



# Coordinated Electricity Tariff and Import Planning for Kyrgyzstan Using Rolling MILP Optimization Under Seasonal Hydropower Constraints

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## Abstract

Kyrgyzstan relies heavily on hydropower generation, which results in a pronounced seasonal mismatch between electricity supply and demand, posing significant challenges to power system reliability and supply security. During winter, reduced hydropower availability and increased electricity consumption often lead to power shortages and a growing dependence on electricity imports. To support more effective operational planning, this study proposes a mixed-integer linear programming (MILP) model for the coordinated optimization of electricity tariffs and import procurement under seasonal supply constraints. The proposed model incorporates tariff-responsive demand, domestic generation limits, electricity imports from neighboring countries, affordability requirements, and revenue adequacy constraints. A rolling optimization framework is developed to

support annual, quarterly, and monthly planning updates. The model is applied to a case study of the Kyrgyz power system using publicly available electricity statistics for 2025 and seasonally adjusted monthly scenarios. Results indicate that coordinated tariff and import planning can alleviate winter supply pressure and improve system reliability, as measured by the Energy Not Supplied (ENS) indicator, compared with a benchmark planning approach. Under the studied scenarios, the optimized strategy reduces annual import requirements and lowers import expenditures while maintaining affordability and revenue-related constraints. The rolling optimization framework also provides greater flexibility for adapting to changing hydrological conditions and import market uncertainties. The proposed approach offers a practical decision-support tool for hydropower-dominated power systems facing seasonal electricity shortages and increasing import dependence.

**Keywords:** Kyrgyzstan power system, electricity tariff, electricity import planning, mixed-integer linear



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programming, hydropower, rolling optimization, supply reliability.

## 1 Introduction

Kyrgyzstan is a hydropower-dominated country whose electricity supply strongly depends on the operation of large hydropower plants, particularly the Toktogul hydropower cascade. Hydropower contributes the majority of domestic electricity generation, while thermal generation plays a supplementary role in maintaining system reliability [1, 2]. Although the country possesses substantial hydropower resources, the electricity sector faces a persistent seasonal imbalance. Electricity demand increases significantly during winter because of heating requirements and higher residential consumption, whereas hydropower availability is often constrained by reservoir operation and hydrological conditions. As a result, Kyrgyzstan frequently experiences winter electricity deficits and relies on electricity imports from neighboring countries to maintain supply security [3–5].

To address electricity shortages and improve system efficiency, tariff reform and demand-side management have received increasing attention in recent years. Previous studies have shown that electricity tariffs can influence consumer behavior and contribute to peak-demand reduction when appropriate pricing mechanisms are implemented [9–12]. In Kyrgyzstan, recent tariff reforms introduced differentiated pricing structures and increasing-block tariffs for residential consumers [6–8]. These measures aim to improve cost recovery and encourage more rational electricity consumption. However, tariff policies alone cannot fully resolve seasonal supply shortages, particularly when domestic generation is limited by hydrological conditions.

At the same time, cross-border electricity trade has become an important component of power system operation in Central Asia. Regional electricity exchanges can help balance seasonal mismatches between supply and demand and improve overall system reliability [1, 13, 14]. Nevertheless, import planning involves multiple uncertainties, including import prices, transmission availability, contract arrangements, and geopolitical factors. Excessive dependence on emergency winter imports may increase operational costs and expose the power sector to additional risks.

Optimization techniques have been widely applied to

power system planning and operation. Mixed-integer linear programming (MILP) has proven particularly effective for addressing electricity scheduling, generation planning, and energy market problems, as it can simultaneously represent operational constraints, economic objectives, and policy requirements [15–18]. Existing studies have extensively investigated demand response, electricity market operation, hydropower scheduling, and generation planning. However, most studies treat electricity tariff design and import procurement as separate decision problems. For hydropower-dominated systems such as Kyrgyzstan, these decisions are inherently interconnected because tariff policies affect electricity demand, which in turn influences import requirements and system reliability.

Motivated by this practical planning challenge, this study develops a coordinated optimization framework for electricity tariff design and import planning in Kyrgyzstan. The framework is formulated as a mixed-integer linear programming model that incorporates tariff-responsive demand, domestic generation constraints, source-specific electricity imports, affordability requirements, revenue adequacy conditions, and seasonal reliability considerations. To improve practical applicability, a rolling optimization mechanism is adopted to support annual, quarterly, and monthly decision updates.

The main contributions of this study are summarized as follows:

- A coordinated MILP framework is proposed to jointly optimize electricity tariffs and import procurement under seasonal hydropower constraints.
- A rolling planning mechanism is developed to support annual, quarterly, and monthly decision making while incorporating updated demand and supply information.
- A case study based on the Kyrgyz electricity system is conducted to evaluate the effectiveness of the proposed framework in reducing winter supply pressure, import dependence, and procurement costs.

The remainder of this paper is organized as follows. Section 2 reviews related studies on electricity tariffs, regional power trade, power system reliability, and optimization methods. Section 3 presents the mathematical formulation of the proposed optimization model. Section 4 describes the rolling optimization procedure. Section 5 introduces the

case study and data construction process. Section 6 discusses the results and sensitivity analyses. Finally, Section 7 concludes the paper and outlines future research directions.

## 2 Related Work

### 2.1 Electricity Tariffs and Demand Response

Electricity tariff design is widely recognized as an important tool for improving power system efficiency and influencing consumer behavior. Time-varying and dynamic pricing mechanisms have been extensively studied as approaches for reducing peak demand and improving the utilization of generation resources. Borenstein [9] demonstrated the long-term efficiency benefits of electricity prices that reflect system marginal costs, while Joskow and Wolfram [10] discussed the role of dynamic pricing in modern electricity markets. Empirical evidence from multiple pilot programs indicates that consumers can respond to price signals by adjusting electricity consumption patterns, although the magnitude of the response varies across regions and customer groups [11].

Demand response has also been investigated as a mechanism for enhancing power system reliability. Albadi and El-Saadany [12] reviewed a wide range of demand-response programs and highlighted their potential contributions to peak-load reduction and system operation. In the context of Kyrgyzstan, Muktarbek kyzy and Alfnes [8] examined household responses to increasing-block electricity tariffs in Kyrgyzstan and found that tariff structures can influence residential electricity consumption behavior. These studies suggest that tariff policy can serve not only as a revenue-recovery mechanism but also as an operational instrument for managing electricity demand.

Despite these developments, most existing studies focus primarily on demand-side responses or market efficiency. Comparatively less attention has been given to the interaction between tariff decisions and electricity import requirements in hydropower-dependent power systems.

