Supply Chain and Operations Decision Making

www.scodm.reapress.com

Sup. Chain Oper. Decis. Mak. Vol. 3, No. 3 (2026) 212–222.

Paper Type: Original Article

Biomass-Power Competitive Supply Chain Network Design Considering Buyback Contract

Mohammad Amin Maftoon[1,*], Razieh Keshavarzfard[1]

[1] Department of Industrial Engineering, NT.C., Islamic Azad University, Tehran, Iran; mohammadamin.maftoon@iau.ac.ir; r.keshavarzfard@iau.ac.ir.

Citation:

Received: 19 February 2026 Revised: 05 April 2026 Accepted: 25 June 2026	Maftoon, M. A., & Keshavarzfard, R. (2026). Biomass-power competitive supply chain network design considering buyback contract. *Supply Chain and Operations Decision Making, 3*(3), 212-222.

Abstract

With the increase in environmental energy and the development of renewable energies, their replacement in traditional electricity supply networks is unaffordable. This study designs a competitive power supply chain network considering two players (power plants and Distributed Generation (DG) units). Using DG units, users can produce their own energy. Also, this study shows the existence of refund policies for companies and users. Based on the buyback contract, users who own DG can determine their required electricity and, if necessary, purchase their required electricity from the power company or sell their excess production to it. The complex consists of biomass planting centers, suppliers, warehouses, power plants, DG units, ash sales centers, and finally electricity users. Raw materials (biomass) for electricity production by the power plant are purchased from customers or biomass planting centers and, considering ease of access, are transferred to the power plant location and, through a process in the power plant, are converted into the final product, namely electricity. The numerical results can be used as a reference for power plant engines or DG units.

Keywords: Power supply chain network, Renewable energy, Game theory, Biomass, Microgrid, Buyback contract.

1 | Introduction

Nowadays, the limited availability of fossil fuel resources and the environmental risks associated with their use have led to increased attention and investment in renewable energy. Expanding the utilization of renewable energy as an alternative energy source, along with restructuring electricity supply chain networks, can contribute to optimizing the electricity supply chain. Given the growing importance of renewable energy, which addresses not only economic concerns but also environmental sustainability, electricity generation from renewable sources has become increasingly significant. The design of electricity supply chain networks incorporating Renewable Energy Sources (RES), such as solar, wind, and biomass, is an issue that requires country-specific and specialized investigation. Determining the optimal electricity price is also of considerable importance, as electricity companies and consumers may have conflicting interests regarding pricing strategies

Corresponding Author: Mohammadamin.maftoon@iau.ac.ir

https://doi.org/10.48313/scodm.vi.63

aimed at minimizing electricity prices while simultaneously maximizing profitability. Given the importance of competitive electricity pricing, this study specifically focuses on designing a competitive biomass-to-electricity supply chain network while considering a buyback contract.

