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Dynamic Shadow Pricing of Electricity under Renewable Surplus: Evidence from a Regulated Power System

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ABSTRACT

Many regulated electricity systems operate without real-time market pricing, relying instead on administratively determined tariffs that fail to reflect short-run scarcity and surplus conditions. As variable renewable energy penetration increases, temporal mismatches between generation and demand create recurring periods of surplus and tightness within the same day, leading to renewable curtailment, inefficient dispatch, and underutilisation of storage and demand-side flexibility. This paper develops a deterministic shadow-pricing framework that infers the marginal value of electricity directly from observable system conditions rather than market-clearing prices. Using realised solar, wind, and demand data, we construct a dynamic proxy for the shadow price based on the relaxation or tightening of the short-run energy balance constraint. The resulting signal captures continuous variation in system scarcity and reveals economically meaningful price spreads that persist even under regulated dispatch. Empirical evidence from Sri Lanka shows that renewable surplus systematically depresses implied marginal value, while evening demand peaks restore scarcity, creating predictable windows for storage arbitrage and flexible demand. The framework provides a practical, low-complexity mechanism for improving operational efficiency, investment decisions, and tariff design in renewable-rich systems without requiring wholesale market reform.

Keywords: Electricity Pricing, Renewable Energy İntegration, Energy Storage, Shadow Pricing, Regulated Power Systems, Scarcity Signals
JEL Classifications: C61, Q41, Q48, L94

1. INTRODUCTION

Many electricity systems, particularly in developing and state-regulated contexts, operate without real-time market pricing. Retail tariffs are typically fixed or determined through a small number of administratively defined time-of-use blocks that change infrequently and do not adjust to short-run system conditions. As a result, prices often fail to reflect contemporaneous scarcity or surplus. Such pricing structures can mask operational stress, weaken incentives for flexibility investment, and perpetuate inefficient outcomes including renewable curtailment and continued reliance on high-cost thermal generation (Trimble et al., 2016). Empirical studies of regulated power sectors further show that the absence of cost-reflective and time-differentiated signals constrains efficient dispatch and discourages private investment in storage and demand response (Jamasb et al., 2016).

These challenges become more pronounced as variable renewable energy penetration increases (Ueckerdt et al., 2013). Solar and wind generation are inherently time-dependent and only weakly aligned with demand patterns, creating predictable cycles of surplus and scarcity within the same day. Even when aggregate capacity is adequate, temporal mismatches produce periods in which renewable output exceeds the system's absorption capability and periods in which supply is tight. Integration studies demonstrate that these short-run imbalances give rise to balancing costs, curtailment, and ramping requirements that reflect operational constraints rather than long-run capacity shortages (Holttinen et al., 2010). Broader reviews confirm that, as renewable shares grow, the marginal value of electricity becomes increasingly determined by timing and flexibility rather than by average production cost (Che et al., 2025; Huber et al., 2014; Heptonstall et al., 2017).

In market-based systems, these variations are typically conveyed through continuously adjusting prices, enabling economically rational arbitrage. Storage and flexible demand create value by shifting energy from low-value surplus periods to high-value scarcity periods, thereby improving overall system efficiency (Luo et al., 2014; De Sisternes et al., 2016). The effectiveness of such technologies therefore depends fundamentally on temporally differentiated scarcity signals. Without these signals, flexibility resources may remain underutilised even when economically beneficial (More, 2014).

However, where explicit market-clearing prices are absent, the marginal value of electricity is not directly observable. In such environments, alternative approaches are required to infer scarcity from physical and operational conditions. Researchers have proposed that indicators derived from dispatch constraints and system balance can act as proxies for prices, revealing economically meaningful differences in system tightness even in non-market settings (Kim et al., 2021; Ela et al., 2011). By linking operational constraints to implied marginal value, these indicators can guide storage charging, demand shifting, and tariff design without requiring wholesale market reform. Related work further emphasises the importance of flexibility, reserves, and tariff structures in enabling efficient renewable integration (Papaefthymiou and Dragoon, 2016; Spiller et al., 2023; Denholm et al., 2008).

This paper develops a deterministic shadow-pricing framework that operationalises this idea for a renewable-rich regulated power system. Using realised generation and demand data, we construct a dynamic proxy for the marginal value of electricity based on the relaxation or tightening of the short-run energy balance constraint. The resulting signal captures continuous variation in system scarcity and identifies windows for economically rational arbitrage despite the absence of real-time pricing. Empirical results show that renewable surplus systematically depresses implied marginal value while evening demand peaks restore scarcity, generating persistent temporal spreads that can inform operational decisions, storage valuation, and tariff design.

By demonstrating how price-like scarcity signals can be constructed from observable system conditions alone, the framework offers a practical pathway for regulated electricity systems to capture many of the efficiency benefits of dynamic pricing without the institutional complexity of fully liberalised markets.

2. METHODOLOGY

2.1. Deterministic Modelling Framework and Temporal Mismatch

This study adopts a deterministic modelling framework based on realised generation and demand conditions. No stochastic optimisation, scenario analysis, or probabilistic forecasting is employed. All quantities are treated as observed time series, and the analysis focuses on how time-varying physical and behavioural conditions translate into implied system scarcity signals.

