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Internalization of External Cost in the Geothermal Power Generation on Social Welfare Maximization

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Abstract:
Against the background of the deleterious impacts of fossil fuel power generation, considerable attention has been given to developing renewable and clean sources of energy. Over the past few decades, geothermal energy has increased significantly across the world due to its low impact on climatic change. Although it is considered one of the most promising sources of renewable and clean energy, it is not exempt from environmental and social well-being drawbacks. In this study, we evaluate the external cost of electricity generated by geothermal power plants in Kenya. Both survey data and secondary data were used. The analysis was conducted using externality valuation and welfare maximization approaches, and the research hypotheses were tested using a negative binomial regression model. The results of both survey data and secondary data analysis show that geothermal power generation is attributed to negative environmental, public health, and socio-economic impacts as a result of emissions and sitting. Overall, the geothermal power generation annual external cost ($/2022) was determined to be $ 162,330.75 with the following distribution: Environmental at $ 90,905.22, Public health at $ 42,206.00, and Socio-economic at $ 29,219.53. Equally, the geothermal power generation marginal social cost ($/2022) was determined to be 0.02 $cents/kWh with the following distribution: Marginal Private Cost (MPC) at 0.02 $cents/kWh, and Marginal External Cost (MEC) at 0.000045 $cents/kWh. The established marginal social cost (MSC) (i.e. Σ MPC+MEC) was 0.02 ($cents/kWh). This is less than the established social marginal benefit (SMB) of 0.089 ($ cents/kWh); hence, we conclude that the burden of social welfare loss is insignificant, making geothermal power a sustainable energy source.

Keywords: *External cost, internalization, marginal social benefit, marginal social cost, and Social welfare maximization*

1. Introduction

Energy is regarded as a prerequisite for sustaining a nation's economic growth and improving its standards of living and social integration. However, the development and provision of energy services along the fuel cycle are associated with serious health and environmental impacts. While there is a common consensus that geothermal energy has tremendous potential for environmentally friendly power generation (Schifflechner et al., 2020), its development and use can, however, have significant multi-dimensional sustainability implications. For instance, geothermal power generation produces pollutants such as carbon dioxide (CO_2), sulphur dioxide (SO_2), particulate matter (PM), hydrogen sulphide (H_2S) and carbon monoxide (CO) which cause critical environmental and public health issues, such as ground-level ozone, acid rain, global warming, respiratory illness and effect on bio-systems (Ghoddousi & Talebi, 2021). In a purely economic context, these undesirable side effects are termed external costs or negative externalities (Bielecki et al., 2020). Internalization of external costs into the full energy production cost is considered a potentially efficient policy instrument with regard to energy to reduce its undesirable impacts and move towards a more sustainable energy supply capable of maximizing social welfare (Antoinette, 2021).

With the increasing global concern about the causes and deleterious impacts of climate change, policymakers and researchers have focused on the external costs of energy production. Several major research projects have examined the issue of quantifying and valuing externalities associated with electric power production. Extensive studies have been conducted in European and North American countries, whereas moderate studies have been conducted in Asia-Pacific countries. Despite increasing interest in the assessment and valuation of external costs arising from electricity production, African countries have fallen behind, with only limited related studies performed in South and North Africa, and evidence of related studies in other regions is sparse. Thus, significant efforts are still needed as more African countries endeavor to diversify the future power generation technology mix to meet the increased demand.

Little research has been conducted in this field in Kenya, which makes it an area of interest. Kenya is one of the countries in Africa that is in the process of implementing climate-policy frameworks such as the National Adaptation Programs of Action (NAPAs) and Nationally Appropriate Mitigation Actions (NAMAs). Given the certainty that geothermal energy production and usage are set to increase substantially, it is important to ensure that geothermal resources are developed in a sustainable manner, particularly for electricity generation projects.

Over the years, the Kenyan government has been involved in medium-to-long-term planning of the energy sector through the Least Cost Power Development Plan (LCPDP), which sets a clear direction for the development of the power generation sector (the Republic of Kenya, 2023). The LCPDP approach tends to advantage the "least-cost" technology for project development (based on internal cost) without fully considering factors external to the power generation mix. In LCPDP (2020-2040), carbon dioxide (CO_2) emissions are considered the only major risk (due to its impact on climatic change), while overlooking other risks of the power generation mix.

1.1. Hypotheses of the Study

The following hypotheses were tested against the survey data;

- Ho1: Internalization of environmental external cost in geothermal power generation has no significant effect on social welfare maximization
- Ho2: Internalization of public health external cost in geothermal power generation has no significant effect on social welfare maximization
- Ho3: Internalization of socio-economic external cost in geothermal power generation has no significant effect on social welfare maximization

1.2. Contribution of This Study

The contribution of this study is threefold: First, it assessed the external costs of geothermal power generation for internalization on social welfare maximization in Kenya. Second, the study outcomes shed light on the explicit magnitude of the direct external costs borne by the society from geothermal power generation. Third, the works introduce to the body of literature a geothermal power generation external cost study in Kenya.

