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Article

Evaluating the profitability of forest biomass power generation: A mathematical modeling approach

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Abstract: This article presents a detailed assessment of the economic feasibility of establishing a forest biomass power plant using a mathematical programming model that incorporates various operational and economic factors. Results indicate that this power plant is currently unprofitable, highlighting the financial challenges renewable energy projects face. Multiple factors, such as transportation costs, CO_2 penalties, and local employment impacts, significantly affect the net revenue generated from electricity derived from wood products. The need for strategic interventions to improve revenue generation and enhance the profitability of forest biomass power plants is evident. In this article, in addition to examining the challenges, suggestions will be provided to improve the economic status of biomass power plants, which can assist stakeholders in their future decision-making.

Keywords: forest biomass; transportation; profitability; CO_2 limitation; renewable energy

1. Introduction

The environmental problems caused by greenhouse gases (GHGs) are undeniable. The accumulation of these gases in the Earth's atmosphere prevents the energy from the sun from escaping, leading to an increase in the Earth's temperature. Carbon dioxide (CO_2) constitutes 70% of total GHGs. However, 80% of the world's total energy demand is still met by fossil fuels, which are the primary source of CO_2 emissions [1].

In addition to the Paris Agreement, Europe has devised the Green Deal, under which the continent aims to become the first climate-neutral region by 2050. This will be achieved by balancing GHG emissions entering the atmosphere with the amount naturally removed by atmospheric processes [2]. The Green Deal also includes provisions for economic growth and the creation of new jobs, ensuring that no one suffers social or economic losses [3].

The transition towards carbon-neutral solutions, like the Green Deal, presents both challenges and opportunities for industries such as forest biomass. Phasing out fossil fuels and reducing CO_2 emissions may increase the demand for renewable energy sources like biomass. Forest biomass, as a low-carbon alternative, can play a significant role in this transition by providing sustainable energy [4]. However, the supply chain for forest biomass faces its own set of challenges, including the need for sustainable harvesting, efficient transportation, and the management of emissions during processing. To align with the goals of the Paris Agreement and Green Deal, the forest biomass industry must focus on improving its supply chain to reduce carbon emissions further, potentially by optimizing energy usage during biomass production and distribution [5].

The forest biomass supply chain, encompassing harvesting, processing, and transportation, is pivotal in advancing sustainable energy practices, particularly using wood biomass for energy production [6]. Biomass energy is recognized globally as a renewable source, especially in Europe, where governments are striving to cut greenhouse gas emissions and adopt cleaner energy alternatives [7]. Research by Anderson et al. highlights the carbon-neutral potential of biomass, asserting that when sourced sustainably, biomass significantly contributes to climate change mitigation by reducing dependency on fossil fuels [8]. Johnson and Lee also emphasize that biomass energy can stimulate rural economies by creating jobs and providing a stable energy supply [9]. Da Silva et al.'s work demonstrates that optimizing briquetting process parameters can significantly reduce production costs, highlighting the potential for improved economic feasibility in biomass-based energy solutions, particularly when scaling up production [10].

In Scotland, the utilization of forest biomass holds particular significance due to the country's abundant forest resources and commitment to renewable energy. The forest biomass supply chain is crucial in driving Scotland's transition toward a sustainable energy future [8,11]. Ensuring forest health and biodiversity remains a key priority within this process, and the transportation of processed biomass, primarily dry wood, to power plants or other energy facilities forms an integral part of the supply chain [12]. Scotland's biomass industry is supported by policies aimed at promoting renewable energy and reducing carbon emissions [13].

According to a report from the Scottish Government, biomass energy accounted for approximately 2% of Scotland's total renewable energy generation, derived from forest biomass, agricultural residues, and waste materials [14]. The Scottish Forestry Strategy advocates for sustainable management practices, while the Renewable Energy Action Plan outlines ambitious goals to increase the share of renewables in Scotland's energy portfolio, with biomass playing a key role.

In recent years, Scotland's forest biomass supply chain has experienced steady growth, bolstered by investments in biomass power plants and the infrastructure necessary for sustainable sourcing and processing [15,16]. The Scottish government continues to actively promote biomass energy as a clean, renewable alternative to fossil fuels, with the dual goals of reducing carbon emissions and fostering local economic growth.