2 | Literature Review

Karimi et al. [1] proposed a bi-level optimization problem to model the interconnection between a Virtual Power Plant (VPP) and Private Owners (POs) in distribution systems. The upper level of the model focuses on the sustainable operation of the distribution system, where the VPP solves a multi-objective optimization problem to simultaneously maximize profit and minimize excessive water withdrawal. Acting as an intermediary, the VPP facilitates interactions between wholesale and retail electricity markets by purchasing energy from the wholesale market and selling it to POs in the retail market. At the lower level, POs participate in the retail market with the objective of minimizing their costs and can either generate electricity using their own resources or purchase it from the VPP. The coordination between the VPP and POs is formulated as a bi-level optimization problem.Testado et al. [2] addressed the challenge of supplying electricity to isolated areas by developing an innovative optimal sizing tool for hybrid power plants integrating biomass gasifiers. The proposed tool was specifically designed for isolated regions with access to locally produced biomass. Their study was motivated by the fact that millions of people living in remote areas lack an uninterrupted power supply because they are not connected to the main electricity grid. Under such circumstances, local electricity generation is generally the only feasible means of obtaining access to electricity and often relies on diesel engine–generator sets or Photovoltaic (PV) arrays. In many cases, however, such configurations do not fully utilize all locally available resources, including biomass. Indeed, most isolated regions have access to biomass generated through local agricultural activities, which can be used for local electricity generation through gasification. Erol and Filik [3] found that microgrid energy management algorithms have attracted increasing attention because of their potential to ensure efficient operation and coordinate active end users. In developing such algorithms, leader–follower game-theoretic approaches can provide effective strategies for incorporating the behavioral and operational characteristics of active end users into the decision-making framework. Nevertheless, because these approaches require the accurate implementation of the strategy determined by the leader, addressing uncertainties associated with renewable energy generation, the charging and discharging of energy storage systems, and load consumption is of considerable importance. Alizadeh et al. [4] identified Transactive Energy Control (TEC) as a market-based control mechanism and a critical concept for scheduling Multi-Carrier Energy Systems (MCESs) in local networks and forming an Energy Hub (EH). Nevertheless, implementing TEC for the scheduling and control of MCESs remains highly challenging because of the absence of a collaborative TEC model that simultaneously accounts for network constraints and uncertainties associated with RESs. Dianat et al. [5] investigated energy development scenarios in countries characterized by intense competition in the renewable energy sector and proposed appropriate policies by evaluating alternative development plans. By integrating system dynamics, agent-based modeling, and game theory, they developed a framework for analyzing energy development trends and the responses of competitors and investors. Li et al. [6] proposed a stochastic programming approach based on Conditional Value at Risk (CVaR) to address a retailer's expected losses under renewable energy uncertainty. They formulated a nonlinear bi-level model and transformed it into a Mixed-Integer Linear Programming (MILP) problem in the first stage by applying the Karush–Kuhn–Tucker (KKT) optimality conditions. Bi and Li [7] employed a real-options model to evaluate valley–peak pricing and subsidy policies under uncertainty and incorporated a policy-adjustment mechanism into their framework. Their results demonstrated that the optimal subsidy decreases while the optimal peak-to-valley price ratio increases. However, cost fluctuations create uncertainty among investors and consequently slow PV development. Tsao et al. [8] developed a distribution network design model incorporating voltage control and electricity pricing mechanisms, including dynamic pricing. The model aimed to maximize network profit under uncertain demand and parameters such as generation capacity, investment and production costs, and penalty budgets. Jamali and Rasti-Barzoki [9] applied game theory to examine the roles of governmental support and licensing contracts in promoting innovation under market failure. They analyzed two policy instruments, Feed-in Tariffs (FITs) and

Government Subsidies (GSs), as well as cooperation among competitors through Royalty Licensing (RL) and Joint Venture (JV) contracts. Tan et al. [10] analyzed the development and operation of VPPs from multiple perspectives and proposed prospective marketing models and market mechanisms for China. Using the business model canvas, they also designed the VPP business development pathway across the initial, development, and maturity stages.

3 | Research Contributions and Novelty

The primary contribution of this research is the development of an integrated competitive biomass-to-electricity supply chain network model in which centralized power plants and Distributed Generation (DG) units are examined simultaneously as competing actors within a common decision-making framework. Unlike many previous studies that have focused exclusively on power plant operation, microgrid energy management, or electricity pricing, the present research models the entire supply chain from biomass procurement and electricity generation to market competition and the electricity buyback mechanism. Furthermore, users, represented by DG units, are not regarded solely as electricity consumers. When they generate surplus electricity, they can sell it back to the grid under a buyback contract. Accordingly, supply and demand decisions are analyzed within an interactive and bidirectional framework. This structure explicitly captures the dual role of users as both consumers and producers, or prosumers, in the electricity market. Previous studies have generally examined individual aspects of the problem, such as microgrids, VPPs, biomass gasification, or electricity pricing. In contrast, the proposed model integrates these components into a unified competitive supply chain network. Compared with conventional energy network design frameworks, the present model simultaneously incorporates the biomass supply chain, competition between centralized power plants and DG units, and the dual consumer–producer role of users. It also models the purchase and sale of surplus electricity through a buyback contract.

Consequently, the main contributions of this study can be summarized as follows:

I. Developing an integrated competitive biomass-to-electricity supply chain network that covers biomass procurement, electricity generation, market competition, electricity consumption, and surplus electricity transactions.

II. Simultaneously modeling centralized power plants and DG units as competitive participants within a unified decision-making framework.

III. Capturing the dual role of DG units as both consumers and producers, thereby representing bidirectional electricity transactions between users and the main grid.

IV. Incorporating a buyback contract through which surplus electricity generated by DG units can be sold to the grid.

V. Integrating supply chain design and competitive electricity pricing decisions, rather than addressing network configuration, operational management, and pricing as isolated problems.

VI. Bridging multiple streams of the existing literature, including biomass gasification, microgrid energy management, VPP operation, competitive electricity pricing, and prosumer participation, within a single modeling framework.