2. Literature Review

2.1. The External Cost (Negative Externalities) and Welfare Maximization

The concept of externalities in the general sense was first mentioned by economist Alfred Marshall and then developed and analyzed in further detail by Arthur Pigou. According to Hutchinson (2017), an externality is a cost or benefit resulting from an economic transaction borne or received by parties not directly involved in the transaction. Sundaram (2016) posits that an externality exists if two conditions exist: First, an impact (which can be negative or positive) is generated by economic activity and is imposed on third parties. Second, the impact must not be priced in the marketplace; for example, if the effect is negative, no compensation is paid by the generator of the victim's externality. If the effect is positive, the generator of the externality does not receive any gains from the benefiter.

Real resource costs in power generation should include both private and external costs. The most debated externalities in the electricity sector are those related to environmental damage, individual and collective health impacts, and interference with social arrangements (Rochedo et al., 2018). As Streimikiene et al. (2021) recalled, a power plant that generates emissions causing damage to building materials, biodiversity, and human health imposes an external cost on different members of society.

External costs constitute a loss of social welfare due to their negative impact on environmental, individual, and collective health and interferences in social arrangements. Wherever the prices of goods or services do not reflect full costs, markets are distorted, and society bears the burden of this loss of social welfare (Antoinette, 2021). Therefore, the internalization of externalities is a fundamental step in the definition of energy policies. This process defines the real impacts of these externalities and translates them into monetary values to be properly included in benefit/cost models, which will result in better solutions from the perspective of sustainability and welfare maximization (Bielecki et al., 2020).

2.2. Theoretical Literature

The theoretical foundation is guided by welfare maximization theory and externality valuation theory.

As applied in economics, welfare theory is used to evaluate the consequences of alternative situations or public policies regarding social welfare, generally considering social welfare to be tightly linked to individual well-being (Antoinette, 2021). Figure 1 illustrates the basic theoretical issue addressed by full-cost accounting. Consider a polluter, a power generating utility, for example, operating with no emissions controls at point F and imposing environmental damages borne by society equivalent to the area under the damage curve OBCF. Maximizing social welfare requires that either a regulator impose an emissions limit of Q* or impose an optimized tax on the polluter that equals Q*E, at which point the marginal benefits equal the marginal costs and justify an emissions reduction to point Q*. Further emissions reduction to the left of Q* cannot be justified because the cost of each emissions reduction unit exceeds the damage reduction (or, in this idealized case, the tax saved). Without an instrument to enforce the socially optimal level of emissions, society is bearing a loss of welfare equivalent to the area ECF in figure 1, the actual magnitude of which is unknown (Henry & Stephan, 2003).

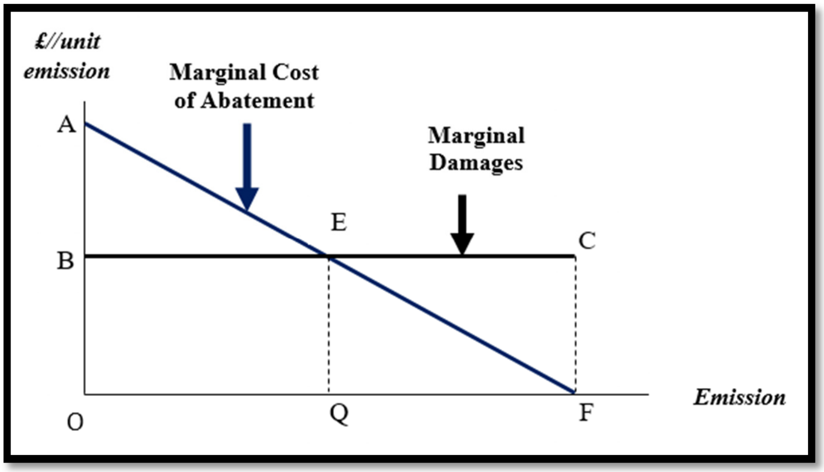

Figure 1: Socio-environmental Damages and Costs
Source: Externe (1999): Adapted from Henry and Stephan (2003)

Theorizing the concept of externality valuation and internalization, Varian (1992) used a simple production model of the form: Consider a firm, ***J*** that operates in a competitive market. Furthermore, assume that firm ***J*** produces output ***y*** that sells at market price ***p***. The following profit maximization problem can then be formulated for firm ***J***:

$\pi_j = max_j \; py - c(y)$……………………………………………………………………………………………………1

where $c(y)$ is the (private) cost and π_j is the profit from producing ***y*** units of output for firm ***j***. The equilibrium amount of output, y^*, is given by the first-order condition

$p = c'(y^*)$ ………2

Shows that firm ***j*** should produce up to the point at which prices equal marginal (private) costs. However, suppose that the productive activity of firm ***j*** gives rise to an external cost $e(y)$. For example, the production of ***y*** *units* of output also yields ***y*** *units* of pollution. The output y^* is then too large from a society's point of view. Thus, in its optimization firm ***j*** only accounts for its private (i.e., internal) costs and not for the external costs that it imposes on society. To determine the efficient level of production, the firm should internalize the externality, thus incorporating the external costs into its profit maximization problem, so that

$\pi_j = \; max_y \; py - c(y) - e(y)$……………………………………………………………………………………3

with the corresponding first-order condition:

$P = \; c'(y^e) + e'(y^e)$…………………………………………………………………………………………………4

The output y^e is Pareto efficient; the price is set to equal the sum of the marginal private cost and marginal external cost, that is, the marginal social cost. However, as Štreimikienė (2017) posits, unregulated markets do not internalize external costs (externalities). If external costs can be "internalized" (i.e., made private), decision-makers will have an incentive to undertake actions that help mitigate negative socio-economic and environmental impacts.