Figure 1 shows the potential distribution and above-ground biomass of Scots pine [17]. Forests cover about 18% of Scotland's land area, presenting substantial potential for harnessing forest biomass for energy production, particularly through sustainable management practices that maintain forest health and biodiversity [18,19].

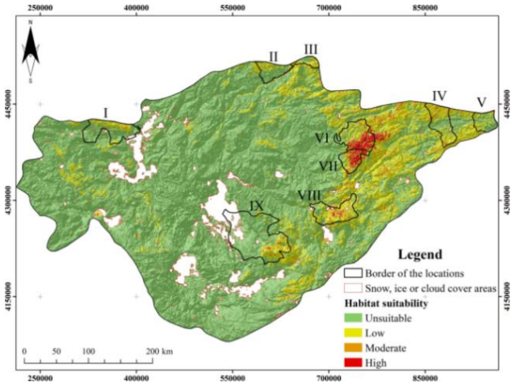

Figure 1. Potential distribution and above-ground biomass of Scots pine [17].

Numerous studies have assessed the economic viability of biomass power plants [20,21]. Makepa et al. highlighted the importance of analyzing transportation costs and CO_2 penalties when evaluating the profitability of biomass energy projects, emphasizing that logistical challenges often impact the feasibility of these initiatives [22]. Moreover, Zandi et al. introduced an integrated modeling approach to optimize biomass supply chains, accounting for feedstock availability and transportation logistics [23]. Despite these advancements, there remains a notable gap in the literature regarding comprehensive mathematical programming models that encompass local employment constraints while simultaneously evaluating the economic feasibility of forest biomass power plants in Scotland.

This paper addresses these existing gaps by presenting a unique mathematical programming model specifically designed to evaluate the feasibility of a forest biomass power plant in Scotland. Unlike previous studies, this model integrates a broader set of constraints, including net revenue from electricity generated, transportation costs, CO_2 penalties, and local employment benefits. The incorporation of local employment considerations is particularly innovative, as it underscores the social implications of renewable energy projects, aligning with the Scottish Government's focus on supporting local economies and promoting job creation [24,25].

Furthermore, the study expands upon existing models by integrating environmental impact assessments into the feasibility analysis. By employing a life cycle assessment (LCA) framework, the research evaluates not only the direct economic implications but also the environmental benefits associated with reduced carbon emissions and the sustainable management of forest resources. This holistic approach provides a more comprehensive understanding of the biomass supply chain's role in supporting Scotland's renewable energy targets and its potential to contribute to a circular economy.

The novelty of this research lies in its comprehensive approach to modeling the forest biomass supply chain. By integrating economic, environmental, and social factors to assess profitability, this study provides a multifaceted analysis that contributes to the existing body of knowledge. The research utilizes an integer linear programming (ILP) framework, allowing for the quantification of potential profit or loss while identifying key constraints impacting the feasibility of biomass energy projects. ILP is used because it is a simple yet powerful method for optimizing decisions with discrete variables and multiple constraints. Its straightforward formulation ensures compliance with economic, environmental, and operational constraints while modeling real-world decisions such as the number of employees to hire or the amount of biomass to purchase. This comprehensive modeling approach enhances understanding of the economic viability of biomass power plants, facilitating better decision-making for policymakers and stakeholders in the renewable energy sector. Ultimately, the findings aim to support sustainable energy practices while contributing to Scotland's renewable energy goals, emphasizing the importance of considering local employment and environmental sustainability in energy planning and policy development. In **Table 1** the key acronyms and their contexts in this study on biomass energy optimization has been introduced.

Table 1. Key acronyms and their contexts in this study on biomass energy optimization.

