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Reframing ESG as Tangible Economic Inputs to Techno-Economic Analysis in Geothermal Projects

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ABSTRACT

This paper explores a novel approach to integrating Environmental, Social, and Governance (ESG) considerations into techno-economic analyses (TEA) of geothermal projects by assigning tangible, monetary values to ESG-related impacts. While ESG has become a prominent lens for evaluating project sustainability, its incorporation into TEA models remains largely qualitative, often relegated to risk factors or external narratives rather than being embedded directly in financial projections. This work proposes a conceptual framework for treating ESG elements such as carbon credit revenues, renewable energy certificate (REC) trading, local economic stimulation, and idle capital opportunity costs as quantifiable economic inputs. While no single methodology is prescribed, the discussion highlights existing data on REC pricing, water shadow pricing, carbon pricing trajectories under the Output-Based Pricing System (OBPS), and labor market multipliers associated with drilling activity. By framing ESG not as an externality but as a set of internal cash flow modifiers, this study opens the way for a more grounded, economically coherent analysis of renewable energy project viability. The goal is to stimulate discourse and further research into standardized, regionally adapted methodologies that reconcile ESG goals with investor-grade economic modelling through quantitative values which can be directly compared.

1 INTRODUCTION

Techno-economic analysis (TEA) provides the foundational structure for evaluating energy projects by estimating capital costs, operating expenses, and expected output. Levelized Cost of Electricity (LCOE) has emerged as the dominant investor metric derived from TEA because it condenses project economics into a single value that determines commercial viability and guides capital deployment (ECOFYS/Fraunhofer, 2014). While effective for investor decision-making, this framework captures only the subset of economic drivers that directly translate into project cash flows. As a result, LCOE excludes a range of environmental and social impacts that materially influence the broader economic value of energy development.

In parallel, governments and public institutions often rely on measures of social welfare such as social net present value (social NPV) to assess community impact, environmental performance, and long-term societal benefit. These metrics capture effects that matter to policy and society, such as water savings, employment, and local economic stimulation, but they remain analytically isolated from investor-centric TEA. The result is a structural disconnect: LCOE drives investor decisions, social NPV drives policy expectations, and the two metrics remain economically unaligned. Technologies that deliver substantial societal benefit, including geothermal energy, frequently remain commercially marginal not because they lack value, but because their value cannot be expressed in investor-relevant terms.

Geothermal development illustrates this divide clearly. Geothermal projects deliver quantifiable external benefits such as emissions avoidance, reduced freshwater demand, stable long-term employment, and utilization of underused drilling assets. These factors contribute meaningfully to regional economic performance and environmental outcomes, yet they do not appear in LCOE unless an explicit market-based incentive exists. At present, only a subset of ESG-related impacts, such as carbon credits or renewable certificate revenues, translate into actual revenue streams. Unpriced benefits remain stranded on the “policy side” of the analysis.

This paper does not propose replacing LCOE or subsuming social metrics into investor economics. Instead, it introduces a framework that quantifies non-priced ESG benefits in a form that can be converted into investor-relevant units. By expressing both market-priced and non-priced ESG effects within a consistent, time-resolved economic framework, the framework equips investors with a tool to communicate to regulators exactly the level of incentive required to make a high social-value geothermal project financially viable. In this sense, the

proposed approach operates as a translation layer between LCOE and social metrics: it reveals the magnitude of the unpriced benefits and demonstrates how they could be incorporated into cash flows if transformed into policy instruments such as water credits, labor credits, or other targeted incentives.

By reframing ESG factors in this way, TEA can more accurately reflect the full set of economic impacts associated with geothermal development, while maintaining a clear distinction between investor reality and societal value. The purpose of the framework is not to artificially lower LCOE, but to accurately capture existing material revenue streams and illuminate the policy gap that separates socially beneficial projects from commercial feasibility. We aim to provide a transparent, quantitative basis for designing incentives intentionally to close the gap.

2 BACKGROUND

2.1 History of ESG Analysis

The modern conception of Environmental, Social, and Governance (ESG) performance as a business metric originated with the 2004 United Nations Global Compact report, "Who Cares Wins." This report articulated, for the first time in a formal international context, a clear relationship between strong ESG performance and improved long-term financial returns. Following its publication, ESG analysis rapidly became an important tool for investors seeking to identify and mitigate project risk. As a result, firms demonstrating high ESG performance increasingly benefited from preferential lending terms, reduced insurance costs, and enhanced market valuations.