### 2.2 Electricity Imports and Regional Power Trade

Cross-border electricity trade plays an increasingly important role in maintaining supply security in regions characterized by seasonal variations in electricity availability. For hydropower-dominated countries, electricity imports can provide a flexible mechanism for compensating domestic generation

deficits during periods of low water availability. International Energy Agency reports emphasize that regional cooperation and cross-border electricity exchanges are important components of power system security in Kyrgyzstan and Central Asia [1, 2].

Several studies have highlighted the strategic importance of regional energy integration and hydropower development in Central Asia. The World Bank has identified regional hydropower projects and electricity interconnections as key elements for improving long-term energy security and facilitating clean-energy development [13, 14]. However, electricity imports are associated with multiple uncertainties, including price fluctuations, transmission constraints, contract arrangements, and geopolitical considerations. As a result, import planning requires balancing reliability objectives against economic and operational risks.

Existing research generally analyzes electricity imports from the perspectives of energy security, regional cooperation, or market integration. Limited attention has been paid to coordinating import decisions with domestic tariff policies and demand-side management measures.

### 2.3 Optimization Approaches for Power System Planning

Optimization methods have been widely applied in power system planning and operation. Early studies demonstrated the effectiveness of mathematical optimization for resource allocation and generation planning in electric utilities [15]. With the increasing complexity of modern power systems, mixed-integer linear programming (MILP) has become one of the most widely adopted approaches because it can represent operational constraints, discrete decisions, and economic objectives within a unified framework.

MILP models have been successfully applied to unit commitment, generation scheduling, and power market optimization problems. Carrion and Arroyo [16] proposed an efficient MILP formulation for thermal unit commitment, while Morales-España et al. [17] developed compact formulations that improved computational performance. In addition, optimization-based approaches have been extensively used for renewable energy integration and electricity market operation under uncertainty [18].

The flexibility and transparency of MILP make it particularly suitable for policy-oriented planning studies. Economic objectives, operational limits,

affordability requirements, and reliability constraints can all be represented within a single optimization framework. However, most existing MILP applications focus on generation scheduling, market operation, or resource planning. Comparatively few studies consider the joint optimization of electricity tariffs and import procurement under seasonal hydropower constraints.

## 2.4 Research Gap and Motivation

The literature provides valuable insights into electricity tariff design, demand response, regional electricity trade, and optimization-based power system planning. Nevertheless, several research gaps remain relevant to hydropower-dominated electricity systems such as Kyrgyzstan.

First, tariff design and electricity import planning are typically investigated separately, despite their strong operational interdependence. Changes in electricity tariffs affect consumer demand, which subsequently influences import requirements and system reliability.

Second, many existing studies focus on annual energy balances or short-term operational scheduling. Such approaches may not adequately capture the seasonal mismatch between electricity demand and hydropower availability that characterizes the Kyrgyz power system. Third, although MILP has been widely applied in power system optimization, relatively limited research has explored its application to integrated tariff and import planning under affordability, revenue adequacy, and reliability considerations.

To address these gaps, this study develops a coordinated MILP framework that jointly optimizes electricity tariffs and import procurement within a rolling planning structure. The proposed approach aims to support practical decision making in hydropower-dominated electricity systems facing seasonal supply-demand imbalances and growing dependence on electricity imports.

## 3 Problem Formulation

### 3.1 Planning Horizon and Sets

The coordinated tariff and import planning problem is formulated over a monthly planning horizon represented by the set  $T = \{1, \dots, 12\}$ . To capture seasonal variations in electricity demand and hydropower availability, the months are grouped into winter  $W$ , summer  $S$ , and shoulder  $R$  periods. For the Kyrgyzstan case study, winter corresponds

to November–March, summer corresponds to June–September, and the remaining months are classified as shoulder periods.

Let  $Q = \{1, \dots, 4\}$  denote the quarterly planning periods and  $I$  denote the set of electricity import sources. The framework adopts a rolling planning structure in which annual decisions provide policy guidance, while quarterly and monthly updates incorporate revised information on electricity demand, hydropower availability, and import conditions.

The principal notation used in the proposed model is summarized in Table 1.

**Table 1.** Principal notation.

| Symbol                                   | Definition                                                                                              |
|------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $D_t^0, \hat{D}_t$                       | baseline and tariff-adjusted demand in month $t$                                                        |
| $p_t, z_{k,t}$                           | selected tariff and binary tariff-option variable                                                       |
| $H_t, G_t^{\text{th}}, O_t$              | hydropower, thermal, and other domestic generation                                                      |
| $M_{i,t}, y_{i,q}$                       | import quantity from source $i$ and quarterly contract variable                                         |
| $L_t, E_t, C_t$                          | unserved energy, export, and curtailment variables                                                      |
| $V_t, A_t, R^-$                          | tariff-volatility, affordability-deviation, and revenue-shortfall slacks                                |
| $c_{i,t}, \rho_i$<br>$G^{\text{th,ann}}$ | import price and source-risk coefficient<br>annual thermal generation total used for monthly allocation |
| $B, R^{\text{req}}$                      | annual import budget and revenue requirement                                                            |

### 3.2 Demand and Tariff Representation

Let  $D_t^0$  denote the baseline monthly electricity demand before tariff adjustment. Demand response is represented through a discrete tariff-selection mechanism. Let  $K$  be the set of feasible tariff options. Parameter  $P_{k,t}$  denotes the tariff level associated with option  $k$  in month  $t$ , and  $\hat{D}_{k,t}$  denotes the corresponding electricity demand after tariff adjustment.

Binary variable  $z_{k,t}$  equals one when tariff option  $k$  is selected in month  $t$ . The selected tariff level  $p_t$  and

tariff-adjusted demand  $\hat{D}_t$  are determined by

$$\sum_{k \in K} z_{k,t} = 1, \quad \forall t \in T, \quad (1)$$

$$p_t = \sum_{k \in K} P_{k,t} z_{k,t}, \quad \forall t \in T, \quad (2)$$

$$\hat{D}_t = \sum_{k \in K} \hat{D}_{k,t} z_{k,t}, \quad \forall t \in T. \quad (3)$$

The formulation maintains linearity while representing seasonal tariff schedules and tariff-responsive demand. Demand-response coefficients can be estimated from observed tariff elasticities or assumed elasticity ranges when detailed consumer-level data are unavailable. Their impacts are further examined through sensitivity analysis.

### 3.3 Supply and Import Variables

Domestic electricity supply consists of hydropower generation  $H_t$ , thermal generation  $G_t^{\text{th}}$ , and other generation resources  $O_t$ . Imported electricity from source  $i$  in month  $t$  is denoted by  $M_{i,t}$ . Additional variables include load shedding  $L_t$ , electricity exports  $E_t$ , and curtailment  $C_t$ .