Electricity demand exhibits pronounced temporal structure driven by consumer behaviour, institutional schedules, and sectoral activity patterns (Gammanpila et al, 2024). Daily and seasonal load profiles reflect these behavioural regularities and are largely predictable over short horizons. In contrast, the availability of variable renewable energy, particularly solar and wind is governed by Intra-day cycles and meteorological conditions that are only weakly aligned with consumption patterns. As a result, renewable-rich power systems frequently experience temporal mismatches between generation potential and electricity demand, even when aggregate renewable capacity is sufficient to meet annual energy requirements (Joskow, 2011).

Such temporal misalignment has been shown to be a primary driver of surplus renewable generation, curtailment risk, and time-varying system scarcity in high-renewable systems (Hirth, 2013). From a system-assessment perspective, recent sustainability and performance studies emphasise that temporal variability and operational constraints are central to understanding electricity system outcomes under renewable transition (Gammanpila et al., 2026).

2.2. Assessment of Excess Renewable Generation

We consider an electricity system with significant solar and wind penetration. Let R_t^{solar} and R_t^{wind} denote solar and wind generation at time *t*, respectively, and define total renewable generation as Equation (1).

$$R_t = R_t^{solar} + R_t^{wind} \tag{1}$$

In non-market electricity systems, renewable generation is typically dispatched with priority and displaces oil-fired thermal generation whenever available. Let R_t^{disp} denote the maximum volume of renewable generation that can be absorbed through displacement of oil-based generation at time *t*, given contemporaneous demand and operational constraints as Equation (2).

Excess renewable generation is defined as below in

$$R_t^{excess} = \max\left(0, R_t - R_t^{disp}\right) \tag{2}$$

Periods with positive excess renewable generation arise when renewable supply potential exceeds the system's short-run ability to absorb energy through conventional dispatch. Economically, these periods correspond to states of low system scarcity, in which the marginal value of electricity is reduced due to abundant low-cost supply (Newbery et al., 2018; Hirth., 2013).

To facilitate comparison across time, excess renewable generation is normalised as as Equation (3)

$$\tilde{R}_t = \frac{R_t^{excess}}{\max_t\left(R_t^{excess}\right)}, \tilde{R}_t \in [0,1] \tag{3}$$

The normalised index captures the relative intensity of renewable surplus driven by the joint evolution of solar and wind output and time-dependent demand behaviour.

2.3. Energy Balance, Scarcity, and Marginal Value

At each time interval, electricity supply must equal electricity demand. When renewable generation is fully absorbed through displacement of thermal generation, the energy balance constraint remains tight. However, when excess renewable generation arises, the constraint is effectively relaxed, indicating increased short-run flexibility in meeting demand.

From an economic perspective, the tightness of the energy balance constraint determines the marginal value of electricity. When supply flexibility is limited relative to demand, the marginal value is high, reflecting scarcity. When renewable surplus is abundant, the marginal value declines. These variations arise from temporal mismatches between generation potential and consumption behaviour, rather than from changes in long-run capacity adequacy (Joskow, 2011).

2.4. Baseline Marginal Cost as a Reference Value

In the absence of market-clearing prices, the marginal cost of the last dispatched generating unit provides a natural reference for the system's short-run marginal value of electricity as Equation (4)

$$p_t = MC_t^{marginal} \tag{4}$$

where $MC_t^{marginal}$ denotes the marginal operational cost of the marginal oil-fired generator at time t.

In regulated and non-market power systems, marginal generation cost is commonly used as an operational proxy for scarcity and system stress when explicit price signals are unavailable (Newbery et al., 2018). Temporal variation in p_t reflects changes in dispatch conditions, fuel use, and system tightness over time.

To characterise the scale of marginal cost variation, we define as Equation (5) which serves as a scaling parameter in the construction of the dynamic price signal.

$$\theta = \max_t \left(p_t \right) - \min_t \left(p_t \right) \tag{5}$$

2.5. Lagrangian Interpretation and Shadow-price Equivalence

Consider a stylised system-operation problem in which the system operator minimises short-run generation cost subject to an energy balance constraint where G_t denotes dispatchable generation, R_t renewable generation, and D_t electricity demand at time t as Equation (6)

$$\min_{\{G_t\}} \sum_t C(G_t) \tag{6}$$

subject to;

$$G_t + R_t = D_t \forall t.$$

The associated Lagrangian is as Equation (7) where λ_t denotes the Lagrange multiplier associated with the energy balance constraint.

$$\mathcal{L} = \sum_t C(G_t) + \sum_t \lambda_t \left(D_t - G_t - R_t \right) \tag{7}$$

In constrained optimisation, λ_t represents the marginal change in total system cost resulting from a marginal relaxation of the energy balance constraint. Economically, λ_t corresponds to the shadow price of electricity, reflecting the marginal value of energy under prevailing operational conditions and system scarcity (Hogan, 2022).

An exogenous increase in renewable generation reduces reliance on dispatchable generation and relaxes the energy balance constraint. Holding demand fixed, this relaxation lowers the shadow price λ_t, particularly during periods in which renewable availability exceeds the system's short-run absorption capacity. As a result, variation in λ_t over time is driven not only by marginal generation costs, but also by the degree to which renewable generation relaxes the energy balance constraint.

