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

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ABSTRACT: For decades, Kenya has incorporated thermal power technology into its grid to generate electrical energy using fossil fuels such as petroleum, natural gas, and coal. The burning of fossil fuels has become a major source of air pollutants and is associated with several undesirable side effects on the environment and human health. However, the impact of pollutants on environmental sustainability and public welfare has yet to be evaluated. Therefore, the purpose of this study is to evaluate the external cost of electricity generated by thermal 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 annual external cost ($/2022) was determined to be $ 1,333,904,970.76, with the following distribution: environmental at $ 993,488,336.26, Public health at $ 86,760,038.01, and socio-economic at $ 253,656,596.49. Equally, the thermal power generation marginal social cost ($/2022) was determined to be 1.22 $cents/kWh with the following distribution: Marginal Private Cost (MPC) at 0.01 $cents/kWh and Marginal External Cost (MEC) at 1.21 $cents/kWh. The established marginal social cost (MSC) (i.e. Σ MPC+MEC) was 1.22 ($cents/kWh). Thus, MSC is significantly greater than the established social marginal benefit (SMB) of 0.089 ($ cents/kWh); hence, we conclude that the burden of social welfare loss is highly significant, making thermal power a non-sustainable and economic energy source.

KEY WORDS: External costs, Internalization, Marginal social cost, Marginal social benefit, Social welfare maximization

I. Introduction

Electricity is regarded as a prerequisite for sustaining a nation's economic growth and improving its standards of living and social integration. Electric power production has several undesirable side effects on the environment and public welfare. For instance, the combustion of fossil fuels in thermal power plants produces pollutants, such as greenhouse gases (GHGs), sulphur oxides (SO_x), nitrogen oxides (NO_x), and soot, which cause critical environmental and public health issues, such as ground-level ozone, acid rain, and global warming (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).

Against the background of the causes and deleterious impacts of climate change and public health risks, policymakers and researchers have focused on the external costs of electricity 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). It faces a policy framework challenge with its current electricity generation mix that includes non-renewable energy sources, mainly thermal power generation, whose total contribution to the national grade as of June 2023 is 13 percent (KenGen Report, 2023).

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 (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.

A. Hypotheses of the study

The following hypotheses were tested against the survey data;

Ho_1: Internalization of environmental external cost in thermal power generation has no significant effect on social welfare maximization

Ho_2: Internalization of public health external cost in thermal power generation has no significant effect on social welfare maximization

Ho_3: Internalization of socioeconomic external cost in thermalpower generation has no significant effect on social welfare maximization

B. Contribution of this study

The contribution of this study is threefold. First, it assessed the external costs of thermal 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 thermal power generation. Third, the works introduces to the body of literature a thermal power generation external cost study in Kenya.

II. LITERATURE REVIEW

A. 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 that are 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 gain from the benefit.

Real resource costs for 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 that cause 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 the social arrangement. 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 for proper inclusion in benefit/cost models, which will result in better solutions from the perspective of sustainability and welfare maximization (Bielecki et al., 2020).

B. 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 on social welfare, generally considering social welfare to be tightly linked to individual well-being (Antoinette, 2021). Figure 1 illustrates the basic theoretical issues addressed by full cost accounting. Consider a polluter, a coal-based electrical utility, 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 imposes an emission limit of Q* or imposes an optimized tax on the polluter that equals Q*E, at which point the marginal benefits equal the marginal costs and justify an emission reduction to point Q*. Further emission reduction to the left of Q* cannot be justified because the cost of each emission 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 and Stephan, 2003).

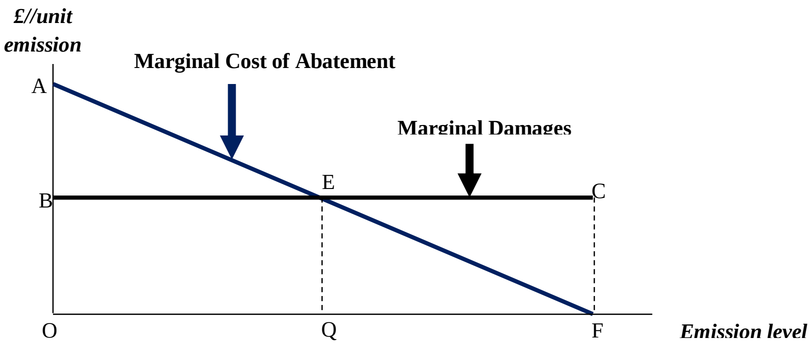

Figure 1 Socio-environmental damages and costs

Theorizing the concept of externality valuation and internalization, Varian (1992) used a simple production model of the form: consider firm J, which operates in a competitive market. Furthermore, we 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:

$$\pi_j = \max_j py - c(y)$$

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

$$p = c'(y^*) \qquad (2)$$

indicates 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. Thus, the output y* is too large from a societal perspective. 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 external costs into its profit maximization problem, such that