Acronym	Full Form/Meaning	Context
GHG	Greenhouse Gases	Refers to gases like CO_2 that contribute to the greenhouse effect and global warming.
CO_2	Carbon Dioxide	The primary greenhouse gas contributing to climate change.
ILP	Integer Linear Programming	Optimization technique used in the model for decision-making with discrete variables.
LCA	Life Cycle Assessment	Framework used to evaluate the environmental impacts of biomass supply chain operations.
IP	Integer Programming	A mathematical method for solving optimization problems with integer decision variables.
MINLP	Mixed Integer Non-Linear Programming	A more complex programming model for biomass supply chain optimization.
MW	Megawatt	Unit of power, used to describe the capacity of power plants.
kWh	Kilowatt-hour	Unit of energy measurement, commonly used for electricity generation and consumption.
E	Electricity Generated (kWh)	Represents the electricity produced for sale in the objective function.
Y	Quantity of Wood Product Purchased (tons)	Represents the quantity of biomass procured for energy production.
Z	Number of Employees	Decision variable for the number of employees required for internal biomass production.

The flowchart shown in **Figure 2** illustrates the process described in this paper, providing a clear and visual representation of the key steps and interactions.

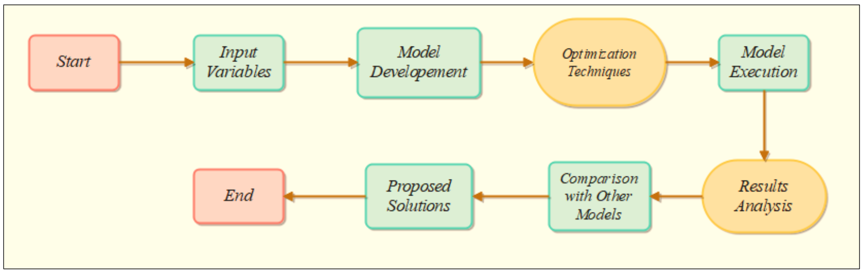

Figure 2. Model developement flowchart.

2. Model description

The design of a forest biomass mathematical programming model tailored for Scotland aims to optimize the utilization of forest biomass for diverse applications, including energy production, carbon sequestration, and sustainable forest management. This model is critical for efficiently harnessing the rich forest resources available in Scotland, considering various ecological, economic, and social factors.

To achieve this, the model incorporates a variety of variables that play essential roles in optimizing forest biomass usage. Key variables include forest growth rates, which influence the availability of biomass over time; carbon sequestration rates, reflecting the ecological benefits of forest management; land use regulations that may restrict biomass harvesting; transportation costs associated with moving biomass to processing facilities; and market demand for biomass products, which drives production decisions.

The primary objective of this model is to maximize the economic return from forest biomass while ensuring adherence to ecological and environmental constraints. In this context, it is crucial to balance economic interests with sustainability goals. The model will integrate various constraints related to demand, supply, cost, CO_2 emissions, and local employment, ensuring a comprehensive approach to biomass management. While the spatial distribution of forests, transportation distances, and availability of processing facilities are important considerations, they will be neglected in this initial version of the model to focus on the core components. As discussed in several papers, transportation and operational energy costs are critical to maximizing revenue [26].

Mathematical programming techniques, such as linear programming, integer programming, and dynamic programming, are employed to solve this optimization problem. These techniques are essential for handling multiple objectives and the complex interdependencies among various variables [27]. For instance, integer programming (IP) is particularly effective in scenarios where the decision variables must take on integer values, such as the number of employees to hire or the quantity of biomass to purchase. This method allows for more realistic modeling of real-world scenarios, leading to solutions that are both feasible and practical.

Overall, the forest biomass mathematical programming model serves as a vital tool to support sustainable forest management practices and the efficient utilization of forest resources. It seeks to benefit both the economy and the environment, fostering a harmonious relationship between resource exploitation and ecological preservation.

