 7. Structural configuration of repurposed offshore oil and gas wells for geothermal utilization, showing the physical layout of open-loop and closed-loop systems at the offshore platform and wellbore level [1].

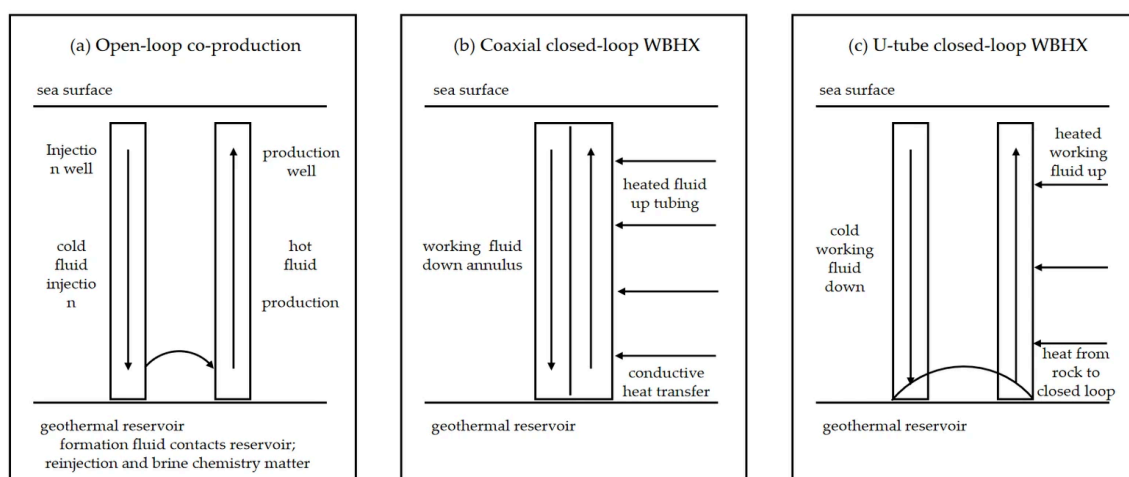


Figure 8. Wellbore-based offshore geothermal heat-extraction routes: (a) open-loop co-production with injection and production wells; (b) coaxial closed-loop WBHX; (c) U-tube closed-loop WBHX.

Micallef et al. reviewed renewable energy systems in offshore platforms and emphasized that offshore platform applications require attention to space, weight, corrosion, maintenance accessibility and safety constraints [16]. Their findings reinforce the need to evaluate wellbore reuse as part of platform-level energy system design. A technically

feasible heat-extraction system may still be unsuitable if its equipment layout conflicts with platform operation or maintenance windows.

3.3. Working Fluids for Closed-Loop Offshore Geothermal Systems

For closed-loop offshore geothermal systems, the working fluid is isolated from the formation and must be selected according to heat-transfer capacity, pressure drop, chemical stability, compatibility with casing and heat-exchanger materials, safety classification and offshore handling requirements. Water or water-glycol mixtures are simple and low-cost options for moderate temperatures. CO₂ or supercritical CO₂ may reduce pumping demand under suitable pressure–temperature conditions, but it introduces sealing, pressure-control and equipment-qualification requirements. Organic fluids can be efficient in surface ORC modules, but they are generally less suitable for long subsurface loops because of safety, leakage and thermal-stability concerns. Offshore applications should therefore treat working-fluid selection as a coupled thermodynamic, safety and maintainability decision rather than as a single efficiency optimization problem.

3.4. Corrosion, Scaling and Wellbore Integrity

Corrosion and scaling are among the most important barriers to offshore geothermal development. Geothermal brines may contain chloride, carbon dioxide, hydrogen sulfide, dissolved silica, carbonate, sulfate and metal ions. Offshore environments also expose equipment to salt spray, humidity, vibration and wave-induced dynamic loading. When geothermal fluids, old well materials and marine exposure are combined, the risk profile becomes more complex than that of conventional onshore geothermal systems.

Alias and Go analyzed the conversion of decommissioning platforms into offshore solar systems for green hydrogen production from seawater and emphasized that platform reuse must account for the harsh offshore environment and the durability of converted assets [17]. Although their study focuses on solar-to-hydrogen conversion, the durability issue is even more pronounced for geothermal systems because heat exchangers, valves, casings and pumps may contact high-temperature brines or undergo repeated thermal cycling.

Neumann et al. studied the role of a hydrogen network in Europe and showed that reuse of existing energy infrastructure can reduce system costs under certain conditions, but infrastructure substitution is never complete and must be assessed against technical limits [18]. This principle also applies to geothermal platform reuse. Existing wells and platforms can reduce costs, but they cannot eliminate the need for integrity testing, corrosion monitoring, material qualification or regulatory review.

Wellbore integrity is particularly critical because abandoned wells may have aged cement, corroded casing, unknown completion details or micro-annulus leakage paths. Thermal cycling can create additional stress in casing and cement. A closed-loop WBHX avoids direct fluid production but still depends on casing integrity and heat-transfer reliability. An open-loop system can extract more heat but requires more stringent fluid control and reinjection management. Figure 9 summarizes the corrosion-scaling-integrity mechanism. It shows that brine chemistry affects material response, which affects wellbore integrity and ultimately determines system availability and life-cycle cost.