According to Lehmann et al. (2019), the approaches used in the valuation of externality impact in the energy sector include:

- Non-market valuation approaches (e.g., Productivity changes, Income changes, replacement cost, etc.),
- Market valuation approaches (e.g., Stated preference) and
- Other approaches (e.g., damage (opportunity) cost, benefit transfers, etc.)

Indirect or non-market valuation techniques are used when there are limited or non-existent markets for socially valued items, such as clean air, for which there is no market price. On the other hand, direct methods assess economic value using values, as well as non-use values (such as existence values).

2.3. Empirical Literature

The classification scheme embraced to determine the scope of the quantification and valuation is organized into three broad categories centered on the point of impact as follows:

- Environmental impact
- Public health risk, and
- Socio-economic impact

2.3.1. Geothermal Power Environmental Impact

Schifflechner et al. (2020) assessed the external costs caused by power generation through geothermally driven ORCs with different working fluids, investigating impact categories of global warming, acidification, eutrophication, and ozone depletion and obtained external costs between 0.16 €ct/kWh el,net and 1.7 ct/ kWh el,net. Yilmaz and Kaptan (2017) assessed the environmental impact of geothermal power plants in Aydın, Turkey and reported that geothermal energy generation could cause substantial environmental and human health deleterious effects. The authors established that the utilization of energy from geothermal wells releases greenhouse gases trapped in the earth's core, such as carbon dioxide, hydrogen sulfide, methane, and ammonia. Additionally, they concluded that geothermal waters pose a large potential risk to water quality if released into the environment due to high concentrations of toxins, including boron, antimony, arsenic, lead, and mercury, but that the risk of release can be virtually eliminated through proper design and engineering controls. It is known that Boron toxicity has a negative effect on the metabolic functions of the plant. The boron toxicity leads to a reduction in yield and yield components of plants owing to plant tissue death, as well as the reduction of the active leaf area and photosynthetic activity due to the high level of boron. Boron toxicity can easily occur, especially in arid and semi-arid regions worldwide, owing to the fact that the range of B deficiency and B toxicity is narrow. Fanney et al. (2010) conducted a study on methods to evaluate externalities from a Geothermal energy plan, a case study of the Nesjavellir plant in Iceland, and the study outcome showed that the amounts of the emissions per Nesjavellir lifetime estimated external costs associated with carbon dioxide (CO_2) was € 73,290.788 (2002/t). The external costs due to methane (CH_4) were mainly connected with its impacts as a greenhouse gas, thus a global impact of € 4,820.606 (2002/t). The external cost due to ozone (O_3) on global warming impact was € 2710 (2002/t). The external costs due to nitrous oxide (N_2O) were mainly connected with its impacts as a greenhouse gas, thus a global impact of € 447,734 (2002/t). The external costs due to Sulphur dioxide (SO_2) were mainly connected with its potential for causing acid rain and affecting human health as well as other parts of the biosystems (fauna and flora), thus causing a global impact in the form of material damage at € 307.545.232 (2002/t).

2.3.2. Geothermal Power Public Health Risk

Hydrogen sulphide (H2S) is the most significant air quality parameter in geothermal power generation in the immediate environment. If not correctly disposed of, hydrogen sulphide (H2S) can cause health and safety problems. Fanney et al. (2010) undertook a study on methods to evaluate externalities from a geothermal energy plan, a case study of the Nesjavellir plant in Iceland and established the external costs related to H2S within the human well-being (health impacts-respiratory diseases) stood at € 1,266.871(2002/t). In addition, the external costs due to Carbon monoxide (CO), which is extremely toxic to humans and animals and the most common type of fatal air poisoning, were quantified at € 2.545.938 (2002/t). Yilmaz and Kaptan (2017) undertook a study on the environmental impact of geothermal power plants in Aydın, Turkey and established that geothermal wells release heavy metals that can have deleterious effects on human health, for instance, damage to the central nervous system, dementia, loss of memory, listlessness, severe trembling, Alzheimer's disease, lung embolism, respiratory failure, birth defects, asthma and chronic bronchitis, allergic reactions such as skin rashes mainly from jewelry, heart disorders, and more.