Economically, the shadow price λ_t can be viewed as consisting of two components. The first is a baseline scarcity component, reflecting the marginal cost of meeting demand using dispatchable generation under tight supply demand conditions. The second is a relaxation component, capturing the extent to which exogenous renewable generation reduces the tightness of the energy balance constraint.Formally, this intuition can be expressed as as Equation (8), where $\phi(\tilde{R}_t)$ is a non-negative, increasing function of excess renewable generation. When renewable surplus is absent, the energy balance constraint is tight and the shadow price coincides with the marginal generation cost. As renewable surplus increases, the constraint is progressively relaxed and the shadow price declines.

$$\lambda_t \approx MC_t^{marginal} - \phi(\tilde{R}_t) \tag{8}$$

Given the absence of direct observations of λ_t, and in the interest of transparency and tractability, we approximate the relaxation effect using a first-order linear specification as Equation (9) where $\tilde{R}_t \in [0,1]$ measures the relative intensity of excess renewable generation and $\theta > 0$ scales the magnitude of the relaxation effect.

$$\phi\left(\tilde{R}_t\right) \approx \theta \cdot \tilde{R}_t \tag{9}$$

Given the absence of direct observations of λ_t, and in the interest of transparency and tractability, we approximate the relaxation effect using a first-order linear specification as Equation (9). A linear form is chosen for parsimony and interpretability, allowing the effect of renewable surplus on marginal value to be captured with a single scaling parameter. Alternative nonlinear specifications were explored and did not materially alter the qualitative behaviour of the resulting scarcity signal.

2.6. Reduced-form Dynamic Electricity Price Signal

In non-market electricity systems, the shadow price is not directly observable. We therefore construct a reduced-form proxy that approximates its behaviour using observable system variables.

Because this signal is analytical rather than behavioural, we do not model demand response. The constructed value represents system marginal cost conditions rather than an equilibrium price.

We take the marginal cost of the last dispatched generator, $p_t = MC_t^{marginal}$, as a baseline measure of system scarcity. To capture the relaxation of the energy balance constraint due to excess renewable generation, we assume that the shadow price declines monotonically with the intensity of renewable surplus. A first-order linear approximation yields as Equation (10), where $\tilde{R}_t \in [0,1]$ is the normalised measure of excess renewable generation and θ scales the magnitude of the relaxation effect.

$$\lambda_t \approx p_t - \theta \cdot \tilde{R}_t \tag{10}$$

Accordingly, we define the dynamic electricity price signal as as Equation (11)

$$p_t^{dyn} = p_t - \theta \cdot \tilde{R}_t \tag{11}$$

This reduced-form signal approximates the time-varying shadow price of electricity implied by the energy balance constraint. When excess renewable generation is absent $(\tilde{R}_t = 0)$, the constraint is tight and the implied price equals the marginal generation cost. As renewable surplus increases, the constraint is progressively relaxed and the implied marginal value of electricity declines.

The constructed signal is not a market price or equilibrium outcome, but an analytical indicator of system scarcity derived from the economic interpretation of constrained system operation. This specification captures the qualitative behaviour of λ_t when excess renewable generation is absent $(\tilde{R}_t = 0)$, the energy balance constraint is tight and the implied price signal equals the marginal generation cost. As excess renewable generation increases, the constraint is progressively relaxed and the implied marginal value of electricity declines proportionally.

The resulting signal provides an analytical indicator of time-varying system scarcity driven by renewable variability and time-dependent demand behaviour. It is not a market price or equilibrium outcome, but a reduced-form approximation of the shadow value of electricity in a renewable-rich, non-market power system.

The framework is fully deterministic and based on realised generation and demand profiles. Demand is treated as exogenous, and no demand-side response, behavioural adaptation, or stochastic uncertainty is modelled. As a reduced-form approximation, the dynamic price signal captures relative changes in marginal value rather than absolute price levels.

3. RESULTS

3.1. Seasonal and Intra-day Misalignment between Renewable Availability and Electricity Demand

Figures below jointly illustrate how the interaction between realised solar and wind generation and electricity demand varies across seasons at a intra-day scale. Taken together, the figures demonstrate that temporal alignment, rather than aggregate renewable availability, is the dominant determinant of short-run system conditions. Across all months, electricity demand follows a relatively stable intra-day pattern with an evening peak, while renewable generation exhibits strong technology-specific and seasonal timing.

This systematic misalignment gives rise to alternating periods of renewable surplus and system tightness within the same day, even in the absence of changes in installed capacity or average demand levels. The figures therefore provide direct empirical evidence that excess renewable generation and scarcity emerge from timing effects, forming the basis for the excess renewable metrics and shadow-price interpretation developed in subsequent sections (Mills and Wiser, 2015).

The figures reveal systematic seasonal differences in the timing and intensity of renewable availability relative to demand.

Figure 1 illustrates the intra-day profiles of solar and wind generation and electricity demand for a representative day in January, corresponding to the dry season in Sri Lanka. Solar generation exhibits a pronounced mid-day peak under predominantly clear-sky conditions but declines sharply by mid-afternoon, while electricity demand continues to rise into the evening. Wind generation remains modest during peak demand hours, reflecting weaker dry-season wind regimes. As a result, temporal overlap between renewable availability and system load is limited, and evening hours are characterised by relatively tight system conditions despite the presence of renewable capacity.

Figure 2 presents the corresponding profiles for March, a transitional pre-monsoon month. Solar output reaches higher levels around midday, consistent with increased solar irradiance prior to the onset of the southwest monsoon. However, wind generation remains relatively weak during daylight hours. This creates short-lived periods in which solar generation coincides with moderate demand, giving rise to potential renewable surplus around midday. As solar output declines in the afternoon and wind generation remains subdued, system conditions tighten again during the late afternoon and evening.