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

with the corresponding first-order condition:

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

The output y^e is Pareto efficient; the price is set to equal the (3) 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 environmental, public health and socioeconomic impacts.

According to Lehmann et al. (2019), the approaches used in valuation of externality impacts in the energy sector include: 1) non-market valuation approaches (e.g., productivity changes, income changes, replacement-cost, etc.); 2) market valuation approaches (e.g., stated preference); and 3) 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 and non-use values (such as existence values).

C. Empirical Literature

The classification scheme embraced to determine the scope of quantification and valuation is organized into three broad categories centered on the point of impact as follows: i) environmental impact, ii) public health risk, and iii) socioeconomic impact.

1) Thermal Power Environmental Impact: Srinivasan and Shekhar (2021) conducted a study on internalizing the external cost of gaseous and particulate matter emissions from coal-based thermal power plants in India, revealing that the external cost of coal-based power production was INR 2.92 per kWh in 2018. Projection of total annual external cost of sulphur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), and carbon monoxide (CO) emissions were estimated to be INR 29.31 trillion, INR 72.59 trillion, INR 14.02 trillion and INR 7.89 trillion respectively for 2030. Ghoddousi and Talebi (2021) evaluated the external cost of electricity generation in Iran. The results of the study based on thermal power plants (steam, gas, and combined cycle) showed that on average, the predicted (2023) external costs (cents/kWh) of emissions, PM_{10}, NO_X, CO, CO_2 and SO_2 in the low, medium,

and high scenarios were 0.32, 0.84, and 4.79, respectively. Coffel and Mankin (2021) in their seminal work established that very high amount of carbon dioxide (CO_2) emission (0.9-0.95 kg/kwh) from thermal power plants contribute to global warming leading to climate change. Likewise, the study established that sulphur dioxide (SO_2) released from thermal power plants, though not technically a greenhouse gas, is associated with the formation of sulphuric acid in the atmosphere, which returns to Earth as acid rain and impacts various ecosystems. In the same line of study, the authors established that because of the deposition of suspended particulate matter (SPM) on plants, the photosynthetic process of plants is severely affected.

2) Thermal Power Public Health Risk: Fouladi et al. (2016) assessed the health impacts and external costs of a natural gas power plant in Iran and established that the annual external cost of emissions for selected gas power plants with a 714 MW generation capacity was approximately 4.76 million US$. The study revealed that NO_x has the highest share of emissions and the highest external costs compared to PM_{10}, CO, and SO_2 in gas power plants. Lukas et al. (2019) established that ash is a major atmospheric pollutant. Ash contains PM2.5, as well as heavy metals capable of entering the respiratory airways and alveoli. Thus, micro particles can reach the blood and different organs and negatively impact the cardiovascular system or directly cause respiratory illnesses, especially when the levels exceed the recommended maximum tolerable limits of NAAQ, that is, SO_2 (60 μg/m^3), NO_x (60 μg/m^3), and SPM (140 μg/m^3).

3) Thermal Power Socioeconomic Impact: Martins et al. (2019) established that ash can enter waterways and soil wherever it falls (it does not have to be the local environment) and change the alkalinity of the soil/water, which can render the soil unusable for agricultural purposes and undrinkable water, and can cause visibility issues. Pokale (2012) established that effluents from thermal plants have significant impacts on local ecosystems. Because of the deposition of SPM on plants, the photosynthesis process of plants is affected because the particles penetrate inside the plants through leaves and branches, thereby creating an imbalance of minerals and micro-and major nutrients in the plants, thereby affecting plant growth. Similarly, continuous and long-term deposition of SPM on soil disturbs the contents of minerals and micro- and major nutrients and causes the fertile and forest land to be unproductive for plants and farming. Furthermore, the deposition of PM_{10} on the buildings leads to soiling as well as the aging of galvanized iron sheets coupled with corrosion and weathering of building materials from acid rain resulting from sulphuric acid.