2.3.3. Geothermal Power Socio-economic Impact

Fanney et al. (2010) study on methods to evaluate externalities from geothermal energy plan, a case study of Nesjavellir plant in Iceland, established that external costs related to H_2S damage of material assets (manufactured assets) were estimated at € 141,943.451(2002/t). Luis (2014) performed a study on the environmental impacts of geothermal energy generation and utilization on volcanoes of the eastern Sierra Nevada and established that the installation of pipelines to transport geothermal fluids and the construction of ancillary structures affect animal and plant life and the landscape.

3. Data and Methodology

3.1. Data

The extent of the internalization of external costs in geothermal power generation on social welfare maximization was determined by analyzing both primary and secondary data. Quantification of external cost estimates was undertaken on four geothermal power plants located in Olkaria, Kenya. The survey participants were selected from the population elements of the immediate community and interested and affected groups within the area of influence of the power generation plant. A stated preference approach was adopted to elicit survey data. Secondary data on the annual average concentration of air quality monitoring of chemical emissions from the four geothermal power plants were used to quantify and monetize the impact. A meta-analysis-unit value transfer approach was used to estimate the damage costs of geothermal power generation. The ExternE (2018) study and related series unit cost for SO_2, NO_2, H_2S, CO_2 and CO emissions, and PM were used. Damage costs were transferred from Western European practices to Kenya's conditions by scaling according to gross domestic product (GDP) per capita measured in purchasing power parity (PPP) terms.

3.2. Model and Methods

Externalities can be considered in the model as a restriction (Huang et al., 2016; Lv et al., 2020), or they can be included in the cost function to be optimized (Pereira et al., 2017). In other cases, a mixed approach is used; some externalities are addressed as restrictions and others are included in the objective function (Georgiou, 2016; Tang et al., 2017). This study adopted a mixed approach. The models considered include negative binomial regression, externality internalization, and social welfare maximization. While the negative binomial regression model is mainly used to address the effect of externalities on welfare maximization using survey data and to test the three null hypotheses, the externality internalization model is used to determine the power generation mix marginal social cost (MSC) (USD cent/kWh). Likewise, utilizing the social welfare maximization approach "marginal" argument, the marginal social benefit (MSB) ($ cents/kWh.) was determined, and the results were used to support hypothesis testing.

- *The Negative Binomial Regression Model:* The Negative Binomial regression model equation is written as:

$$y_i = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n)$$

Where $y_i = \ln\mu$,represents the expected counts' natural logarithm, β_0 is the constant coefficient…………………………. 5
$\beta_1, \beta_2, \ldots \beta_n$ Represent the coefficients associated with the respective covariates. The coefficient vector β is usually estimated by maximizing the following log-likelihood function:

$$L(\beta, \theta) = \prod_{i=1}^{n} \left(\prod_{r=0}^{y_i - 1} (r + \theta^{-1}) \right) \frac{1}{(y_i!)} \left(\frac{1}{(1+\theta\mu_i)} \right)^{\theta^{-1}} \left(\frac{\theta\mu_i}{(1+\theta\mu_i)} \right)^{y_i} \quad \text{…… 6}$$

Simultaneously test the significance of the negative binomial regression model using the Maximum Likelihood Ratio Test with the following hypothesis (Dobson, and Barnett, 2018).

$H_0: \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$ Against $H_1: \beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4$

Test Statistics: $D(\hat{\beta}) = -2ln\left(\frac{L(\hat{\omega})}{L(\hat{\Omega})}\right)$ ……7

The rejection area is rejected H_0 if $D(\hat{\beta}) > \mathcal{X}^2_{p\,(a)}$ or $p - value < \alpha$, which means that the four covariates affect the response variable.

- *Externality Internalization Model (EIM):* In addressing the impacts of internalization of externalities from thermal electric power generation, the externality internalization model is used. This modelling approach imposes additional charges on electricity generation, which reflects the costs of environmental damage, individual and collective health impacts, and interference in the social arrangement (Costa & Ferreira, 2023). Following Drennen et al. (2003), the total electricity generation optimization system cost function for a producer is specified as:

$$TGC = \frac{I*CRF}{Q} + \frac{FIXO\,\&\,M}{Q} + \frac{VARO\,\&\,M}{Q} + \frac{F}{Q} + \frac{E}{Q}. \quad \text{…… 8}$$

Where:
I is the capital investment cost,
CRF is the capital recovery factor,
Q is the annual plant output (kWh),
FIXO&M is Fixed operation and maintenance costs,
VARO&M is the variable operation and maintenance cost,
F is the fuel cost, $CRF = df * \frac{(1+df)^n}{(1+df)^n - 1}$ where df is the discounting factor, n is the plant lifetime, and E is the external cost (externalities) specified as $E = SI * VD$ where SI is the size of the insult (i.e., the quantified impact) in physical units, and VD is the value of damage, expressed in monetary terms per physical unit of output.