Figure 1: Intra-day profiles of solar and wind generation and electricity demand for a representative day in January

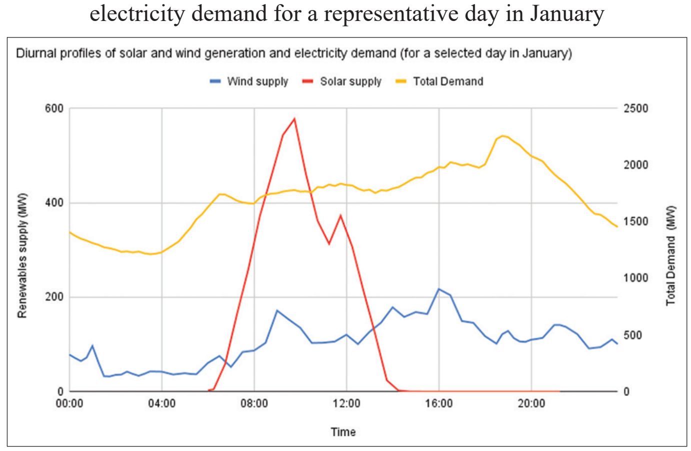


Figure 3 shows Intra-day profiles for June, during the southwest monsoon season. Persistent monsoon winds lead to elevated and sustained wind generation throughout the day, while solar output, though present, exhibits an asymmetric and attenuated profile due to increased cloud cover and convective activity. Renewable output remains relatively high for extended daylight periods, while demand displays a comparatively flat Intra-day pattern. This alignment increases the likelihood that renewable generation approaches or exceeds the system's short-run absorption capacity, indicating sustained periods of excess renewable generation and reduced marginal system scarcity.

Figure 4 depicts the August profiles, corresponding to the latter phase of the southwest monsoon. Solar generation peaks sharply around midday, reflecting intermittent cloud clearing, but declines rapidly in the afternoon as convective cloudiness intensifies. Wind output strengthens into the afternoon and evening, consistent with monsoon wind dynamics. Although demand levels are higher than in June, renewable generation remains concentrated outside peak demand hours. This again produces periods of renewable surplus during daylight hours, followed by a pronounced reduction in renewable availability during the evening demand peak, resulting in renewed tightening of system conditions despite the presence of substantial renewable capacity (Batalla-Bejerano and Trujillo-Baute, 2016).

Figure 2: Intra-day profiles of solar and wind generation and electricity demand for a representative day in March

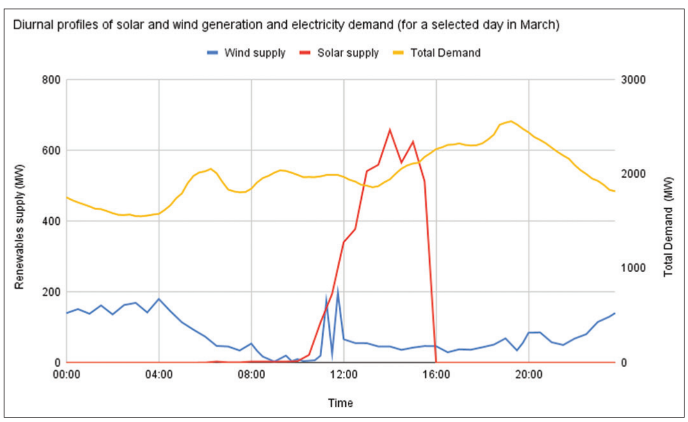
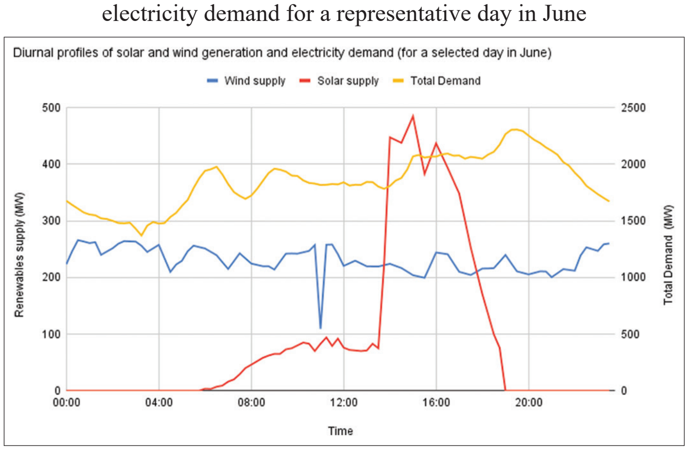


Figure 3: Intra-day profiles of solar and wind generation and electricity demand for a representative day in June



3.2. Quantification and Intra-day Concentration of Excess Renewable Generation

Building on the temporal misalignment identified in Section 3.1, this section quantifies excess renewable generation across the full observation period using all available high-resolution data. The focus is on the timing and persistence of surplus conditions rather than on aggregate energy balances.

Figure 5 shows the average Intra-day profile of excess renewable generation. Surplus exhibits a pronounced temporal structure, with higher average values during early morning and late-morning hours and substantially lower levels during the evening demand peak. Excess renewable generation reaches its highest levels during mid-morning to midday periods, before declining steadily through the afternoon and evening.

The concentration of surplus during non-peak demand hours indicates that excess renewable generation arises systematically from the timing of renewable availability relative to demand, rather than from isolated events or random fluctuations. These results confirm that renewable surplus is a recurring feature of system operation and provide the empirical basis for the subsequent analysis of time-varying system scarcity and shadow-price dynamics.