2.1. Objective function

The model's objective function is designed as an optimization framework that aims to maximize the net revenue derived from selling electricity generated from wood products. This objective function considers a variety of factors that influence profitability, including transportation costs, CO_2 penalties, and the benefits associated with local employment. The formulation of the objective function can be mathematically represented as follows:

$$\begin{aligned} Maximize &: (Revenue\ from\ Selling\ Electricity - Transportation\ Cost \\ &\quad - CO2\ Penalty – Local\ Employment) \end{aligned} \tag{1}$$

where:

- Revenue: The total revenue from electricity sales, calculated as:

$$Revenue = Electricity \times lectricity\ Price \tag{2}$$

- Transportation Cost: The cost incurred for transporting wood products, expressed as:

$$Transportation\ Cost = [\frac{Y}{Car\ Capacity}] \times Fee\ For\ Each\ CarPric \tag{3}$$

- CO_2 Penalty: The cost associated with carbon emissions, represented by:

$$CO_2\ Penalty = (Y + a \times Z) \times Emission\ Factor \times Penalty\ CostPrice \tag{4}$$

- Local Employment: The cost associated with local employment, calculated as:

$$Local\ Employment = Z \times Employee\ Salary \tag{5}$$

The variables included in the model represent the key elements that must be optimized to achieve the goal of maximizing net revenue. These variables guide decisions regarding the purchase of wood products, the hiring of employees, and the overall production of electricity for sale while considering various constraints, including revenue generation, transportation costs, CO_2 penalties, and local employment expenses.

- Y: quantity of wood product to purchase from suppliers (integer)
- Z: number of employees to hire (integer)
- E: electricity generated for sale (integer)

By integrating local employment considerations into the objective function and treating all variables as integers, this integer linear programming (ILP) formulation ensures that the model can optimize the entire forest supply chain. It seeks to maximize revenue while minimizing costs, reducing CO_2 emissions, and enhancing the value of local employment. A summary of the parameters used in the model is provided in **Table 2**.

Table 2. Factors and quantities.

Factor	Quantity	Source
Electricity Price	19 p/kwh (0.19 €/kWh)	The average cost of south and north Scotland [28]
Fee For Each Car	1200 €/month	An ideal price without considering the distance
Car Capacity	33,000 kg (33 tons)	[29]
Emission Factor	1560–1620 (g/kg wood) = 1590 g/kg wood = 159,000 g/ton	[30]
CO_2 Penalty Cost	30 €/ton CO_2	pessimistic scenario
Maximum Allowable Transportation Cost	80,000 €	-
Employee Salary	25,000 €/year	based on the salary range in Scotland 20000–40000 euro a year
Power Plant Size	5500 kW	30% efficiency

2.2. Constraints

2.2.1. The demand constraint

The demand constraint within the forest supply chain model represents the necessity to satisfy the specific demand for wood products. This constraint is critical in ensuring that the total quantity of wood products produced internally aligns with the overall demand for these products. The demand constraint can be expressed mathematically as follows:

X = Demand

Where:

X represents the quantity of wood product (integer).

Demand reflects the total demand for wood products, specified based on market requirements or consumer needs. This constraint guarantees that the combined volume of all internally produced wood products meets the total market demand. Meeting this demand ensures that the organization's production aligns with market conditions and operational requirements. For instance, it is noted that approximately 2% of Scotland's electricity is generated from forest biomass, equating to about 534,160,000 kWh annually. Assuming that this power plant aims to supply about 0.1% of this demand, the total electricity requirement is approximately 500,000 kWh per year. Given that each kWh requires about 2 kg of wood for combustion [31], the total wood requirement would be approximately 250 tons per year.

2.2.2. The supply constraint

The supply constraint within the forest supply chain model addresses the balance between wood products sourced from external suppliers and those produced internally. This constraint accounts for the procurement of raw materials necessary to produce wood products. The supply constraint can be expressed as:

$$Y + \alpha \times Z = X \tag{6}$$

where:

- Y denotes the quantity of wood product k sourced from suppliers.
- α represents the wood produced by each employee.
- Z is the number of employees hired for internal production.
- X signifies the total quantity of wood demand.

This constraint ensures that the total quantity of wood products purchased from suppliers, along with the labor input for internal production, equates to the total quantity of wood required. Essentially, it ensures that the organization's total supply of wood products—both from internal production and external suppliers—meets the overall demand for these products. Additionally, it is important to note that the amount of wood must not be less than 5 tons, as even in scenarios where the power plant is shut down, wood would still be stored within the facility, effectively utilizing it as a wood storage location.