4 | Problem Description and Mathematical Modeling

This section develops a competitive biomass-to-electricity supply chain network design model to determine the optimal economic distribution of electricity flows from the power plant and DG units to end users while maximizing total system profit. Under the proposed framework, the users and the power plant enter into a buyback contract that allows DG units to sell their surplus electricity to the power plant. Each user is equipped with a smart meter to monitor electricity consumption and determine the amount of renewable electricity sold back to the power company. This mechanism enables bidirectional electricity transactions and allows users to participate in the market as both consumers and producers (prosumers). The users' electricity demand is defined as a nonlinear function of the electricity price, as follows:

$$\mathrm{Dem}_{C\tau} = \mathrm{M}_{C\tau} - \beta_{C\tau} \left(\mathrm{P}_{C\tau}\right)^{\alpha_{C\tau}}, \tag{1}$$

where $\mathrm{P}_{C\tau}$ denotes the electricity price charged to users per unit of electricity at time period τ. In practice, the electricity price should be greater than or equal to the electricity generation cost to ensure the economic viability of electricity suppliers. The DG units and the power plant make their decisions independently. To represent the strategic interactions among market participants, a game-theoretic decision-making scheme is adopted. In this framework, the power plant acts as the leader, while DG units act as the followers. Accordingly, the power plant first determines its strategic decisions, such as electricity selling price and electricity buyback price, and then the DG units respond by determining their electricity generation, consumption, purchase, and surplus electricity selling decisions. The interaction between the power plant and DG units is therefore modeled as a leader–follower game, also known as a Stackelberg game. The assumptions of the proposed model are described as follows:

I. A decentralized supply chain model is used to formulate and solve the problem.

II. In the proposed problem, the power plant also serves as the electricity distribution company.

III. The system includes one power plant.

IV. The location of each DG unit is known in advance, and each DG unit is assumed to serve its own associated user.

V. Multiple potential biomass suppliers are considered.

VI. Multiple potential warehouses are available for biomass storage and distribution.

VII. Multiple potential biomass cultivation centers are considered.

VIII. The electricity demand of each user is modeled as a nonlinear function of the electricity price.

Table 1. Sets, parameters, and decision variables of the model.

Index	Description
ω	Index of biomass cultivation centers
Λ	Index of biomass suppliers
Γ	Index of warehouses
C	Index of electricity users
ν	Index of vehicles
Δ	Index of power plants
θ	Index of DG units
Д	Index of ash sales centers
τ	Index of time periods
Parameter	Description
CCOF_{ω}	Fixed connection cost associated with biomass cultivation center ω
CCOS_{Λ}	Fixed connection cost associated with biomass supplier $\boldsymbol{\Lambda}$
$\mathrm{C_L}$	Cost per unit of electricity power loss
l	Electricity power loss
R_{θ}	Electrical resistance associated with DG unit θ
C_{ν}	Procurement cost of vehicle ν
$\mathrm{P}_{\mathrm{buyback}}$	Electricity buyback price paid by the power plant to DG units
$\mathrm{P}_{Д}$	Selling price per unit of ash
ψ	Biomass-to-electricity conversion coefficient
η	Electricity-to-ash conversion coefficient
$\mathrm{TC}_{\omega\Lambda\nu\tau}$	Unit transportation cost of biomass from cultivation center ω to supplier Λ using vehicle ν in period τ

Table 1. Continued.

