Discussion Paper

Techno-Economic Evaluation of Shallow Geothermal Cooling in Saudi Arabia

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Key Points

- Cooling is a major driver of electricity demand and emissions in Saudi Arabia, creating grid stress and highlighting the need for high-efficiency cooling solutions.
- Ground source heat pumps (GSHPs) deliver much higher efficiency than conventional HVAC units, with seasonal COPs around 5.0 and 40%-50% lower electricity use.
- At scale, geothermal cooling can deliver large system benefits, including 7-9 TWh/year electricity savings and 3-7 Mt CO_2 reductions under a 40% penetration scenario.
- Despite higher upfront costs, geothermal systems are economically competitive, achieving levelized cooling costs of $20-$45/MWh-th and payback periods of 5-12 years in suitable applications.
- Geothermal cooling significantly reduces water use and improves reliability, nearly eliminating cooling-tower water consumption and maintaining performance under extreme heat.
- Wider deployment depends on enabling conditions, including site-specific geology, supportive policies, streamlined permitting, and innovative financing models.

Abstract

Saudi Arabia's rapidly growing cooling demand, driven by harsh climatic conditions, urban expansion, and rising living standards, places increasing strain on the national electricity grid and contributes to higher carbon emissions. This study evaluates the technical, economic, and environmental feasibility of shallow geothermal cooling using ground source heat pumps (GSHPs) as a high-efficiency alternative to conventional air-based heating, ventilation, and air-conditioning (HVAC) systems in the Kingdom. Drawing on field data, thermal response tests, aquifer pumping trials, and detailed techno-economic modeling, the analysis develops a standardized evaluation framework and applies it to representative case studies on the Eastern and Western coasts. Results show that geothermal systems consistently achieve seasonal coefficients of performance (SCOP) near 5.0, almost double those of conventional HVAC systems, reducing electricity consumption by 40%-50% and significantly lowering CO_2 emissions. Regional extrapolation using measured performance and building-stock electricity profiles indicates that achieving a 40% penetration rate across commercial and governmental facilities could reduce national electricity demand by approximately 7-9 terawatt-hours (TWh) annually, avoid 3-7 million metric tons (Mt) of CO_2 emissions, and defer substantial grid-capacity investments. Economic assessments indicate levelized cooling costs of $20-$45/MWh-th, payback periods of 5-12 years, and favorable life-cycle returns, particularly in large, continuously operated buildings. Despite these advantages, high upfront costs, largely associated with drilling and subsurface works, remain a key barrier, alongside financing constraints and integration challenges in existing infrastructure. Overall, shallow geothermal cooling could support Saudi Arabia's energy-efficiency and decarbonization goals, though its contribution will depend on site-specific geological conditions, supportive policies, streamlined permitting, and risk-mitigating financing mechanisms.

Keywords: Cooling, Energy Efficiency Geothermal Cooling, Air Conditioning, Buildings

List of Acronyms

ATES	Aquifer thermal energy storage
BMS	Building management system
CCE	Circular carbon economy
CaaS	Cooling as a Service
COP	Coefficient of performance
EER	Energy efficiency ratio
ESIA	Environmental and social impact assessment
GSHPs	Ground source heat pumps
GW	Gigawatts
HVAC	Heating, ventilation, and air-conditioning
IRR	Internal rate of return
MEPS	Minimum energy performance standards
MENA	Middle East and North Africa
Mt	Metric tons
NPV	Net present value
NREP	National Renewable Energy Program
PLC	Programmable logic controller
PPPs	Public-private partnerships
R&D	Research and development
SASO	Saudi Standards, Metrology and Quality Organization
SBC	Saudi Building Code
SCOP	Seasonal coefficient of performance
SEEC	Saudi Energy Efficiency Center
SERA	Saudi Electricity Regulatory Authority
TRTs	Thermal response tests
TWh	Terawatt-hours

Introduction

01

Shallow geothermal systems have been used commercially for decades and have gained renewed attention in recent years as sustainable, high-efficiency solutions for space heating and cooling, particularly in regions with substantial air-conditioning demand, such as the Middle East. By 2020, the installed capacity of ground source heat pumps (GSHPs), a core component of shallow geothermal systems, reached 77 gigawatts thermal (GWth) worldwide (Lund, Huttrer, and Tóth 2022).

Previous studies show that GSHPs typically reduce electricity consumption by 30%-60%, translating into cost savings of up to 48%. Moreover, accelerated adoption of heat pumps could reduce carbon emissions by approximately 500 million metric tons of CO_2 when deployed at scale across residential and commercial sectors in the United States (IEA 2022).

The spillover effects of shallow geothermal technology adoption are increasingly evident beyond early markets. Countries with arid, hot climates across the Middle East and North Africa (MENA) are exploring shallow geothermal applications for cooling in response to growing concerns over energy efficiency and grid reliability (Mahmoud et al. 2024). In Saudi Arabia, where cooling accounts for the majority of electricity demand, shallow geothermal systems present an opportunity to support integrated building energy strategies. In addition to reducing electricity consumption, deployment of these systems could significantly lower peak loads, decrease carbon emissions, and support national objectives to diversify energy sources and reduce dependence on hydrocarbons for power generation.

Saudi Arabia is experiencing substantial urban expansion, particularly in rapidly growing cities such as Riyadh, where large-scale infrastructure and housing developments are advancing quickly. This urbanization, combined with rising living standards, is significantly increasing demand for space cooling across residential, commercial, and institutional facilities (Belaïd and Mikayilov 2025). Concentrated growth in major cities intensifies energy consumption patterns, placing increasing stress on the national electricity grid and heightening the urgency for sustainable cooling solutions. These trends pose challenges for power system capacity, peak-load management, and long-term sustainability.

Although all cooling technologies rely on electricity, conventional HVAC systems – ranging from split units in residential buildings to central chillers in large building complexes – tend to consume significantly more energy, especially during peak summer months. This higher consumption increases grid stress and operating costs and contributes to elevated carbon emissions. Improving cooling efficiency therefore represents a major opportunity for energy

savings, peak-demand reduction, and progress toward national emissions targets.

Despite growing interest in shallow geothermal systems, implementation remains strongly influenced by site-specific geological, hydrological, and urban-infrastructure conditions. Ground-temperature stability, subsurface thermal conductivity, and groundwater availability vary widely across regions, affecting both system performance and economic feasibility. In many parts of the Middle East, subsurface conditions range from conductive sedimentary formations to fractured volcanic terrains and deep aquifers, requiring careful site characterization to ensure long-term performance. These uncertainties, together with the specialized drilling and engineering expertise required, contribute to higher upfront costs relative to conventional cooling systems.

Broader energy-system dynamics in Saudi Arabia also shape the case for geothermal adoption. Potential benefits must be evaluated alongside local electricity tariffs, as relatively low tariffs can weaken private investment incentives by reducing the financial returns from electricity savings, despite potential system-level benefits. These considerations intersect with evolving power-sector decarbonization pathways and the rapid deployment of renewable energy. As solar and gas-fired capacity expands, the value of efficiency gains becomes increasingly sensitive to tariff structures and regulatory changes. Assessing geothermal cooling therefore requires not only technical analysis but also alignment with long-term energy-system planning.

Integration challenges further influence feasibility. Many existing buildings in Saudi Arabia were not designed to accommodate well fields, boreholes, or geothermal mechanical configurations. Retrofitting can be constrained by limited land availability, structural layouts, and conflicts with underground utilities. In greenfield projects, although integration is more flexible, developers must weigh geothermal options against capital allocation, land use planning, and life-cycle cost considerations.

Given these complexities, a systematic techno-economic evaluation tailored to Saudi Arabia's climatic and geological conditions is essential. Such an assessment can help identify where shallow geothermal cooling is technically and economically viable and where alternative solutions may remain more suitable.

02 Overview of Shallow Geothermal Technology

There are various shallow geothermal configurations, each with its own advantages and disadvantages (the most common configurations are summarized in Table 1). When compared with conventional HVAC systems, shallow geothermal systems operate under fundamentally different principles that influence performance and resource use. Airsource systems exchange heat with outdoor air, which in Saudi Arabia can reach extremely high temperatures in summer.

Under such thermal stress, these systems often experience reduced efficiency, as performance declines when outdoor temperatures approach or exceed the indoor set point. In contrast, GSHPs use the relatively stable subsurface temperature as a heat sink, which remains significantly cooler than ambient air during peak cooling seasons. This thermal stability supports more consistent operating conditions and reduces the need for oversizing or auxiliary cooling.

Similarly, cooling tower systems employ evaporative cooling mechanisms, relying on large volumes of water to reject heat. This method, although effective, can be resource-intensive, particularly in arid environments such as Saudi Arabia, where water scarcity is a significant concern. These systems also require regular maintenance and chemical treatment to prevent scaling and microbial contamination. By comparison, GSHPs typically use closed-loop systems with minimal water consumption, reducing exposure to environmental constraints and operational risks. These differences in operational mechanisms highlight the suitability of GSHPs for long-term, efficient cooling in hot and dry climates (U.S. EPA 2017).

Table 1. Types of geothermal configurations.

System type	Description	Key characteristics
Open-loop system	Draws groundwater directly from a well, passes it through a heat exchanger, and then discharges it back into the ground or into another body of water.	Highly efficient but dependent on local groundwater availability and water quality.
Closed-loop system	Circulates a heat-transfer fluid through a closed network of pipes installed horizontally or vertically underground. The fluid absorbs or dissipates heat depending on the operating mode.	Most commonly used in residential and commercial applications because the system is environmentally contained.
Standing column well system	A hybrid of open- and closed-loop systems that uses a single well for both water extraction and reinjection, with partial recirculation of the extracted water.	Well suited to deep bedrock conditions often found in urbanized or mountainous regions.

A typical GSHP system includes the following key components:

- A ground heat exchanger, such as a borehole or loop field, that facilitates heat transfer between the earth and the refrigerant loop.
- A heat pump unit responsible for compressing and expanding the refrigerant to absorb or reject heat from the conditioned space.
- An indoor distribution system, typically consisting of air ducts or hydronic networks, that delivers conditioned air or water.
- Control and monitoring equipment that optimizes system performance and manages energy use.