Gea-Bermudez et al. analyzed offshore market design in an integrated North Sea energy system and showed that system value is sensitive to operational and market rules [19]. For geothermal reuse, system value is also sensitive to reliability. Frequent corrosion-related shutdowns can undermine any theoretical advantage in LCOE or LCOH. Therefore, economic assessment should include reliability-related parameters such as forced-outage rate, maintenance frequency, replacement interval and inspection cost.

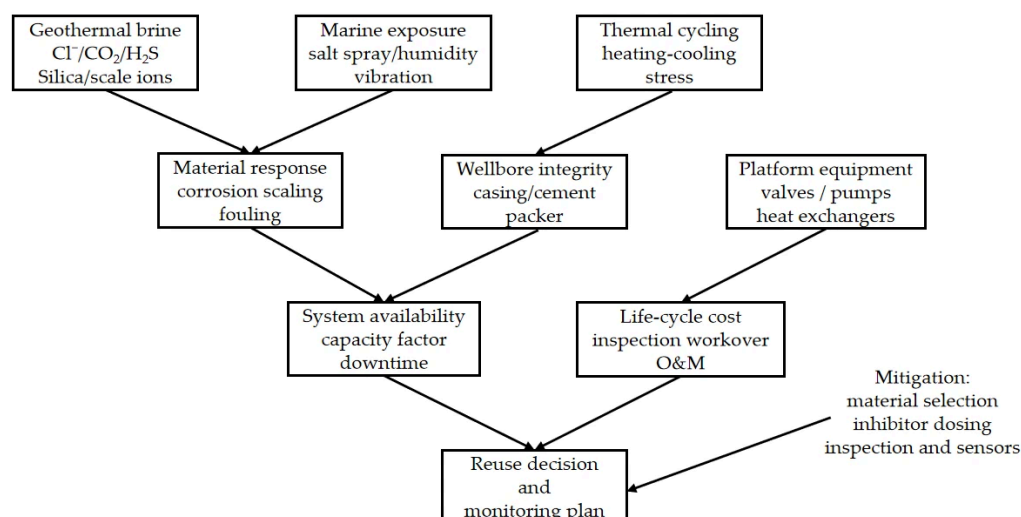


Figure 9. Corrosion-scaling-integrity mechanism for offshore geothermal reuse.

3.5. Platform Reuse Pathways

The most realistic near-term reuse pathway is not necessarily large-scale offshore geothermal power generation. In many mature offshore oil and gas fields, medium- and low-temperature geothermal resources may first be used for platform auxiliary heat, waste-heat recovery, thermal management, desalination or hybrid power support. High-temperature baseload electricity could be attractive in selected basins, but it requires stronger resource confirmation and larger conversion equipment.

Wang et al. reviewed in situ green hydrogen production from offshore wind farms and concluded that the offshore hydrogen chain is promising but still needs adaptation to variable marine environments, water treatment, storage and transport requirements [20]. Offshore geothermal energy can support this chain by providing stable heat or auxiliary power, improving electrolyzer utilization and reducing the storage burden required to smooth intermittent renewable generation.

In summary, platform and wellbore reuse should be evaluated through a staged pathway. The first stage is screening: temperature, well depth, structural condition, access and regulatory feasibility. The second stage is pilot operation: small-scale heat extraction, corrosion monitoring and operational data collection. The third stage is system integration: ORC, hydrogen, desalination, OTEC or platform electrification. The fourth stage is standardized deployment: repeatable engineering packages, verified risk models and bankable techno-economic assumptions.

4. Energy Conversion and Offshore Multi-Energy Complementary Systems

4.1. ORC and Binary-Cycle Conversion

Most offshore geothermal resources that overlap with oil and gas infrastructure are expected to be medium- or low-temperature resources. For this reason, binary cycles, especially the Organic Rankine Cycle (ORC), are more relevant than conventional flash-steam systems. In an ORC system, geothermal heat evaporates an organic working fluid with a relatively low boiling point. The vapor drives a turbine and generator, and the working fluid is then condensed and pumped back to the evaporator.

Figure 10 summarizes typical geothermal temperature ranges and corresponding utilization technologies. For resources below about 30 °C, a heat pump cannot operate solely from the low-temperature geothermal source; it requires external input electricity from the offshore grid, platform power system, offshore wind power or another auxiliary

source. In such cases, geothermal energy acts as the low-temperature heat source while electricity drives the compressor, and the feasibility should be evaluated using the coefficient of performance, available electricity price, offshore maintenance conditions and the temperature lift required by the final load [21].