Index	Description
$TC_{\Lambda\Gamma\nu\tau}$	Unit transportation cost of biomass from supplier Λ to warehouse Γ using vehicle ν in period τ
$TC_{\Gamma\Delta\nu\tau}$	Unit transportation cost of biomass from warehouse Γ to power plant Δ using vehicle ν in period τ
$TC_{\Delta Д\nu\tau}$	Unit transportation cost of ash from power plant Δ to ash sales center Д using vehicle ν in period τ
$CPT_{\Delta C\tau}$	Unit electricity transmission cost from power plant Δ to user C in period τ
$CPT_{\theta\Delta\tau}$	Unit electricity transmission cost from DG unit θ to power plant Δ in period τ
$CPT_{\Delta\theta\tau}$	Unit electricity transmission cost from power plant Δ to DG unit θ in period τ
$PC_{\Delta\tau}$	Unit electricity generation cost of power plant Δ in period τ
$PC_{ASH\Delta\tau}$	Unit ash processing cost at power plant Δ in period τ
$PC_{\theta\tau}$	Unit electricity generation cost from RES (wind and solar) at DG unit θ in period τ
$CP_{\omega\tau}$	Unit biomass cultivation, harvesting, and maintenance cost at cultivation center ω in period τ
$CP_{\Lambda\tau}$	Unit biomass processing cost at supplier Λ in period τ
$Dem_{\theta\tau}$	Electricity demand of DG unit θ in period τ
$Dem_{C\tau}$	Electricity demand of user C in period τ
Variable	Description
$Cont_{\omega}$	Binary variable equal to 1 if a connection is established with biomass cultivation center ω; 0 otherwise
$Cont_{\Lambda}$	Binary variable equal to 1 if a connection is established with biomass supplier Λ; 0 otherwise
L_{Γ}	Binary variable equal to 1 if a warehouse is established at location Γ; 0 otherwise
AS_{ν}	Binary variable equal to 1 if vehicle ν is procured; 0 otherwise
$PWG_{\Delta\tau}$	Amount of electricity generated by power plant Δ in period τ
$EG_{\theta\tau}$	Amount of electricity generated by DG unit θ in period τ
$P_{C\tau}$	Electricity selling price charged to user C in period τ
$ABM_{\omega\Lambda\nu\tau}$	Amount of biomass transported from cultivation center ω to supplier Λ using vehicle ν in period τ
$ABM_{\Lambda\Gamma\nu\tau}$	Amount of biomass transported from supplier Λ to warehouse Γ using vehicle ν in period τ
$ABM_{\Gamma\Delta\nu\tau}$	Amount of biomass transported from warehouse Γ to power plant Δ using vehicle ν in period τ
$A_{\Delta Д\nu\tau}$	Amount of ash transported from power plant Δ\DeltaΔ to ash sales center Д using vehicle ν in period τ
$PT_{\Delta C\tau}$	Amount of electricity transmitted from power plant Δ to user C in period τ
$PT_{\theta\Delta T}$	Amount of electricity transmitted from DG unit θ to power plant Δ in period τ
$PT_{\Delta\theta\tau}$	Amount of electricity transmitted from power plant Δ to DG unit θ in period τ

4.1 | Power Plant Model

The power plant, acting simultaneously as the electricity generation facility and the electricity distribution company, is considered the leader of the decentralized supply chain. Its decisions include selecting biomass cultivation centers and suppliers, establishing warehouses, procuring vehicles, determining biomass and electricity flows, generating electricity from biomass, selling electricity to users and DG units, purchasing surplus electricity from DG units under the buyback contract, and transferring ash to ash sales centers.

$$
\begin{aligned}
\operatorname{Max} \pi_{\Delta} = & \sum_{c} \cdot \sum_{\tau} P_{C\tau}\, Dem_{C\tau} + \sum_{\nu} \cdot \sum_{Д} \cdot \sum_{\tau} P_{Д}\, A_{\Delta Д \nu\tau} + \sum_{\theta} \cdot \sum_{\tau} P_{\theta\tau}\, (Dem_{\theta\tau} - EG_{\theta\tau}) \\
& - \sum_{\theta} \cdot \sum_{\tau} P_{buyback}\, (EG_{\theta\tau} - Dem_{\theta\tau}) - \sum_{\nu} C_{\nu} AS_{\nu} - \sum_{\omega} CCOF_{\omega} Cont_{\omega} \\
& - \sum_{\Lambda} CCOS_{\Lambda} Cont_{\Lambda} - \sum_{\Gamma} CEST_{\Gamma} L_{\Gamma} - \sum_{\omega} \cdot \sum_{\Lambda} \cdot \sum_{\nu} \cdot \sum_{\tau} CP_{\omega\tau} ABM_{\omega\Lambda\nu\tau} \\
& - \sum_{\Lambda} \cdot \sum_{\Gamma} \cdot \sum_{\nu} \cdot \sum_{\tau} CP_{\Lambda\tau} ABM_{\Lambda\Gamma\nu\tau} - \sum_{\omega} \cdot \sum_{\Lambda} \cdot \sum_{\nu} \cdot \sum_{\tau} TC_{\omega\Lambda\nu\tau} ABM_{\omega\Lambda\nu\tau} \\
& - \sum_{\Lambda} \cdot \sum_{\Gamma} \cdot \sum_{\nu} \cdot \sum_{\tau} TC_{\Lambda\Gamma\nu\tau} ABM_{\Lambda\Gamma\nu\tau} - \sum_{\Gamma} \cdot \sum_{\nu} \cdot \sum_{\tau} TC_{\Gamma\Delta\nu\tau} ABM_{\Gamma\Delta\nu\tau} \\
& - \sum_{\Lambda} \cdot \sum_{\Gamma} \cdot \sum_{\nu} \cdot \sum_{\tau} HCBM_{\Gamma} ABM_{\Gamma\Delta\nu\tau} - \sum_{C} \cdot \sum_{\tau} CPT_{\Delta C\tau} (1 + l) Dem_{C\tau} \\
& - \sum_{\theta} \cdot \sum_{\tau} CPT_{\theta\Delta\tau} (EG_{\theta\tau} - Dem_{\theta\tau}) + \\
& - \sum_{\theta} \cdot \sum_{\tau} CPT_{\Delta\theta\tau} (1 + l)(Dem_{\theta\tau} - EG_{\theta\tau}) - \sum_{Д} \cdot \sum_{\nu} \cdot \sum_{\tau} TCA_{\Delta Д \nu\tau} A_{\Delta Д \nu\tau} \\
& - \sum_{\tau} PC_{\Delta\tau} PWG_{\Delta\tau},
\end{aligned} \tag{2}
$$

s.t.