The monthly energy-balance constraint is expressed as

$$H_t + G_t^{\text{th}} + O_t + \sum_{i \in I} M_{i,t} + L_t = \hat{D}_t + E_t + C_t, \quad \forall t \in T. \quad (4)$$

which ensures that total supply satisfies electricity demand after accounting for exports and curtailment. Generation and import quantities are bounded by

$$H_t^{\min} \leq H_t \leq H_t^{\max}, \quad \forall t \in T, \quad (5)$$

$$G_t^{\text{th},\min} \leq G_t^{\text{th}} \leq G_t^{\text{th},\max}, \quad \forall t \in T, \quad (6)$$

$$0 \leq M_{i,t} \leq \bar{M}_{i,t}, \quad \forall i \in I, t \in T. \quad (7)$$

where hydropower availability reflects seasonal water conditions, thermal generation is constrained by available capacity, and imports are limited by cross-border transmission capability and contractual arrangements.

To represent winter supply adequacy, the following peak-support constraint is introduced:

$$\eta_t \hat{D}_t \leq \bar{P}_t^{\text{dom}} + \bar{P}_t^{\text{imp}} + U_t, \quad \forall t \in W, \quad (8)$$

where  $U_t$  is a penalized adequacy-violation variable. Although the model operates at monthly resolution, this constraint helps ensure that winter demand requirements remain consistent with available supply capability.

### 3.4 Import Contracts, Diversification, and Budget Constraints

Import planning is modeled through quarterly contract decisions and monthly import scheduling. Binary variable  $y_{i,q(t)}$  indicates whether an import contract with source  $i$  is active during quarter  $q$ . Monthly import quantities are linked to contract decisions through

$$M_{i,t} \leq \bar{M}_{i,t} y_{i,q(t)}, \quad \forall i \in I, t \in T. \quad (9)$$

To improve supply security and reduce dependence on individual suppliers, source diversification is represented by

$$M_{i,t} \leq \alpha_i \sum_{j \in I} M_{j,t}, \quad \forall i \in I, t \in T, \quad (10)$$

where  $\alpha_i$  denotes the maximum allowable import share for source  $i$ . The annual import budget is constrained by

$$\sum_{t \in T} \sum_{i \in I} c_{i,t} M_{i,t} \leq B \quad (11)$$

where  $c_{i,t}$  is the import price and  $B$  is the available annual budget. Import dependence can be limited through

$$\sum_{i \in I} M_{i,t} \leq \gamma_t \hat{D}_t, \quad \forall t \in T \quad (12)$$

where  $\gamma_t$  specifies the maximum allowable share of imported electricity in total monthly demand. This constraint provides flexibility for balancing reliability objectives and import dependence.

### 3.5 Tariff Smoothing, Affordability, and Revenue Adequacy

To ensure policy feasibility, monthly tariff levels are restricted within predefined bounds:

$$p_t^{\min} \leq p_t \leq p_t^{\max}, \quad \forall t \in T. \quad (13)$$

Abrupt tariff changes between consecutive months are controlled through the auxiliary variable  $V_t$ :

$$V_t \geq p_t - p_{t-1}, \quad t = 2, \dots, 12, \quad (14)$$

$$V_t \geq p_{t-1} - p_t, \quad t = 2, \dots, 12, \quad (15)$$

$$V_t \leq \Delta_t^p, \quad t = 2, \dots, 12. \quad (16)$$

Affordability considerations are represented by

$$A_t \geq p_t - p_t^{\text{aff}}, \quad \forall t \in T, \quad (17)$$

$$A_t \geq 0, \quad \forall t \in T, \quad (18)$$

where  $p_t^{\text{aff}}$  denotes an affordability benchmark and  $A_t$  measures deviations above that benchmark. Revenue adequacy is represented through pre-calculated tariff-option revenues  $R_{k,t}$ :

$$\sum_{t \in T} \sum_{k \in K} R_{k,t} z_{k,t} + R^- \geq R^{\text{req}}, \quad (19)$$

where  $R^{\text{req}}$  is the annual revenue requirement and  $R^-$  is a non-negative revenue-shortfall variable. This formulation preserves linearity while ensuring that tariff decisions remain consistent with financial sustainability requirements.

### 3.6 Objective Function

The objective of the coordinated planning model is to minimize total system cost while maintaining supply reliability and tariff affordability. The objective function includes import procurement costs, load-shedding penalties, tariff volatility, affordability deviations, import-risk exposure, and revenue shortfalls:

$$\begin{aligned} \min Z = & w_1 \sum_{t \in T} \sum_{i \in I} c_{i,t} M_{i,t} + w_2 \sum_{t \in T} L_t + w_3 \sum_{t=2}^{12} V_t \\ & + w_4 \sum_{t \in T} A_t + w_5 \sum_{t \in T} \sum_{i \in I} \rho_i M_{i,t} + w_6 R^-. \end{aligned} \quad (20)$$

where  $w_1$ – $w_6$  are weighting coefficients representing the relative importance of different planning objectives.

The weights reflect a policy preference structure appropriate for a hydropower-dominated electricity system facing seasonal supply stress. In the baseline specification used in this study, import cost minimization ( $w_1$ ) and reliability ( $w_2$ ) are assigned the highest weights, consistent with the primary planning challenge of maintaining winter supply security at reasonable cost. Tariff smoothing ( $w_3$ ), affordability ( $w_4$ ), import-source risk ( $w_5$ ), and revenue adequacy ( $w_6$ ) are assigned lower but nonzero weights to ensure that the optimization does not pursue cost savings at the expense of consumer welfare or financial sustainability. The baseline weight values are set as follows:  $w_1 = 10$ ,  $w_2 = 100$ ,  $w_3 = w_4 = 5$ ,  $w_5 = 3$ ,  $w_6 = 8$ . The weights are not uniquely determined; they can be adjusted by planners to reflect alternative policy priorities. A sensitivity analysis on weight variations is presented in Section 6.4, which demonstrates that the main qualitative conclusions remain stable across a reasonable range of weight combinations.

The first term minimizes electricity import expenditure. The second term penalizes unserved energy (load shedding) to preserve system reliability. The third and fourth terms reduce tariff volatility and affordability impacts on consumers. The fifth term represents import-related risk exposure weighted by source-specific risk coefficients  $\rho_i$ . The final term penalizes revenue inadequacy relative to the annual revenue requirement.