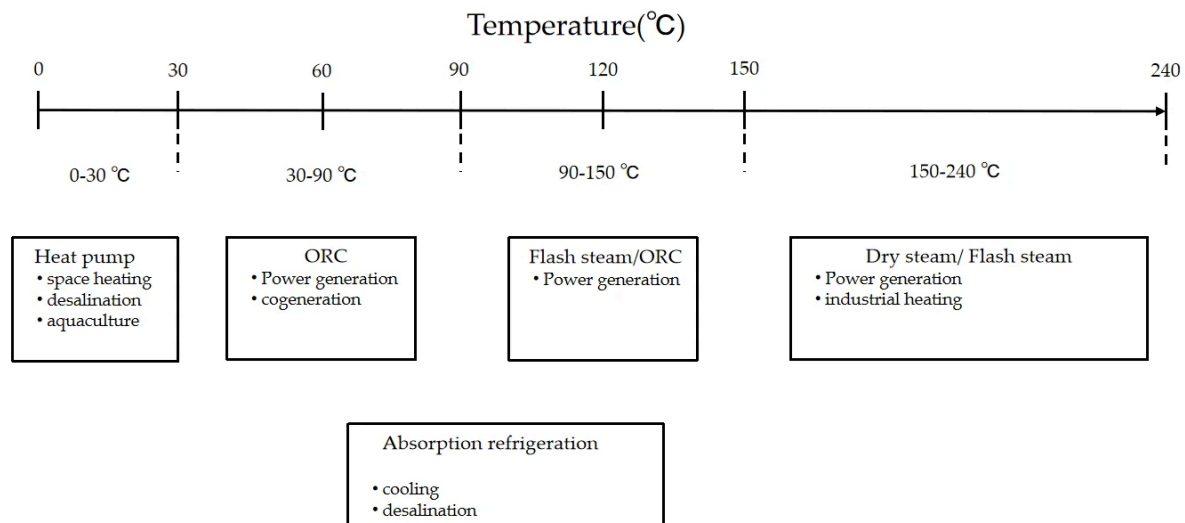


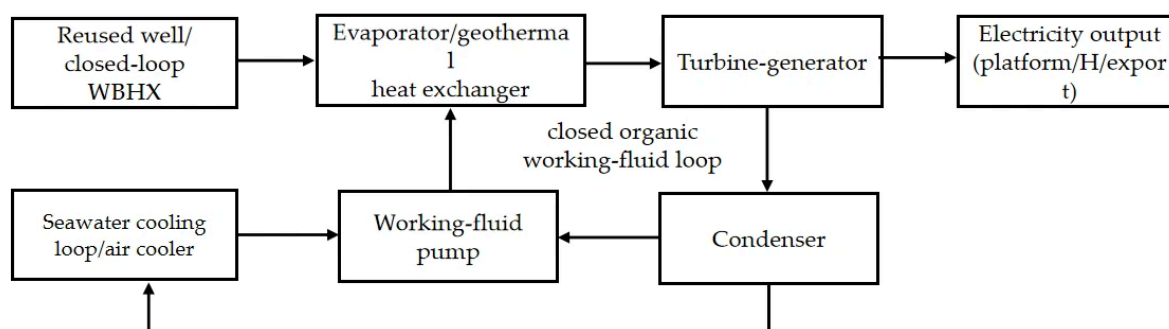
Figure 10. Typical temperature ranges and applicable energy conversion technologies for offshore geothermal resources [21].

Quoilin et al. reviewed ORC systems and identified working-fluid selection, cycle architecture, heat-exchanger design and operating strategy as key factors affecting performance [22]. These issues become more complex offshore because the available deck area is limited, maintenance access is difficult and equipment must be compact, modular and corrosion resistant. Tchanche et al. reviewed low-grade heat conversion using ORC technology and showed that ORC is suitable for converting low-temperature heat sources into power when the cycle is carefully matched with the heat-source temperature [23].

Hettiarachchi et al. studied optimum design criteria for ORC systems using low-temperature geothermal heat sources and emphasized that working-fluid thermodynamics, turbine inlet temperature and heat-exchanger pinch points strongly affect system efficiency [24]. These parameters are important for offshore geothermal applications because the heat source may be constrained by wellbore thermal loss, flow-rate limits and platform safety requirements. Franco and Villani analyzed the optimal design of binary-cycle power plants for geothermal applications and showed that binary systems must be optimized as whole plants rather than as isolated turbines or heat exchangers [25].

Figure 11 presents the ORC-based offshore geothermal power-generation principle. The schematic clarifies how geothermal heat from an existing well or WBHX can be transferred to an organic working fluid, converted into electricity and cooled by a seawater loop. It also highlights an offshore-specific issue: seawater is an abundant cooling sink, but its use increases corrosion-control requirements for condensers, piping and auxiliary systems.

Bina et al. reviewed geothermal power plant cycles and main components and showed that binary-cycle performance depends on both thermodynamic cycle selection and balance-of-plant configuration [26]. In offshore settings, balance-of-plant considerations include lifting and installation, module weight, hazardous-area zoning, vibration, remote monitoring and spare-part logistics. The ORC unit must therefore be selected not only for maximum efficiency but also for reliability and maintainability.



Geothermal heat is transferred to a closed ORC loop; the cooling sink is available offshore but requires corrosion-control design.

Figure 11. ORC-based offshore geothermal power-generation configuration for a reused well or closed-loop WBHX.

4.2. Coupling with Offshore Wind, Hydrogen and Storage

Offshore geothermal energy has greater system value when it is combined with intermittent marine renewables. Offshore wind power can provide large electricity output but fluctuates with wind conditions. Geothermal energy can provide a stable thermal or electrical baseline. Together, they can reduce the size of storage systems required to meet platform loads or to operate electrolyzers. Zhang et al. proposed a thermodynamic and techno-economic offshore floating wind-geothermal integrated energy system for hydrogen production, showing that geothermal energy can support more stable hydrogen production when combined with offshore wind [14].

For hydrogen production, the key value of geothermal energy is not only additional energy input. It can improve equipment utilization by reducing low-load periods, support desalination or water pretreatment through waste heat, and provide thermal management for electrolyzer systems. Offshore green hydrogen projects often face a trade-off between export cable expansion, offshore electrolysis, pipeline transport and storage. A geothermal baseload source may not eliminate this trade-off, but it can improve the operating profile of local equipment.