Figure 4: Intra-day profiles of solar and wind generation and electricity demand for a representative day in August

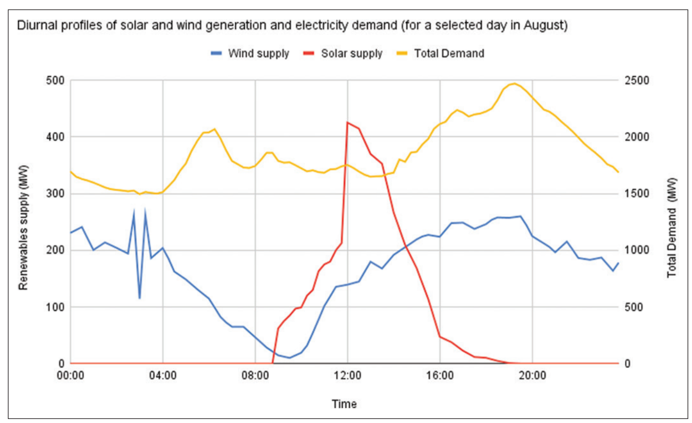
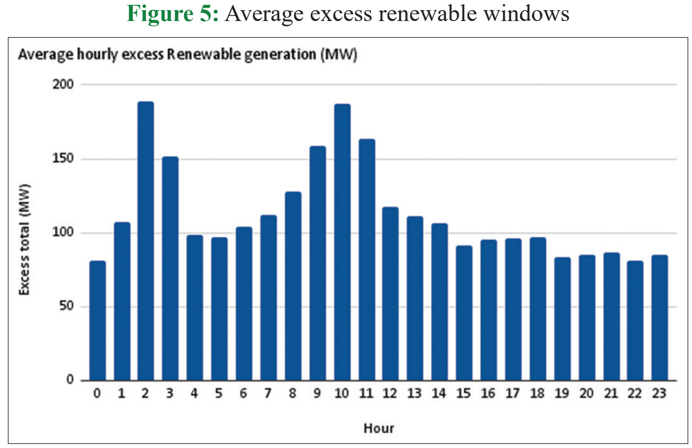


Figure 5: Average excess renewable windows



3.3. System Scarcity under Stable Marginal Cost Conditions

Baseline marginal generation costs remain largely stable over the study period, reflecting regulated dispatch and the dominance of oil-fired thermal generation. Short-run variation in marginal cost is therefore limited and provides little information about changes in system conditions over time.

In contrast, system scarcity varies substantially with renewable availability. Periods of high renewable surplus correspond to a relaxation of the energy balance constraint, while periods of low renewable availability, particularly during evening demand peaks are associated with tighter system conditions. This indicates that short-run scarcity is driven primarily by renewable-induced timing effects rather than by fluctuations in marginal generation costs.

These results motivate the use of a dynamic scarcity indicator that adjusts baseline marginal cost to reflect the effect of excess renewable generation as depicted in Table 1.

3.4. Renewable Sufficiency Relative to Oil-based Generation

Observed system operation reveals three distinct outcomes with respect to the ability of renewable generation to offset oil-fired generation. For a substantial share of time, oil-fired generation remains marginal, indicating that renewable supply is insufficient to fully cover oil-based generation requirements. Within these oil-marginal conditions, renewable output nevertheless contributes to partial displacement of oil-fired generation, reducing but not eliminating reliance on oil.

In a smaller subset of hours, renewable generation fully covers oil-based generation and additional renewable energy remains unabsorbed, resulting in positive excess renewable generation. These surplus outcomes are concentrated during daylight hours and coincide with periods of elevated solar and wind output. Periods in which renewable generation is insufficient to materially offset oil-based generation are predominantly observed during evening demand peaks. It can be depicted as follows in Table 2.

3.5. Price Differentiation Driven by Excess Renewable Intensity

Observed system operation generates positive excess renewable generation whenever realised renewable output exceeds the system's short-run absorption capacity after displacement of oil-based generation, as captured by R_t^{excess} as depicted in Figure 6 and Table 3. These instances identify operating conditions in which renewable supply is sufficient to meet demand and residual renewable energy remains unabsorbed. In contrast, periods with $R_t^{excess} = 0$ indicate that renewable generation is insufficient to fully offset oil-based generation. Normalisation of excess renewable generation according to Equation (3) yields a bounded index $\tilde{R}_t \in [0,1]$, allowing direct comparison of surplus intensity across time. Values of $\tilde{R}_t = 0$ correspond to fully tight system conditions, while higher values indicate increasing degrees of surplus after oil displacement. This scaling converts absolute surplus quantities into a relative measure of system slack.

Figure 6: Price differentiation driven by excess renewable intensity

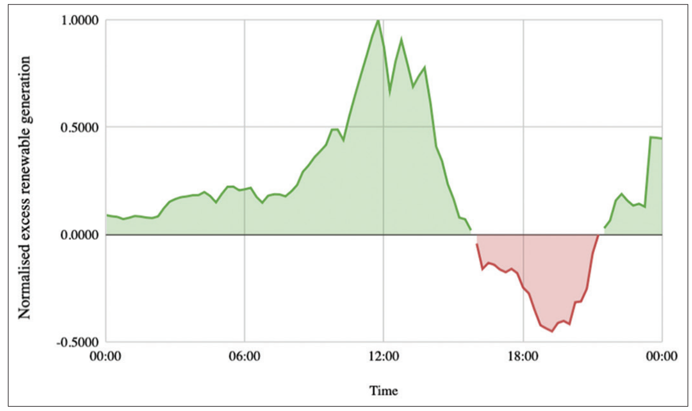


Table 1: Marginal cost regimes under regulated dispatch

Marginal fuel	Marginal cost (LKR/unit)
Coal	22
Oil	68

Table 2: Observed renewable displacement regimes relative to oil-based generation