The variable  $L_t$  represents unserved energy in month  $t$ , i.e., the electricity demand that cannot be met by available domestic generation and imports. The shortage-risk proxy reported in the results is the cumulative unserved energy aggregated over the planning horizon, defined as

$$L^{\text{risk}} = \sum_{t \in T} L_t, \quad (21)$$

measured in TWh. This metric corresponds to the Energy Not Supplied (ENS) indicator widely used in power system reliability assessment, providing a supply-security-oriented measure of planning performance. This quantity is penalized in the objective function to discourage solutions that achieve apparent cost savings through load shedding. Practically, a lower value of  $L^{\text{risk}}$  indicates that a larger share of electricity demand is reliably served under the given planning strategy. In the case study, the optimized scenario reduces  $L^{\text{risk}}$  from 0.540 TWh (benchmark) to 0.182 TWh, corresponding to an approximately two-thirds reduction in potential unserved energy.

## 4 Rolling Optimization Framework

### 4.1 Rolling Optimization Architecture

The proposed framework adopts a rolling optimization strategy consisting of annual, quarterly, and monthly decision layers. The annual layer establishes the overall planning targets, including tariff corridors, import budgets, and reliability requirements. The quarterly layer updates import procurement plans and tariff schedules using revised forecasts of electricity demand, hydropower availability, and import market conditions. The monthly layer performs short-term adjustments based on the most recent operational information.

This hierarchical structure allows long-term planning decisions to be coordinated with short-term operational updates. Annual decisions provide strategic guidance, while quarterly and monthly optimization improve adaptability under changing system conditions.

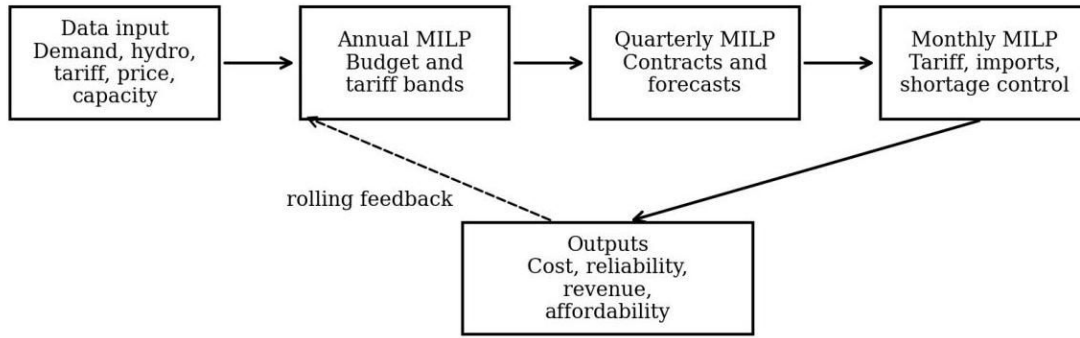


Figure 1. Overview of the rolling optimization framework.

As illustrated in Figure 1, the annual optimization is performed over the full twelve-month planning horizon. Its outputs include annual import budgets, seasonal tariff ranges, source-diversification targets, and reliability indicators. Quarterly optimization updates the planning decisions using revised forecasts while maintaining consistency with annual policy targets. Monthly optimization determines operational decisions for tariff levels, import quantities, generation utilization, and shortage management.

The rolling framework enables the integration of newly available information while preserving planning consistency across decision stages.

## 4.2 Solution Procedure

The optimization procedure is implemented sequentially through annual, quarterly, and monthly decision updates. Table 2 summarizes which forecasts are updated and which decision variables are optimized at each stage.

**1) Annual Stage** The annual stage is executed once at the beginning of the planning year. Input forecasts include projected monthly electricity demand, domestic generation capability (hydropower and thermal availability bounds), import prices by source, cross-border transmission capacities, and fiscal constraints. The annual MILP model determines the annual import budget  $B$ , seasonal tariff corridors  $[p_t^{\min}, p_t^{\max}]$ , source-diversification targets, and annual reliability indicators. These outputs serve as binding constraints and policy guidance for subsequent quarterly and monthly stages.

**2) Quarterly Stage** At the beginning of each quarter  $q$ , the following forecasts are updated using the most recently available information: demand forecasts for the upcoming three months, revised hydropower availability based on updated hydrological observations, current import prices

and transmission availability for each source. The quarterly MILP model revises import contract activation decisions  $y_{i,q}$ , source-specific procurement targets for the quarter, and the tariff trajectory for the upcoming quarter. All decisions must remain consistent with the annual policy corridors established in the annual stage.

**3) Monthly Stage** The monthly stage uses the latest available information to determine short-term operating decisions. At the beginning of month  $t$ , observed demand realizations, actual domestic generation, and confirmed import availability are incorporated. The monthly MILP model optimizes tariff level  $p_t$ , source-specific import quantities  $M_{i,t}$ , domestic generation dispatch, and shortage management variables  $L_t$ .

Once a monthly decision has been implemented, i.e., the corresponding month has passed, the associated decision variables ( $p_t, M_{i,t}$ , dispatch quantities) are treated as fixed parameters in all subsequent optimization runs. Formally, these variables are replaced by their realized values in the constraint set, so that the optimization horizon effectively shortens as the year progresses. After each monthly execution, the realized import expenditure  $\sum_i c_{i,t} M_{i,t}$  is subtracted from the annual budget  $B$ , and the remaining budget is updated as  $B_{t+1}^{\text{rem}} = B_t^{\text{rem}} - \sum_i p_{i,t} M_{i,t}$ . This remaining budget  $B_{t+1}^{\text{rem}}$  is passed as a binding parameter to the next optimization stage, ensuring that all subsequent decisions remain consistent with the overall annual fiscal constraint. The overall procedure is summarized in Algorithm 1.

## 4.3 Implementation Considerations

The model is implemented in Python 3.10 using Pyomo 6.x [19] as the algebraic modeling environment. CBC (Coin-or Branch and Cut, version 2.10) is used as the default open-source MILP solver; Gurobi