$$
PWG_{\Delta\tau} + \sum_{\theta} (EG_{\theta\tau} - Dem_{\theta\tau}) = \sum_{c} (1 + l) Dem_{C\tau} + \sum_{\theta} (1 + l)(Dem_{\theta\tau} - EG_{\theta\tau}), \ \ \forall \tau, \tag{3}
$$

$$
\sum_{\omega} \cdot \sum_{\nu} ABM_{\omega\Lambda\nu\tau} = \sum_{\nu} \cdot \sum_{\Gamma} ABM_{\Lambda\Gamma\nu\tau}, \quad \forall \Lambda, \tau, \tag{4}
$$

$$
\sum_{\Lambda} \cdot \sum_{\nu} ABM_{\Lambda\Gamma\nu\tau} = \sum_{\nu} ABM_{\Gamma\Delta\nu\tau}, \ \ \forall \Gamma, \tau, \tag{5}
$$

$$
\sum_{\Gamma} \cdot \sum_{\nu} \eta ABM_{\Gamma\Delta\nu\tau} = \sum_{Д} \cdot \sum_{\nu} A_{\Delta Д \nu\tau}, \quad \forall \tau, \tag{6}
$$

$$
\sum_{\Gamma} \cdot \sum_{\nu} \psi ABM_{\Gamma\Delta\nu\tau} = PWG_{\Delta\tau}, \ \ \forall \tau, \tag{7}
$$

$$
\begin{aligned}
& PWG_{\Delta\tau}, ABM_{\Gamma\Delta\nu\tau}, ABM_{\Lambda\Gamma\nu\tau}, ABM_{\omega\Lambda\nu\tau}, A_{\Delta Д \nu\tau}, P_{\theta\tau}, P_{C\tau} \geq 0, \\
& AS_{\nu}, Cont_{\omega}, Cont_{\Lambda}, L_{\Gamma} = \{0,1\}.
\end{aligned} \tag{8}
$$

4.2 | DG Unit Model

The DG units are modeled as followers in the proposed Stackelberg game framework. Each DG unit independently determines its renewable electricity generation, electricity consumption, electricity purchases from the power plant, and the amount of surplus electricity sold back to the power plant under the buyback contract. Each DG unit can generate electricity using local RES, such as solar and wind energy. The generated electricity is first used to satisfy its own demand. If the electricity generated by a DG unit exceeds its demand, the surplus amount may be transmitted to the power plant and sold at the predetermined buyback price. Conversely, if the DG unit's generated electricity is insufficient to meet its demand, it can purchase the required electricity from the power plant.

$$
\begin{aligned}
\operatorname{Max} \pi_{\theta} = & \textstyle\sum_{\theta} \cdot \sum_{\tau} P_{buyback}\, (EG_{\theta\tau} - Dem_{\theta\tau}) - \sum_{\theta} IV_{\theta} - \sum_{\theta} \cdot \sum_{\tau} P_{\theta\tau}\, (Dem_{\theta\tau} - EG_{\theta\tau}) - \\
& \textstyle\sum_{\theta} \cdot \sum_{\tau} C_{L}\, R_{\theta} (EG_{\theta\tau} / V_{\theta})^{2},
\end{aligned} \tag{9}
$$

$$EG_{\theta\tau} \geq 0. \tag{10}$$

5 | Transformation of the Bi-Level Model into a Single-Level Model

To solve the proposed bi-level model using the Stackelberg approach, the decision variables controlled by the upper-level player (i.e., the main power plant as the leader) are first considered fixed. Subsequently, the lower-level model corresponding to the DG units, as followers, is solved. In particular, the first-order optimality condition of the lower-level problem is obtained by taking the partial derivative of the DG objective function with respect to the follower-controlled decision variable $EG_{\theta\tau}$, namely the electricity generated by DG unit θ during time period τ, and setting it equal to zero:

$$\frac{\partial_{\pi_\theta}}{\partial_{EG_{\theta\tau}}} = P_{buyback} - 2\frac{C_L R_\theta{}^2}{V_\theta} EG_{\theta\tau} + P_{\theta\tau} = 0, \tag{11}$$

$$EG_{\theta\tau} = \frac{P_{buyback} + P_{\theta\tau}}{2C_L R_\theta}.V_\theta{}^2. \tag{12}$$