The above literature review provides a thorough insight into past studies on the external cost of thermal power generation. However, the review revealed that not much has been done on the same line of study in Kenya. Given the planned increase in energy harnessing in Kenya, it is vital to have information on the actual external costs (damage to common goods, human health, social patterns, and other related costs) of using thermal energy sources as well as other energy sources. This information forms a basis for mitigation considerations as well as input into reasoning for future energy planning.

III. DATA AND METHODOLOGY

A. Data

The extent of the internalization of external costs in thermal power generation on social welfare maximization was determined by analyzing both primary and secondary data. Quantification of external cost estimates was undertaken on three major thermal power plants with capacities of 40 MW and above, which were operational for more than five years at the time of study and not located within the vicinity of other key heavy industrial plants. The survey participants were selected from the population elements of the immediate community and the interested and affected groups within the area of influence of the power generation plant. A stated preference approach was adopted to elicit the survey data. Secondary data on the annual average concentration of air quality monitoring of chemical emissions from the three thermal 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 the thermal power generation. The ExternE (2018) study and related series unit costs for SO_x, NO_x, 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.

B. Model and Methods

Externalities can be considered in the model as a restriction (Huang et al., 2016; Chen et al., 2019; 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 adopts a mixed approach. The models considered included 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.

1)The Negative Binomial Regression Model: The Negative Binomial regression model equation is written as:

$$y_i = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_n x_n) \qquad (5)$$

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

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

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

$$H_0: \beta_1 = \beta_2 = \beta_3 = 0$$

Against $H_1: \beta_1 \neq \beta_2 \neq \beta_3$

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

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

2) 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 and Ferreira, 2023). Following Drennen et al. (2003), the total electricity generation optimization system cost function for a producer is specified as

$$TGC = \frac{I * CRF}{Q} + \frac{FIXO\ \&\ M}{Q} + \frac{VARO\ \&\ M}{Q} + \frac{F}{Q} + \frac{E}{Q} \qquad (8)$$

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 cost, 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.

3) 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 Max. Social Welfare as follows:

$$F_{Obj} = \text{Max}\left(\sum_{i \in S} B_j\left(P_{sj}^{p}\right) - \sum_{i \in G} C_{pi}\left(P_{gi}^{p}\right) - \sum_{i \in G} C_{ei}\left(E_{gi}^{p}\right) \right) \qquad (9)$$

Where {G} is generator set, {S} is societal benefit set, $C_{pi}\left(P_{gi}^{p}\right)$ is the private (internal) power production cost function of generator i modeled by a quadratic function as $C_{pi}\left(P_{gi}^{p}\right) = a_{gi}\ P_{gi}^{2} + b_{gi}\ P_{gi} + c_{gi}$ where a, b and c are predetermined coefficients, $C_{ei}\left(E_{ei}^{p}\right)$ is the external power production cost function of generator i, modeled as $C_{ei}\left(E_{ei}^{p}\right) = a_{gi}\ P_{gi}^{2} + b_{gi}\ P_{gi} + c_{gi}$, $B_j\left(P_{sj}^{p}\right)$ is the benefit function of the society modeled as $B_j\left(P_{sj}^{p}\right) = a_{sj}\ P_{sj}^{2} + b_{sj}\ P_{sj} + c_{sj}$, B_j is the total benefit function for each MW of energy per unit generated, $\mathbf{C_{pi}}$ and $\mathbf{C_{ei}}$ are the total private cost and total external cost of the generator respectively, P_{gi}^{p} is the vector of pool of power generator specified as $P_{gi}^{p} = \left\{P_{gi}^{p} : i = 1,2,3, \ldots\ldots.. n\right\}$ where n is the number of generators, and P_{sj}^{p} is a vector of power generation social benefits specified as $P_{sj}^{p} = \left\{P_{sj}^{p} : j = 1,2,3, \ldots\ldots.. m\right\}$ where m is the benefit from the output (MW) of electricity generated by the generator. The social welfare objective function (equation 9) is maximized subject to the constraint

$$P_{sj} - P_{gi} - E_{gi} = 0 \qquad (10)$$

$$P - C'(y^e) - e'(y^e) = 0 \qquad (11)$$

P_{sj} is taken as the MSB ($ cents/kWh), and sum of P_{gi} and E_{gi} represent Marginal Social Cost (MSC) ($ cents/kWh). where P is the price ($ cents/kWh), $C'(y^e)$ is marginal private cost ($ cents/kWh), and $e'(y^e)$ is the marginal external cost (MEC) ($ cents/kWh).