- *Social Welfare Maximization Model:* According to Ferguson (1972), the objective function of the optimization model is to maximize social welfare, which is the difference between the marginal social costs and marginal social benefits of electric power generation. Social welfare maximization occurs when Marginal Social Costs (MSC) equal Marginal Social Benefits (MSB) (Hutchinson, 2017)

  Following Ferguson (1972), the social welfare maximization objective function is specified as follows:

Max. Social Welfare

$$F_{Obj} = Max\left(\sum_{i \in S} B_j\left(P^p_{sj}\right) - \sum_{i \in G} C_{pi}\left(P^p_{gi}\right) - \sum_{i \in G} C_{ei}\left(E^p_{gi}\right) \right) \quad \text{……9}$$

Where {G} is generator set, {S} is the societal benefit set, $C_{pi}\left(P^p_{gi}\right)$ is the private (internal) power production cost function of generator i modeled by a quadratic function as $C_{pi}\left(P^p_{gi}\right) = a_{gi}\ P^2_{gi} + b_{gi}\ P_{gi} + c_{gi}$ where a, b and c are predetermined coefficients, $C_{ei}\left(E^p_{ei}\right)$ is the external power production cost function of generator i, modeled as $C_{ei}\left(E^p_{ei}\right) = a_{gi}\ P^2_{gi} + b_{gi}\ P_{gi} + c_{gi}$, $B_j\left(P^p_{sj}\right)$ is the benefit function of the society modeled as $B_j\left(P^p_{sj}\right) = a_{sj}\ P^2_{sj} + b_{sj}\ P_{sj} + c_{sj}$, B_j is the total benefit function for each MW of energy per unit generated, C_{pi} and C_{ei} are the total private cost and total external cost of the generator respectively, P^p_{gi} is the vector of the pool of power generator specified as $P^p_{gi} = \{P^p_{gi} : i = 1,2,3, \ldots \ldots .. n\}$ where n is the number of generators and, P^p_{sj} is a vector of power generation social benefits specified as $P^p_{sj} = \{P^p_{sj} : j = 1,2,3, \ldots \ldots .. m\}$ where m is the benefit from the output (MW) of the electricity generated by the generator.
The social welfare objective function (equation 3.5) is maximized subject to the constraint.

$$P_{sj} - P_{gi} - E_{gi} = 0 \quad \text{……10}$$

$$P - C'(y^e) - e'(y^e) = 0 \quad \text{……11}$$

P_{sj} is taken to the MSB ($ cents/kWh), and the sum of $P_{gi}\ and\ E_{gi}$ represents Marginal Social Cost (MSC) ($ cents/kWh). P is the price ($ cents/kWh), $C'(y^e)$ is marginal private cost ($ cents/kWh), and $e'(y^e)$ is the MEC ($ cents/kWh). Since the additional units are all priced at marginal cost, the price represents the marginal cost society must incur to have an additional unit produced (Hutchinson, 2017). Hence, the price is set to equal the sum of marginal private cost and marginal external cost. On the other hand, the demand (kWh) represents the marginal social valuation or the marginal social benefit derived from an additional unit of energy ($ cents/kWh) consumed.

4. Results and Discussions

4.1. Negative Binomial Regression Estimation

Survey data elicited using the stated preference approach were analyzed using a negative binomial regression (NBR) model. NBR was performed on counts from both the response and explanatory variables. Each response variable in social welfare maximization was regressed with the three externality variables (environmental, public health, and socio-economic) to ascertain their effects on each of the responses. Table 1 represents the parameter estimation output.

Response Variable (SWM)	Explanatory Variable	Estimator	P-Value
Geothermal	*Constant*	*2.9965*	*0.00034*
	Environmental	-0.09435	2.24×10^{-10}
	Public Health	0.06256	0.000202
	Social-Economic	0.2815	4.11×10^{-5}

Table 1: Parameter Estimation to the Negative Binomial Regression

Based on the output in table 1, the corresponding negative binomial regression models are obtained:

$SWM = \exp\big(2.9965 - 0.09435\ (EE) + 0.06256(PHE) + 0.2815(SE)\big)$……………………………………………12

Model 12 demonstrates the effect of the three externalities, namely, environmental externalities (EE), public health externalities (PHE), and socio-economic externalities (SE), on the sub-variable responses in social welfare maximization (SWM). The SWM responses were fitted against the EE, PHE and SE. The model output showed that EE had a -0.09435 effect on SWM; thus, a unit change in EE had a corresponding -0.09435 effect on SWM. PHE had a 0.06256 effect on SWM, while the contribution of SE to SWM was 0.2815. The output shows all $-value < \alpha$. That is: EE $p - value = 2.24 \times 10^{-10} < 0.05$; PHE $p - value = 0.000202 < 0.05$; and SE $p - value = 4.11 \times 10^{-5} < 0.05$. Given that all the p-values were less than 0.05, all the parameters were significant, implying that the three variables provided reliable information for determining welfare maximization.

4.2. Externality Internalization

The external cost of geothermal power generation was realized using secondary data on the burden and impact of the four geothermal power generation plants. The burdens examined included carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), carbon monoxide (CO) and particulate matter (PM). The annual average concentration of air quality monitoring of chemical emissions data, summarized in table 2, was used to estimate the cost of damage to the environment, public health, and socio-economic impact. A meta-analysis-unit value transfer function based on global data obtained from the ExternE series (2018) and other related studies was used to estimate the damage cost. For application to Kenya, the globally averaged valuation (price tag) of specific emission impacts in euro figures was scaled using a PPP GNP scaling factor.