**Table 2.** Information updated and decisions optimized at each stage of the rolling MILP procedure.

| Item                                     | Annual Stage                                                                                                                                                                                                                | Quarterly Stage                                                                                                                                                                                                                                                      | Monthly Stage                                                                                                                                     |
|------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Execution timing</b>                  | Once, start of planning year                                                                                                                                                                                                | Start of each quarter $q \in \{Q1, Q2, Q3, Q4\}$                                                                                                                                                                                                                     | Start of each month $t$                                                                                                                           |
| <b>Input forecasts updated</b>           | Annual demand forecast $D^{\text{ann}}$ ; annual hydropower availability $H^{\text{ann}}$ ; thermal capacity $G^{\text{th,ann}}$ ; annual import prices by source $\bar{p}_i$ ; annual budget $B$ ; revenue requirement $R$ | Revised monthly demand forecast for upcoming 3 months $\hat{D}_t$ ; updated hydropower availability $\hat{H}_t^{\text{max}}$ based on latest hydrological observations; current import prices $\hat{c}_{i,t}$ and cross-border transmission capacity $\hat{f}_{i,t}$ | Observed demand realization $D_t^{\text{obs}}$ ; actual domestic generation availability; confirmed import capacity and spot prices for month $t$ |
| <b>Decision variables optimized</b>      | Annual import budget allocation; seasonal tariff corridors $[p_t^{\text{min}}, p_t^{\text{max}}]$ ; source-diversification targets; annual reliability targets                                                              | Quarterly import contract activation $y_{i,q}$ ; source-specific procurement targets for the quarter; tariff trajectory for upcoming 3 months                                                                                                                        | Monthly tariff level $p_t$ ; source-specific import quantities $M_{i,t}$ ; domestic generation dispatch; unserved energy $L_t$                    |
| <b>Decisions fixed from prior stages</b> | None                                                                                                                                                                                                                        | Annual tariff corridors $[p_t^{\text{min}}, p_t^{\text{max}}]$ treated as binding constraints                                                                                                                                                                        | All decisions for months $t' < t$ fixed at realized values; quarterly contract activation $y_{i,q}$ fixed                                         |
| <b>Output passed to next stage</b>       | Tariff corridors; budget $B$ ; reliability targets                                                                                                                                                                          | Revised procurement targets; updated remaining budget $B^{\text{rem}}$                                                                                                                                                                                               | Realized expenditure; updated $B_t^{\text{rem}}$ ; realized $L_t$ for performance tracking                                                        |

10.x is supported as an optional high-performance alternative for larger-scale instances. All computations were performed on a standard desktop workstation equipped with an Intel Core i7 processor and 16 GB of RAM running Windows 11. No parallel computing or specialized hardware was required.

**Model size.** The annual-stage optimization problem contains approximately 300–400 decision variables (continuous and binary) and 250–350 constraints, depending on the number of tariff options  $|K|$  and import sources  $|I|$ . Each quarterly-stage problem is of comparable size. Each monthly-stage problem is considerably smaller, typically involving fewer than 100 active variables after previously implemented decisions are fixed.

**Computational time.** Typical solution times are under 5 seconds for the annual-stage MILP and under 1 second for each monthly-stage update when using CBC on the hardware described above. The full twelve-month rolling procedure, including all quarterly and monthly updates, completes in well under two minutes. These results confirm that the proposed framework is computationally tractable for practical planning applications.

To preserve model linearity, tariff-response relationships are represented through discrete tariff options. Each option  $k \in K$  is associated with a predefined demand level  $d_{k,t}$  and revenue value  $\text{Rev}_{k,t}$ , avoiding nonlinear price-demand interactions. All data are normalized to consistent energy (TWh), tariff (USD/kWh), and currency (million USD) units prior to optimization.

The rolling structure further improves computational tractability and only a limited portion of the planning horizon is re-optimized at each update stage. As the year progresses, an increasing share of decisions is fixed at their realized values, and the active optimization horizon shrinks accordingly. This property ensures that the framework remains efficient even if solver performance were to degrade for larger problem instances.

## 5 Case Study

### 5.1 Data Sources and System Background

The proposed framework is evaluated using the Kyrgyzstan electricity system as a case study. Kyrgyzstan is a hydropower-dominated power system characterized by pronounced seasonal variations in

**Algorithm 1:** Rolling MILP Optimization Procedure

**Input** : Annual demand forecast, domestic generation forecasts, hydropower availability, import prices by source, tariff options  $K$ , import capacities, annual budget  $B$ , revenue requirement  $R$ .

**Output**: Monthly tariff schedules  $p_t$ , source-specific import quantities  $M_{i,t}$ , reliability indicators, affordability measures, annual planning outcomes.

1. Classify months into winter  $W$ , summer  $S$ , and shoulder  $R$  periods. 2. Construct annual planning inputs; initialize remaining budget  $B_t^{\text{rem}} \leftarrow B$ . 3. **Annual stage**: Solve annual MILP  $\rightarrow$  obtain tariff corridors  $[p_t^{\min}, p_t^{\max}]$ , annual import budget allocation, and reliability targets.
4. **for each quarter**  $q = 1, \dots, 4$  **do**
  - 4.1. Update demand forecast, hydropower availability, import prices, and cross-border capacity;
  - 4.2. Solve quarterly MILP  $\rightarrow$  revise contract activation  $y_{i,q}$  and quarter-ahead tariff path;
  - 4.3. **for each month**  $t$  **in quarter**  $q$  **do**
    - 4.3.1. Update observed demand, domestic generation, and import availability;
    - 4.3.2. Fix all decisions for months  $t' < t$  as realized parameter values;
    - 4.3.3. Solve monthly MILP  $\rightarrow$  determine  $p_t, M_{i,t}, L_t$ ;
    - 4.3.4. Update remaining budget:  
 $B_{t+1}^{\text{rem}} \leftarrow B_t^{\text{rem}} - \sum_i c_{i,t} M_{i,t}$ ;
- end**
5. Report annual planning outcomes and performance indicators;

electricity supply and demand. Publicly available reports indicate that national electricity consumption reached approximately 19.3 TWh in 2025, while domestic electricity generation was approximately 15.4 TWh [3, 4]. Electricity imports amounted to approximately 3.886 TWh during the same period [5].

Hydropower represents the dominant source of domestic electricity generation, accounting for approximately 12.8–12.9 TWh of annual production, while thermal generation contributes approximately 1.8–2.0 TWh and serves primarily as a winter backup resource [1, 2]. Reported winter peak demand reached approximately 3.6 GW, highlighting the

seasonal supply-security challenge faced by the power system.

The principal case-study parameters used in this work are summarized in Table 3. These values serve as annual reference quantities for the construction of monthly planning inputs.

**Table 3.** 2025 Kyrgyzstan electricity context used in the case study.

| Parameter                | Value               |
|--------------------------|---------------------|
| Electricity consumption  | about 19.3 TWh      |
| Domestic generation      | about 15.4 TWh      |
| Electricity imports      | about 3.886 TWh     |
| Hydropower generation    | about 12.8–12.9 TWh |
| Thermal generation       | about 1.8–2.0 TWh   |
| Winter peak load         | about 3.6 GW        |
| Installed capacity       | about 3.46 GW       |
| Summer surplus potential | 0.5–1.0 TWh         |

The objective of the case study is to evaluate whether coordinated tariff and import planning can reduce winter supply pressure, lower import dependence, and improve reliability indicators while satisfying affordability and revenue-related constraints.

## 5.2 Monthly Data Construction

Because publicly available electricity statistics are primarily reported at annual resolution, monthly planning inputs were derived through a normalization and seasonal allocation procedure that preserves annual energy balances. The procedure is described below for each input category.