Literature Review

03

Technical studies on shallow geothermal applications in hot-arid environments in the MENA region have gained momentum in recent years, driven by growing interest in energy efficiency and climate resilience. A review of shallow geothermal system fundamentals for hot climates emphasizes the importance of accurate ground thermal property data and hybrid system solutions to ensure long-term performance (Mahmoud et al. 2024).

Experimental campaigns in the United Arab Emirates have validated the thermal performance of vertical GHEs under high cooling loads, showing that deeper boreholes and high-conductivity grouts significantly improve coefficients of performance (COP) and seasonal performance factors (Mahmoud et al. 2024). Simulation studies by Ougazzou et al. (2024) indicate that shallow geothermal systems can reduce households' annual electricity bills by at least 20% in Morocco. In Jordan, a simulation study shows that GSHPs have the potential to reduce annual operating and maintenance costs by up to 60% in residential buildings (Al-Khasawneh, Albatayneh, and Althawabiah 2019). In addition, GSHPs in that study demonstrated a potential reduction in CO_2 emissions by 70%, relative to conventional systems. Hybrid systems mitigate thermal imbalance by injecting solar heat in winter, thereby improving annual efficiency and ground temperature stability (Jaafar and Maragna 2021).

The literature on space cooling and geothermal technologies in Saudi Arabia, in particular, reflects growing recognition of the sector's energy and emissions challenges, as well as the potential for innovative low-carbon solutions. A recent KAPSARC study highlighted that low- to medium-temperature geothermal gradients exist in many parts of the western region and could support direct-use applications such as cooling and desalination (Alsuwailem et al. 2024a).

Recent building energy efficiency studies have further emphasized the critical importance of retrofitting and optimized design to enhance cooling energy efficiency. Krarti, Dubey, and Howarth (2017) conducted a bottom-up simulation of the Saudi building stock and found that even basic improvements in cooling energy efficiency could reduce electricity consumption by more than 10 TWh annually and peak demand by 2.3 gigawatts (GW). These savings are especially relevant given that over 70% of buildings in the Kingdom lack proper thermal insulation (Alshahrani and Boait 2019). Their study also highlighted the role of behavioral interventions and smart thermostats in curbing peak electricity loads, particularly in Riyadh, where occupancy-driven HVAC usage is widespread.

Studies also highlight numerous barriers that hinder the adoption of shallow geothermal technology. High capital costs, uncertain resource characterization, and regulatory gaps are repeatedly cited as deterrents in both global and local literature (Ramos-Escudero and García-Cascales 2022; Bhatnagar et al. 2022). The importance of establishing national targets, clear permitting pathways, and incentive schemes has

been emphasized as necessary for scaling geothermal in the Saudi context (Alsuwailem et al. 2024b). Moreover, the oil and gas sector's technical capabilities in drilling and subsurface management offer opportunities to accelerate geothermal adoption, primarily through public-private partnerships and risk-sharing frameworks.

In summary, existing studies show that shallow geothermal systems offer promising efficiency gains for hot-arid regions, but empirical evidence, particularly in Saudi Arabia, remains limited. Key gaps include reliable ground thermal data, standardized performance assessments, and locally adapted system designs. Addressing these gaps will require coordinated data collection efforts, targeted innovation, and well-structured pilot projects to validate performance and reduce uncertainty. Such initiatives are essential for guiding policy, de-risking investment, and accurately assessing the potential of GSHP technology in the buildings sector.

Scope and Methodology

04

This section outlines the techno-economic approach adopted to evaluate shallow geothermal cooling systems under Saudi Arabia's climatic and economic conditions. The methodology integrates engineering-based simulations of thermal loads and ground source system performance with life-cycle cost analysis to quantify energy, water, and carbon impacts relative to conventional air-based cooling systems.

The analysis focuses on representative Saudi urban centers that capture distinct climatic and geological contexts: the Eastern Province, characterized by hot and humid coastal conditions, and the Western Area, such as Madinah and the Makkah Province, where high temperatures coincide with variable subsurface characteristics. Together, these case examples illustrate the performance envelope and economic feasibility of shallow geothermal cooling systems across contrasting Saudi environments. The framework presented here provides the foundation for the subsequent subsections detailing sectoral definitions, system boundaries, and key calculation steps. Detailed derivations and technical inputs supporting that framework are documented in Appendix A, which consolidates the full set of equations, assumptions, thermal parameters, and Saudi-specific adjustments used to compute cooling loads, seasonal COP values, electricity use, and savings, along with the underlying ground and aquifer characterization data.

4.1 Sector Definitions and Study Focus

Saudi Arabia's cooling demand spans several sectors with distinct needs. For clarity, this analysis adopts the Saudi Electricity Regulatory Authority's classification (SERA 2024):

- **Residential**: Villas, apartments, and other dwellings.
- **Commercial**: Offices, retail outlets, hotels, shopping malls, towers, private schools, universities, and healthcare facilities.
- **Government**: Ministries, municipal and defense buildings, public schools, airports, transport stations, and hospitals.
- **Industrial**: Manufacturing plants, petrochemical complexes, refineries, and other facilities requiring process and comfort cooling.
- **Agriculture**: Farms, greenhouses, and agricultural processing sheds.
- **Others**: High-intensity facilities such as private hospitals, data centers, laboratories, and mission-critical operations.

The quantitative analysis centers on large buildings, including Commercial, Government, and Others categories. Residential, Industrial, and Agriculture are included for context but are not central to the baseline results, as the commercial segment represents the largest and most policy-relevant share of Saudi Arabia's nonresidential cooling demand. It also pays the highest electricity tariffs, making efficiency gains and alternative cooling technologies particularly impactful both economically and environmentally.

4.2 Project Typologies: Green-Field vs. Brown-Field

The choice of technology and performance depends on whether the project is a new build or a retrofit. We therefore separate the analysis for the two typologies wherever performance or cost drivers differ materially.

- **Greenfield development.** New sites can be optimized for the selected technology, including orientation, envelope, shafts, plant rooms, and site works. The plant is sized for the design peak, and distribution is integrated from the outset.
- **Brownfield retrofit.** Existing facilities in which the new plant must adapt to legacy distribution and structural constraints. Typical scopes include load segregation, staged cutover, parallel running during commissioning, and selective reuse of pumps or towers.

4.3 Techno-Economic Evaluation Framework

The following framework outlines the sequential steps used to evaluate the technical and economic performance of shallow geothermal cooling systems in Saudi Arabia. It applies to both new (green-field) and existing (brown-field) developments. For greenfield sites, the full design optimization sequence, from baseline load estimation through system sizing and life-cycle costing, is implemented. For brownfield retrofits, the same analytical structure is followed, but boundary conditions are constrained by existing plant layouts and distribution systems.

The assessment proceeds through six structured stages. First, a building energy baseline is established to characterize cooling demand and operating conditions. Second, conventional and geothermal systems are sized and simulated under identical thermal and operational assumptions. Third, the resulting thermal outputs are converted into equivalent electricity use, water consumption, and CO_2 emissions to quantify performance and environmental benefits. Fourth, these technical outcomes are integrated into a detailed cost model capturing both capital and operating expenditures. Fifth, life-cycle financial indicators such as the levelized cost of cooling (LCOC), net present value (NPV), and internal rate of return (IRR) are calculated to assess economic feasibility. Finally, sensitivity analyses are conducted to test the impact of temperature variations, efficiency ranges, and cost uncertainties.

This structured sequence provides a consistent techno-economic basis for comparing shallow geothermal cooling with conventional systems across Saudi climatic and market conditions. Further description of each of these six steps is provided below, with comprehensive technical details and equations given in Appendices A and B.

- **Step 1:** Establish the building baseline by defining geometry, total conditioned volume, envelope class, operating hours, and internal gains. From this baseline, the peak cooling load is determined, and annual cooling energy demand is estimated using bin-hour methods under the Saudi temperature profile. A central adjustment of +7°C is applied across the full cooling season to represent elevated condenser air temperatures resulting from radiant gains, restricted ventilation, and exhaust recirculation at rooftop or façade installations. Relative humidity is included in the hourly bin dataset, following Eastern Province and Western Area conditions, such as Madinah and the Makkah Province, with monthly averages (45%-70%) to reflect latent cooling needs.
- **Step 2:** Size and simulate the HVAC system (air-based). Select a compliant HVAC plant and apply SCOP = 2.7 (baseline), consistent with Saudi SEEC and SASO MEPS data for commercial packaged and chiller systems. Control settings assume a 24°C indoor cooling set point, 50% relative humidity, and standard occupancy schedules. Sensitivity bands reflect ambient conditions and control assumptions.

- **Step 3:** Size and simulate geothermal cooling.
  - **Closed-loop:** Use derived ground thermal conductivity, borehole thermal resistance, allowable ground temperature swing, and bore spacing to compute borefield size and SCOP.
  - **Open-loop:** Use pumping-test transmissivity and specific capacity, along with allowable drawdown, to set yields, well spacing, and reinjection temperature rise, and compute seasonal performance.
- **Step 4:** Convert thermal energy into equivalent electricity use, then estimate CO_2 emissions using grid-intensity factors, calculate water use based on the intensities outlined in Section 5.2, and assess land footprint based on the required equipment pads or wellfield area.
- **Step 5:** Economics. Estimate CAPEX by subsystem (drilling and wells, or borefield; heat exchangers; plant; auxiliaries; and integration) and OPEX (power, water and chemicals, and maintenance). Calculate LCOC, NPV, IRR, and payback over 20-25 years using Saudi tariffs and escalation assumptions from national scenarios.
- **Step 6:** Sensitivities. Temperature adjustment (+5, +7, and +10 °C); SCOP ranges; grid-intensity trajectory; water pricing and chemistry; and drilling and mechanical cost ranges by coast.

4.4 Case-Study Design: East and West Coasts

To anchor the framework in real operating climates and subsurface regimes, two reference commercial facilities are modeled with identical functional programs and set points, one on each coast. Each is evaluated as both a greenfield development and a brownfield retrofit.

- **East Coast commercial example.** Hot, humid summers; shallow coastal aquifer with brackish-to-saline groundwater for a brownfield installation (retrofit).
- **West Coast commercial example.** Hot-dry to hot-humid conditions with strong inland solar loading and variable hydrogeology for a greenfield installation (new system).