Regime	Conditions
Full displacement	R_t^{excess} >0 after displacement of oil-based generation
Partial displacement	$\tilde{R}_t \in [0,1]$, renewable generation displaces part of oil-based generation but oil remains marginal
Insufficient renewables	Renewable generation is negligible and oil-based generation supplies the marginal unit

Table 3: Price outcomes under signed normalised renewable surplus-deficit conditions

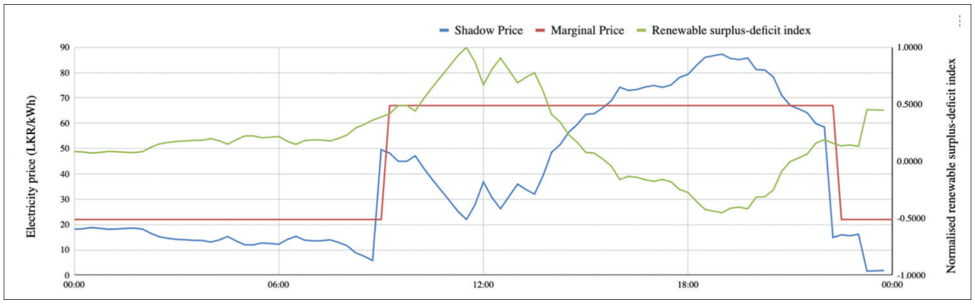
Renewable condition	Normalised surplus	Interpretation	Resulting price level
Renewable defeciet	$\tilde{R}_t < 0$	Renewables insufficient to displace oil	Baseline marginal cost
No net surplus	$\phi(\tilde{R}_t)$	Renewables just sufficient to displace oil	Baseline marginal cost
Moderate surplus	$0 < \tilde{R}_t < 1$	Partial relaxation after oil displacement	Reduced price
Maximum observed surplus	$\tilde{R}_t \approx 1$	Strong relaxation with excess renewables	Lowest price

Application of the constructed pricing mechanism maps this normalised surplus intensity into price differentiation. When $\tilde{R}_t = 0$, the constructed price coincides with the baseline marginal cost determined by the marginal fuel. As $\tilde{R}_t$ increases, the constructed price declines proportionally, with the maximum observed surplus defining the upper bound of the adjustment. Consequently, multiple price levels emerge within the same marginal fuel regime, reflecting variation in renewable surplus intensity rather than changes in fuel costs or dispatch hierarchy (Prol and Schill, 2021).

3.6. Dynamic Shadow Price Formation under Renewable Surplus and Deficit Conditions

Figure 7 illustrates the joint behaviour of the constructed shadow price, the baseline marginal cost, and the normalised renewable

Figure 7: Constructed shadow price and normalised renewable surplus–deficit index under oil-dominated dispatch



surplus-deficit index over a representative operating day. The figure highlights how the shadow price evolves in response to changing renewable conditions while the identity of the marginal fuel remains fixed for extended periods.

As depicted above, the periods in which the normalised renewable surplus-deficit index takes non-positive values $(\tilde{R}_t \leq 0)$, renewable generation is insufficient to generate excess after displacement of oil-based generation. Under these conditions, the energy balance constraint remains binding, and the constructed shadow price coincides with the baseline marginal cost. This outcome is observed both during renewable deficit conditions $(\tilde{R}_t < 0)$ and at the binding threshold $(\tilde{R}_t = 0)$, indicating that partial renewable contribution alone does not induce price adjustment.

In contrast, periods with positive values of the normalised index $(\tilde{R}_t > 0)$ correspond to operating conditions in which renewable generation fully displaces oil-based generation and residual renewable energy remains unabsorbed. During these intervals, the constructed shadow price departs downward from the baseline marginal cost. The magnitude of this departure increases with surplus intensity and is governed by the scaling parameter θ, which determines the maximum extent of price reduction achievable under the highest observed renewable surplus.

Hence, the Figure 7 shows that substantial variation in the shadow price occurs within prolonged intervals of oil-marginal operation. While the baseline marginal cost remains constant throughout these periods, the shadow price spans a continuous range bounded above by the marginal cost and below by the maximum adjustment implied by θ. This demonstrates that short-run system conditions vary significantly over time even when marginal fuel identity and installed capacity remain unchanged (Schweppe et al., 1988).

While Figure 7 illustrates the intra-day mechanics of shadow-price formation under varying renewable conditions, these dynamics operate persistently across seasons and give rise to systematic differences in average system value. To characterise these broader patterns, the hourly surplus–deficit outcomes are aggregated into seasonal summary statistics. This aggregation allows the frequency, magnitude, and economic consequences of renewable surplus to be compared across representative months rather than individual operating days. Table 4 therefore reports, for each season, the share of intervals with surplus conditions, the mean and maximum excess renewable energy, and the implied reductions in the constructed shadow price. Together, these statistics provide a compact quantitative view of how short-run scarcity regimes vary over time.