Monthly electricity demand  $D_t$  is obtained by distributing the annual consumption total of 19.3 TWh using seasonal demand weights  $\omega_t^D$ . The weights reflect the pronounced winter peak in Kyrgyzstan, where residential heating and reduced daylight hours drive significantly higher electricity consumption during November–March compared with the summer period. These weights are derived from typical seasonal consumption patterns documented in IEA country reports [1, 2] and are consistent with the reported winter peak load of approximately 3.6 GW.

Monthly hydropower availability  $H_t^{\max}$  is derived from the annual hydropower generation total of approximately 12.85 TWh using seasonal hydropower weights  $\omega_t^H$ . The weights reflect the typical seasonal pattern of the Toktogul cascade, where runoff and reservoir levels are higher during the spring snowmelt and summer rainfall season (June–September) and

significantly lower during the winter drawdown period (November–March).

Monthly thermal generation capacity  $G_t^{\text{th,max}}$  is allocated using weights  $\omega_t^T$  that reflect the greater utilization of thermal backup resources during winter supply stress.

Monthly import prices  $c_{i,t}$  for each source  $i$  are constructed using a seasonal adjustment factor applied to a reference annual average price. Import prices are assumed to be higher during winter months, reflecting increased regional demand and tighter cross-border supply availability during the heating season. These assumptions are consistent with publicly available information on Central Asian regional electricity trade patterns and are examined through sensitivity analysis in Section 6.4.

Monthly profiles were calculated using Eqs. (22)–(24), which preserve annual totals while generating seasonally differentiated monthly planning inputs.

$$D_t = D^{\text{ann}} \frac{\omega_t^D}{\sum_{\tau \in T} \omega_\tau^D}, \quad (22)$$

$$H_t^{\text{max}} = H^{\text{ann}} \frac{\omega_t^H}{\sum_{\tau \in T} \omega_\tau^H}, \quad (23)$$

$$G_t^{\text{th,max}} = G^{\text{th,ann}} \frac{\omega_t^T}{\sum_{\tau \in T} \omega_\tau^T}. \quad (24)$$

This approach ensures consistency between annual statistics and monthly optimization requirements. Similar data-construction procedures have been widely adopted in power-system planning studies when high-resolution operational data are unavailable [15, 18].

Figures 2, 3 and 4 illustrate the resulting annual generation structure, monthly demand-supply balance, and seasonal deficit-surplus pattern used in the optimization model.

The category values are annual scenario anchors derived from public annual reports and scaled to the domestic total.

The annual totals match the case-study anchors, while the monthly allocation follows the scenario construction method.

Positive bars indicate deficit pressure, and negative bars indicate summer surplus potential.

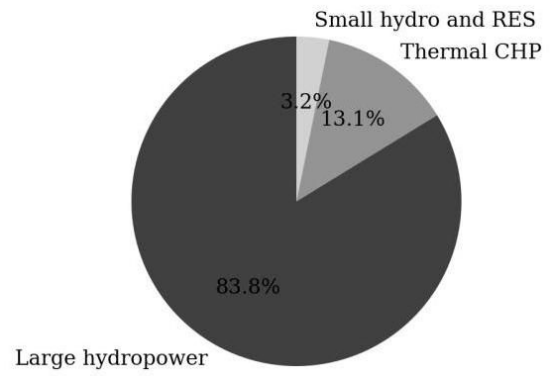


Figure 2. Domestic generation structure used in the 2025 case study.

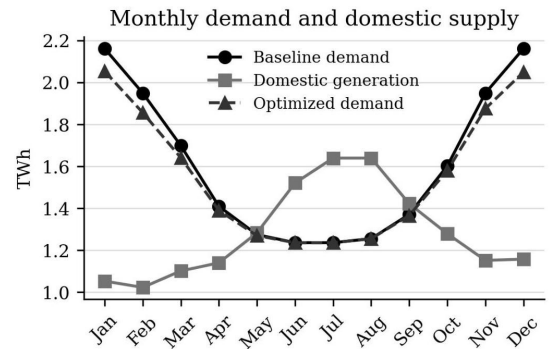


Figure 3. Monthly demand and domestic generation profiles.

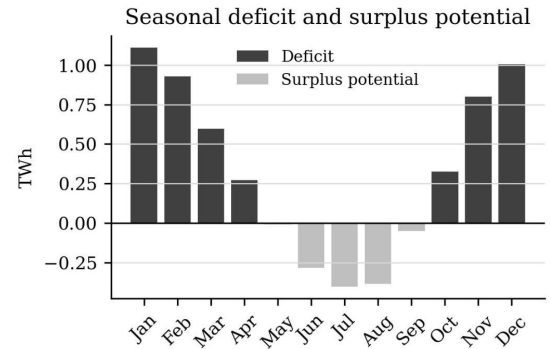


Figure 4. Seasonal deficit and surplus-potential pattern.

### 5.3 Scenario Settings

To evaluate the effectiveness of the proposed framework, several tariff and import-planning scenarios were examined.

For tariff analysis, four alternative strategies were considered:

1. Benchmark tariff scenario, representing the reported residential tariff structure applied in 2025;
2. Fixed tariff scenario, maintaining a constant tariff throughout the year;

3. Seasonal tariff scenario, applying administratively defined winter and summer tariff adjustments;
4. Optimized tariff scenario, generated by the proposed rolling MILP framework.

For import planning, three alternative procurement strategies were considered:

1. Benchmark import scenario, corresponding to the reported annual import level in 2025;
2. Reactive import scenario, emphasizing short-term winter procurement;
3. Rolling optimization scenario, integrating annual, quarterly, and monthly planning decisions.

Representative monthly import-price profiles and source-capacity limits were developed using publicly available information on regional electricity trade and cross-border electricity exchanges. These inputs were designed to reflect typical seasonal market conditions and were subsequently examined through sensitivity analysis.

The scenario design allows the impacts of tariff adjustment, import scheduling, and coordinated optimization to be evaluated separately. Table 4 summarizes the principal model inputs and their corresponding data sources.