Metrics are reported as absolute values and normalized by m^3 of conditioned volume and m^2 of gross floor area.

Beyond the two facility-level case studies, a high-level regional extrapolation is performed to approximate the potential for geothermal cooling deployment along both coasts of Saudi Arabia. For the East Coast example, the extrapolation envelope covers the Eastern Province, while for the West Coast example, it encompasses the Makkah and Madinah provinces.

The assumed 40% penetration rate of geothermal cooling within each region represents a long-term target drawn from international analogs and system-size feasibility. This assumption is applied only to the technically and economically suitable segment of the nonresidential sector, particularly new construction, major retrofits, and large commercial and institutional buildings. Globally, markets with established regulatory support and cost-competitive technology, such as parts of the United States, Northern Europe, and East Asia, have reached geothermal adoption levels in the range of 30%-50% across large commercial and institutional buildings, typically those exceeding 200 TR of cooling capacity, where system performance and economics are most favorable (Lund, Huttrer, and Tóth 2022; IEA 2022). The 40% value is therefore used as a representative mid-range scenario for potential adoption under comparable enabling conditions in Saudi Arabia.

This regional extrapolation applies consistent assumptions for indoor set point, operating hours, volumetric load density, and seasonal performance metrics, including SCOP, water intensity, and CO_2 intensity, as established in Section 5.4. The resulting outputs provide indicative, order-of-magnitude estimates of aggregate peak thermal capacity, annual cooling energy, electricity use, CO_2 and water savings, and associated capital and operating costs, framing the overall scale of opportunity for geothermal cooling across the Kingdom's major urban and industrial centers.

4.5 Sources and Data Governance

Climate and cooling-demand assumptions draw on recent Saudi studies that quantify the sensitivity of electricity consumption to temperature and assess regional power-system pathways.

Seasonal performance metrics are applied in line with Saudi minimum energy performance standards (MEPS) and energy efficiency ratio requirements (EER) to enable fair comparison under local conditions.

To reflect operating conditions during peak cooling periods, the analysis applies an explicit +5 to +10°C design-hour operating-temperature uplift in system sizing and sensitivity analysis. This uplift approximates the higher effective air temperatures experienced at air-conditioning condensers due to radiant heat exposure, limited ventilation, exhaust-air recirculation, and rooftop or facade-level installation. Incorporating this adjustment helps reconcile differences between rated equipment performance and observed field performance under Saudi operating conditions (Khan, Ilyas, and Doost 2025).

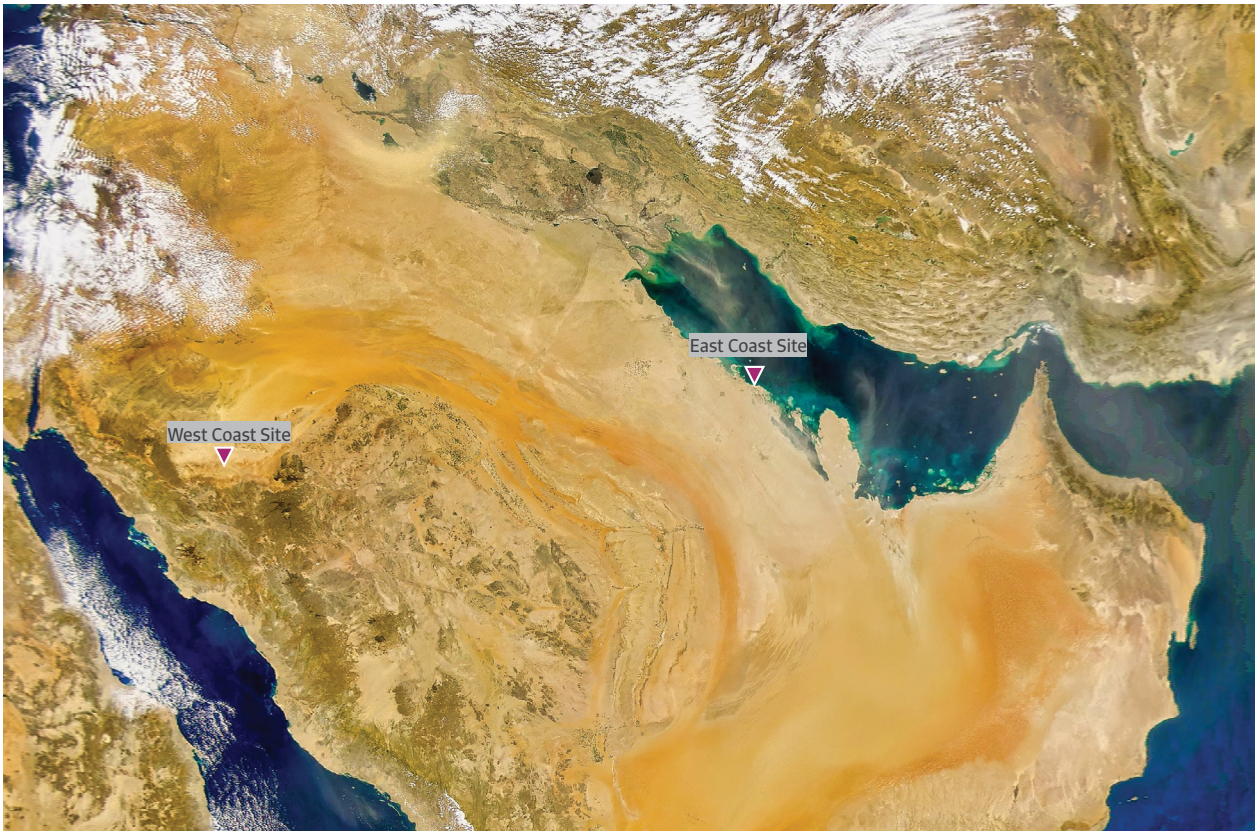
Data used in this study are sourced primarily from national-level datasets (SEC, GASTAT, and MEWA) and validated studies of Saudi building energy performance. Provincial population, building stock, and electricity intensity values are derived from the most recent SEC statistical yearbooks and GASTAT construction census (SEC 2024; GASTAT 2025). Efficiency, cost, and CO_2 factors are benchmarked against local project data where available and supplemented by modeled outputs from comparable climatic and geological settings.

Technical Feasibility Analysis

05

This section evaluates the technical feasibility of shallow geothermal cooling, including open-loop and closed-loop systems, in Saudi Arabia, as defined in the previously outlined scope and methodology. Two representative commercial deployments are assessed: an East Coast brownfield retrofit and a West Coast greenfield system. The analysis then scales these results to regional opportunity envelopes (as illustrated in Figure 1).

Figure 1. Locations of the prototypical projects.



Source: Authors.

5.1 East Coast Commercial Example (Brownfield Retrofit, Hot-Humid Coastal Setting)

This brownfield retrofit is located in Dammam, Eastern Province, at a central-plant health care campus serving multiple inpatient and outpatient buildings. The design peak cooling load is 10 MW-th, corresponding to a conditioned volume of approximately 222,000 m^3. A site investigation program installed three pilot wells into the coastal aquifer system, two for production and one for reinjection. The program included step-drawdown trials at rates of 50-200 m^3/h, two 72-hour constant-rate pumping tests, and paired reinjection tests with continuous temperature and conductivity logging. To capture peak wet-bulb conditions and assess seasonal stability, field campaigns were conducted in late August and mid-September, with a shorter verification round in December to screen aquifer thermal energy storage (ATES) feasibility. In total, five test runs were executed over approximately 14 field days.

Climate and Geological Suitability

The Eastern Province's coastal cities (e.g., Dammam, Khobar, Dhahran, Jubail) experience extremely hot and humid summers with frequent nighttime dew points of 25-30°C. Under these conditions, air-cooled condensers and cooling towers experience pronounced performance degradation, while the near-surface ground (~27°C) provides a humidity-independent heat sink. The sedimentary stack (Wasia-type sandstones and carbonates) and extensive brackish aquifers enable high-capacity water production and reinjection, drawing on regional well-drilling expertise established by the oil and water-injection industries. Shallow open-loop or hybrid designs are therefore favored for large installations, with ATES serving as a seasonal enhancer for winter "coolth" banking where hydrogeology permits.

Energy Efficiency and Performance Metrics

We consider a brownfield retrofit of a ~10 MW-th commercial plant that removes the current HVAC system (air-cooled chillers) and installs water-cooled chillers coupled to an open-loop geothermal heat-rejection system. Under Section 5's seasonal conventions, the electricity required for cooling is kWh-e = kWh-th / SCOP; shifting heat rejection to 27-30°C groundwater allows the chiller to operate at a higher SCOP than the HVAC baselines during peak humidity. Open-loop flow testing indicates measured capacity of ~200 m^3/h, scalable – subject to drawdown and interference – to ~600 m^3/h per wellbore, with verified injectivity up to ~300 m^3/h on the disposal leg; final sizing is matched to the 10 MW-th envelope per the Section 5 load-to-volume translation and bin-hour factors. Seasonal performance stability (reduced lift, lower condensing temperature) limits the summer COP collapse common to air systems; we retain the Section 5 SCOP bands for offices versus 24/7 facilities and apply them directly in the annualization.

Integration with Existing Infrastructure

The retrofit preserves the existing primary and secondary chilled-water loop and building air-handling units, replacing the heat-rejection subsystem (towers and air-cooled condensers) with geothermal wells, plate exchangers, and filtration and chemical control. Controls integrate through the plant Programmable Logic Controller (PLC) and Building Management System (BMS); standby HVAC capacity may be retained for redundancy. Reinjection returns essentially all produced water to an appropriate horizon, aligning with the project's nonconsumptive water objective.

Compatibility With District Cooling and Building HVAC

The retrofitted plant is capable of delivering standard chilled-water temperatures (≈6-7°C supply / 12-14°C return) and is therefore drop-in compatible with conventional commercial coils, air handlers, and district cooling headers. The design can be co-optimized with thermal storage, redundant electric chillers, or absorption machines, where site electricity tariffs or backup strategies warrant.