Formally, PPP = (PPP GNP_ y/PPP GNP_ x) ^{E}, Where PPP GNP is the purchasing power parity to Gross National Product for country y, y in this case is Kenya (policy site), x is the European Union (study sites), and E denotes the elasticity factor (income elasticity of demand for the analyzed environmental good). The gross domestic product per capita in Kenya was recorded at 4,743.49 US dollars in 2022 when adjusted by purchasing power parity (PPP), while the gross domestic product per capita in European Union was recorded at 44,138.04 US dollars in 2022 when adjusted by purchasing power parity (PPP) (World Bank statistics, 2022). Hence, by applying an elasticity factor equal to 1 (Zainal et al., 2012; ExternE, 2018), the PPP for Kenya was obtained as PPP GNP for Kenya = $(4,743.49 / 44,138.04)^{1}$ = 0.107. The obtained PPP GNP for Kenya was converted to Euros by an average annual exchange rate of 2022, 1 $ = 0.921242 € (Federal Reserve Statistical Release, 2022). The used PPP GNP for Kenya was 0.0986 (0.921242×0.107)

- *Estimation of External Cost:* To quantify and cost damage, data were compiled from the emission measurement reports of the four sampled geothermal power plants. The emission concentrations were expressed in $\mu g/Nm^3$. Concentrations standards set in terms of parts per million (ppm) were converted to $\mu g/m^3$ for ease of comparison.

Geothermal Power Station	Capacity (MW)	Gases						Particulates		
		O_2	CO	N_2O	CO_2	SO_2	H_2S	PM_{10}	$PM_{2.5}$	TSP
		%	ppm	Ppm	%	ppm	ppm	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$
Olkaria I	185	20.62	0.10	0.10	0.05	1.50	0.075	6.60	15.00	25.50
Olkaria II	105	20.83	0.15	0.15	0.08	4.50	-	6.00	11.00	19.00
Olkaria IV	140	20.68	0.10	0.15	0.06	8.00	-	4.00	6.00	30.00
Olkaria V	158	20.76	0.10	0.05	0.04	5.50	0.48	10.50	21.50	79.00
Total	588	82.89	0.45	0.45	0.23	19.5	0.555	27.1	53.5	153.5
Note: Gas levels are in Parts Per Million (ppm)										

Table 2: A Summary of Annual Average Concentration of Air Quality Monitoring Results
Source: Kengen Environmental Audit Report, 2022

To standardize the quantification and cost, the emission rate was converted into kg/day and tons/year. The specific impact and damage cost of the emissions released per unit of electricity generation were calculated based on the globally averaged price tag (ExternE series and other related studies). Table 3 represents the emissions impact and damage cost per unit (€2022/t) of electricity generation.

Emission	Impact on	Conc. Daily 24-hr mean	Emission Rate kg/day	Emission Rate (t/day)	Emission Rate (t/yr)	Cost Price Tag €/kg	Cost Price Tag €/t	Annual Cost€/t
PM_{10} (mg/Nm^3)	Health	53..5	18.75	0.1875	68.438	15.4	15400	1053945.2
$PM_{2.5}$ (mg/Nm^3)	Health	27.1	9.49	0.0095	3.468	15.4	15400	53407.2
SO_2 (mg/Nm^3)	Health, crops, biodiversity, materials	28.28	9.90	0.0099	3.614	10.55	10550	38127.7
NO_2 (mg/Nm^3)	Global warming	0.65	0.228	0.00023	0.084	0.103	102.96	0.648
CO (mg/Nm^3)	Health, crops, biodiversity, materials	0.65	0.228	0.00023	0.084	3.722	3722	262.248
CO_2 (mg/dsm^3) %	Global warming	0.334	0.117	0.00012	0.037	0.029	29	0.764
H_2S (mg/Nm^3)	Health, crops	0.805	0.282	0.00028	0.102	0.0768	76.78	7.831
Total External Cost €/t								1145751.59

Table 3: Emission's Impact and Damage Cost per Unit (€2022/T) of Electricity Generation

The PPP GNP for Kenya scaling factor value of 0.0986 is used as the scaling factor in table 4 to adjust the emission cost estimates to suit the Kenyan economy.