**Table 4.** Scenario inputs and source type.

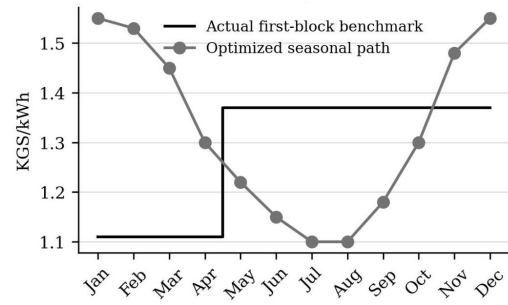
| Inputs                 | Value/Design        | Source Type             |
|------------------------|---------------------|-------------------------|
| Annual demand          | 19.3 TWh            | Public statistics       |
| Annual domestic supply | 15.4 TWh            | Public statistics       |
| Annual imports         | 3.886 TWh           | Public statistics       |
| Monthly demand profile | Seasonal allocation | Derived dataset         |
| Monthly hydro profile  | Seasonal allocation | Derived dataset         |
| Import prices          | Seasonal profile    | Market-based assumption |

## 6 Results and Discussion

### 6.1 Optimized Tariff Strategy

Figure 5 compares the benchmark tariff structure with the tariff trajectory obtained from the proposed rolling MILP framework. The optimized solution introduces higher tariffs during winter months and lower tariffs during summer periods, reflecting seasonal differences in supply adequacy and electricity scarcity.

The result is consistent with the economic principle that electricity prices should better reflect system



**Figure 5.** Actual first-block tariff benchmark and optimized seasonal tariff path.

conditions and resource availability [9]. During winter, when hydropower availability declines and import dependence increases, higher tariffs provide additional incentives for demand moderation. During summer, when hydropower generation is relatively abundant, lower tariff levels help reduce affordability pressures without compromising system reliability.

The optimized tariff path also satisfies the smoothing constraints imposed in the model. Rather than producing abrupt month-to-month adjustments, the optimization generates a gradual seasonal transition. This characteristic improves policy feasibility and may enhance consumer acceptance of tariff reforms.

The results suggest that tariff policy can contribute to seasonal demand management, although tariff adjustment alone is insufficient to eliminate winter supply deficits. Consequently, tariff measures should be considered as one component of a broader electricity-planning strategy that includes import procurement and supply-side coordination.

### 6.2 Import Planning Performance

Figure 6 presents the monthly import quantities obtained under the benchmark and optimized planning strategies. Compared with the benchmark case, the rolling optimization framework reduces annual imports from 3.886 TWh to approximately 3.50 TWh.

The reduction in import requirements is primarily driven by two factors. First, seasonal tariff adjustments decrease electricity demand during high-stress winter periods. Second, the coordinated optimization framework improves the timing of procurement decisions and reduces dependence on emergency imports.

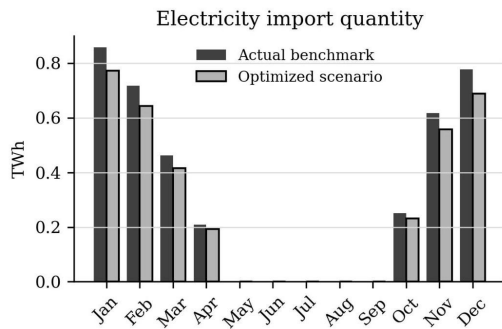
Figure 7 further demonstrates the economic benefits of coordinated planning. Under the assumed import-price profiles, annual import expenditure

**Table 5.** Performance summary for benchmark and optimized scenarios.

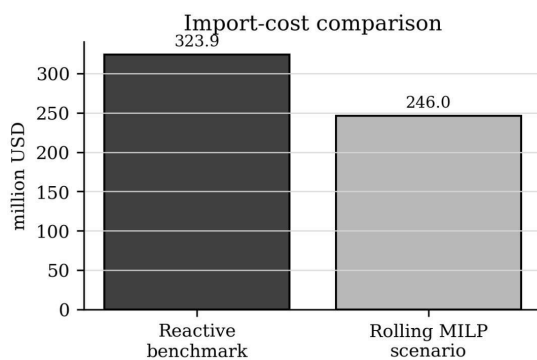
| Indicator                 | Benchmark     | Optimized Scenarios   |
|---------------------------|---------------|-----------------------|
| Annual demand (TWh)       | 19.30         | 18.80                 |
| Annual imports (TWh)      | 3.886         | 3.500                 |
| Import cost (million USD) | 323.9         | 246.0                 |
| Shortage-risk proxy (TWh) | 0.540         | 0.182                 |
| Tariff volatility         | low           | controlled seasonal   |
| Revenue adequacy          | not optimized | constrained in model  |
| Affordability             | benchmark     | bounded by constraint |

**Table 6.** Sensitivity analysis of the optimized planning scenario.

| Scenario                     | Annual Imports (TWh) | Import Cost (Million USD) | Shortage-Risk Proxy (TWh) |
|------------------------------|----------------------|---------------------------|---------------------------|
| Base optimized case          | 3.500                | 246.0                     | 0.182                     |
| Import price +20%            | 3.500                | 295.2                     | 0.182                     |
| Hydropower availability -10% | 3.760                | 276.8                     | 0.246                     |
| Demand growth +5%            | 3.930                | 289.5                     | 0.284                     |
| Import capacity -15%         | 3.210                | 238.6                     | 0.337                     |

**Figure 6.** Benchmark and optimized monthly import quantities under the rolling procurement strategy.

decreases from approximately 323.9 million USD to 246.0 million USD. Although the exact magnitude depends on market conditions and input assumptions, the direction of the result indicates that forward planning can generate significant cost savings.

**Figure 7.** Import-cost comparison under specified import-price profiles.

demand-side measures with import planning. When tariff decisions and procurement strategies are optimized independently, opportunities for reducing import costs may be overlooked. The coordinated framework captures these interactions and therefore provides a more comprehensive planning approach.

### 6.3 Reliability and Economic Trade-offs

Table 5 summarizes the principal performance indicators under the benchmark and optimized scenarios. In addition to reducing import volumes and procurement costs, the proposed framework decreases the shortage-risk indicator from 0.540 TWh to 0.182 TWh.

The reliability improvement arises from the joint optimization of demand response and import procurement. Rather than relying exclusively on additional imports during winter periods, the model simultaneously adjusts electricity demand, allocates available domestic generation, and schedules imports more efficiently. As a result, the system can achieve a lower shortage risk with reduced import dependence.

An important feature of the proposed framework is the explicit consideration of affordability and revenue adequacy constraints. These constraints prevent the optimization from pursuing cost minimization through excessive tariff increases or financially unsustainable pricing strategies. Consequently, the resulting solution represents a compromise among economic efficiency, system reliability, and social acceptability.

These findings highlight the importance of integrating The results illustrate a broader planning trade-off

frequently encountered in hydropower-dominated electricity systems. Improving reliability generally requires either higher imports, increased domestic generation, stronger demand management, or some combination of these measures. The proposed framework provides a structured approach for balancing these competing objectives within a unified optimization model.

#### 6.4 Sensitivity Analysis

To evaluate the robustness of the proposed framework, a series of sensitivity analyses were conducted around the optimized planning scenario. Four representative sources of uncertainty were considered: import-price variation, hydropower availability reduction, electricity-demand growth, and import-capacity restriction. These factors were selected because they directly influence the seasonal supply-demand balance of the Kyrgyz electricity system. Table 6 summarizes the resulting performance indicators under alternative operating conditions.