In summary, the coastal sedimentary aquifers of the Eastern Province proved favorable for open-loop geothermal cooling, with stable subsurface temperatures and high transmissivity. Key measured and modeled parameters are summarized in Table 2.

Table 2. Eastern Province sedimentary aquifer parameters.

Parameter	Description / conditions	Measured or estimated value
Subsurface temperature	Stable at depth under high wet-bulb conditions	27-30°C
Sustainable production rate	Step-drawdown test (per production well)	~200 m^3/h (scalable to 600 m^3/h)
Injection capacity	Step-injectivity test (per well)	~300 m^3/h
Operating temperature difference (ΔT)	Conservative design range	4-6°C
Configuration	Production and injection layout	3 producers and 3 injectors
Cooling plant capacity	Thermal rating of system	10 MW-th
Seasonal COP (geothermal system)	Water-cooled, geothermal-supported	5.5
Baseline HVAC COP	Conventional air-based systems	2.3-2.7
Electricity reduction	Relative to conventional HVAC	40%-50%
Location	Eastern Province (Dammam area)	—

Under these conditions, geothermal cooling can achieve notably higher seasonal efficiency compared to conventional HVAC systems. In many cases, this translates into approximately 40%-50% electricity savings during peak periods, along with more stable and predictable performance under humid evening conditions.

5.2 West Coast Commercial Example (Greenfield, Inland Solar Loading; Variable Hydrogeology)

This greenfield system is sited in the Al-Madinah region and serves a hospitality development designed around a district chilled-water network. The design peak cooling load is 28 MW-th, with a total conditioned volume of nearly 622,000 m^3. Subsurface characterization included six pilot wells arranged as three production – injection pairs across two proposed pads, with 96-hour constant-rate pumping and reinjection tests at 100 m^3/h, recovery profiling, and short-interval tracer pulses to verify connectivity and residence times; three thermal response tests in adjacent test holes were also conducted to parameterize conductivity for potential hybridization. Fieldwork was executed in two main windows, May-June and August, to bracket early- and peak-summer conditions, totaling about five weeks on site.

Climate and Geological Suitability

In the western region (the Red Sea coastal plain and Hejaz uplands), extreme summer dry-bulb temperatures and high land-surface temperatures exacerbate sensible cooling loads. At many sites, the shallow subsurface remains cooler and more stable than peak ambient temperatures, offering an effective thermal sink. Fractured volcanic settings and coral limestones alternate with unconsolidated coastal sands, with multiple warm-spring manifestations confirming fluid circulation at shallow depths. Field campaigns in the region (thermal response tests and open-loop pilots) have demonstrated viable transmissivity and seasonal cycling potential.

Energy Efficiency and Performance Metrics

We analyze a greenfield ~28 MW-th district-ready plant, sized according to Section 5's volumetric load density and bin-hour methodology. The plant utilizes production and reinjection well pairs as the primary heat-rejection path for water-cooled chillers; SCOP is computed per the Section 5 seasonal bins and is materially higher than the HVAC baseline under inland summer peak conditions. The design targets constant capacity at extreme ambient temperatures (≥45°C), thereby limiting seasonal efficiency drift and peak-power excursions. Electricity, water, and CO_2 are then evaluated using the formula kWh-e = kWh-th/SCOP, where SCOP is the grid Emissions Factor, and the Section 5.2 water-intensity factors are applied.

Table 3. Western Province sedimentary aquifer parameters.

Parameter	Description / conditions	Measured or estimated value
Subsurface temperature	Stable shallow conditions below surface dry-bulb	~26-29°C
Effective thermal conductivity	From thermal response tests	3.7-4.3 W/m·K
Production-injection pair output	Open-loop test result	>3 MW-th per pair
Operating temperature difference (ΔT)	Design range	~5 °C
Wellfield configuration	Modular layout	9-10 production-injection pairs
Plant capacity	Greenfield geothermal cooling system	28 MW-th
Seasonal COP (geothermal system)	Derived from modeled performance	4.9
Baseline HVAC COP	Conventional air-based cooling	2.3-2.7
Electricity reduction	Relative to conventional HVAC	~40-50 %
Location	Madinah (Red Sea coastal plain)	—

Integration With Existing Infrastructure

As a greenfield site, the wellfield, heat-exchanger gallery, and central chiller plant are co-sited to minimize headers and interference; tie-in is to a standard district chilled-water loop. Wells are placed to avoid structural foundations and to maintain hydrogeologic separation between production and injection zones. The electrical design emphasizes reduced peak kW-e at the feeder during summer afternoons.

Compatibility With District Cooling and Building HVAC

The plant is specified for standard supply and return temperatures and readily integrates with conventional buildings. It can be augmented with modular HVAC machines for maintenance or shutdowns, or with stratified chilled-water storage for load shifting. Without cooling towers, make-up water, and chemical treatment, the system footprint collapses materially.

In summary, across the Red Sea coastal plain and adjacent Hejaz uplands, the geology is technically supportive of shallow geothermal cooling. Fractured volcanic units and coral limestones provide transmissive pathways, while shallow ground temperatures remain below inland dry-bulb levels, offering favorable thermal conditions. Key findings from the Madinah site investigation and performance simulations are summarized in Table 3.

Under these site conditions, the geothermal cooling plant achieves roughly double the efficiency of conventional HVAC systems, translating to 40%-50% lower electricity use and reduced summer feeder peaks. This demonstrates the technical feasibility and superior performance of shallow geothermal cooling in Madinah.

5.3 East Coast Province Extrapolation: Commercial-Building Electricity Baseline From Actual Data

For a high-level extrapolation of commercial-building potential on the East Coast, we focus on the Eastern Province and define "commercial buildings" as the sum of SEC categories Commercial, Government, and Other. The *Annual Statistical Booklet for Electricity 2022* reports national energy sales of 309 TWh, with category shares as follows: Residential, 46.1%; Commercial, 16.2%; Government, 11.7%; Industrial, 19.6%; and Other, 6.3%. Regional shares of total energy sales are: Central, 30%; Eastern, 27%; Western, 32%; and Southern, 11%. Accordingly, the Eastern Province's total electricity sales are ~0.27 × 309,523 = ~83.6 TWh in 2022 (SERA 2023).

To isolate the Eastern Province's industrial portion, we draw on regional evidence: industrial consumption is overwhelmingly concentrated in the East (≈72% of national industrial output in 2019). Applying that share to 2022 national industrial sales (60 TWh) yields an Eastern industrial total of ~43.7 TWh.

KAPSARC's regional work also notes that the Eastern region's residential share is atypically low, close to 30% of the region's total, versus 50%-60% elsewhere. Applying ~30% to the Eastern total implies ~25.1 TWh of residential energy. Residual nonindustrial, nonresidential electricity (= Eastern total − industrial − residential) is therefore ~83.6 − 43.7 − 25.1 ≈ 14.8 TWh, which we take as the commercial-building electricity baseline (Commercial + Government + Other) for the Eastern Province in 2022.

As discussed in the previous section, applying a 40% penetration of shallow geothermal cooling to the commercial-building stock yields an addressable electricity baseline of ≈0.40 × 14.8 ≈ 5.9 TWh-e/year. Section 5 converts electricity to thermal cooling through SCOP: EkWh-th = EkWh-e × SCOP. Using the Section 5 SCOP ranges (office-dominant versus 24/7), we obtain a band for aggregate annual cooling thermal energy. Peak kW-th is estimated from the volume-to-load mapping (qv W/m^3) and bin-hour method in Section 5. The annual load factor (LF) (e.g., 0.40 for offices; higher for 24/7 facilities) yields annual cooling energy ($E_{cool, annual}$) consistent with the electricity baseline and SCOP.

In summary, the Eastern Province's aquifer systems and decades of well performance consistently indicate favorable conditions for open-loop geothermal cooling, with recent retrofit testing confirming sustainable yields (≈200-600 m^3/h per well) and reliable reinjection at an operating ΔT of 4-6°C. At the district scale, these parameters enable towerless plants that avoid wet-bulb penalties; for performance translation, we adopt a seasonal COP exceeding 5 (e.g., 5.5), versus ≈2.3-2.7 for HVAC baselines, which drives order-of-magnitude reductions in electricity use and CO_2 at the assumed 40% penetration across Commercial, Government, and Other facilities.

5.4 Makkah and Madinah Provinces Extrapolation; Commercial-Building Electricity Baseline From Actual Data

Within the Western region, industrial electricity demand is significantly lower than in the Eastern Province. Drawing on combined evidence from Section 5 field campaigns and regional demand studies, and consistent with the *Energy Sales by Consumption Category and Region* dataset published in the Saudi Electricity Regulatory Authority (SERA) *Annual Statistical Booklet for Electricity 2022* (SERA 2022), the total industrial load for the Western region is estimated at ~15 TWh per year (rounded from the operating-region breakdown). Residential consumption represents roughly half of total regional demand. Using a typical range of 50%-60% and adopting a midpoint value of ~55%, residential electricity use is estimated at ~54 TWh in 2022. Subtracting these two components from the Western region's total of ~99 TWh yields an estimated ~30 TWh per year for the combined Commercial, Government, and Other building categories. This order-of-magnitude estimate aligns with the region's socioeconomic composition and trends reported in the regional energy-consumption literature.

Since the available SEC data attachments report electricity sales aggregated at the operating-region level (Central, Eastern, Western, and Southern) rather than by individual province, the Western regional commercial-building electricity total is apportioned to the Makkah and Madinah provinces, which together contain most of the region's commercial floor area and cooling demand, notably the Jeddah-Makkah corridor and the Madinah metropolitan area.

Applying a 40% penetration to the ~30 TWh-e/y Western-envelope commercial-building baseline yields ~12 TWh-e/y of addressable demand. Translating this to thermal cooling via Section 5's SCOP bands provides $E_{cool, annual}$ annual for the envelope. Peak cooling load is estimated using the volumetric load-density method and converted to annual energy through a representative load factor (LF) from Section 5. Standard West-region ground temperatures and hydrogeology stabilize summer performance and reduce peak feeder kW-e relative to HVAC baselines.