Initially, ESG performance at the project level was evaluated almost entirely through qualitative frameworks. These assessments relied on environmental and social impact studies, permitting reviews, community consultation records, and compliance with lender guidelines. Projects were categorized by perceived risk, but the ratings were not standardized across projects. In practice, ESG evaluation functioned as a narrative and compliance-driven exercise, shaping investor perception and due diligence requirements rather than producing an objective score or recognizing material economic impact.

2.2 Levelized Cost of Electricity

Levelized Cost of Electricity (LCOE) represents the average price at which electricity must be sold over a project's lifetime to recover all capital, operating, and financing costs. It is widely used as an investor metric because it provides a single, comparable measure of cost across energy technologies (although the original authors of the technique discouraged such comparisons, they have become widely used). However, LCOE is constrained: it excludes both monetizable revenue streams, such as carbon credits or renewable energy certificates (RECs), and non-priced externalities with material economic impact. In practice, project finance already incorporates policy-driven revenues such as tax credits or production incentives by treating them as effective cost reductions. Monetized carbon offsets and RECs can be incorporated on the same basis when they are contractible and priced, since they function as predictable cash flows that reduce the net cost of energy.

Recognizing that standard LCOE fails to capture system-level value, analysts introduced extensions such as LCOE-plus (Lazard, 2025) or VALCOE (Yang et al., 2024), which incorporate factors such as storage value, intermittency, and grid integration costs. These adjustments improve competitiveness comparisons at the market scale but remain aggregated, high-level corrections. They do not integrate project-specific ESG benefits or region-specific externalities, nor do they bridge the gap between investor and societal-value metrics, such as social NPV. As a result, LCOE and social value calculations continue to operate as separate, unaligned frameworks.

2.3 Techno Socio-Economic Analysis (TSEA)

Techno-Socio-Economic Assessment (TSEA) extends TEA by monetizing environmental and social impacts and incorporating them into a social net present value (social NPV). This structure is also helpful for policy evaluation, where welfare impacts such as job creation or emissions reduction are central. For example, Almena et al. (2025) demonstrate how including these factors can materially shift the perceived value of a Bioenergy with Carbon Capture and Storage (BECCS) facility.

However, TSEA outputs are not formatted in a way that aligns with investor metrics such as LCOE. Because social NPV does not translate directly into project cash flows, its results cannot be incorporated into investment decisions. For this reason, TSEA and TEA remain parallel but disconnected analytical frameworks. The present work draws on TSEA's treatment of social benefits but adapts it to make those values compatible with the TEA structure introduced earlier.

2.4 Social and Market Discount Rates

When considering how to value ESG drivers, several precedents support the approach of uniquely discounting social benefits. Market discount rates represent the opportunity cost of private capital and are derived from observable financing conditions, risk premia, and expected returns, while social discount rates reflect society's valuation of future welfare, consumption, and environmental or intergenerational outcomes. This distinction is important for ESG economic drivers as these factors do not represent investor cash flows and align more naturally with the lower rates used in social appraisal. A distinct social discount rate is incorporated into the framework to ensure that higher market discount rates do not overshadow social value. Although social discount rates historically reflect welfare impacts rather than investor cash flows, the present analysis evaluates both interpretations to support the dual-outcome structure introduced later. Guidance for social discount rates can be found in the public investment rationale (HM Treasury, 2022).

3 CONCEPTUAL FRAMEWORK

The energy industry, researchers, and regulators have made significant progress in recent years toward objectively normalizing emerging and conventional technologies on a standardized scale through methods such as LCOE-plus and TSEA. As a natural next step, we propose applying the LCOE-plus concept at the project level and expanding it to include monetizable ESG market factors.

In parallel, to support alignment between project viability and societal benefit, we introduce an analytical tool to explore the magnitude of new incentives required to internalize social value into project economics. These two outcomes together provide a clearer picture of both existing market-supported drivers and the potential pathways for integrating social welfare considerations into investor decision-making.

3.1 Framework Outcomes

3.1.1 Investor Grade Economic Drivers

At the project level, localized ESG factors can be quantified explicitly, enabling a more objective and context-appropriate assessment of levelized cost for a specific opportunity. With project-level metrics that reflect region-specific conditions across technologies, investors will be armed with more comprehensive information to support balanced portfolio decisions in practice.