The derived response function represents the optimal renewable electricity generation decision of each DG unit in response to the decisions of the power plant. It is then substituted into the upper-level objective function and constraints. Consequently, the original bi-level Stackelberg model is transformed into an equivalent single-level optimization model, which can be solved using appropriate nonlinear or mixed-integer nonlinear programming methods. The optimal value obtained for $EG_{\theta\tau}$ is then substituted into the upper-level model. Consequently, the main power plant incorporates the optimal reaction of each DG unit into its own decision-making process. Accordingly, the original bi-level Stackelberg model is transformed into a single-level optimization model, which can be solved to determine the optimal decisions of the power plant, including electricity generation, electricity pricing, biomass procurement and transportation flows, warehouse establishment, electricity transactions with users and DG units, and the buyback of surplus electricity generated by DG units.

$$\begin{aligned}
\text{Max}\,\pi_C = {} & \textstyle\sum_{C}.\sum_{\tau} P_{C\tau}\, Dem_{C\tau} + \sum_{\nu}.\sum_{Д}.\sum_{\tau} P_{Д}\, A_{\Delta Д \nu\tau} + \sum_{\theta}.\sum_{\tau} P_{\theta\tau}\Big(Dem_{\theta\tau} - \\
& \tfrac{P_{buyback}+P_{\theta\tau}}{2C_L R_\theta}.V_\theta{}^2\Big) - \textstyle\sum_{\theta}.\sum_{\tau} P_{buyback}\Big(\tfrac{P_{buyback}+P_{\theta\tau}}{2C_L R_\theta}.V_\theta{}^2 - Dem_{\theta\tau}\Big) - \sum_{\nu} C_\nu AS_\nu - \\
& \textstyle\sum_{\omega} CCOF_\omega Cont_\omega - \sum_{\Lambda} CCOS_\Lambda Cont_\Lambda - \sum_{\Gamma} CEST_\Gamma L_\Gamma - \sum_{\omega}.\sum_{\Lambda}.\sum_{\nu}.\sum_{\tau} CP_{\omega\tau} ABM_{\omega\Lambda\nu\tau} - \\
& \textstyle\sum_{\Lambda}.\sum_{\Gamma}.\sum_{\nu}.\sum_{\tau} CP_{\Lambda\tau} ABM_{\Lambda\Gamma\nu\tau} - \sum_{\omega}.\sum_{\Lambda}.\sum_{\nu}.\sum_{\tau} TC_{\omega\Lambda\nu\tau} ABM_{\omega\Lambda\nu\tau} - \\
& \textstyle\sum_{\Lambda}.\sum_{\Gamma}.\sum_{\nu}.\sum_{\tau} TC_{\Lambda\Gamma\nu\tau} ABM_{\Lambda\Gamma\nu\tau} - \sum_{\Gamma}.\sum_{\nu}.\sum_{\tau} TC_{\Gamma\Delta\nu\tau} ABM_{\Gamma\Delta\nu\tau} - \\
& \textstyle\sum_{\Lambda}.\sum_{\Gamma}.\sum_{\nu}.\sum_{\tau} HCBM_{\Gamma} ABM_{\Gamma\Delta\nu\tau} - \sum_{C}.\sum_{\tau} CPT_{\Delta C\tau}(1+l)Dem_{C\tau} - \\
& \textstyle\sum_{\theta}.\sum_{\tau} CPT_{\theta\Delta\tau}\Big(\tfrac{P_{buyback}+P_{\theta\tau}}{2C_L R_\theta}.V_\theta{}^2 - Dem_{\theta\tau}\Big) + -\sum_{\theta}.\sum_{\tau} CPT_{\Delta\theta\tau}(1+l)\Big(Dem_{\theta\tau} - \\
& \tfrac{P_{buyback}+P_{\theta\tau}}{2C_L R_\theta}.V_\theta{}^2\Big) - \textstyle\sum_{Д}.\sum_{\nu}.\sum_{\tau} TCA_{\Delta Д\nu\tau} A_{\Delta Д\nu\tau} - \sum_{\tau} PC_{\Delta\tau} PWG_{\Delta\tau},
\end{aligned} \tag{13}$$

s.t.