In summary, across Makkah and Madinah, the combination of coastal sands and coral limestones grading into fractured Harrat basalts provides transmissive, thermally stable settings for open-loop cooling. Pilot wells and thermal response tests (TRTs) at analogous sites show pair throughputs and ΔT values suited to modular, multi-megawatt district plants that maintain capacity during afternoons exceeding 45°C. Applying the Section 5 framework, we use a geothermal seasonal COP close to 5.0 (e.g., 4.9), contrasted with ≈2.3-2.7 for HVAC, to convert the regional commercial electricity baseline into thermal load, electricity, and CO_2 outcomes at 40% penetration.

5.5 Synthesis: Implications for Grid, Water, and Urban Integration

Across both coasts, shallow geothermal cooling aligns with the objectives of (i) lifting seasonal SCOP and capping summer peak kW-e, (ii) shrinking cooling-tower make-up water and chemical use where reinjection is applied, and (iii) providing district-compatible chilled-water service without HVAC retrofits beyond the plant boundary.

In the Eastern brownfield context, reinjection into brackish horizons supports water-stewardship goals while decoupling chiller condensing temperature from coastal humidity; on the West Coast, the same decoupling holds during the most severe inland afternoons. The extrapolation envelopes above, ~5.9 TWh-e/y addressable in the Eastern Province and ~12 TWh-e/y at the Western operating-region scale (an upper-bound proxy for Makkah plus Madinah), indicate order-of-magnitude potential that is sufficient to warrant province-level disaggregation and sensitivity testing in the next phase. Combined, these two regions represent roughly 18 TWh-e per year of addressable electricity savings potential and several gigawatts of avoided peak load, equivalent to the annual output of multiple large-scale power plants.

Economic and Financial Assessment

06

6.1 Cost and Lifecycle Dynamics

As established in Section 2, air conditioning drives the majority of Saudi Arabia's electricity consumption and is the principal cause of summer peak demand. Within this context, this study evaluates shallow geothermal cooling using GSHPs as a candidate alternative to conventional air-cooled systems, assessing whether GSHPs can deliver competitive techno-economic and environmental performance under Saudi-specific conditions.

By leveraging stable ground temperatures for heat rejection, GSHPs achieve substantially higher COPs than conventional air-cooled systems, thereby lowering operating expenditure and extending system life.

As detailed in Section 5, GSHP installations have a distinct cost structure that varies by project typology. In brownfield retrofits, integration with existing HVAC networks increases mechanical complexity but minimizes distribution upgrades, whereas greenfield developments allow full optimization of layout, borefield spacing, and plant design. Drilling and subsurface components typically represent about 40%-50% of total capital expenditure in Saudi projects (Strataphy 2025). Upfront cost is therefore higher, typically two to three times that of air-cooled chillers, or ~SAR 3,200-5,000 per ton for conventional systems versus SAR 4,000-9,500 per ton for GSHPs, depending on local geology and drilling depth (Al Shehri et al. 2020; Strataphy 2025). In return, GSHPs deliver seasonal COPs of ~5.0 compared with 2.0-2.5 for air-cooled chillers, reducing electricity use by 40%-50% for equivalent cooling output.

GSHPs also eliminate the need for cooling towers, reducing water and chemical use by up to 95%, an especially valuable advantage under arid conditions. Underground heat-exchange loops are shielded from thermal cycling and dust exposure, providing lifespans of 25-50 years, while heat-pump units typically exceed 20 years, compared with ~15 years for air-cooled chillers. These factors yield ~40% lower capital replacement expenditure and 20%-30% lower annual maintenance budgets, leading to overall OPEX per ton-year roughly 50% below standard chiller plants (Strataphy 2025).

High upfront costs can be mitigated through performance-based financing. CaaS and blended-finance models distribute CAPEX across the system's life and monetize efficiency gains. When evaluated using the tariff and escalation assumptions in Section 5.5 and Appendix B, these mechanisms produce favorable net present values (NPV) and competitive LCOC, allowing GSHP projects to become cash-flow positive from their first operational year. Although customer experience and user interface do not change materially with geothermal systems,

Table 4. Financial performance values.

Metric	Value range	Remarks
LCOC	~$20-$45 per MWh-th	Competitive even against grid power; SAR 0.08-0.17 per kWh-th.
Payback period	~5-12 years	Shorter (<7 years) for high-tariff/high-utilization commercial cases; longer for residential.
IRR	~8%-20%+	Large, constant-load systems may exceed 15% IRR (Strataphy 2025).
CAPEX per cooling ton	SAR 4,000-9,500	Lower for shallow aquifers/soft sediments; higher for deep or rocky sites
Annual OPEX savings	40%-60% of cooling energy cost	Includes electricity, water, and maintenance.

adoption will need to overcome trust barriers and reluctance to adopt new technologies for a service as critical as cooling.

6.2 TechnoEconomic Metrics from Saudi Applications

Empirical data from Strataphy pilot projects and regional feasibility studies demonstrate consistent financial and technical performance across Saudi climates and geological settings. LCOC values were derived using the standardized framework established in Section 5, incorporating local tariff tiers and computed over a 25-year life with a 6% real discount rate. The metric reflects annualized capital, energy, and O&M costs under local tariffs and observed performance data. Representative performance ranges are summarized in Table 4.

At the lower bound, open-loop geothermal systems installed in favorable aquifers have achieved levelized cooling costs near $22/MWh-th (≈ SAR 0.082/kWh-th), reflecting substantially higher energy efficiency than conventional air-cooled chillers powered by grid electricity. In such configurations, the same electrical input produces roughly twice as much cooling output due to the stable subsurface heat-rejection temperature.

Closed-loop systems in harder or deeper geology exhibit levelized costs of $40-$45/MWh-th, which are comparable to the cost of delivering cooling through standard air-conditioning systems powered by the grid at SAR 0.18/kWh$_e$ (≈$30/MWh-th assuming a COP of 3). In both cases, the systems are grid supplied; the difference lies in how efficiently each converts electrical energy into cooling.

As a result, geothermal cooling delivers the same comfort service while consuming 40%-50% less electricity, reducing both energy expenditure and grid load during peak demand. Payback periods typically range from 5-7 years in high-utilization commercial or industrial facilities, extending beyond 10 years in residential or low-tariff settings, with internal rates of return between 8% and 20% depending on project scale and duty cycle.

6.3 Economic Impact of 40% Geothermal Cooling Penetration in the Eastern and Western Regions

This section quantifies the economic and environmental impacts of applying a 40% market penetration of GSHP cooling systems within the two regional envelopes defined and analyzed in Sections 5-6. These envelopes, representing the Eastern Province (brownfield retrofit archetype) and the combined Makkah-Madinah corridor (greenfield archetype), capture the most technically and economically suitable regions for shallow geothermal deployment.

As outlined in Section 6, the Eastern Province exhibits a total commercial-building electricity baseline of 14.8 TWh$_e$/year, while Section 6.4 identifies approximately 30 TWh$_e$/year for the Makkah-Madinah region. Applying the 40% geothermal penetration scenario defined in Section 5.6 yields an addressable electricity baseline of 5.9 TWh$_e$/year in the East and 12.0 TWh$_e$/year in the West, together amounting to 17.9 TWh$_e$/year of commercial and governmental cooling demand potentially served by GSHP systems.

Table 5. Economic impact of 40% geothermal-cooling penetration within eastern and western regional envelopes.

Impact category	Estimated value (SAR)	Underlying assumptions / notes
Annual electricity OPEX savings	≈ 1.3 billion SAR per year	7.2 TWh_e avoided × 0.18 SAR/kWh average commercial and governmental tariff
Avoided asset replacements (lifecycle)	≈ 3.6 trillion SAR over 25 years	GSHP lifespan ≥25 years versus ~15 years for conventional chillers, implying a ~30% reduction in replacement frequency (Sections 6.1-6.2).
Deferred grid capacity investment	≈ 3.6 billion SAR (one time)	Peak-load reduction: ≈0.72 GW (40% of a 1.8 GW regional peak), with an implied capacity cost of ≈SAR 5,000/kW (Section 5.5).
Annual CO_2 emissions avoided	≈ 3.6 Mt CO_2 per year	Grid emission factor of 0.5 kg CO_2/kWh × 7.2 TWh_e avoided (Section 5.2).
Water savings	Qualitatively high	Elimination of cooling-tower make-up water and reduced thermal-generation cooling demand (Section 6.5).

Based on the measured and modeled efficiency differentials reported (an average 40% reduction in electrical energy consumption relative to conventional air-cooled chillers), this 17.9 TWh_e/y baseline corresponds to approximately 7.2 TWh_e/y of avoided electricity use. Using a representative commercial and governmental tariff of 0.18 SAR/kWh, this translates into direct operating expenditure (OPEX) savings of roughly SAR 1.3 billion annually, as shown in Table 5.

These results indicate that implementing geothermal cooling across 40% of the commercial and governmental building stock in the modeled regions yields significant and measurable economic benefits. Annual electricity savings of approximately 7.2 TWh_e/y reduce both consumer costs and government exposure by roughly SAR 1.3 billion each year. On a lifecycle basis, the extended service life of GSHP assets (25-50 years for ground loops and more than 20 years for heat-pump units) lowers equipment replacement requirements.

Although this assessment is limited to representative cases in the Eastern and Western regions, it demonstrates that, under the specific geological, tariff, and operational conditions modeled, shallow geothermal cooling can deliver both fiscal and environmental benefits at moderate market penetration. These results should be interpreted as indicative rather than universally applicable. They illustrate the mechanisms through which localized geothermal deployment can reduce electricity consumption, improve equipment lifetimes, and support system resilience in suitable settings, while extrapolation to other regions will require region-specific geological, tariff, and load assessments.

Key summary metrics for representative Eastern and Western region cases are summarized in Table 6, which consolidates LCOC, payback, IRR, CAPEX per ton, and OPEX savings across realistic geology, tariff, and utilization scenarios.

Translating these unit-level outcomes into system-level value, Table 7 estimates potential annual and life-cycle impacts under moderate market penetration. Assumptions are stated for transparency and follow the same scenario basis used in this section.

Table 6. Summary of findings and potential impact.