Zhao et al. demonstrated that offshore integrated energy systems can be optimized across multiple objectives, including energy supply, economic cost and environmental performance [15]. Their work supports the view that geothermal, wind, storage, hydrogen and water systems should be designed together. If an offshore platform only adds a geothermal module without revising dispatch logic, the system value may be limited. If the system is designed around coordinated electricity–heat–hydrogen–water flows, geothermal energy may improve both stability and utilization.

4.3. Coupling with OTEC and Desalination

In tropical and subtropical waters, geothermal systems may also be coupled with ocean thermal energy conversion and desalination. OTEC uses the temperature difference between warm surface seawater and cold deep seawater. Its cycle efficiency is usually low, but it can provide stable cold-water resources and sometimes freshwater co-products. When geothermal heat is added, the hot-side temperature of a coupled system can increase, while deep seawater can serve as a cooling sink for ORC condensation. This heat–cold matching may improve the overall performance of a multi-energy offshore hub.

Shelare et al. reviewed the role of geothermal energy in sustainable water desalination and emphasized that geothermal heat can support desalination processes in water-stressed regions when matched with suitable thermal technologies [27]. Offshore platforms and

energy islands often face freshwater limitations, making desalination a natural load for geothermal or waste-heat systems. Multi-effect distillation and membrane distillation are particularly relevant because they can use low-grade heat.

Karapekmez and Dincer modelled hydrogen production from hydrogen sulfide in geothermal power plants, showing that geothermal systems can be linked with hydrogen-related conversion pathways beyond simple power generation [28]. Although offshore geothermal hydrogen concepts remain early stage, such studies demonstrate that geothermal systems can be part of broader chemical and energy conversion networks.

Figure 12 clarifies the energy-flow relationship among geothermal heat, offshore wind power, hydrogen production, seawater desalination and OTEC. Zhang et al. showed that offshore floating wind and geothermal energy can be coupled for hydrogen production [14]. Zhao et al. demonstrated that offshore integrated energy systems should be optimized across energy supply, cost and environmental objectives [15]. Ma et al. provided a useful hybrid renewable CCHP design logic for coordinating multiple conversion routes [29]. On this basis, Figure 12 presents the offshore platform as an energy hub rather than a single-purpose geothermal generation unit.

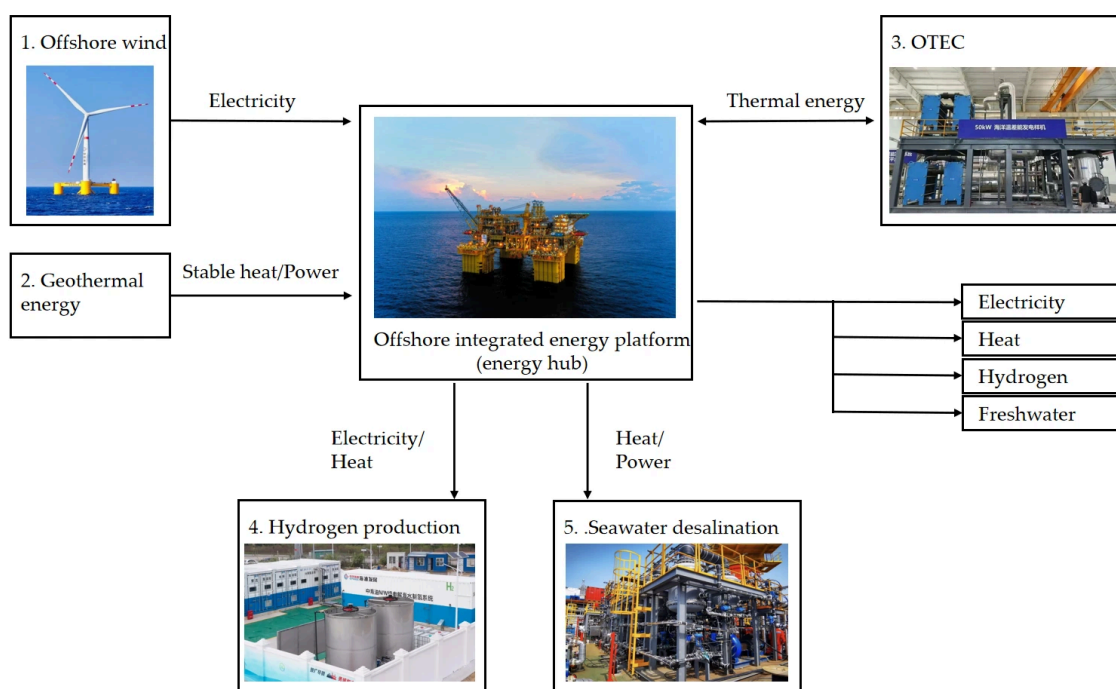


Figure 12. Schematic diagram of an offshore multi-energy complementary system integrating geothermal energy, offshore wind, OTEC, hydrogen production and desalination. The diagram is synthesized from offshore wind-geothermal hydrogen, offshore integrated-energy optimization and hybrid renewable CCHP design studies discussed in the text.

4.4. Critical Minerals and Resource Co-Development

Geothermal brines may contain lithium, boron and other critical minerals. Co-extraction is not yet a mature offshore business model, but it could improve the economics of selected geothermal projects and reduce scaling risk by removing certain dissolved components before reinjection. Kölbel et al. studied lithium extraction from geothermal brines in the Upper Rhine Graben and showed that brine chemistry, extraction technology and project economics must be assessed together [30].