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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, 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.

IV. RESULTS AND DISCUSSIONS

A. *Negative Binomial Regression estimation*

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

Table I. Parameter Estimation to the Negative Binomial Regression

Response Variable (SWM)	Explanatory Variable	Estimator	P-Value
Thermal	Constant	5.5521	4.87 x 10^{-10}
	Environmental	-0.02832	0.037
	Public Health	0.01984	0.00052
	Social-Economic	-0.0415	0.03329

Based on the output in Table I, the corresponding negative binomial regression models were obtained:

$$\mathrm{TSWM} = \exp(5.5521 - 0.02832(\mathrm{TEE}) + 0.01984(\mathrm{TPHE}) - 0.0415(\mathrm{TSE})) \tag{12}$$

Model (12) demonstrates the effect of three externalities, namely, environmental externalities (TEE), public health externalities (TPHE), and socioeconomic externalities (TSE), on the sub-variable responses in social welfare maximization (TSWM). The TSWM responses were fitted against the TEE, TPHE, and TSE. The model output showed that TEE had a -0.028325 effect on TSWM; thus, a unit change in TEE had a corresponding -0.028325 effect on TSWM. TPHE has a 0.01984 effect on TSWM, whereas TSE has a -0.0415 effect on TSWM. The output indicates $\mathrm{p-value} < \alpha$ That is: TEE $\mathrm{p-value} = 0.037 < 0.05$; TPHE $\mathrm{p-value} = 0.00052 < 0.05$; and TSE $\mathrm{p-value} = 0.03329 < 0.05$. Given that all p-values are less than 0.05, all parameters are significant, implying that the three variables provide reliable information on determining welfare maximization.

B. Externality Internalization

The external cost of thermal power generation was realized using secondary data on the burden and impact of the three thermal power generation plants. The examined burdens included sulphur oxides (SO_x), nitrogen oxides (NO_x), carbon dioxide (CO_2), carbon monoxide (CO) emissions, and particulate matter (PM). The targeted facilities were the Gulf, Rabai, and Thika power Plants.The annual average concentration of air quality monitoring of chemical emissions data, summarized in Table II was used to estimate the cost of damage to the environment, public health, and socioeconomic 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 2022, 1 $ = 0.921242 € (Federal Reserve Statistical Release, 2022). The used PPP GNP for Kenya was 0.0986 (0.921242×0.107)

1) Estimation of External Cost: To quantify and cost damage, data were compiled from the emission measurement reports of the three sampled 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. To standardize the quantification and cost, the emission rate expressed in kg/h was converted into the emission rate in tons/year. A summary of the total for each pollutant is presented in Table I

Table II. Summary Thermal Power Emission Rate in tons/year

Thermal Power Plant	Capacity MW	Emission rate tons/yr				
		Particulate Matter (PM$_{10}$)	Sulphur Dioxide (SO$_2$)	Nitrogen Oxide (NO$_x$)	Carbon Monoxide (CO)	Carbon Dioxide (CO$_2$)
Gulf power	80.32	383.25	7756.25	92330.40	394.20	-
Rabai	90	220.46	2186.715	8032.555	325.960	470474.78
Thika	80	212.065	5101.970	8057.375	380.695	445000.00
Total	250.32	815.775	15044.935	108420.33	1100.855	915474.78
Emissions values are corrected to 273K, 101.3kPa, 15% O2 Ref, for liquid fuel powered engines						

Emission Testing Report (April - May 2022) - Gulf power ltd; Emission Testing Report (August, 2022) - Rabai Power Ltd,and Emission Testing Report (November, 2022) - Thika Power Ltd 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). However, it has been modified to suit Kenya's economy. Table III represent the emissions impact and damage cost per unit (€/kg) of electricity generation

Table III. Specific Damage Cost, €2022/ton of Emissions

Emission	Impact on	Emission rate (t/yr)	Cost price tag €/kg	Cost price tag €/t	Annual Total Cost€/t
PM$_{10}$ (mg/Nm^3)	Health	815.78	15.4	15400	12,563,012
SO$_2$ (mg/Nm^3)	Health, crops, biodiversity, materials	15044.94	10.55	10550	158,724,117
CO (mg/Nm^3)	Health, crops	1100.86	3.722	3722	4,097,400.92
CO$_2$ (mg/dsm^3) %	Climate	915474.78	0.029	29	26,548,768.62
NO$_x$ (mg/Nm^3)	Health, crops, biodiversity, materials	108420.33	16.0	16000	1,734,725,280
Total External Cost €/t					1,936,658,579

The PPP GNP for Kenya scaling factor value of 0.0986 is used as the scaling factor in

Table IV to adjust the emission cost estimates to suit the Kenyan economy.