Metric	Value range	Remarks
LCOC	~$20-$45 per MWh-th	Competitively low, even against subsidized grid power (GSHP often delivers cooling at SAR 0.08-0.17 per kWh-th).
Payback period	~5-12 years	Shorter paybacks (<7 years) in high-tariff or high-utilization scenarios (e.g., large commercial), longer in low-tariff residential settings.
IRR	~8%-20%+	Highly project-specific; larger systems with constant loads can exceed 15% IRR, whereas small-scale residential systems may be single-digit IRR (Strataphy 2025).
CAPEX per cooling ton	SAR 4,000-9,500	Varies with geology and scale. Lower end for favorable sites (shallow aquifer, soft geology), higher end for deeper or rocky sites.
Annual OPEX savings	40%-60% of the cooling energy cost	Relative to conventional AC. Savings include electricity (primary) and reduced water and maintenance costs (Strataphy 2025).

Table 7. Potential impact of our assumed market penetration.

Impact category	Estimated value (SAR)	Assumptions
Annual electricity OPEX savings	~1.23 billion SAR per year	17.1 TWh offset, average tariff 0.18 SAR/kWh, ~40% energy saving per cooling unit (Al Shehri et al. 2020)
Avoided asset replacements (life cycle)	~4.7 trillion SAR (over 25 years)	Conventional HVAC lifespan ~15 years vs. 25+ for GSHP; ~30% reduction in replacement needs across installed base (Strataphy 2025)
Deferred grid capacity Investment	~4.9 billion SAR (one time deferral)	Peak load reduction of ~0.98 GW (assuming GSHP cuts 50% of peak AC load), with a capacity cost of ~5,000 SAR/kW installed.

6.4 Quantitative Calculation Framework

The economic and system-level indicators reported in this chapter are derived from a transparent quantitative framework that is fully documented in Appendix B, which consolidates the key equations and assumptions used to move from project-level geothermal performance to regional electricity, cost, and emissions impacts for the Eastern and Western envelopes.

At the project scale, Appendix B formalizes the comparison between conventional air-cooled chillers and GSHP systems using seasonal coefficients of performance (COPs). Annual electricity use is expressed as a function of cooling demand and COP, and the resulting fractional electricity saving η_{sav} is calculated directly from the ratio of COP_{conv} to COP_{GSHP}. This provides the basis for the 40%-50% electricity-saving range reported for representative Saudi commercial applications, while making clear that the exact value is case specific and must be computed from measured or modeled COPs.

For cost metrics, Appendix B adopts the standard LCOC formulation over a 25-year project life and a real discount rate. The framework aggregates initial investment, reinvestment, operation and maintenance, and electricity costs into a present value and divides by the discounted cooling output to obtain LCOC in SAR/kWh_{th}. NPV, IRR, and simple payback are then defined in terms of incremental cash flows between GSHP and conventional cooling, including energy, water, O&M, and replacement effects, using standard project-finance relationships.

Finally, Appendix B links these project-level metrics to system-level indicators. Regional electricity savings are obtained by applying the fractional saving η_{sav} to the modeled baseline cooling demand and assumed GSHP penetration. Annual bill (OPEX) savings are computed using representative commercial and governmental tariffs, while deferred grid-capacity expenditure is estimated from peak-load reductions and a unit cost of new capacity. Together, these relationships provide a consistent, Saudi-specific basis for the LCOC ranges, payback and IRR estimates, and macro-level electricity and emissions impacts presented in this chapter, with full derivations and notation available in Appendix C for verification and reuse.

Environmental and Energy Impact Assessment

07

This section synthesizes the technical and economic results presented above into a focused evaluation of environmental outcomes. The analysis emphasizes CO_2 emissions reduction, electricity and peak-demand savings, and water-stewardship implications relative to conventional HVAC systems operating under Saudi conditions.

7.1 Energy Savings and Efficiency Gains

The combined East and West Coast extrapolations represent an addressable ~18 TWh-e/year of commercial-building electricity demand (about 6% of total Saudi electricity sales). Substituting SCOP = 5.0 geothermal systems for SCOP = 2.5 HVAC systems reduces this requirement by nearly half, yielding ~9 TWh-e/year of electricity savings.

Beyond annual energy savings, the improved part-load performance of geothermal systems stabilizes efficiency during summer afternoons, thereby reducing peak feeder kW-e. This peak-load relief is especially valuable in inland areas (Madinah and Makkah), where afternoon dry-bulb temperatures exceed 45°C and place stress on the grid. Reducing peak demand can defer investments in generation and transmission capacity, thereby improving system reliability during high-load events.

Lower electricity demand also reduces reliance on liquid-fired peaking generation and supports the National Renewable Energy Program (NREP) by freeing capacity for renewable integration. As Saudi Arabia shifts its generation mix toward gas and solar PV, efficiency gains from geothermal cooling lower the absolute quantity of new capacity required to serve cooling loads, helping the Kingdom progress toward its Vision 2030 target of a 50% renewable share in the power mix without overbuilding infrastructure.

7.2 Carbon Footprint Reduction

Within the methodological framework outlined in Section 5, the seasonal COP (SCOP) serves as the basis for translating thermal loads into electricity consumption. Conventional air-based HVAC systems in Saudi commercial settings operate at seasonal SCOP values between 2.3 and 2.7 under hot-humid or hot-dry conditions. In contrast, the modeled geothermal-supported water-cooled systems achieve a SCOP of ~5.0 (Sections 6.1-6.2).

This near-doubling of seasonal efficiency yields approximately 40%-50% lower cooling electricity consumption, translating directly into a proportional reduction in grid-related CO_2 emissions. Using a baseline grid intensity of 0.55 kg CO_2/kWh-e estimated by Matar, Mansouri, and Umeozor (2024) (with sensitivities of 0.40 and 0.70), the Eastern Province 40% penetration scenario can avoid roughly 3.2 million metric tons of

CO_2 annually, while Makkah and Madinah collectively can avoid on the order of 6.6 million metric tons annually, both relative to baseline HVAC (Matar, Mansouri, and Umeozor 2024). Together, the avoided CO_2 emissions in the two regions account for roughly 2% of total CO_2 emissions in the Kingdom (IEA 2022).

These reductions directly advance Saudi Arabia's circular carbon economy framework and its net-zero 2060 commitment. By reducing emissions without sacrificing service levels or requiring behavioral change, shallow geothermal cooling supports the "Reduce" and "Recycle" pillars of the CCE, while providing a scalable pathway for decarbonizing one of the most electricity-intensive end uses in the commercial sector. When extrapolated nationwide, mature market penetration of 30%-40% across commercial facilities could eliminate 10-12 million tons of CO_2 annually, significantly easing pressure on power-sector decarbonization targets.

7.3 Water Consumption Assessment

Conventional cooling towers consume 1.5-2.5 L/kWh-th of make-up water through evaporation and blowdown. By replacing towers with reinjection-based geothermal heat rejection, consumptive water use is effectively reduced to ~0 L/kWh-th, except for minor bleed required for plume control (≤0.1 L/kWh-th, site specific). In a water-stressed region such as Saudi Arabia, this represents a 90%-95% reduction in consumptive water use, aligning with national water-stewardship priorities and the National Water Strategy.

In terms of water contamination, both closed- and open-loop designs are engineered for nonconsumptive and environmentally safe operation, with full reinjection of produced water into suitable aquifer horizons. Chemical control and filtration (Section 6.1) prevent scaling and biofouling while maintaining reinjection quality. Continuous monitoring of conductivity and temperature during field trials confirmed that reinjected water remained within acceptable limits, thereby minimizing the risk of aquifer contamination. Site-specific environmental permitting and plume modeling ensure compliance with Saudi environmental regulations and groundwater-protection standards.

In summary, shallow geothermal cooling may provide multiple advantages for Saudi Arabia's commercial sector. By using stable subsurface temperatures, these systems reduce electricity use and peak demand, improving grid reliability and operational efficiency. The resulting reduction in CO_2 emissions supports the Kingdom's CCE and net-zero 2060 targets, while the near elimination of cooling-tower water losses addresses critical water-scarcity concerns. Together, these energy, environmental, and water gains position geothermal cooling as a potential supporting element of Saudi Arabia's Vision 2030 sustainability goals, as summarized in Table 8.

Table 8. Comparison summary of conventional and GSHP cooling systems.

Dimension	Baseline (conventional HVAC)	Geothermal cooling (SCOP ≈ 5.0)	Key benefit
Energy efficiency	≈ 18 TWh_e/year electricity demand	≈ 9 TWh_e/year demand (≈ 50 % lower)	~9 TWh_e annual savings; improved part-load performance; reduced peak load and grid stress.
Environmental impact	SCOP 2.3-2.7 ⟶ high CO_2 intensity (0.55 kg CO_2/kWh_e)	40%-50 % lower CO_2 intensity	≈10-12 Mt CO_2 avoided annually (nationwide 30%-40% penetration); supports CCE and net-zero 2060.
Water use	1.5-2.5 L/kWh_{th} (cooling towers)	≈ 0 L/kWh_{th} (closed/reinjection loops)	90%-95% reduction in consumptive water use; minimal contamination risk; aligns with the National Water Strategy.

Pathways to Realization

08

Shallow geothermal systems offer significant long-term benefits, but their adoption in Saudi Arabia faces several financial challenges. Chief among these is the high initial cost, which can be more than three times higher than that of traditional air-source HVAC systems (Alshehri et al. 2019). Expenses associated with drilling boreholes, installing ground loops, and procuring specialized heat-pump units create a financial hurdle for many potential adopters. Moreover, the cost effectiveness of shallow geothermal systems is influenced by Saudi Arabia's relatively low domestic energy prices, which reduces the perceived return on investment.

As discussed, shallow geothermal systems are highly dependent on local geological and spatial conditions, posing several challenges in Saudi Arabia's diverse terrain. Soil composition and moisture content directly influence system efficiency, as thermal conductivity varies significantly with ground conditions. For example, clay soils generally offer better heat transfer than sandy soils, which dominate much of the Kingdom's landscape. In unsuitable areas, site preparation or modification may be necessary, which can increase project costs and complexity.

Land availability poses another significant constraint, particularly in urban environments where horizontal loop systems require extensive surface areas. Vertical systems offer a more space-efficient alternative but involve deep drilling, which is costly and technically demanding, particularly in regions with hard rock formations or high groundwater levels. Furthermore, zoning regulations, underground utilities, and measures to protect the water table can restrict drilling activities or require special permits.