Goldberg et al. analyzed challenges and opportunities for lithium extraction from geothermal systems in Germany and emphasized that reinjection of extraction brine is a key issue for long-term reservoir and environmental management [31]. This point is

relevant offshore because reinjection is already a major constraint for open-loop geothermal systems. If mineral recovery is introduced, it must be integrated with scaling control, brine handling, environmental monitoring and reinjection permits.

5. Techno-Economic and Environmental Performance

5.1. Cost Structure and Economic Feasibility

The economics of offshore geothermal energy are strongly affected by drilling cost, platform intervention cost, offshore installation cost, conversion efficiency and operating reliability. Reusing existing wells can reduce drilling investment, but it may also require expensive workover, testing, corrosion control and integrity remediation. Reusing a platform can avoid new offshore construction, but it may require life-extension certification, deck strengthening, module integration and updated safety systems.

Li et al. assessed the life-cycle sustainability and circularity of geothermal power plants and emphasized that sustainability evaluation must include material consumption, operational emissions, water use, circularity and end-of-life treatment [32]. For offshore geothermal systems, these boundaries are even more important because platform reuse changes both the capital-cost structure and the environmental burden allocation between decommissioning and new energy production.

Lund and Boyd reviewed direct utilization of geothermal energy worldwide and showed that geothermal heat can be used across a wide range of temperature levels, including direct heating, industrial heat and agricultural applications [33]. This finding is important for offshore systems because direct heat use may be more feasible than electricity generation in some medium-temperature settings. If a reused platform has thermal loads or can support desalination, geothermal energy may be valuable even when ORC electricity efficiency is modest.

Bertani reviewed geothermal power generation worldwide and showed that installed geothermal electricity capacity has historically been concentrated in regions with favorable high-temperature resources [34]. Offshore geothermal platform reuse is different: it may often involve lower-temperature resources, smaller-scale modules and hybrid use with offshore renewables. Therefore, its economic benchmark should not always be conventional high-temperature geothermal power plants. It should be compared with offshore alternatives such as diesel generation, gas-turbine self-generation, cable electrification, offshore wind plus batteries and hydrogen import.

Available quantitative studies provide several order-of-magnitude benchmarks for Section 5.1. Li et al. cited earlier geothermal-cost work indicating that the use of existing wellbores may reduce total geothermal capital costs by 42–95% because drilling requirements are reduced, but this estimate should be treated as an order-of-magnitude benchmark rather than a guaranteed offshore cost saving [3]. Quoilin et al. showed that drilling can account for up to 70% of the total investment cost of a geothermal ORC plant, and that auxiliary pumps in low-temperature geothermal ORC plants may consume 30% to more than 50% of gross power output [22]. For offshore platform retrofit studies, Alias and Go reported grid-connected LCOE values of 0.06–0.07 USD/kWh for a repurposed offshore-platform solar concept, whereas the battery-supported grid-connected case and the off-grid diesel-backup case increased to 1.10 and 0.29 USD/kWh, respectively; after the partial decommissioning cost was included, the LCOE values of the three scenarios were 0.68, 1.86 and 0.51 USD/kWh, and the corresponding LCOH values were 10.95, 27.45 and 14.53 USD/kg H₂ [17]. These values are not direct offshore geothermal LCOE results, but they show that offshore reuse economics are highly sensitive to drilling avoidance, storage or backup requirements, decommissioning boundaries and annual energy output.

Economic evaluation should be grounded in transparent, quantitative indicators rather than qualitative statements. For offshore geothermal repurposing projects, levelized cost metrics and life-cycle emission metrics are formulated below to disaggregate annualized capital investment, fixed and variable operation costs, workover and integrity management expenditures, and end-of-life decommissioning liabilities. The core cost and environmental performance indicators adopted in this review are expressed as Equations (1)–(4):

$$\text{LCOE} = \frac{\text{CAPEX} \times \text{CRF} + \text{OPEX}_{\text{fixed}} + \text{OPEX}_{\text{variable}} + C_{\text{workover}} + C_{\text{integrity}} + C_{\text{decommissioning}}}{E_{\text{annual}}} \quad (1)$$

$$\text{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (2)$$

$$\text{LCOH} = \frac{C_{\text{annualized}}}{H_{2,\text{annual}}} \quad (3)$$

$$\text{GHG}_{\text{LCA}} = \frac{\sum_{i=1}^m E_i}{E_{\text{annual}}} \quad (4)$$

where

LCOE: Levelized Cost of Electricity, representing the unit cost of net electricity generation over the full project lifecycle;

CAPEX: Total capital expenditure of the geothermal repurposing project, including platform retrofitting, well intervention and energy conversion system installation;

CRF: Capital Recovery Factor, a coefficient that converts upfront lump-sum capital investment into equal annual payments over the project lifetime;

OPEX_{fixed}: Annual fixed operational expenditure, covering routine inspection, platform management and fixed labor costs;

OPEX_{variable}: Annual variable operational expenditure, proportional to system output, including chemical agent consumption and utility costs;

C_{workover}: Annualized workover cost for wellbore maintenance and remedial operations;

C_{integrity}: Annualized wellbore integrity management and long-term monitoring cost;

C_{decommissioning}: Annualized end-of-life decommissioning and site restoration cost;

E_{annual}: Annual net electricity output of the geothermal system;

r: Nominal discount rate applied for techno-economic evaluation;

n: Design operational lifetime of the repurposed geothermal system, in years;

LCOH: Levelized Cost of Hydrogen, representing the unit cost of green hydrogen production from the integrated system;

C_{annualized}: Total annualized cost of the wind-geothermal-hydrogen coupled system;

H_{2,annual}: Annual net hydrogen production of the integrated energy system;

GHG_{LCA}: Life-cycle greenhouse gas emission intensity per unit of electricity generated;

$\sum_{i=1}^m E_i$: Cumulative greenhouse gas emissions across the full project lifecycle, covering emissions from (or avoided by) drilling, platform retrofitting, material manufacturing, system operation, chemical treatment, maintenance vessel mobilization and end-of-life decommissioning activities.