2.2.3. The cost constraint

The cost constraint within the forest supply chain model establishes a cap on the total costs incurred by the power plant throughout its supply chain operations. This constraint is essential for ensuring that the organization adheres to budgetary limitations. The cost constraint can be mathematically expressed as follows:

$$Total\ Cost \leq BudgetPrice \tag{7}$$

where:

- Total Cost represents the aggregate sum of all costs incurred within the supply chain.

Budget denotes the financial limit within which the organization must operate. Based on existing forest biomass funding in Scotland, the budget is approximately 4,500,000 pounds [32].

By imposing this constraint, stakeholders ensure that the cumulative costs across different aspects of the supply chain do not surpass the allocated budget, thereby promoting fiscal responsibility and sustainability in biomass project operations.

2.2.4. CO_2 constraint

The CO_2 constraint within the forest supply chain model pertains to the regulation of CO_2 emissions associated with biomass energy production. This constraint is crucial for aligning operational practices with environmental regulations and sustainability targets. The CO_2 constraint can be articulated mathematically as:

$$Total\ CO_2\ Emissions \leq Emission\ Limit\ Price \tag{8}$$

where:

- Emission Limit represents the maximum allowable level of CO_2 emissions, typically defined based on environmental standards, sustainability objectives, or other recognized benchmarks for carbon emissions reduction. For power plants with capacities under 10 MW, the CO_2 emission limit is set at 13 g CO_2 eq/kWh. Therefore, the total CO_2 production for this power plant, given its output of 500,000 kWh per year, would amount to 6,500,000 g CO_2 [33].
- Incorporating the CO_2 constraint into the optimization process allows decision-makers to account for environmental implications alongside economic and operational considerations. This encourages the development of strategies aimed at minimizing CO_2 emissions while maintaining operational efficiency, thereby contributing to responsible and sustainable forest supply chain management.

Table 3 summarizes the relevant parameters and their values used in the calculation of CO_2 emissions for the biomass power plant.

Table 3. CO_2 emission limits and calculation details.

Parameter	**Value**
CO_2 Emission Limit	13 g CO_2 eq/kWh
Annual Electricity Demand	500,000 kWh
CO_2 Emission per kWh	1590 g CO_2 per kg of wood (or 159,000 g/ton)
Total CO_2 Emissions (Annual)	6,500,000 g CO_2 (500,000 kWh×13 g CO_2/kWh)
CO_2 Penalty Cost	30 €/ton CO_2

2.2.5. The local employment constraint

The local employment constraint within the forest supply chain model reflects an organizational commitment to prioritizing and maintaining a certain level of employment for local residents in the areas where the organization operates. This constraint emphasizes the importance of supporting local workforce participation and fostering economic development within the community.

Overview of the Local Employment Constraint:

The local employment constraint can be expressed mathematically as follows:

$$Total\ Local\ Employees \geq Minimum\ RequirementPrice \tag{9}$$

where:

- Total Local Employees: This term represents the cumulative number of employees engaged in the organization's supply chain operations who are hired or recruited locally. It includes individuals from the surrounding communities who directly contribute to the organization's activities.
- Minimum Requirement: This denotes the specified threshold or target for the minimum number or percentage of local employees that must be employed by the organization. In this analysis, a minimum local employment number of 10 has been established.

The inclusion of the local employment constraint in the forest supply chain model serves as a fundamental component that underscores the significance of supporting the local workforce and economy. It encourages decision-makers to carefully consider how their operational choices impact local employment opportunities and community well-being. By prioritizing local hiring practices, organizations can contribute to sustainable and socially responsible business practices, thereby fostering a more equitable economic landscape within the forest supply chain.