The proposed framework adopts the underlying philosophies of LCOE-plus by incorporating material techno-economic factors into the discounted cashflow structure before computing the levelized cost. It advances the approach further by embedding these factors as discrete, time-resolved parameters rather than aggregated adjustment terms. The framework presented here enables ESG drivers to function as first-class financial modifiers.

A strength of the proposed first-class approach is the enhanced traceability of assumptions, as ESG parameters are documented individually within each model. This granularity enables identifying the specific drivers of changes in project economics, evaluating the sensitivity of individual factors, and auditing the rationale for each adjustment. It also facilitates more transparent communication among stakeholders, enabling regulators, investors, and project developers to understand precisely how external revenue streams influence the overall economics.

3.1.2 Analytical Insights for Policy Makers

The framework also yields a second analytical outcome relevant to policy development. Social-value drivers can be monetized and expressed on the same temporal basis as project cash flows. When combined with investor-grade results, these values illustrate the scale of the incentive required to internalize societal benefits and achieve the targeted LCOE.

This policy-oriented perspective is not presented as an investable metric. Instead, it functions as a diagnostic tool that highlights where social value remains unpriced and quantifies the potential economic signals that could bridge the gap between social benefit and investor feasibility. In doing so, the framework provides a structured means for evaluating regulatory pathways that could support the deployment of projects with both direct value to investors and broader societal value for a sustainable future.

3.2 Categories of ESG Financial Modifiers

In conventional ESG assessments, qualitative scoring of energy projects may consider the following categories of factors (which can be extended with this methodology if other categories can be identified and quantified as critical to stakeholders):

- Carbon pricing and credit revenues
- Renewable certificate revenues
- Resource usage offset (water)
- Idle capital/opportunity cost multipliers
- Local economic stimulus

These ESG assessment categories serve as a guideline for developing quantifiable parameters that demonstrate the investor-grade ESG-TEA framework described below. Tax credits and other direct financial incentives associated with renewable projects are not listed, as these benefits are typically already included in standard TEA analysis for energy projects.

Examples of categories not included in this calculation but that could be considered important policy drivers include the contribution of geothermal to a national goal of baseload energy independence. Another category that is not quantified in conventional investor frameworks is the degree of non-technical risk. Although the literature contains occasional references to resilience and security of supply as decision considerations, these concepts are not included in established ESG methodologies and therefore are not incorporated into the present analysis (prior work does not provide a basis for monetizing this benefit, which places it outside the scope of this study). Energy independence is an urgent driver influencing energy market development, and further exploration of methods to quantify this contribution would strengthen both policy and investment evaluations.

3.3 ESG Parameterization

The drivers introduced in the following section illustrate how the proposed ESG-TEA approach can be applied in practice, though they are intended to demonstrate useful patterns rather than represent an exhaustive set. Each parameter is informed by earlier work exploring the economic advantages of geothermal energy and is accompanied by a proposed method for monetizing its contribution or offset. Each parameter below is dynamically calculated for each period, using inputs such as energy production or water usage that are already generated in the conventional TEA framework.

3.3.1 Carbon Offset

Geothermal energy can displace energy generation technologies that would otherwise emit $\mathrm{CO_2}$. The value of that displacement is proportional to a regional carbon benchmark price. The carbon price is drawn from the prevailing regulatory body, supplemented by regional shadow carbon values and documented voluntary or internal prices. This ensures that carbon offsets are valued in accordance with the economic mechanisms that would apply to avoided emissions in each jurisdiction or commercial context.

Carbon offsets are a commonly used mechanism in renewable energy projects. The monetary value of carbon offset is detailed in avoided-emissions equations (World Bank, 2023).

$$B_{carbon} = I_{avoided} \cdot E \cdot P_{carbon}$$

where B_{carbon} is the monetary value of carbon offset; $I_{avoided}$ is emissions avoided per unit ($\mathrm{tCO_2/MWh}$); E is the amount of renewable energy produced (MWh); and P_{carbon} is the applicable carbon price ($\$/\mathrm{tCO_2}$).