To mitigate these issues, collaboration between municipal authorities, developers, and urban planners is necessary. Creative land-use strategies, such as installing GHE loops beneath large-scale buildings and infrastructure projects, can optimize space while maintaining land functionality. By addressing these site-specific challenges, Saudi Arabia can facilitate the integration of shallow geothermal systems even within dense urban developments.

8.1 Business Models

Advancing shallow geothermal systems in Saudi Arabia requires innovative business models that reduce upfront capital barriers and distribute risk between developers and end users. The CaaS model offers a compelling solution by allowing clients to pay for cooling output rather than system ownership. Under this model, private developers finance, install, operate, and

maintain the geothermal system, while users pay a recurring fee based on cooling tons delivered and realized cost savings. This approach shifts geothermal cooling from a capital expense to an operating expense, easing adoption for commercial and industrial customers that are hesitant about long-term investments. By aligning developer revenue with client savings, the CaaS model creates shared incentives for efficiency, performance, and reliability, which are key drivers for scaling shallow geothermal technologies.

Leveraging existing public-private partnership (PPP) mechanisms, developers can access financing while retaining operational control, thereby expediting project timelines and reducing administrative delays. The model's flexibility supports decentralized deployment, which offers scalability and speed unmatched by traditional large-scale power projects. When integrated with supportive regulatory and financial incentives, such as tax credits, green financing, or energy-savings contracts, the CaaS model can unlock a competitive geothermal market, transforming cooling from a cost center into a sustainable service industry in the Kingdom.

8.2 Policy and Regulatory Levers

Establishing a straightforward and streamlined legal framework is essential for advancing shallow geothermal development in Saudi Arabia. Current permitting pathways are fragmented across multiple agencies, slowing project execution. A more effective approach would centralize geothermal regulation under a single authority, similar to existing water-well governance. This authority would oversee land leasing, shallow drilling permits, and environmental and social impact assessments (ESIA), ensuring consistency and efficiency throughout the development cycle. Simplifying the process from feasibility to commissioning could reduce project timelines from several years to a few months.

The legal framework should also address the definition of resource ownership and liability boundaries for shallow geothermal systems, clearly distinguishing them from deeper geothermal power operations. Specific guidelines for drilling depth limits, groundwater protection, and reinjection practices should be incorporated into the Saudi Building Code (SBC) and enforced through the Saudi Energy Efficiency Center (SEEC) and the Saudi Standards, Metrology and Quality Organization (SASO).

Including geothermal cooling in the national renewable energy strategy, alongside formal recognition of geothermal thermal energy as a clean energy source, would further strengthen legal certainty. Together, these measures would provide developers, financiers, and consumers with a stable regulatory environment that accelerates the adoption of geothermal cooling while safeguarding environmental and public interests.

8.3 Research and Development

Both the public and private sectors play pivotal roles in driving research and development (R&D) for shallow geothermal technologies. Government initiatives can encourage PPPs to fund pilot projects, reduce technology costs, and foster innovation. Private firms, in turn, can invest in developing more efficient, affordable, and locally adapted shallow geothermal systems suitable for Saudi Arabia's climatic and geological conditions, as discussed earlier.

A critical R&D step involves establishing a national database of ground thermal properties, similar to those maintained in the United States by the National Renewable Energy Laboratory. Such a database would provide engineers and developers with essential information on soil and rock characteristics, improving design accuracy and reducing the need for costly site-specific testing. In Saudi Arabia, there are more than 140,000 licensed water wells, most of which are operated privately (Arab News 2014). These wells provide water for drinking and agricultural purposes. Water samples and downhole temperature measurements from these assets could support the development of an atlas of subsurface temperatures across elevations. Achieving this outcome will require collaboration between government entities, universities, and research institutions to ensure that the data are regionally representative and continuously updated.

This research infrastructure would not only enhance project feasibility and cost optimization but also encourage domestic innovation in system design and performance monitoring.

8.4 Capacity Building, Local Content, and Employment

Saudi Arabia's industrial base and energy expertise, particularly in the oil and gas sector, provide a strong foundation for localizing shallow geothermal technology. The country's established service infrastructure can support manufacturing, installation, and maintenance, leveraging existing technical capabilities to diversify into clean energy applications. Drawing lessons from countries such as China, Türkiye, and the U.S., which have successfully promoted local content in geothermal projects to reduce costs and improve accessibility (Zhu et al. 2015; Hepbasli and Ozgener 2004), Saudi Arabia can encourage local content development through incentives for domestic manufacturing of heat pumps and related components.

To ensure successful implementation, capacity building is essential. Training programs and curricula in universities and vocational institutions should incorporate GSHP design, installation, and operation.

Globally, the adoption of ground-source systems has spurred job creation not only in direct system deployment but also in manufacturing, logistics, education, and technical training. Similarly, in Saudi Arabia, expanding the shallow geothermal market would increase demand for skilled technicians, engineers, and system designers, as well as roles in sales, marketing, and after-sales services. Localization of manufacturing would further multiply employment opportunities across the supply chain.

As of 2022, the HVAC sector employed only 4,666 Saudi nationals, partly due to perceptions of limited prestige and financial appeal. However, economic incentives and green job initiatives under Vision 2030 can make this sector more attractive to local workers. By promoting shallow geothermal systems, the Kingdom can stimulate sustainable job creation, build human capital in the clean energy domain, and foster an inclusive transition toward a low-carbon economy.

Conclusion

09

This study demonstrates that shallow geothermal cooling, through GSHPs, could offer a technically viable, economically competitive, and environmentally sustainable pathway for reducing Saudi Arabia's growing cooling-related energy demand. Under the country's extreme climatic conditions, geothermal systems consistently outperform conventional air-cooled HVAC technologies, achieving SCOP near 5.0 compared with 2.3-2.7 for baseline systems.

This efficiency translates into 40%-50% reductions in electricity consumption and up to 3.6 Mt of annual CO_2 savings in the modeled regions, aligning directly with the Kingdom's Vision 2030 objectives and its circular carbon economy framework.

From a financial standpoint, GSHP installations require a substantially higher upfront investment, driven primarily by drilling and ground-loop components, which remains one of the main barriers to adoption. However, these systems have been shown to deliver notable life-cycle returns through lower operating expenses, extended equipment lifetimes, and avoided grid-capacity expansion. Payback periods of 5-12 years and levelized costs of cooling between $20-$45/MWh-th position geothermal cooling as a cost-effective solution for commercial, institutional, and district-scale applications.

The environmental and resource benefits extend beyond carbon reduction. Water consumption for cooling can be reduced by up to 95%, and peak-load pressures on the electricity grid are alleviated during high-temperature periods. Together, these effects enhance system resilience, improve energy security, and support the integration of renewables into the national power mix.

However, achieving large-scale deployment requires coordinated policy action and market innovation. Regulatory clarity, geological data transparency, and incentive mechanisms must evolve alongside business models such as CaaS and PPPs to overcome initial cost barriers. Parallel investments in R&D, capacity building, and local manufacturing will be essential to localize technology and capture broader economic co-benefits, including job creation and industrial diversification.

In summary, shallow geothermal cooling offers a promising high-efficiency, low-emission option for Saudi Arabia's climatic and economic context. Its broader deployment, however, will require careful consideration of key obstacles, including higher upfront costs, drilling and land-use constraints, and the need for skilled contractors and regulatory support. If these challenges are addressed, integrating geothermal systems into urban planning, building codes, and national energy strategies could gradually shift cooling from a growing energy burden toward a more sustainable component of the Kingdom's long-term development.

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Appendix A. Derivation of Section 4 Numbers, Assumptions, and Equations

A.1 Cooling Demand, Seasonal Performance, and Electricity Use

A.1.1 Annual Cooling Demand

Annual cooling energy demand is:

$$E_{cool,annual}\ [\text{kWh-th/year}]$$

This quantity is derived using the bin-hour cooling methodology described in Section 5 and is based on the following inputs:

- Peak cooling load derived from volumetric load density (qv, W/m^3).
- Load factor (LF ≈ 0.40 for office buildings; higher for 24/7 facilities).
- Meteorological adjustments of +5 to +10°C to account the higher effective air temperatures experienced at air-conditioning condensers in Saudi Arabia due to radiant heat exposure, limited ventilation, exhaust-air recirculation, and rooftop or façade-level installations.
- Humidity profile of 45%-70%, incorporated to account for latent cooling loads.

A.1.2 Seasonal COP Values Used in Section 4

Baseline HVAC (air-cooled)

$$SCOP_{HVAC} = 2.3 - 2.7$$

Based on Saudi SEEC and SASO minimum energy performance standards.

Geothermal GSHP / Prime Loop

$$SCOP_{GSHP} = 5.0 - 5.5$$

Supported by TRT results, aquifer pumping tests, and modeled values.

A.1.3 Electricity Use for Cooling

Electricity consumption is computed as:

$$E_{elec} = \frac{E_{cool,annual}}{SCOP}$$

A.1.4 Fractional Electricity Savings

Given identical cooling load:

$$S = 1 - \frac{E_{elec,GSHP}}{E_{elec,HVAC}}$$

With equal cooling duty, substituting the SCOP relationship:

$$S = 1 - \frac{SCOP_{HVAC}}{SCOP_{GSHP}}$$

This formula is used in Section 4 to justify the 40%-50% electricity savings, which naturally result from SCOP 2.3-2.7 vs. SCOP 5.0-5.5.

A.2 Geothermal System Technical Inputs

A.2.1 Closed-Loop Systems

Inputs obtained from TRT:

- Ground thermal conductivity (k).
- Borehole thermal resistance (R_β).
- Allowable ground ΔT swing.
- Bore stepping and spacing for thermal balance.

A.2.2 Open-Loop Systems

Inputs derived from aquifer tests:

- Transmissivity.
- Specific capacity.
- Allowable drawdown.
- Reinjection temperature rise (typically 4-6°C).

Testing campaigns included step-drawdown tests, constant-rate pumping tests, and reinjection logging. These parameters directly determine well yield and geothermal SCOP.