$$\begin{aligned}
& PWG_{\Delta\tau} + \sum_{\theta}\left(\frac{P_{buyback} + P_{\theta\tau}}{2C_L R_\theta}.V_\theta{}^2 - Dem_{\theta\tau}\right) \\
& \quad = \sum_{C}(1+l)Dem_{C\tau} + \sum_{\theta}(1+l)\left(Dem_{\theta\tau} - \frac{P_{buyback} + P_{\theta\tau}}{2C_L R_\theta}.V_\theta{}^2\right), \quad \forall\tau,
\end{aligned} \tag{14}$$

$$\textstyle\sum_{\omega}.\sum_{\nu} ABM_{\omega\Lambda\nu\tau} = \sum_{\nu}.\sum_{\Gamma} ABM_{\Lambda\Gamma\nu\tau}, \quad \forall\Lambda,\tau, \tag{15}$$

$$\sum_{\Lambda}.\sum_{\nu} ABM_{\Lambda\Gamma\nu\tau} = \sum_{\nu} ABM_{\Gamma\Delta\nu\tau}, \quad \forall\Gamma,\tau, \tag{16}$$

$$\sum_{\Gamma}.\sum_{\nu} \eta ABM_{\Gamma\Delta\nu\tau} = \sum_{Д}.\sum_{\nu} A_{\Delta Д\nu\tau}, \quad \forall\tau, \tag{17}$$

$$\sum_{\Gamma}.\sum_{\nu} \psi ABM_{\Gamma\Delta\nu\tau} = PWG_{\Delta\tau}, \quad \forall\tau, \tag{18}$$

$$PWG_{\Delta\tau}, ABM_{\Gamma\Delta\nu\tau}, ABM_{\Lambda\Gamma\nu\tau}, ABM_{\omega\Lambda\nu\tau}, A_{\Delta Д\nu\tau}, P_{\theta\tau}, P_{C\tau} \geq 0, \tag{19}$$

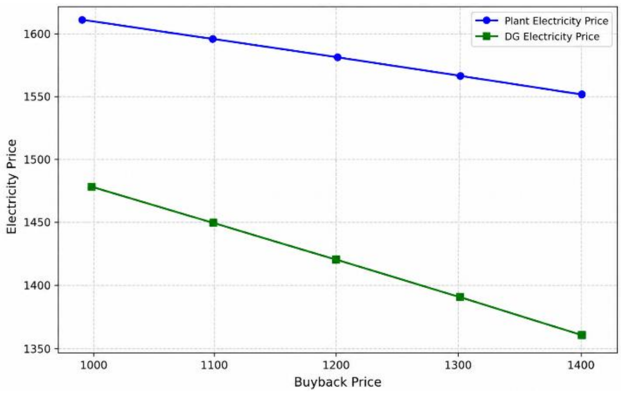
$$AS_{\nu}, Cont_{\omega}, Cont_{\Lambda}, L_{\Gamma} = \{0,1\}.$$

6 | Model Solution and Analysis of Findings

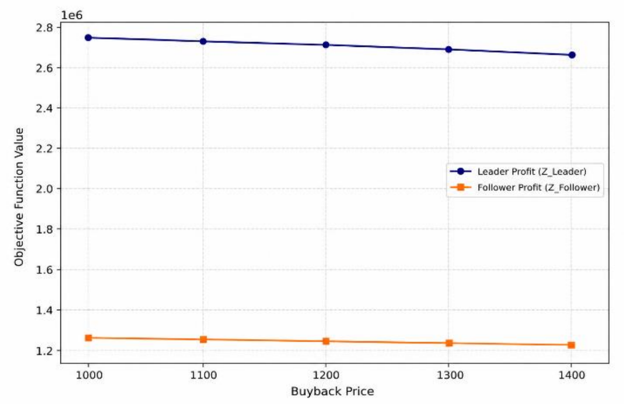
In this study, the proposed model was formulated based on a Stackelberg game to simulate the strategic interactions between the power plant, as the leader, and DG units, as the followers. The bi-level problem was transformed into a single-level model using the followers' optimal reaction functions and was solved for a network comprising four biomass cultivation centers, three suppliers, three warehouses, one power plant, four DG units, one ash sales center, three vehicles, four users, and three time periods. The optimal objective-function value was obtained as 3,847,620 monetary units, representing the total profit of the supply chain over the planning horizon. An analysis of the equilibrium prices during the first, second, and third periods indicates that the electricity prices of the power plant are 1,450, 1,580, and 1,710, respectively, whereas the corresponding electricity prices of the DG units are 1,320, 1,410, and 1,530, respectively. The findings reveal an increasing trend in electricity prices for both the power plant and DG units over the planning horizon. However, the electricity price offered by DG units remains significantly lower than that of the power plant in all periods. This price difference reflects the competitive advantage of DG units and their role in reducing the final electricity cost for consumers. In fact, applying the Stackelberg model not only improves the overall profitability of the supply chain but also provides an effective economic structure for managing biomass-based electricity generation, energy transactions, and the sale of by-products, particularly ash. To examine the robustness of the model under changes in support policies, the parameter $P_{buyback}$, representing the price paid by the power plant to purchase surplus electricity from DG units, was subjected to sensitivity analysis. As shown in *Table 2*, increasing $P_{buyback}$ leads to strategic changes in the objective values of both the leader and the followers.