3.3.2 Renewable Energy Credits (RECs)

Renewable Energy Credits (RECs) function as a commoditized representation of the renewable attributes of electricity generation, carrying a market-determined monetary value that represents a secondary revenue stream. This differs fundamentally from carbon offsets, which are valued on avoided emissions; RECs instead reflect renewable generation attributes and therefore operate as a separate, non-overlapping financial stream.

REC market value is sourced from a mix of compliance markets, voluntary trading platforms, and regional energy attribute registries. In compliance markets, REC prices are published by state or provincial tracking systems and regulatory authorities. Voluntary market REC prices are available through major brokers and exchanges.

$$B_{REC} = E \cdot P_{REC}$$

where B_{REC} is the monetary value of RECs; E is the amount of renewable energy generated (MWh); and P_{REC} is the market price of REC ($/MWh).

When using RECs and carbon offsets simultaneously in an ESG-TEA model, care must be taken to avoid double-counting the same environmental benefit (Bird et al., 2011). REC valuation should reflect an observable commodity price to avoid overlap with monetized carbon offsets.

3.3.3 Water Offset

Water use volumes in geothermal projects are typically lower than those of conventional processes that produce the same amount of energy. The Water Offset adjustment reflects avoidance of scarcity, which is similar in nature to the Carbon Offset.

While tariff-based water costs are published and available, they often underestimate the actual ESG and regulatory risks associated with freshwater withdrawals or makeup water requirements. As an alternative, regional water shadow pricing provides a superior calculation of the economic value of water that reflects scarcity, opportunity cost, and basin-level resource constraints (Bierkens et al., 2019). Shadow pricing of water is commonly used in mining and agriculture TEA, where industrial demand competes with community requirements, as it is a better indicator of actual impact.

$$B_{water} = E \cdot \Delta V_{water} \cdot P_{water}$$

where B_{water} is the monetary value of water offset; E is the renewable energy generated (MWh); ΔV_{water} is the net water savings relative to the displaced technology (m^3/MWh); $and\ P_{water}$ is the shadow price of water ($/$m^3$).

Shadow pricing is regionally sensitive and consistent with World Bank and Organization for Economic Co-operation and Development (OECD) water valuation practice.

3.3.4 Idle Rig Discount

Geothermal project costs are dominated by drilling, and several earlier reports highlight that geothermal projects could benefit when rig capacity is drawn from equipment that would otherwise remain idle. The proposed Idle Rig Discount parameter represents a tactical way to capture the economic value of redeploying underutilized rigs. Instead of assuming a sub-market day rate, the parameter is applied as a discount factor against the prevailing market day rate. This approach preserves the use of market-referenced pricing while providing a defensible explanation for why geothermal drilling may be able to access lower effective rates.

The idle rig discount is expressed as a benefit to remain compatible with the ESG-TEA framework, and reflects the absolute value of reduction in capital expenditure through the discount:

$$B_{rig} = (1 - \alpha) \cdot R_{market}$$

where B_{rig} is the idle rig cost benefit; α is the discount rate for idle assets; and R_{market} is the prevailing market rig rate.

Discount factors used in this model should be grounded in current industry reports or market observations on rig utilization and stacking costs. For internal consistency, the discounted day rate must not fall below the equipment's idle cost. This lower bound corresponds to the minimum economically rational rate, ensuring that any sub-market pricing assumed in the model reflects a real avoided-cost mechanism rather than an unsupported reduction in capital cost. Though rig owner internal costs are unlikely to be available, regional industry trends are periodically reported in market reports. The discount rate may be modeled with uncertainty to reflect the probability of negotiating this benefit. In addition, overlap may exist with the Jobs Benefit when idle assets are utilized; the modeler should avoid double-counting by considering if net new construction jobs were created by keeping an existing rig deployed.

In the drilling industry, rigs can be idled through either warm stacking or cold stacking. Warm stacking retains a reduced crew and maintains key systems, keeping the rig in a state of readiness and often incurring costs comparable to those of active operation. Cold stacking fully releases the crew and shuts down most systems, reducing short-term costs but increasing reactivation risk, accelerating equipment degradation, and creating negative impacts for workers and local communities through job losses. While this parameter does not explicitly quantify those social or operational losses, it encourages geothermal projects to utilize rigs that might otherwise be idle. In doing so, it supports ESG principles by helping preserve skilled employment, maintain community stability, and promote responsible use of existing industrial assets.