Table IV. Thermal Power Annual Emission Damage Cost (€2022/t) estimate

Emission	Impact on	Emission rate (t/yr)	Cost price tag €/kg	Cost price tag €/t	Damage Cost €/t	*Annual External Cost €/t
PM$_{10}$ (mg/Nm^3)	Health	815.78	15.4	15400	12,563,012	1,238,712.98
SO$_2$ (mg/Nm^3)	Health, crops, biodiversity, materials	15044.94	10.55	10550	158,724,117	158,724,117
CO (mg/Nm^3)	Health, crops	1100.86	3.722	3722	4,097,400.92	404,003.73
* CO$_2$ (mg/dsm^3)	Climate	915474.78	0.029	29	26,548,768.62	26,548,768.62
NO$_x$ (mg/Nm^3)	Health, crops, biodiversity, materials	108420.33	16.0	16000	1,734,725,280	1,734,725,280
Total annual External Cost €/t						1,921,640,882.33
*Annual External Cost €/t – Scaling Factor multiplied by Damage Cost €/t *CO$_2$, SO$_2$ & NO$_X$ – Scaling factor not applied						

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To determine the threshold boundary used to apportion the percentage contribution of public health, environmental (global warming damages), and socioeconomic 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 V.

Table V. Percentage contribution of public health, Environmental and Socioeconomic impact to total damages of Thermal Power

Externality Type	Thermal		
	Lower range	*Mid-range	Higher range
Environmental	26%	47%	74%
Public Health	18%	41%	78%
Socioeconomic	3%	12%	34%

*Mid-range- average of cluster/ range

Using the data in Table IV and Table V, the annual external cost estimate contribution to public health, environmental, and socioeconomic impacts of thermal fuel was estimated and is presented in Table VI.

Table VI. Annual external cost (€2022/t) estimate contribution Environmental, on public health and Socioeconomic damage in thermal power generation.

Externality Type	Percentage	Annual Total Cost €/t
Environmental	47%	903,171,214.78
Public Health	41%	787,872,761.83
Socioeconomic	12%	230,596,905.90
Total annual External Cost €/t		1,921,640,882.51

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 VII represent 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:

$$\mathrm{AEC} = \frac{\mathrm{EC}}{\mathrm{Q} \times 8760 \times 1000 \times \mathrm{cf}} \tag{13}$$

Where AEC is adjusted external cost (kWh), EC is external cost (MW/y), Q is plant capacity/output (MW), cf is capacity factor. According to LCPDP 2020-2040, the year 2022 assumed capacity factor (cf) for the thermal power was 89 per cent.

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

Table VII. External Cost (€&$/2022) and Marginal Cost ($cent/kWh, 2022) estimates

External Cost	Cost (€/y)	Cost ($/y)	Marginal Cost ($cent/kWh, 2022)
Environmental	903,171,214.78	993,488,336.26	0.51
Public Health	787,872,761.83	866,660,038.01	0.44
Socio-economic	230,596,905.90	253,656,596.49	0.13
Total External Cost	1,921,640,882.51	2,113,804,970.76	1.08
Total Private Cost	18,532,978.92	20,386,276.81	0.01
Total Social Cost	1,940,173,861.43	2,134,191,247.57	1.09

The external cost per unit of electricity generation in Table VII was determined to be 1.08 $ cent/kWh with the following main impact distribution: Environmental (0.51$ cent/kWh), Public Health (0.44 $ cent/kWh), and Socioeconomic (0.13$ cent/kWh). A marginal social cost of 1.09 $cent/kWh was factored into determining the extent of social welfare maximization in thermal power generation.

3) Determination of 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, 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 equal marginal social benefits.