Here, CRF is the capital recovery factor, *r* is the discount rate, *n* is the project lifetime, E_{annual} is annual net energy output, H_{2,annual} is annual hydrogen output, and $\sum_{i=1}^m E_i$ includes drilling or avoided drilling, platform retrofitting, materials, operation, chemical treatment, maintenance-vessel mobilization and end-of-life activities. Li et al. showed that abandoned-well reuse can reduce environmental burdens only when the avoided drilling benefit is not offset by poor system performance [3]. Li et al. further emphasized the importance of circularity and life-cycle boundaries in geothermal power assessment [32]. Frick et al. demonstrated that binary geothermal LCA results are sensitive to reservoir productivity and plant efficiency [35]. Bravi and Basosi showed that drilling, plant construction and

fluid management can remain important environmental contributors even when operational emissions are low [36]. Table 2 summarizes the main cost drivers and uncertainty sources.

Table 2. Main cost drivers and uncertainty sources for offshore geothermal platform reuse.

Assessment Item	Main Variables	Uncertainty Source	Suggested Treatment
Resource and well	Temperature, flow rate, depth, pressure	Sparse offshore thermal and integrity data	Use probabilistic resource-engineering screening
Platform retrofit	Deck space, weight, residual life, safety zoning	Incomplete ageing and fatigue records	Conduct life-extension certification and sensitivity analysis
Conversion system	ORC efficiency, cooling, working fluid, modularity	Offshore corrosion and O&M accessibility	Compare compact modular designs with reliability penalties
Multi-energy value	Hydrogen, freshwater, heat and export electricity	Market price and by-product revenue uncertainty	Use scenario-based TEA and transparent boundaries
Environment and risk	Brine leakage, inhibitors, replaced materials	Limited offshore geothermal LCA datasets	Apply full-process monitoring and LCA with uncertainty ranges

Table 3 summarizes representative quantitative values that can be used as benchmarks for offshore geothermal reuse. Because field-scale offshore geothermal platform-reuse projects remain rare, the table distinguishes direct abandoned-well geothermal evidence from adjacent offshore platform retrofit and geothermal co-product studies.

Table 3. Representative quantitative economic and environmental values reported in the literature.

Literature Context	Reported Quantitative Values	Implication for Offshore Geothermal Reuse
Abandoned-well geothermal LCA [3]	Li et al. reported climate-change potential of 10.9 g CO ₂ -eq/kWh for the business-as-usual geothermal case (GEObau), and 9.3, 8.4 and 7.2 g CO ₂ -eq/kWh for R-GEOdouble, R-GEOsingle and R-GEOsemi, respectively. These values correspond to 15%, 23% and 34% reductions relative to GEObau. Their breakeven analysis indicates that if repurposed systems reach a 30-year lifetime, about 85% of the impact indicators could become comparable with GEObau, although the authors note that this remains uncertain.	The climate benefit mainly comes from reduced drilling. Overall performance remains sensitive to project lifetime, annual electricity output, ORC construction, unplugging, re-casing and re-cementing requirements for completely abandoned wells, and end-of-life treatment.
Geothermal ORC cost structure [3,22]	Li et al., citing earlier geothermal-cost work, noted that existing wellbores could reduce geothermal capital costs by 42–95%. Quoilin et al. reported that drilling can account for up to 70% of total investment cost in geothermal ORC plants, and that auxiliary pumps in low-temperature geothermal ORC systems may consume 30% to more than 50% of gross output.	Well reuse can be economically meaningful only when saved drilling cost exceeds workover, integrity management, pumping-energy demand and offshore O&M penalties. The 42–95% value should therefore be treated as a benchmark for sensitivity analysis, not as a guaranteed offshore cost reduction.

Table 3. *Cont.*

Literature Context	Reported Quantitative Values	Implication for Offshore Geothermal Reuse
Offshore platform renewable retrofit benchmark [17]	Alias and Go reported 0.06–0.07 USD/kWh for grid-connected offshore-platform PV cases. The battery-supported grid-connected case and off-grid diesel-backup case reached 1.10 and 0.29 USD/kWh, respectively. After partial decommissioning costs were included, the three scenario LCOE values were 0.68, 1.86 and 0.51 USD/kWh, and the corresponding LCOH values were 10.95, 27.45 and 14.53 USD/kg H ₂ .	Although this is not a geothermal case, it quantifies the sensitivity of offshore retrofit projects to grid connection, storage, backup power, decommissioning boundary and annual utilization.
Geothermal-lithium co-product assessment [37]	With geothermal lithium extraction, Weinand et al. found average total annual cost reductions of 22.4 M EUR/a across Upper Rhine Graben municipalities, with a best-case negative annual cost of −54 M EUR. The model estimated 450–3900 t/a of Li ₂ CO ₃ production in suitable locations and, for about 30 plants, avoided emissions of about 800 kt CO ₂ -eq/a, or 24 Mt CO ₂ -eq over 30 years, relative to conventional hard-rock lithium procurement.	Co-product revenue can change project economics, but the reported values are based on Upper Rhine Graben geothermal-lithium systems. Offshore brine chemistry, separation equipment, discharge risk, reinjection compatibility and permitting must be verified before assuming comparable benefits.