The results indicate that the proposed framework remains relatively stable under moderate parameter variations. Import-price increases mainly affect procurement expenditure while having limited impact on physical reliability indicators. Under the assumed 20% price increase, annual import costs rise proportionally, whereas import quantities and shortage-risk indicators remain largely unchanged because electricity demand and supply conditions are not directly affected.

Hydropower availability is found to be one of the most influential factors. A 10% reduction in available hydropower generation increases annual imports to approximately 3.76 TWh and raises the shortage-risk indicator from 0.182 TWh to 0.246 TWh. This result reflects the strong dependence of the Kyrgyz power system on hydropower resources and confirms the importance of maintaining adequate winter reserve margins.

Demand growth also has a significant impact on system performance. Under the assumed 5% increase

in electricity demand, annual imports increase to approximately 3.93 TWh, while the shortage-risk indicator rises to 0.284 TWh. The result suggests that continued demand growth may place additional pressure on both domestic generation resources and import requirements.

The most severe reliability impact is observed under the import-capacity restriction scenario. Although annual import expenditure decreases because fewer imports can be procured, the shortage-risk indicator increases substantially to 0.337 TWh. This finding highlights the importance of cross-border transmission availability and regional electricity cooperation for maintaining winter supply security.

Overall, the sensitivity analysis demonstrates that the proposed rolling MILP framework maintains its effectiveness across a range of plausible operating conditions. Among the tested uncertainties, hydropower availability and import-capacity limitations have the greatest influence on system reliability, while import-price fluctuations primarily affect economic performance. These results suggest that future planning efforts should prioritize hydrological uncertainty management and cross-border supply diversification.

To assess whether alternative weight specifications materially affect the planning outcomes, three additional weight configurations were examined alongside the baseline case. Configuration W1 assigns greater emphasis to reliability ( $w_2$  increased by 50%); Configuration W2 increases the affordability weight ( $w_4$  increased by 50%); Configuration W3 represents a cost-focused policy ( $w_1$  increased by 50%,  $w_2$  decreased by 25%). The results are summarized in Table 7.

#### 6.5 Policy Implications

The results provide several practical insights for electricity planning in Kyrgyzstan.

First, seasonal tariff adjustments can contribute to demand management when implemented within acceptable affordability limits. Although tariff

**Table 7.** Sensitivity of planning outcomes to objective function weight variations.

| Weight Configuration | Annual Imports (TWh) | Import Cost (M USD) | Shortage-Risk Proxy (TWh) | Tariff Volatility |
|----------------------|----------------------|---------------------|---------------------------|-------------------|
| Baseline             | 3.500                | 246.0               | 0.182                     | controlled        |
| W1 (reliability↑)    | 3.620                | 254.3               | 0.141                     | controlled        |
| W2 (affordability↑)  | 3.530                | 248.7               | 0.195                     | lower             |
| W3 (cost-focused)    | 3.380                | 237.5               | 0.221                     | controlled        |

measures alone cannot eliminate winter shortages, they can reduce peak demand and lower import requirements.

Second, forward import procurement appears more cost-effective than reactive winter purchasing. Incorporating updated market information through a rolling planning framework can reduce exposure to price volatility and supply uncertainty.

Third, coordinated planning offers greater benefits than treating tariff policy and import procurement as separate decision processes. The interaction between electricity demand and import requirements is sufficiently strong that independent decision-making may lead to higher costs and lower reliability.

Finally, the proposed framework may also be applicable to other hydropower-dominated electricity systems experiencing seasonal supply-demand imbalances and increasing dependence on electricity imports.

## 7 Limitations

Several limitations of the present study should be acknowledged.

First, the case study relies primarily on publicly available annual electricity statistics. Because detailed monthly operational data were not publicly available, monthly planning inputs were derived through a seasonal allocation procedure consistent with annual energy balances. Although this approach enables the evaluation of the proposed framework at monthly resolution, future studies could benefit from utility-level operational data and higher-resolution demand records.

Second, hydropower availability is represented through monthly generation bounds rather than a detailed reservoir-operation model. While this simplification is appropriate for tariff and import planning analysis, a more comprehensive representation of reservoir dynamics could improve the assessment of inter-seasonal water management decisions.

Third, electricity demand response is modeled using aggregate tariff-elasticity assumptions. Actual consumer responses may vary across customer groups, income levels, and geographic regions. Future work could incorporate household-level or sector-specific demand-response models to improve behavioral representation.

Finally, uncertainties associated with hydrological conditions, import prices, and cross-border electricity availability are represented through scenario-based analysis. The integration of stochastic optimization or robust optimization techniques could further enhance decision support under uncertain operating environments.

Despite these limitations, the proposed framework provides a practical and transparent approach for evaluating coordinated tariff and import planning strategies in hydropower-dominated electricity systems.

## 8 Conclusion

This paper presented a coordinated optimization framework for electricity tariff design and import planning in the Kyrgyz electricity system. Motivated by the country's seasonal imbalance between winter electricity demand and hydropower availability, the proposed approach integrates tariff-responsive demand, domestic generation constraints, electricity imports, affordability requirements, revenue adequacy conditions, and reliability considerations within a unified mixed-integer linear programming framework.

A rolling optimization structure was developed to support annual, quarterly, and monthly planning decisions. The framework was evaluated using a case study based on publicly available electricity statistics for Kyrgyzstan in 2025. The results indicate that coordinated tariff and import planning can reduce electricity import requirements, lower procurement costs, and improve reliability indicators when compared with benchmark planning strategies. The analysis also demonstrates that tariff policy and import procurement are closely interconnected and should be considered jointly rather than as separate planning problems.

Sensitivity analysis further shows that the framework remains effective under a range of operating conditions. Among the investigated factors, hydropower availability and import-capacity limitations exert the greatest influence on system reliability, while import-price fluctuations primarily affect economic performance. These findings highlight the importance of hydrological uncertainty management and regional electricity cooperation in maintaining long-term supply security.

From a practical perspective, the proposed framework can serve as a decision-support tool for electricity planners operating in hydropower-dominated systems

with significant seasonal supply-demand imbalances. By combining demand-side and supply-side measures within a single optimization framework, the approach provides a transparent basis for evaluating trade-offs among reliability, affordability, and economic efficiency.

Future research may extend the framework by incorporating detailed reservoir-operation models, stochastic hydrological scenarios, renewable-energy integration, consumer-level demand-response behavior, and robust optimization techniques. Such extensions would further improve the applicability of the proposed approach for long-term electricity planning under uncertainty.

## Data Availability Statement

Data will be made available on request.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

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