A.3 Saudi-Specific Modeling Adjustments

Section 4 incorporates several Saudi-context-specific adjustments:

- A +5 to +10°C design-hour uplift reflecting desert microclimates and rooftop exposure.

- High latent-load contribution associated with 45%-70% relative humidity.
- Standard indoor setpoint of 24°C and 50% RH.
- SCOP baselines tied to SEEC/SASO MEPS.
- Regional meteorological differentiation between Eastern and Western provinces.

These adjustments ensure that modeled SCOP values and cooling loads reflect Saudi operational conditions.

A.4 Regional Scaling Methodology (Section 4)

A.4.1 Deriving Regional Commercial-Building Cooling Baselines

The Eastern Province baseline and the Western Province baseline (Makkah and Madinah) are derived from Saudi Electricity Company (SEC) electricity sales data and sectoral shares. Since SEC data are aggregated at the operating-region level, the Western region's commercial load is apportioned between Makkah and Madinah, which together account for the majority of the region's commercial floor area and cooling demand.

A.4.2 Penetration Assumption

$$p = 40\%$$

This assumption is supported by international analogs in which heat pump adoption reaches 30%-50% for large buildings.

A.4.3 Electricity Use Under Geothermal Adoption

$$E_{GSHP,region} = p \times E_{baseline}$$

A.4.4 Annual Electricity Savings

$$E_{saved} = S \times E_{GSHP,region}$$

A.5 Peak Load Reduction and Grid Impacts

The peak-load reduction used in Section 4 is derived from the SCOP uplift, which stabilizes performance during Saudi summer afternoons.

Peak reduction follows:

$$\Delta Peak_{cooling} = f(SCOP_{HVAC}, SCOP_{GSHP})$$

Appendix B. Quantitative Method

B.1 Technology Performance and Electricity Use

For each project (e.g., Eastern brownfield retrofit or Western greenfield development), annual cooling demand is denoted by $Q_{cool}(MWh_{th/year})$. Representative seasonal coefficients of performance (COPs) for conventional air-cooled chillers and GSHP systems are written as COP_{conv} and COP_{GSHP}, respectively.

Annual electricity consumption is then

$$E_{conv} = \frac{Q_{cool}}{COP_{conv}},\ E_{GSHP} = \frac{Q_{cool}}{COP_{GSHP}}$$

Assuming $COP_{GSHP} > COP_{conv}$, the fractional reduction in electricity use achieved by GSHPs, relative to the conventional baseline, is

$$\eta_{sav} = \frac{E_{conv} - E_{GHSP}}{E_{conv}} = 1 - \frac{E_{GHSP}}{E_{conv}} = 1 - \frac{COP_{conv}}{COP_{GHSP}}.$$

In the Saudi commercial case studies, the indicative values of COP_{conv} and COP_{GSHP} lead to electricity savings on the order of 40%-50%, but the exact value of η_{sav} is both location and application-specific and is computed from the measured or modeled COPs for each case.

B.2 Levelized Cost of Cooling (LCOC)

Economic performance is evaluated over an assumed project life of $n = 25$ years using a real discount rate of r. The present value (PV) of total costs over the project life is defined as

$$PV_{cost} = CAPEX_0 + \sum_{t=2}^{n} \frac{CAPEX_{rep,t} + C_{O\&M,t} + C_{elec,t}}{(1+r)^t},$$

where:

- $CAPEX_0$ is the initial investment (drilling, subsurface loop, plant, and integration).
- $CAPEX_{rep,t}$ are any reinvestments (e.g., above-ground equipment replacements) in year t.
- $C_{O\&M,t}$ are annual operation and maintenance costs.
- $C_{elec,t}$ are electricity costs in year t, computed from modeled electricity use and the tariff structure and escalation assumptions in Section 5.5.

The present value of useful cooling delivered is

$$PV_Q = \sum_{t=1}^{n} \frac{Q_{cool,t}}{(1+r)^t},$$

where $Q_{cool,t}$ is the delivered cooling (MWh_{th}) in year t.

The levelized cost of cooling is then

$$\mathrm{LCOC} = \frac{\mathrm{PV}_{\mathrm{cost}}}{\mathrm{PV}_{Q}},$$

with units of SAR per kWh_{th} (or \$/MWh_{th} after currency conversion).

For interpretation and cross-checking, an equivalent annual cost (EAC) can also be derived by multiplying the initial CAPEX by the standard capital recovery factor (CRF):

$$\mathrm{CRF} = \frac{r(1+r)^n}{r(1+r)^n - 1}, \quad \mathrm{EAC}_{\mathrm{CAPEX}} \approx \mathrm{CAPEX}_0 \cdot \mathrm{CRF},$$

and adding representative annual O&M and electricity costs in real terms. Dividing this EAC by the corresponding annual cooling output yields a close approximation to LCOC when loads and costs are relatively stable in real terms over the project life.

B.3 NPV, IRR, and Payback Period

Comparisons between GSHP systems and conventional cooling are performed using incremental cash flows. Let ΔCF_t be the net cash-flow benefit of GSHPs relative to the baseline in year t, including all changes in energy, water, O&M, and replacement expenditures (and any differences in residual value at the end of life).

The net present value (NPV) at the discount rate r is

$$\mathrm{NPV} = -\Delta\mathrm{CAPEX}_0 + \sum_{t=1}^{n} \frac{\Delta CF_t}{(1+r)^t},$$

where $\Delta\mathrm{CAPEX}_0$ is the incremental upfront cost of the GSHP option relative to the conventional alternative.

Simple (undiscounted) payback is estimated as

$$\mathrm{Payaback}_j \approx \frac{\Delta CAPEX_{0,j}}{\Delta \bar{C}F_j},$$

where $\Delta \bar{c}F_j$ is the average annual incremental cash-flow benefit over an initial period of operation (for example, the first 5-10 years), using the same underlying data as the NPV and IRR calculations. This approach forms the basis for the payback and IRR ranges reported in the tables in this chapter.

B.4 System-Level Economic and Environmental Indicators

The system-level impacts reported for the Eastern and Western regional envelopes are derived by applying the project-level performance to regional cooling-demand and peak-load estimates.

If $E_{\mathrm{base,r}}$ is the annual electricity consumption for cooling in a region under the conventional baseline and p is the assumed penetration of GSHP systems (e.g., 40 %), then the electricity demand served by GSHPs is

$$E_{\mathrm{addr}} = p \cdot E_{\mathrm{base}}$$

Using the fractional saving $\eta_{sav,j}$ for the representative archetype in that region, the annual electricity saving is

$$E_{sav} = \eta_{sav} \cdot E_{addr}$$

Economic and environmental indicators are then computed as follows:

- Annual electricity bill (OPEX) savings

  $$S_{OPEX} = E_{sav} \cdot T$$

  where T_r is the representative commercial/governmental tariff (SAR/kWh), including any tiered structure and escalation assumptions adopted in previous sections.

- Deferred grid-capacity investment

  Let $K_{peak,r}$ be the baseline peak cooling-related load in region *r*, and ΔK_r the corresponding peak-load reduction attributable to GSHP efficiency (estimated consistently with the hourly/seasonal modeling). If C_{cap} is a representative unit cost of new grid-generation and network capacity (SAR/kW), then

  $$S_{capex} = \Delta K_r \cdot C_{cap}$$

  gives the order of magnitude of deferred capacity-expansion expenditure.

These relationships provide the quantitative link between project-level performance metrics (COP, LCOC, NPV, IRR) and the regional-level results reported for the Eastern and Western envelopes in this chapter. All numerical values presented in the tables are derived by applying these equations using Saudi-specific input data and scenarios.

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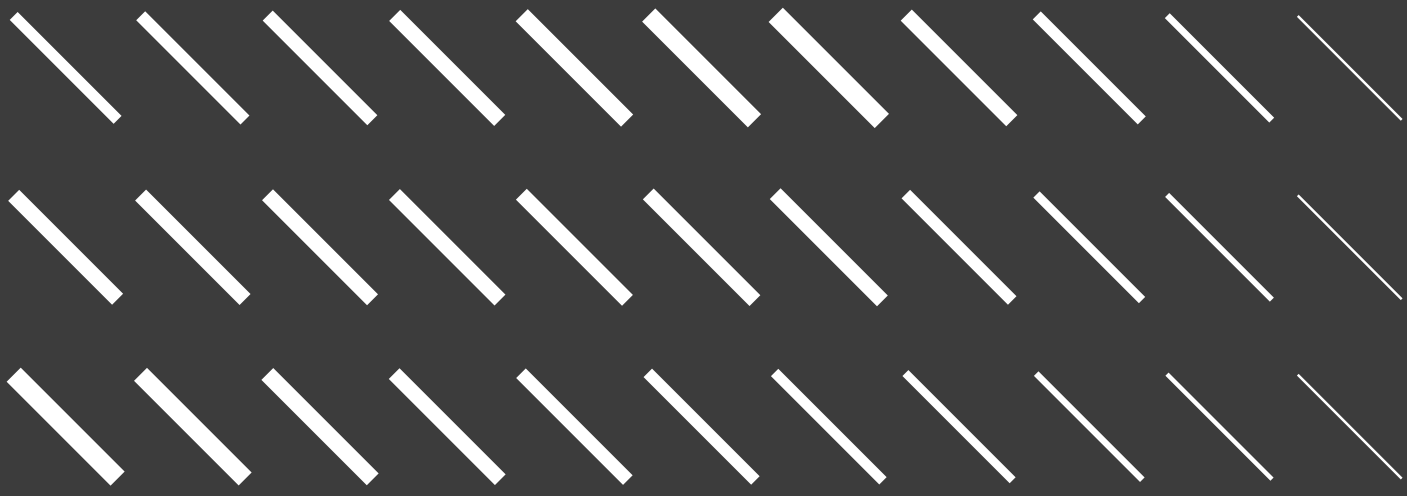
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About the Project

This study is part of a broader project that examines sustainable cooling through three lenses: policy, technology, and alternative energy sources. Specifically, it explores sustainable cooling in Saudi Arabia by focusing on three key areas: doubling energy efficiency, assessing the potential of geothermal energy for cooling, and analyzing the implications of the Kigali Amendment to the Montreal Protocol.





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