2.2.6. Electricity generation

In the forest supply chain model, the electricity generation constraint addresses the limitations or requirements concerning the production and utilization of electricity within the organization's operations. This constraint is essential for effectively managing energy resources, ensuring operational efficiency, and aligning electricity generation with sustainability objectives. Below is a detailed overview of the electricity generation constraint:

Expression of the Electricity Generation Constraint:

The electricity generation constraint can be mathematically represented as follows:

$$Electricity\ Generated = Electricity\ DemandPrice \tag{10}$$

where:

- Electricity Generated: This term signifies the total quantity of electricity produced through the organization's operations. This production may arise from various sources, including:
    - On-site power generation: This could involve using turbines, generators, or other machinery to generate electricity directly at the facility.
    - Utilization of renewable energy sources: This might include solar panels, wind turbines, or biomass systems that harness renewable resources to generate electricity sustainably.
    - Other electricity production methods: This can encompass any alternative technologies or strategies employed to produce electricity as part of the supply chain operations.

In this model, the maximum electricity generation capacity is capped at 500,000 kWh per year. This limitation reflects the operational capabilities of the organization and ensures that the electricity produced does not exceed the designated threshold.

The electricity generation constraint is a fundamental aspect of the forest supply chain model, emphasizing the importance of managing energy resources effectively and aligning electricity production with operational demands. By adhering to this constraint, organizations can enhance operational efficiency, support sustainability objectives, and ensure compliance with regulatory standards while promoting economic viability within the biomass energy sector.

3. Model results

The model is based on yearly results.

$$Maximize: Revenue\ from\ selling\ electricity - Transportation\ cost - CO2\ Penalty - Local\ EmploymentPrice \tag{11}$$

Variables:

- Y: quantity of wood product to purchase from suppliers (ton)
- Z: number of employees to hire (person)
- E: electricity generated for sale (kWh)

Calculations:

$$\text{Revenue} = E \times 0.19$$

$$Transportation\ Cost = \frac{Y}{33} \times 1200 \times 12$$

$$CO_2\ Penalty = (Y + 0.01 \times Z) \times 159{,}000 \times 30 \times 10^{-6}$$

$$Local\ Employment = Z \times 25000$$

Constraints:

- Supply constraint: $Y + 0.01 \times Z \geq 250$
- Cost constraint: $(\frac{Y}{33} \times 1200 \times 12 + (Y + 0.01 \times Z) \times 159000 \times 30 \times 10^{-6} + Z \times 25000) \leq 4{,}500{,}000$
- CO_2 constraint: $(Y + 0.01 \times Z) \times 159000 \leq 6{,}500{,}000$
- Local employment constraint: $Z \geq 10$
- Electricity generation constraint: $E \leq 500{,}000$
- Transportation cost constraint: $\frac{Y}{33} \times 1200 \times 12 \leq 80{,}000$
- Non-negativity constraint: $Y, Z, E \geq 0$

The optimal solution is given in **Table 4**. The results are obtained using Matlab.

As indicated in **Table 3**, the analysis shows that the power plant operates at an annual loss of £264,150. This unprofitability stems from multiple factors, including the low capacity of the plant and the prevailing low price of electricity in Scotland. The operational model reflects the challenges faced by biomass power plants, which often encounter significant cost pressures and regulatory constraints.

Table 4. Optimum solution.

Variable	Value
E	500,000
Y	249.9
Z	10
Optimum Solution	−264,150 pound
Iterations	3
Constraint Violation	0
Algorithm	dual simplex
Solver	Linprog

To evaluate the distinctive features and effectiveness of the proposed model, we compare it with an established mixed integer nonlinear programming (MINLP) model for biomass supply chain optimization presented by Shabani and Sowlati [34]. While their model focuses on tactical value chain optimization, including procurement, storage, production, and ash management, our model emphasizes crisis detection and economic-environmental tradeoffs using integer linear programming (ILP). This comparison highlights the differences in complexity, and applicability, and illustrates how the proposed model uniquely contributes to renewable energy planning by offering computational simplicity and a specialized focus on crisis scenarios. **Table 5** provides a detailed comparison of the two approaches.

Table 5. Comparison of paper model and Shabani & Sowlati model for biomass supply chain optimization.