Table 4: Seasonal summary of renewable surplus and shadow-price outcomes

Month	Surplus hours (%)	Mean excess	Avg price reduction (%)
January	88	103	42.8
March	100	163	18.9
June	98.9	121	17.9
August	100	200	54.5

Table 4 summarises seasonal differences in both the frequency and magnitude of renewable surplus and the associated shadow-price adjustments. Surplus conditions are prevalent across all seasons, occurring in more than 88% of intervals in every month and exceeding 98-100% during March, June, and August.

However, frequency alone masks substantial variation in intensity. While March and June display large peak surpluses, their average levels remain modest relative to their maxima, indicating episodic rather than sustained excess. In contrast, August exhibits both high frequency and high average magnitude, with mean surplus approaching its seasonal maximum, suggesting persistent system slack throughout the day. January shows the lowest average magnitude and greater intermittency, reflecting tighter balance conditions.

These seasonal differences correspond closely to resource availability and demand alignment. During the southwest monsoon period (June-August), sustained wind generation maintains continuous renewable output, resulting in prolonged periods of excess supply. March and early June experience shorter renewable peaks that are concentrated around midday, producing temporary surpluses rather than system-wide relaxation. January, representing the dry season, combines weaker wind availability with evening demand peaks, which reduces both the depth and persistence of renewable surplus episodes.

Because the constructed shadow price is directly proportional to normalised surplus intensity and inversely related to the prevailing marginal fuel cost, these physical conditions translate into distinct economic outcomes. August therefore exhibits the largest average price reductions (≈55%), indicating that marginal system value remains consistently depressed for extended durations. March and June, despite frequent surplus events, display only moderate reductions (≈18-19%), as the surplus is shallower and less persistent. January presents a contrasting mechanism: although surplus intensity is lower, coal frequently remains the marginal unit, resulting in a smaller baseline cost and consequently larger proportional price movements (≈43%) when surplus arises.

Taken together, these findings demonstrate that short-run system value is governed not simply by renewable penetration or surplus frequency, but by the persistence of excess generation and the identity of the marginal fuel. Periods characterised by sustained surplus (August) lead to structurally low marginal values and potential curtailment risk, whereas intermittent surplus (March-June) produces only temporary price softening. This distinction is critical for storage valuation, investment timing, and operational planning, as technologies that benefit from price spreads derive greater value under persistent slack conditions than under short-lived renewable spikes.

4. DISCUSSION AND CONCLUSION

4.1. Interpretation of the Shadow Price and the Role of the Scaling Parameter θ

Recent electricity system studies emphasise that short-run system scarcity in renewable-rich power systems is increasingly driven by temporal mismatch and operational constraints rather than by long-run capacity adequacy or fuel cost variation. In this context, shadow-price–based representations have been widely used to characterise the marginal value of electricity under constrained system operation, even in settings where explicit market prices are absent or distorted (Brown and Reichenberg, 2021; Sepulveda et al., 2018).

The results presented in this study show that when the normalised renewable surplus–deficit index is non-positive $(\tilde{R}_t \leq 0)$, renewable generation is insufficient to relax the system's short-run energy balance constraint. Under these conditions, the constructed shadow price coincides with the baseline marginal cost of the marginal fuel, reflecting tight operating conditions dominated by oil-based generation. In contrast, positive values of the index $(\tilde{R}_t > 0)$ identify periods in which renewable generation fully displaces oil-based generation and residual energy remains unabsorbed, resulting in a systematic downward adjustment of the shadow price. This behaviour is consistent with recent findings that renewable surplus conditions reduce the marginal value of electricity through constraint relaxation rather than through changes in generation cost structures (Ballester and Furió, 2015).

The magnitude of this adjustment is governed by the scaling parameter θ, which determines the maximum deviation of the shadow price from the baseline marginal cost. Rather than acting as a behavioural or market-clearing parameter, θ reflects the observed spread between marginal generation costs under regulated dispatch and therefore captures system-specific cost asymmetries. Recent studies on pricing and scarcity metrics in non-market or hybrid electricity systems similarly rely on cost-based scaling to construct operational price signals that remain grounded in observable dispatch outcomes (Bistline et al., 2018).

By anchoring price adjustment to both renewable surplus intensity and an empirically grounded scaling parameter, the constructed shadow price captures continuous variation in short-run system tightness even under persistent oil-marginal operation. This aligns with emerging evidence that marginal fuel identity alone fails to capture economically relevant scarcity dynamics in renewable-dominated systems, particularly during periods of surplus and curtailment risk (Brown et al. 2018).

4.2. Implications for Non-market and Regulated Electricity Systems

The constructed dynamic shadow price has broader implications for non-market and regulated electricity systems, where explicit market-clearing price signals are absent or limited (Stoft, 2002). In such systems, operational pricing often relies on administrative cost proxies or regulated tariffs, which may not adequately reflect real-time system scarcity driven by renewable variability and temporal mismatch. Recent empirical work on renewable integration and system pricing highlights that increasing shares of variable renewable energy tend to be associated with downward pressure on effective prices and price volatility, even in regions with limited market reform (Owolabi et al., 2021). This underscores the importance of developing alternative signals that can convey short-run scarcity and system tightness without requiring a full market architecture.

Moreover, the interaction between renewable penetration and electricity price dynamics has been documented in studies examining power systems under high variable renewable use. Increasing renewable penetration has been found to be associated with lower average prices and changed price volatility patterns in systems with organized markets, an effect often attributed to the "cannibalisation" or merit-order effect of low-marginal-cost renewables (Owolabi et al., 2021). Although these studies are market-based, the underlying economic mechanism, that higher instantaneous renewable supply reduces the marginal value of electricity is directly analogous to the shadow pricing mechanism developed here, showing that scarcity signals must respond to temporal mismatch rather than static cost hierarchies.