In the aforementioned context, the marginal social valuation of additional unit demand (cents/kWh) for electricity consumed by household based on social policy option was 12.12 KES (KPLC annual report 2022/2023), equivalent to USD 0.089 (cents/kWh) at an exchange rate of 1 USD = 135 KES. However, the thermal power generation marginal social cost (MSC) in Table VII was determined to be USD 1.9 (cent/kWh). This implies that MSC (1.09 USD cents/kWh) is greater than MSB (0.089 USD cents/kWh), an implication that the price charged for electric power was lower than it would be if the external cost were internalized. Equally, marginal external costs were not fully integrated into the electricity pricing system, distorting the market and society bearing the burden of this loss of social welfare.

C. Hypotheses Testing

The results of the research hypotheses test based on primary data supported by secondary data are summarized in Table VIII

Table VIII. Summary of hypotheses testing

Hypothesis	Statement	Test statistics (β & P-value)	Decision	MPC, MEC & MB ($cent/kWh, 2022)
Ho_1:	Internalization of environmental external cost in thermal power generation has no significant effect on social welfare maximization	β_1 = -0.0283, p = 0.037	Reject	MPC=0.01 MEC= 0.51 MSB= 0.089
Ho_2:	Internalization of public health external cost in thermal power generation has no significant effect on social welfare maximization	β_2 = 0.01984 p = 0.000	Reject	MPC=0.01 MEC= 0.44 MSB= 0.089
Ho_3:	Internalization of socioeconomic external cost in thermal power generation has no significant effect on social welfare maximization	β_3 = -0.0415, p = 0.033	Reject	MPC=0.01 MEC= 0.13 MSB= 0.089
MPC= marginal private cost, MEC = marginal external cost, MSB = marginal social benefit				

The test results in Table VIII show that environmental, public heath, and socioeconomic external cost had a negative effect on social welfare maximization which was significant at the 5% level of significance. Equally, since MSC (i.e. Σ MPC+MEC) = 1.09 ($cents/kWh) is greater than MSB = 0.089 ($ cents/kWh), society bears the burden of social welfare loss.

V. CONCLUSIONS, AND RECOMMENDATIONS

A. Conclusion

This study employed an integrated approach that uses both survey and secondary data. The main study outcomes of both primary and secondary data showed that thermal power generation attributed to negative environmental, public health, and socioeconomic impacts as a result of emissions such as carbon dioxide (CO_2), sulphur dioxide (SO_2), particulate matter (PM_{10}), nitrogen oxide (NO_x), 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 $29,203,645.49 (2022/t). The external costs due to PM_{10} were mainly connected with the potential for negatively impacting the cardiovascular system or directly causing respiratory illness at $ 1,362,584.28 (2022/t). The external costs due to CO on the global bio system were $ 444,104.10 (2022/t). The external costs due to NO_x were mainly connected with its impacts as a greenhouse gas known to present visibility and respiratory issues, and can also combine with other atmospheric gases and moisture to form acid rain and smog, thus a global impact at $1,908,197,808 (2022/t). The external costs due to SO_2 were mainly related to its potential to cause acid rain and its effect on human health as well as other parts of the bio systems (fauna and flora), thus a global impact in the form of material damage at $ 174,596,528.7 (2022/t). Overall, the annual external cost ($/2022) of thermal power generation was determined to be $ 1,333,904,970.76 with the following distribution: Environmental at $ 993,488,336.26, Public health at $ 86,760,038.01, and socioeconomic at $

253,656,596.49. Equally, the thermal power generation marginal social cost ($/2022) was determined to be 1.22 $cents/kWh with the following distribution: Marginal Private Cost (MPC) at 0.01 $cents/kWh and Marginal External Cost (MEC) at 1.21 $cents/kWh.

The analysis revealed a significantly strong positive relationship between the internalization of external costs in thermal power generation and welfare maximization. In addition, because MSC (i.e. Σ MPC+MEC) = 1.09 ($cents/kWh) is greater than MSB = 0.089 ($ cents/kWh), society bears the burden of social welfare loss, as marginal external costs are not fully integrated in the electricity pricing system. Similarly, we 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.

B. Recommendations

Since the computed external costs are comparable to the actual cost of power generation without externality, the abatement of emissions released through thermal power plants may be prioritized to foster environmental sustainability and desirable social wellbeing. Likewise, from a social policy perspective, we believe that power generation imposes substantial environmental and societal burdens that are not adequately taken into account either in the Least Cost Power Development Plan (2020-2040) and resource selection process or by the prevailing regulatory controls in Kenya, hence the need to factor the external cost in the prevailing energy systems.

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