Table 2. Sensitivity analysis of $P_{buyback}$ on power plant and DG electricity prices and objective functions.

$P_{buyback}$	$P_{C\tau}$	$EG_{\theta\tau}$	π_{Δ}	π_{θ}	π_c
960	1,610	1,480	2,740,500	1,174,500	3,988,000
1,080	1,595	1,450	2,716,700	1,164,300	3,942,000
1,200	1,580	1,420	2,693,334	1,154,286	3,895,000
1,320	1,565	1,390	2,670,500	1,144,500	3,851,000
1,440	1,550	1,360	2,647,400	1,134,600	3,808,000



a.



b.

Fig. 1. Sensitivity analysis of $P_{buyback}$ on power plant and DG electricity prices and objective functions; a. effects of the buyback price on power plant and DG electricity prices, and b. effects of the buyback price on leader and follower profits.

The results indicate that, across all scenarios, the objective-function value under the centralized configuration, π_c, is greater than the aggregate profits of the leader and followers under the decentralized configuration. This efficiency gap, which results from decentralized decision-making in the Stackelberg model, is a well-recognized phenomenon in supply chain management. The persistence of this gap at different levels of $P_{buyback}$ supports the validity and consistency of the proposed solution algorithm. Moreover, as $P_{buyback}$ increases, DG units reduce their electricity selling prices in order to maintain their competitiveness. This strategic response affects the profit distribution between the leader and the followers, while the power plant's profit decreases at a relatively moderate rate. To further ensure the reliability and logical behavior of the model under varying operating conditions, the equilibrium prices were evaluated over three time periods with different demand levels. To further evaluate the pricing behavior and stability of the proposed model under different demand conditions, the equilibrium electricity prices of the power plant and DG units were compared across the three time periods. The results, including the price spread and the corresponding stability status, are presented in *Table 3*.

Table 3. Comparison of equilibrium prices across time periods.

τ	$P_{C\tau}$	$EG_{\theta\tau}$	Price Spread	Stability Status
1	1,450	1,320	130	Stable
2	1,580	1,410	170	Stable
3	1,710	1,530	180	Stable

The persistence of a stable price difference across all time periods demonstrates the model's logical and consistent response to demand fluctuations. As peak-related costs increase, the proposed pricing model maintains the price difference within a stable competitive margin. This finding quantitatively confirms the structural validity and computational reliability of the proposed model.

7 | Conclusion

This study developed a competitive biomass-to-electricity supply chain network design model considering buyback contracts between the power plant and DG unit owners. One of the most important issues in electricity supply chains is the use of biomass as an input for electricity generation. Depending on climatic and geographical conditions, biomass can be considered a reliable renewable energy source compared with other renewable sources, such as wind and solar energy. In the proposed model, DG units generate their required electricity using solar and wind energy. When a DG unit produces surplus electricity, it sells the excess power to the power plant, which also represents the electricity distribution company, at a predetermined buyback price. Conversely, when the generated electricity is insufficient to meet its demand, the DG unit purchases the required electricity from the power plant at an agreed price. The proposed supply chain network includes four biomass cultivation centers, three biomass suppliers, three warehouses, one power plant, four DG units, one ash sales center, and four users. The resulting model was solved using GAMS. The results demonstrate that integrating biomass-based electricity generation, DG, competitive pricing, and buyback contracts can provide an effective framework for coordinating electricity supply and demand while improving the economic performance of the supply chain. Several extensions can be considered for future research. First, different forms of cooperation and non-cooperation between the electricity company and DG units may be incorporated into the model. Second, time-dependent demand functions can be developed to provide a more realistic representation of electricity consumption patterns. Further extensions may also include uncertainty in biomass availability, renewable energy generation, electricity demand, and market prices, as well as the integration of energy storage systems and environmental objectives into the proposed framework.

Acknowledgments

The authors sincerely appreciate all those who contributed to the completion of this research.

Funding

This research was conducted without financial support from any public, private, or non-profit organization.

Data Availability

The data used in this study are available from the corresponding author upon reasonable request.

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