In regulated systems where uniform or administered pricing is prevalent, the lack of real-time price differentiation can mask underlying operational stress and surplus conditions. Surveys of electricity pricing frameworks indicate that pricing schemes must evolve to reflect the integration of variable resources and changing operational conditions, including the need for time- and condition-dependent signals that can inform both system operation and investment incentives (Liu et al., 2023). The constructed shadow price, by integrating both the normalised renewable surplus-deficit index and an empirically grounded scaling parameter, provides a candidate signal that fulfils this role in a deterministic, non-market context.

4.3. Implications for Operational Efficiency and Renewable Curtailment

Beyond pricing interpretation, the results have direct operational implications. The empirical evidence indicates that renewable surplus is not sporadic but arises systematically at predictable intra-day and seasonal intervals. Similar persistence of surplus conditions has been observed in high-renewable systems, where temporal mismatch rather than capacity inadequacy drives short-run inefficiencies (Joskow, 2011).Evidence from Sri Lanka further confirms that solar surplus exhibits structured and recurring patterns that create identifiable windows for storage utilisation rather than random fluctuations (Gammanpila et al., 2025). This suggests that excess renewable generation should be interpreted as a structural feature of system operation rather than an exceptional event.

In regulated environments without real-time price signals, such conditions are typically managed through administrative curtailment or rigid dispatch adjustments. Curtailment has increasingly been recognised as an implicit flexibility resource, but one that often reflects underlying economic inefficiency (Olson et al., 2014). The constructed shadow price addresses this gap by translating physical surplus into an economically interpretable marginal value indicator.

When surplus emerges, the implied marginal value declines systematically. This behaviour is consistent with the merit-order effect, whereby low-marginal-cost renewable supply depresses system value during periods of abundance (Clò et al. 2014). By contrast, when renewable availability falls and the energy balance constraint tightens, the shadow price converges toward the marginal cost of oil-fired generation, signalling scarcity.Operationally, this differentiation provides actionable information. Periods of low shadow price identify economically favourable windows for storage charging or flexible demand activation, while high-price intervals signal periods where additional supply or demand reduction carries greater value. Such scarcity-based indicators have long been recognised as central to efficient dispatch in electricity systems (Hogan, 2014).

4.4. Investment and Planning Implications

The shadow-price framework also has important implications for long-run investment and planning. Regulated systems frequently rely on average cost metrics when evaluating new technologies, implicitly assuming stable marginal values across time. This approach overlooks the substantial temporal variation in system value revealed in the present analysis.

The economics literature emphasises that the value of storage and flexibility depends primarily on short-run price spreads rather than average prices (Sioshansi et al., 2008). By explicitly quantifying both surplus and tight conditions, the constructed signal provides a practical proxy for these spreads in settings where observed market prices are unavailable. Empirical assessments of Sri Lanka's system similarly demonstrate that exploiting predictable solar surplus through storage can deliver measurable reductions in both fuel costs and emissions (Gammanpila et al., 2025). These findings reinforce that investment decisions based solely on average costs may underestimate the benefits of flexibility technologies.

Seasonal differences further highlight that persistence of surplus, rather than frequency alone, determines economic value. Systems experiencing prolonged periods of slack exhibit greater opportunities for arbitrage and shifting, consistent with broader evidence that the market value of renewables and storage declines as surplus becomes more concentrated (Hirth, 2013).

4.5. Policy Relevance for Tariff Design and Regulated Pricing

The results also carry implications for tariff design and regulatory policy. Uniform or administratively determined tariffs implicitly assume constant marginal costs and therefore fail to reflect the dynamic value of electricity under surplus and deficit conditions. Such pricing structures may weaken incentives for flexible consumption and obscure signals needed for efficient investment. Reviews of modern electricity pricing frameworks increasingly recommend time-varying or condition-dependent tariffs to accommodate renewable variability (Liu et al., 2023). Experience from high-renewable systems further indicates that market designs incorporating scarcity-based signals improve both operational efficiency and investment outcomes (Newbery et al., 2018).

While full market liberalisation may not be feasible in all jurisdictions, the shadow-price proxy developed here offers a simpler alternative. Because it relies only on observable operational data, the signal can inform time-of-use tariffs, demand response programmes, or storage incentives without requiring a comprehensive wholesale market (Borenstein and Bushnell, 2015; Joskow, 2019).

4.6. Limitations and Directions for Future Research

Several limitations warrant consideration. First, the framework is deterministic and based on realised generation and demand profiles. Although this improves transparency, uncertainty and forecasting error are not explicitly represented. Incorporating probabilistic or stochastic methods could refine the estimation of short-run scarcity under variable renewable conditions.

Second, the reduced-form linear specification offers parsimony and interpretability but may not capture nonlinear scarcity effects during extreme events. Alternative functional forms could be explored in future work.Finally, improvements in short-term demand forecasting may further enhance the usefulness of the shadow-price framework. Data-driven prediction methods based on technical indicators have been shown to improve short-term load estimation accuracy (Gammanpila et al., 2026), suggesting potential synergies between demand forecasting and scarcity measurement.

Notwithstanding these limitations, the results demonstrate that economically meaningful scarcity signals can be constructed even in the absence of explicit market prices. This provides a practical pathway for improving operational decisions, guiding investment, and supporting tariff reform in renewable-rich regulated electricity systems.

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