3.3.5 Jobs Benefit

The creation of jobs, tax revenue, and broader community impacts has previously been incorporated directly into techno-economic assessments (Almena et al., 2025). These effects are widely recognized as providing sustainable, long-term positive economic value to local communities.

For a geothermal plant, employment is generated during the multi-year construction period of a large baseload plant, followed by additional long-term jobs once the facility enters operation. Further indirect employment arises through increased activity in the supporting supply chain. The economic value of this impact can be monetized by estimating the number of people employed and their wages.

$$B_{jobs} = M \cdot N_{jobs} \cdot W$$

where B_{jobs} is the monetary value of created jobs; M is the multiplier to capture indirect jobs created; N_{jobs} is the number of direct jobs created; and W is the average wage of a worker.

Job-related benefits will naturally vary over the life of a project as staffing needs change. This is one of the advantages of applying ESG factors directly on a per-period cashflow basis, as it captures these shifts dynamically rather than relying on static assumptions.

It is important to note that job creation occurs in any project that requires labor and is not unique to geothermal or renewable energy. To compare across technologies fairly within the proposed ESG-TEA framework, the jobs benefit should be applied across all sectors and scaled according to the specific workforce requirements of each technology.

3.4 ESG Parameters in ESG-TEA

3.4.1 Baseline LCOE Calculation

The time-dependent form of LCOE is shown below. The numerator represents the total lifetime costs discounted to present value, while the denominator represents the total lifetime value of energy production.

$$LCOE = \frac{\sum_{t=0}^{N} \frac{CapEx_t + OpEx_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}}$$

where $LCOE$ is the levelized cost of electricity (or more generally, energy); $CapEx_t$ is the capital expenditure at time t; $OpEx_t$ is the operating and maintenance expenditure at time t; r is the market discount rate; and E_t is the value of energy produced at time t.

3.4.2 Categorization of ESG Benefits

Within this framework, ESG parameters are separated into two categories. Market-based components, such as carbon credits or RECs, are incorporated directly into the financial model and discounted at the market rate to produce investor-grade LCOE. Social components, such as water savings or employment impacts, are monetized separately using a social discount rate and can then be evaluated for their potential conversion into incentive structures. This dichotomy allows the model to produce both an investor-aligned LCOE and a policy-oriented analytical outcome within a single framework.

ESG Parameter Categories

ESG Parameter	Symbol	Category
Carbon Offset	B_{carbon}	Market
Renewable Energy Credits (RECs)	B_{REC}	Market
Idle Rig Discount	B_{rig}	Market
Water Offset	B_{water}	Social
Jobs Benefit	B_{jobs}	Social

For each category, an aggregated monetized benefit at any time can be computed, driven by project parameters such as energy produced or people employed during that period.

$$B_{market}(t) = \sum_{i \in \mathcal{M}} B_i(t) \qquad B_{social}(t) = \sum_{j \in \mathcal{S}} B_j(t)$$

The aggregated benefits at each time are then integrated into the LCOE calculation, denoted as $XLCOE$, and computed as follows:

$$XLCOE_m = \frac{\sum_{t=0}^{N} \frac{CapEx_t + OpEx_t - B_{market}(t)}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}}$$

and

$$XLCOE_{m,s} = \frac{\sum_{t=0}^{N} \frac{CapEx_t + OpEx_t - B_{market}(t)}{(1+r)^t} - \sum_{t=0}^{N} \frac{B_{social}(t)}{(1+r_S)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}}$$

where $XLCOE_m$ is LCOE including monetizable, market-priced ESG parameters; $XLCOE_{m,s}$ is $XLCOE_m$ plus social impacts internalized as economic incentives; and r_S is the social discount rate.

The choice of discount rate applied to the social components within $XLCOE_{m,s}$ is left to the discretion of the modeler. Although there is precedent for valuing social impacts using a lower social discount rate, a reasonable counterargument is that once these impacts are translated into monetized incentives, they function as conventional investor-facing cash flows. In that case, the market discount rate may be more appropriate. This flexibility allows the framework to accommodate either interpretation, depending on the policy context and the modeler's assumptions.

Energy production is discounted at the market rate r in both $XLCOE_m$ and $XLCOE_{m,s}$ because the denominator represents investor-relevant energy value, not social welfare; the social discount rate applies only to the monetized social benefits in the numerator and does not alter the investor-facing treatment of delivered energy.