Aspect	Paper Model	Shabani & Sowlati Model
Programming Type	Integer Linear Programming (ILP).	Mixed Integer Non-Linear Programming (MINLP).
Objective Function	Focused on maximizing net revenue while adhering to constraints (e.g., CO_2 penalties, transportation costs).	Aims to maximize profit across the entire supply chain, considering procurement, storage, and ash management.
Complexity	Linear relationships make the model computationally simpler and faster to solve.	Includes non-linear terms, making the model more complex but potentially more accurate for real-world interactions.
Decision Variables	Includes variables like CO_2 emissions, labor, and biomass quantities, emphasizing economic and environmental trade-offs.	Considers variables like biomass procurement, storage levels, and electricity production, along with penalties.
Applications	Tailored for evaluating feasibility and crisis detection within renewable energy systems in Scotland.	Applied to optimize a real biomass power plant in Canada for tactical supply chain decisions.

Proposed Solutions to Enhance Viability:

A. Technological advancements:
  - Rationale: Adopting state-of-the-art biomass conversion technologies can enhance the efficiency of electricity generation. Improved processes may lower production costs and increase the overall energy output.
  - Implementation: Invest in research and development to identify and implement advanced technologies, such as gasification or anaerobic digestion, which can increase conversion efficiency.

B. Policy incentives:

- Rationale: Government support can play a crucial role in promoting renewable energy projects. Subsidies, tax breaks, or grants can significantly alleviate financial burdens and encourage private investment.
- Implementation: Engage with policymakers to advocate for favorable policies that support renewable energy initiatives, including biomass energy.

C. Market restructuring:
  - Rationale: The current market for electricity pricing may not accurately reflect the true value of renewable energy, hindering profitability. Restructuring the market can help ensure that biomass energy is competitively priced.
  - Implementation: Work with industry stakeholders to push for reforms in electricity pricing mechanisms that promote fair compensation for renewable energy producers.

D. Partnerships and collaborations:
  - Rationale: Collaborating with local forestry operations and other renewable energy providers can create synergies that enhance resource efficiency and reduce costs.
  - Implementation: Explore opportunities for joint ventures or partnerships that can lead to shared benefits, such as reduced transportation costs or optimized resource use.

E. Diversification of revenue streams:
  - Rationale: Relying solely on electricity sales can expose the power plant to market volatility. Exploring additional revenue streams can enhance financial stability.
  - Implementation: Investigate potential revenue from carbon credits or the sale of biomass by-products, such as wood chips or pellets.

F. Carbon Credits:
  - Rationale: Biomass power plants can generate revenue through carbon credits by offsetting emissions, as biomass is often considered carbon-neutral. This supports financial viability while aligning with global emission reduction goals.
  - Implementation:
    1) Obtain certification under recognized carbon credit programs.
    2) Enhance credit generation through emission reduction initiatives like carbon capture.
    3) Partner with industries seeking to offset emissions.

4. Conclusion

This study developed a mathematical programming model to assess the economic viability of a forest biomass power plant in Scotland. The model considered key variables such as transportation costs, CO_2 penalties, electricity generation (500,000 kWh per year using 250 tons of biomass), and local employment. Using integer linear programming, economic, environmental and social factors were integrated to provide a system-wide analysis.

The results show that the power plant operates at an annual loss of £264,150. This is due to low electricity prices (19 pence/kWh), the limited capacity of the plant (5500 kW at 30% efficiency), and high operating costs, including transportation (€80,000 cap) and CO_2 penalties (€30/ton). Despite these challenges, the model highlights the potential for strategic interventions to improve economics.

Key recommendations include adopting advanced biomass conversion technologies to improve efficiency, restructuring electricity pricing to reflect the value of renewable energy, and securing government incentives such as subsidies or grants. Losses could be offset by additional revenue streams, such as carbon credits or biomass co-products. Collaboration with local forestry companies could further optimize costs and resource use.

By addressing these challenges, stakeholders can improve the economic prospects of biomass power generation while supporting Scotland's renewable energy goals. It offers practical advice for aligning renewable energy projects with sustainability and economic growth goals.

Statements and declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions: Conceptualization, BP; methodology, ARA; software, BP; validation, ARA; formal analysis, BP; investigation, ARA; resources, BP; data curation, ARA; writing—original draft preparation, BP; writing—review and editing, ARA; visualization, BP; supervision, ARA; project administration, ARA. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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