5.2. Environmental Impacts and Life-Cycle Performance

Explicit environmental values from the reviewed literature help clarify the magnitude of possible emission mitigation from well reuse. Li et al. quantified the climate-change potential of a business-as-usual geothermal plant as 10.9 g CO₂-eq/kWh, compared with 9.3, 8.4 and 7.2 g CO₂-eq/kWh for repurposed double-well, single-well and semi-abandoned-well systems, respectively [3]. These values correspond to reductions of 15%, 23% and 34% relative to the business-as-usual geothermal benchmark. The same study showed that the construction stage contributed more than 70% of the climate-change potential in all options. For the repurposed systems, the lower climate-change potential was mainly linked to reduced drilling, while ORC unit construction became the main construction-stage contributor, accounting for 65%, 73% and 97% of construction-stage climate-change potential in the double-well, single-well and semi-abandoned-well cases, respectively [3]. This means that avoided drilling is beneficial, but high ORC material intensity, short lifetime or low annual electricity output can erode part of the life-cycle advantage.

For co-product pathways, Weinand et al. estimated that lithium extraction integrated with deep geothermal plants could avoid about 800 kt CO₂-eq annually in the Upper Rhine Graben if approximately 30 geothermal-lithium plants were implemented, corresponding to about 24 Mt CO₂-eq over a 30-year lifetime [37]. This estimate was based on avoiding conventional hard-rock lithium procurement, for which a carbon footprint of about 15.8 kg CO₂-eq per kg lithium carbonate equivalent was assumed. The same study also discussed lower carbon-footprint values reported for brine-based lithium extraction pathways, including about 0.3 kg CO₂-eq per kg lithium carbonate equivalent for South American brine deposits and about 3.2–3.3 kg CO₂-eq per kg lithium carbonate equivalent in another brine-extraction assessment [37]. These values should not be transferred directly to offshore projects, but they demonstrate why Section 5.2 evaluates avoided drilling, avoided decom-

missioning, chemical treatment, brine management, vessel mobilization and end-of-life responsibility together.

The environmental performance of offshore geothermal energy depends on avoided drilling, avoided platform removal, reduced fossil-fuel consumption, brine management, chemical use and equipment lifetime. Frick et al. conducted a life-cycle assessment of geothermal binary power plants and showed that environmental impacts are sensitive to reservoir performance, plant efficiency and drilling requirements [35]. For offshore geothermal reuse, reducing drilling can provide a major benefit, but frequent equipment replacement or chemical treatment may offset part of that advantage.

Bravi and Basosi assessed the environmental impact of electricity from selected geothermal power plants and showed that geothermal systems can have low operational emissions but may still have non-negligible impacts related to drilling, fluid management and plant construction [36]. Offshore geothermal systems should therefore be evaluated through full life-cycle accounting. In addition, brine leakage, chemical inhibitors, heavy metals and marine ecological sensitivity should be explicitly included in environmental assessment.

Kölbel et al. studied lithium extraction from geothermal brines and suggested that mineral recovery can create additional value, but it also requires careful brine management and process integration [30]. In offshore settings, the environmental threshold may be higher because accidental discharge could affect marine ecosystems. Therefore, mineral co-extraction should be treated as an optional pathway rather than as an assumed benefit.

5.3. Reliability, Safety and Risk Governance

Reliability is central to offshore economic performance. Maintenance windows are constrained by weather, vessel availability and safety procedures. A small component failure can require expensive mobilization. In geothermal systems, the most important reliability issues include heat-exchanger fouling, pump failure, working-fluid leakage, corrosion, scaling, sensor drift and wellbore integrity degradation.

Allahvirdizadeh reviewed geothermal well integrity issues and emphasized that casing, cement sheath, packer systems, thermal cycling and corrosive fluids can all affect long-term geothermal well safety [38]. This finding supports the need for dedicated offshore integrity models before a hydrocarbon well is repurposed for geothermal operation.

Weinand et al. showed that low-carbon lithium extraction can improve the competitiveness of deep geothermal plants under selected future energy-system conditions [37]. This result suggests that economic outcomes depend on multi-product value and market assumptions, which should be tested through sensitivity analysis rather than assumed as an automatic benefit.

Stringfellow and Camarillo examined solid wastes from geothermal energy production in the context of direct lithium extraction and showed that geothermal operations can generate mineral-rich waste streams requiring dedicated management [39]. Offshore projects must therefore consider how scale, sludge, spent inhibitors, filters and replaced components will be handled at sea or transported to shore.

6. Research Gaps and Future Perspectives

The first research gap concerns demonstration scale and target selection. Offshore geothermal reuse is still largely at the conceptual or early assessment stage, and there are few public field-scale demonstrations based on abandoned offshore wells and existing platforms. Public studies can support basin-scale screening, but many well-level data on casing condition, cement quality, pressure history, flow potential and platform residual life remain commercially sensitive. Therefore, future work should combine public geothermal-

gradient and heat-flow assessment with confidential asset screening under appropriate data-protection arrangements.

The second gap concerns offshore multi-energy integration. Offshore geothermal reuse should be assessed together with offshore wind power, hydrogen production, desalination, OTEC and platform electrification, because system value depends on coordinated electricity–heat–hydrogen–water flows rather than on a single technology. Braga et al. showed that converting offshore oil and gas infrastructure into renewable-energy assets requires both technical feasibility assessment and decommissioning-delay economic analysis [40]. Future studies should therefore clarify load profiles, dispatch logic, conversion efficiency, storage requirements and interface constraints when evaluating offshore geothermal systems as part of integrated energy hubs.