4 METHODOLOGY

To evaluate the impact of the proposed conceptual framework, we will model a sample project with distinct economic drivers and some measure of publicly available ESG data. The analysis will rely on time series cashflow and production data exports from Eavor-Suite™, a commercial tool which models techno-economics for closed loop geothermal systems. This tool was chosen as it is familiar and accessible to the authors, has been validated against the open-source techno-economic model in GEOPHIRES (developed by NREL), and supports realistic large scale development plans on a staggered timeline.

Additional cashflow fields will be computed for the proposed ESG parameters in a spreadsheet. The baseline $LCOE$ value will be compared with the extended $XLCOE_m$ and $XLCOE_{m,s}$ outcomes as described above.

5 ASSUMPTIONS

The sample project is simplified and uses non-rigorous assumptions for a closed-loop geothermal project in the region, based on available data. The purpose of the comparison is to test the assertion that incorporating ESG parameters into TEA can have a material impact on LCOE and overall competitiveness of geothermal projects. The outcomes are not intended to inform a market level LCOE target for geothermal energy or reflect the LCOE of an actual geothermal project.

The sample project will deliver approximately 250MW of power developed over 5 years and will connect directly to California's grid (Western United States). Generic assumptions will be used to generate both the baseline $LCOE$ and extended $XLCOE$ values; a complete inventory is not detailed explicitly as these assumptions are held constant across all three cases. Our objective is to evaluate the relative difference of LCOE values related to the introduction of ESG parameters. The ESG parameter assumptions described below are illustrative rather than rigorous, as public data is limited.

ESG Parameter Assumptions

ESG Parameter	Low Value	High Value	Sample Source
P_{carbon}	\$35 USD/tCO_2	\$35 USD/tCO_2	2024 Cap-and-Trade Program auction (ICAP, 2024)
$I_{avoided}$	0.44 tCO_2/MWh	0.44 tCO_2/MWh	2023 US EIA FAQs; average CO2 emissions for Natural Gas
P_{REC}	\$7 USD/MWh	\$38 USD/MWh	2023 VALLEY CLEAN ENERGY PCC (Levels 1-2)
P_{water}	\$0.25 USD/m^3	\$0.50 USD/m^3	2023 Delta Conveyance Cost-Benefit Analysis estimate (Sunding and Browne, 2024); shadow prices are volatile and based on conditions, upper bound speculative increase due to drought
V_{water} displaced	1.0 m^3/MWh	7.5 m^3/MWh	2023 Today in Energy Report for Natural Gas (EIA, 2023) plants assuming 25%-90% return on average withdrawal of 10 m^3/MWh (nationwide estimate)
α idle discount	5%	10%	Speculative
W	\$4000 /worker/month	\$7000 /worker/month	Glassdoor, Salary.com general aggregations for Rig and Plant workers in California, present day
N_{jobs} construction	37/rig	37/rig	2017 IMF Paper: Employment Impacts of Upstream Oil & Gas Investment… (Agerton, et al., 2017); direct employment
N_{jobs} operation	1.7 /MW	1.7/MW	2015 GEA Brief: Additional Economic Values of Geothermal Power; direct employment
r_S	8%	4%	2016 World Bank Discounting Costs and Benefits average for High Value; market rate for Low Value

Water offset is calculated based on a closed-loop geothermal project design with a leak-off rate of 10%, which is conservative relative to measured data (0.1%; Toews et al., 2021), versus a typical conventional natural gas plant. A geothermal plant could plausibly displace this plant.

Currency values in the ESG Parameters, such as REC prices and wages, are not escalated over the project's lifetime. This proof of concept is simplified; an improved model would escalate these amounts to avoid undervaluing ESG benefits.

6 RESULTS

The experimental results illustrate how project economics shift when ESG factors are incorporated into the TEA structure, for the simplified closed-loop geothermal system studied.

ESG Parameter Set	$LCOE$	$XLCOE_m$	$XLCOE_{m,s}$
Low Values	\$80 USD/MWh	\$69 USD/MWh	\$51 USD/MWh
High Values	\$80 USD/MWh	\$34 USD/MWh	\$11 USD/MWh

It should be noted that outcomes will vary substantially across technologies, locations, displaced sources, and regional social-impact drivers. These variations are not a limitation of the framework but rather its intended purpose. By grounding the analysis in local geological, economic, and social conditions, the model provides a context-specific, defensible financial assessment for each project.