Emission	Impact on	Emission Rate (t/day)	Emission Rate (t/yr)	Cost Price Tag €/kg	Cost Price Tag €/t	Damage Cost €/t	*Annual External Cost €/t
PM_{10}	Health	0.1875	68.438	15.4	15400	10,53,945.20	1,03,919.00
$PM_{2.5}$	Health	0.0095	3.468	15.4	15400	53,407.20	5,265.95
SO_2	Health, crops, biodiversity, materials	0.0099	3.614	10.55	10550	38,127.70	38,127.70
* NO_2	Global warming	0.00023	0.084	0.103	102.955	0.648	0.648
CO	Health, crops, biodiversity, materials	0.00023	0.084	3.722	3722	262.248	258.58
* CO_2	Global warming	0.00012	0.037	0.029	29	0.764	0.764
H_2S	Health, crops	0.00028	0.102	0.0768	76.78	7.831	0.77
Total annual External Cost €/t 147,573.41							
**Annual External Cost €/t – Scaling Factor multiplied by Damage Cost €/t*							
** CO_2, SO_2 & N_2O – Scaling factor not applied*							

Table 4: Geothermal Power Annual Emission Damage Cost (€2022/t) Estimate

To determine the threshold boundary used to apportion the percentage contribution of public health, environmental (global warming damages), and socio-economic impacts on total damages, a meta-analysis of 138 studies by Sovacool et al. (2021) and ExternE (2018) project series was used, as shown in table 5.

Externality Type	Geothermal		
	Lower Range	*Mid-Range	Higher Range
Environmental	19%	56%	78%
Public Health	14%	26%	38%
Socio-economic	8%	18%	24%
*Mid-range average of cluster/ range			

Table 5: Percentage Contribution of Environmental, Public Health and Socio-economic Impact to Total Damages of Geothermal Power

Using the data in table 4 and table 5, the annual external cost estimate contribution to environmental, public health, and socio-economic impacts of geothermal fuel was estimated and is presented in table 5.

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Externality Type	Percentage	Annual Total Cost €/t
Environmental	56%	82,641.11
Public Health	26%	38,369.09
Socio-economic	18%	26,563.21
Total annual External Cost €/t		147,573.41

Table 6: Annual External Cost (€2022/T) Estimate Contribution of Environmental, Public Health and Socio-economic Damage in Geothermal Power Generation

The higher cost estimates corresponding to environmental and public health damage occur because the scaling factor is not applied to CO_2, SO_2 and NO_X emissions, which have a global impact.

Table 7 represents the annual external cost estimates based on the three classification schemes. Using an exchange rate of 1 € = 1.1 US$, the cost in euro pound (€) are converted into US$. Because there are 8,760 h per year, the maximum output of a 1 MW plant is 8,760 MWh. Since there are 1,000 kWh in 1 MWh, to calculate the adjusted external cost of output (energy) per kWh:

$$AEC = \frac{EC}{Q \times 8760 \times 1000 \times cf} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

Where AEC is adjusted external cost (kWh), EC is external cost (MW/y), Q is plant capacity/output (MW) (equivalent to 588 MW), cf is capacity factor. According to LCPDP 2020-2040, the year 2022 assumed capacity factor (cf) for the geothermal power was 71 per cent.

- Determination of the per unit cost ($cent/kWh, 2022) of electricity generation: To make an informed assessment of the overall cost involved in the production of electricity from thermal power generation, both internal cost (private cost) and external cost were factored. Private cost data estimates were taken from the LCPDP (2020-2040) report, which is the main guiding document for electricity generation expansion in Kenya (Republic of Kenya, 2021). Table 7 below represents the estimated external cost (€&$/2022) and marginal cost ($cent/kWh, 2022).

External Cost	Cost (€/y)	Cost ($/y)	Marginal Cost ($cent/kWh, 2022)
Environmental	82,641.11	90,905.22	0.000025
Public Health	38,369.09	42,206.00	0.000012
Socio-economic	26,563.21	29,219.53	0.000008
Total External Cost	147,573.41	162,330.75	0.000045
Total Private Cost	-	64,959,643.19	0.02
Total Social Cost	-	65,121,973.94	0.02

Table 7: External Cost (€&$/2022) and Marginal Cost ($cent/kWh, 2022) Estimates

The external cost per unit of electricity generation in table 7 was determined to be 0.000045 USD cent/kWh with the following main impact distribution: Environmental at 0.000025 USD cent/kWh, Public Health at 0.000012 USD cent/kWh, and Socio-economic at 0.000008 USD cent/kWh. A marginal social cost of 0.000045 USD cent/kWh was factored into determining the extent of social welfare maximization in geothermal power generation.

- *Determination of the extent of Social Welfare Maximization:* Following Ferguson (1972), demand represents the marginal social valuation or the marginal social benefit derived from an additional unit of the commodity in question. Further, since the additional units are all priced at marginal cost, the price represents the marginal cost that society must incur to have an additional unit produced. The "marginal" argument is extended to include the proposition that social welfare maximization occurs when marginal social costs (MSC) equal marginal social benefits (MSB).

In the aforementioned context, the marginal social valuation of additional unit demand (cents/kWh) for electricity consumed by households based on social policy option was 12.12 KES (KPLC annual report 2022/2023), equivalent to 0.089 USD cents/kWh at an exchange rate of 1 USD = 135 KES. However, geothermal power generation MSC in table 7 was determined to be 0.2 USD cent/kWh. This implies that MSC (0.02 USD cents/kWh) is significantly less than MSB (0.089

USD cents/kWh), an implication that society will not bear the burden of social welfare loss, even when MSC are not integrated into the geothermal electricity pricing system.