The third gap concerns heat-extraction physics and working-fluid selection. Adams et al. compared CO₂ plume geothermal and brine geothermal systems under varying reservoir conditions [41]. Randolph and Saar proposed coupling geothermal energy capture with geological CO₂ sequestration, which provides a useful reference for CO₂-based geothermal concepts [42]. Gringarten et al. established fundamental theory for heat extraction from fractured hot dry rock [43]. Olasolo et al. reviewed enhanced geothermal systems and summarized their technical development status [9]. Lu provided a global review of enhanced geothermal systems and highlighted the importance of reservoir creation and heat-extraction sustainability [10]. Limberger et al. assessed the prospective resource base for enhanced geothermal systems in Europe [44].

The fourth gap concerns offshore-specific conversion, safety and assessment boundaries. Pruess proposed the use of CO₂ as a working fluid for enhanced geothermal systems and identified its potential for simultaneous energy generation and carbon storage [45]. Saleh et al. screened working fluids for low-temperature ORC systems and showed that fluid properties strongly affect cycle performance [46]. Chen et al. reviewed thermodynamic cycles and working fluids for low-grade heat conversion [47]. Bao and Zhao reviewed working-fluid and expander selection for ORC systems [48]. DiPippo assessed binary geothermal power plants through second-law analysis, which remains relevant for medium-temperature offshore geothermal conversion [49].

The fifth gap concerns environmental accounting and project bankability. Self et al. reviewed geothermal heat-pump systems and compared them with other heating options, which is relevant when very low-temperature offshore resources require electrically driven heat pumps [50]. Bayer et al. quantified greenhouse-gas savings from ground-source heat-pump systems and showed that environmental benefits depend on electricity mix and system boundary assumptions [51]. Shortall et al. reviewed sustainability-assessment frameworks for geothermal energy and emphasized the need to integrate environmental, economic and social indicators [52]. Chamorro et al. estimated the technical and sustainable potential of enhanced geothermal systems in Europe, illustrating how resource assessment can be linked with realistic sustainability constraints [53]. These studies indicate that future offshore geothermal TEA/LCA should explicitly report residual platform life, workover cost, well success rate, flow rate, capacity factor, working-fluid selection, O&M cost, discount rate and decommissioning responsibility.

7. Conclusions

This paper reviewed offshore geothermal energy and the reuse of oil and gas platforms for integrated offshore energy systems. The central conclusion is that offshore geothermal development should be understood as a resource-engineering-system problem rather than only as a subsurface heat-resource problem. The reviewed offshore-basin evidence indicates that sedimentary basins with hydrocarbon development history can provide meaningful

geothermal potential, especially where geothermal gradients, heat-flow conditions, reservoir temperatures, existing wells and platform access overlap. However, resource potential alone does not guarantee project feasibility without well integrity, platform life-extension, corrosion control, conversion efficiency and economic boundary assessment.

The reuse of abandoned wells can reduce drilling demand and shorten development cycles, but its success depends on casing condition, cement quality, thermal loss, corrosion, scaling and pressure management. Open-loop systems may provide higher heat output, while closed-loop WBHX systems offer better fluid-containment performance. The selection between these routes should be based on reservoir properties, brine chemistry, environmental sensitivity and downstream energy demand.

The reuse of offshore platforms can provide deck space, access, power systems, maintenance logistics and connection to surrounding offshore energy resources. Nevertheless, platform reuse is constrained by structural fatigue, load margin, corrosion, safety zoning, life-extension certification and regulatory liability. Field photographs are useful only when their engineering meaning is explained. Therefore, this revised paper adds text descriptions and schematic diagrams to clarify what each platform or well image represents.

Medium- and low-temperature geothermal resources are most likely to be converted through ORC or binary-cycle systems. Coupling geothermal output with offshore wind, hydrogen production, desalination, OTEC and possibly mineral recovery can improve system stability and equipment utilization. However, multi-generation should be justified by actual load demand and project conditions, not assumed as automatic value creation.

The major future research priorities include field-scale offshore demonstration, standardized resource-engineering classification, long-term integrity monitoring, corrosion-resistant materials, comparable TEA/LCA models, risk-based regulatory frameworks and digital operation and maintenance. If these gaps are addressed, offshore geothermal energy may become an important component of low-carbon offshore energy hubs and a practical pathway for extending the life-cycle value of mature oil and gas infrastructure.

Author Contributions: Conceptualization, J.M. and L.G.; methodology, J.M. and L.L.; formal analysis, J.M., L.L. and N.S.; investigation, J.M. and L.L.; resources, J.M. and L.L.; data curation, L.L.; writing—original draft preparation, J.M. and L.L.; writing—review and editing, N.S. and L.G.; visualization, L.L. and N.S.; supervision, L.G.; project administration, J.M.; funding acquisition, L.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: Authors Jie Ma and Lintong Liu were employed by CNOOC Energy Economics Institute. The remaining authors declare no conflicts of interest. This statement is made for transparency only and merely indicates that some authors are affiliated with a company; it does not imply any vested interest, commercial interest or financial influence on the interpretation of the reviewed literature. The views expressed in this review are those of the authors and do not necessarily represent the official position of their affiliated institutions.

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