7 DISCUSSION

The results reveal the striking implication of applying the proposed ESG-TEA framework. Incorporating market and social parameters into the economic assessment reduced the effective LCOE of the example closed-loop

geothermal project by as much as 86 percent under the high-value ESG scenario. The updated, comprehensive ESG-TEA outcome shifts the sample project from economically marginal to strongly competitive. This outcome establishes clearly that ESG parameters fundamentally reshape the economic profile of the project and therefore merit explicit treatment in techno-economic analysis.

Continuing work on the proposed ESG-TEA framework requires consideration of uncertainties in parameter inputs, regional variability, and the limited availability of consistent ESG data. The following subsections outline these considerations and identify areas where the framework can be refined to better support both investor analysis and policy design.

7.1 Value of ESG Drivers

7.1.1 Renewable Energy Certificates

The geothermal sector is currently experiencing rapid growth and strong demand as a reliable, autonomous baseload energy source. However, policy and regulatory adjustments have not yet been deployed to reflect its rising position in the energy market. Due to this lag, geothermal RECs are often priced at the lowest tier in open and compliance markets. As REC pricing evolves, the ESG benefit's impact will be reflected in this market-driven framework.

7.1.2 Idle Equipment Discount

Leveraging idle equipment and expertise is a recognized conceptual approach to improve the economics of geothermal (Schlumberger, 2013); however, quantifying this impact is the most speculative of the ESG parameters. The authors are not aware of any published information to prove that this idle capacity has been secured, or at what discount, by any geothermal project. As day rates are negotiated and project-specific, we recommend starting with a conservative range until negotiations solidify or concrete external incentives are proposed to fund the discount.

7.1.3 Water Offset Value

The proposed valuation of water use avoidance is based on water shadow pricing. The World Resources Institute (WRI) Aqueduct additionally publishes an atlas of watershed stress indicators. Their map indicates the level of overdraw in local aquifers, a consideration not included in water shadow pricing. A future extension to the Water Benefit calculation would include this factor (perhaps time-variant), as the impact of water usage could be further scaled by the degree of stress the basin. To address this, the value between 0 (best) and 1 (worst) should be scaled in an economically defensible manner to increase its impact when the stress basin factor is high.

7.2 Access to ESG Data

A considerable challenge in this effort was finding reliable data sources for ESG parameter inputs. Much of the real-time market data on REC values, rig utilization, and carbon credits is not publicly available. When published reports do exist, they often omit segmentation by technology (which can significantly affect the market value of RECs). The proposed framework will have limited value in areas where data on market drivers of ESG parameters is unavailable. Regulated, public release of reliable data on ESG factors would facilitate broader and more defensible adoption of the ESG-TEA framework proposed here.

8 CONCLUSION

The sample analysis in this work shows that incorporating ESG factors into project-level techno-economic assessments can meaningfully influence geothermal project viability. Market-based components alone measurably shift the levelized cost. Adding monetized social-value drivers reveals a much larger pool of unpriced benefits and shows how these could, in principle, be translated into material economic incentives. This demonstrates that both investor-focused and policy-oriented perspectives gain clarity when ESG parameters are represented in a structured, time-resolved form.

Several challenges were encountered during the proof-of-concept development. Public ESG datasets are limited, inconsistently reported, and often not segmented by technology or region. Social impacts require careful treatment, particularly with respect to discounting and valuation methods. The application of more sophisticated, commercial ESG datasets will improve the integrity of subsequent studies that use this proof of concept as a guide.

Even with these limitations, the approach offers clear value. It provides defensible investor-grade metrics that already exist in the market. At the same time, it generates a policy-oriented view that quantifies the incentive

needed to internalize social benefits. The general trends observed were expected, but the magnitude of the impacts was not. This reinforces the importance of continued work in this area.

Next steps include refining parameter inputs, expanding the analysis to additional regions and technologies, and improving access to reliable ESG market data. Engagement with regulators and industry stakeholders will also be important to assess how monetized social-value drivers can inform incentive design. As these areas advance, the framework can support more aligned investment decisions, data-driven policy development, and broader deployment of high-value geothermal and other clean energy technologies.

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