4.3. Hypotheses Testing

The results of the research hypotheses test based on primary data supported by secondary data are summarized in table 8.

Hypothesis	Statement	Test Statistics (β & P-value)	Decision	MPC, MEC & MB ($cent/kWh, 2022)
Ho_1:	Internalization of environmental external costs in geothermal power generation has no significant effect on social welfare maximization	$\beta_1 = -0.09435$, $p = 2.24 \times 10^{-10}$	Reject	MPC=0.01 MEC= 0.000025 MSB= 0.089
Ho_2:	Internalization of public health external costs in geothermal power generation has no significant effect on social welfare maximization	$\beta_2 = 0.06256$ $p = 0.000202$	Reject	MPC=0.01 MEC= 0.000012 MSB= 0.089
Ho_3:	Internalization of socio-economic external costs in geothermal power generation has no significant effect on social welfare maximization	$\beta_3 = 0.2815$, $p = 4.11 \times 10^{-5}$	Reject	MPC=0.01 MEC= 0.000008 MSB= 0.089
MPC= marginal private cost, MEC = marginal external cost, MSB = marginal social benefit				

Table 8: Summary of Hypotheses Testing

The test results in table 8 show that environmental, public heath, and socio-economic external cost had a negative effect on social welfare maximization which was significant, given that all the p-values were less than 0.05. However, since MSC (MPC+MEC) = 0.02 ($cents/kWh) is less than MSB = 0.089 ($ cents/kWh), society bears an insignificant burden of social welfare loss.

5. Conclusion and Recommendations

5.1. Conclusion

This study employed an integrated approach that used both survey and secondary data. The main study outcomes of both primary and secondary data showed that geothermal power generation attributed to negative environmental, public health, and socio-economic impacts as a result of emissions such as carbon dioxide (CO_2), sulphur dioxide (SO_2), particulate matter ($PM_{10\&2.5}$), nitrogen dioxide (NO_2), hydrogen sulphide (H_2S), and carbon monoxide (CO). Secondary data analysis showed that the annual estimated external costs associated with carbon dioxide (CO_2) on global warming impact were € 0.764 (2022/t). The external costs due to PM_{10} and $_{2.5}$ were mainly connected with the potential for negatively impacting the cardiovascular system or directly causing respiratory illness at € 109,184.95 (2022/t). The external costs due to CO on the global biosystem were € 2710 (2022/t). The external costs due to NO_2 were mainly connected with its impacts as a greenhouse gas, thus a global impact at € 0.648 (2022/t). The external costs due to SO_2 were mainly connected with its potential for causing acid rain and affecting human health as well as other parts of the biosystems (fauna and flora), thus a global impact in the form of material damage at € 38,127.7 (2022/t). The external costs related to H_2S within human well-being (health impacts-respiratory deceases) stood at € 0.77 (2022/t). The reported cases of high concentrations of heavy metals in the human body leading to asthma and chronic bronchitis disorders were evidenced by the majority of the respondents and secondary data (GoK, 2022). Geothermal power generation sitting observation evidenced impairment/degradation of terrestrial ecology. Also, the installation of pipelines to transport geothermal fluids and the construction of ancillary structures negatively affected world life, interrupting their natural habitat and their migration routes. Likewise, the commissioning of geothermal power generation facilities led to social-economic disruptions in the Maa nomadic community whose grazing land was taken. Overall, the annual external cost ($/2022) of geothermal power generation was determined to be $ 162,330.75 with the following distribution: Environmental at $ 90,905.22, public health at $ 42,206.00, and socio-economic at $ 29,219.53. Equally, the geothermal power generation marginal social cost ($/2022) was determined to be 0.02 $cents/kWh with the following distribution: Marginal Private Cost (MPC) at 0.02 $cents/kWh, and Marginal External Cost (MEC) at 0.000045 $cents/kWh.

The analysis revealed a significantly weak positive relationship between the internalization of external costs in geothermal power generation and welfare maximization. In addition, because MSC (MPC+MEC) = 0.02 ($cents/kWh) is less than MSB = 0.089 ($ cents/kWh), society will not bear a significant burden of social welfare loss, even when marginal external costs are integrated into the electricity pricing system. Similarly, the study established that the current medium to long-term planning of the energy sector through Least Cost Power Development Plan (LCPDP) is unlikely to offer a sustainable power generation approach since it tends to advantage the "least-cost" technology for a project development (based on internal cost), without considering and integrating comprehensively factors external (external cost) to the power plant subsequently making the society to bear the burden of social welfare loss.

5.2. Recommendations

Based on the current study, it is clear that geothermal energy utilization is not devoid of environmental and social well-being drawbacks. This calls for putting in place effective controls and monitoring mechanisms to mitigate against any undesirable drawbacks that may emerge in the course of geothermal energy utilization, given that it contributes a majority share (39 per cent) in the national grid. In addition, baseline data and continuous monitoring of the deleterious emissions within geothermal power plants will thus assure the social acceptability of such projects in the promotion of sustainable energy systems capable of maximizing social welfare.

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