Economics of Grid-Supported Electric Power Markets: A Fundamental Reconsideration

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U.S. electric power systems are linked Transmission & Distribution (T&D) systems consisting of complex intertwined economic, technological, and physical processes.

Conceptually-coherent product definitions, settlement rules, and bid/offer formulations – able to cope effectively with increasing climate-change & power-resource diversification pressures -- have not yet been achieved for such systems.

This presentation will focus on wholesale market redesign at the transmission level.
U.S. RTO/ISO-Managed Wholesale Power Markets: Spatial Configuration

Fig. 2: Seven U.S. RTOs/ISOs (CAISO, ERCOT, ISO-NE, MISO, NYISO, PJM, SPP) operate over a high-voltage AC transmission grid consisting of three separately-synchronized parts.
Major Concern:

➢ Increasing reliance on *Intermittent Power Resources (IPRs)* (e.g., wind farms & large solar PV panel arrays not fully firmed by storage)

➢ Increasing encouragement of more active participation by *distribution-level* power resources and customers (*FERC Order 2222, Final Rule, 17 September 2020*)

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Increasing Volatility and Uncertainty of Real-Time Net Load

\[ \text{Net Load} = \text{Power Withdrawals} + \text{Power Losses} - \text{Non-Dispatched Power Injections} \]

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Increasing Volumetric Grid Risk (*Grid power outflow ≠ Grid power inflow*)

➢ RTOs/ISOs must operate as “*fiduciary conductors*” tasked with orchestrating:
  - *advance* availability and *just-in-time* dispatch of *increasingly diverse* power resources
  - to service *just-in-time* power demands of *increasingly diverse* customers
  - while meeting *just-in-time* power requirements for grid reliability.

➢ Grids must function as “*flexibility-support mechanisms*”
Potential Remedy for Major Concern

➢ Increase dependable advance availability of flexible dispatchable power-production capabilities ...

• from wholesale-level power resources
  — Ensure revenue sufficiency for essential suppliers
  — Firm-up the RTO/ISO-dispatchability of Intermittent Power Resources (IPRs)

• from distribution-level power resources (FERC Order 2222)
  — Implement Transactive Energy System (TES) designs that permit aggregators (T&D linkage entities) to participate in wholesale power markets as suppliers of RTO/ISO-dispatchable power flows harnessed contractually from managed collections of diverse distributed power resources.

Difficulty:
Conceptually-problematic legacy market-design features affecting operations in current RTO/ISO-managed markets are hindering pursuit of this potential remedy.
1. Product Definition & Pricing Issues (Short-to-Long Resource Planning)

- **Primary stress** on locational marginal pricing ($/MWh) for energy delivery (MWh) scheduled in short-term markets (DAM/RTM) for near-term operating periods.

- **Secondary stress** on RTO/ISO procurement of ancillary services – e.g., *unencumbered generation capacity* (MW) and *ramp* (MW/min) – to support the continual real-time balancing of net load across the grid.

**Problem: Strong Product Correlation**

- These ancillary services are not independently-produced products. Rather, they are the strongly-correlated (“jointly produced”) physical attributes of the individual flows of power (MW) available for possible RTO/ISO dispatch at designated grid locations during designated time periods whose dispatched accumulations determine energy deliveries (MWh) at these locations for these time periods.

- This **strong product correlation** greatly limits the ability of these ancillary services to support scheduled energy deliveries & to ensure, more generally, the continual real-time balancing of net load across the grid.

Growing need for **Out-of-Market (OOM) dispatch & uplift payments** to ensure continual real-time balancing of increasingly volatile & uncertain net load.
2. **Settlement Timing Issues:** *(Time-Inconsistent Payments)*

- Payment for market-scheduled performance (energy delivery) prior to verified actual performance

  > *growing need for *ex-post* payment adjustments.*

3. **Supply-Offer Issues:** *(Supplier Revenue Insufficiency)*

- Reliance on conceptually-problematic *two-part partition* of supplier cost into static “variable” and “fixed” components;

- Narrow focus on ensuring market-revenue coverage of *start-up cost* ($/start), *production cost* ($/MWh) for grid-delivered energy (MWh), & *opportunity cost* ($/MW) for unencumbered generation capacity (MW)

  > *growing need for OOM make-whole payments to ensure the solvency -- i.e., revenue sufficiency [revenue ≥ avoidable cost] -- of market-cleared suppliers.*
The Linked Swing-Contract Market Design *
A Conceptually-Consistent Alternative

Purpose:
Facilitation of transition to efficient reliable decarbonized grid operations & FERC Order 2222 initiatives

Key Design Differences:
-- Conceptually-coherent product definitions, time-consistent settlements, & flexible supply offer forms
-- Insurance approach that permits efficient reliable long-to-short resource planning as well as assured supplier revenue sufficiency.

Linked Collection of Forward Reserve Markets M(T) for Future Operating Periods T:
Market look-ahead horizons LAH(T) and operating periods T can vary in duration from years to minutes.

Reserve for T = Physically-Covered Insurance for T:
Guaranteed availability of power-production capabilities offered in advance of T by Dispatchable Power Resources (DPRs) for possible RTO/ISO dispatch during T to protect against volumetric grid risk.

Reserve Offers = Insurance Contracts:
Swing-contracts in two-part pricing form permit DPRs participating in M(T) to offer reserve for T with “swing” (flexibility) in physical attributes and with assurance of revenue sufficiency.

RTO/ISO Optimal Contract-Clearing for M(T):
Objective: Max expected net benefit of M(T) participants, subject to nodal-based system constraints

First Key Design Innovation: A New Product Conceptualization

➢ Conceptualization of a “power-path” as the fundamental product that ought to be transacted in grid-supported centrally-managed wholesale power markets.

**Fig. 3:** A power-path \( p_m(T) =: (p_m(t) \mid t \in T) \) offered by a dispatchable power resource \( m \) for a future operating-period \( T \) is a sequence of injections and/or withdrawals of power \( p_m(t) \) (MW) to take place at a single designated grid location \( b(m) \) during \( T \).

➢ **Support for Incentive Alignment**

The power-path product conceptualization permits designs for grid-supported centrally-managed wholesale power markets to align the **local goals and constraints of distributed market participants** with the **system goals and constraints of the central manager**.
Second Key Design Innovation: Reserve Offers in 2-Part Pricing Swing-Contract Form

Let \( m \) denote a Dispatchable Power Resource (DPR) participating in an RTO/ISO-managed reserve market \( M(T) \) for a future operating period \( T \).

The reserve offer submitted to \( M(T) \) by \( m \) takes the swing-contract form:

\[
SC_m = (\alpha_m, T^\text{ex}_m, PP_m, \phi_m)
\]

The swing contract \( SC_m \) consists of four components specified by \( m \):

- **Offer Price** \( \alpha_m \) ($), the insurance premium to be paid to \( m \) (in amortized or lump-sum form) if \( SC_m \) is cleared;

- **Exercise Set** \( T^\text{ex}_m \) giving all times between the close of market \( M(T) \) and the start of operating period \( T \) when the RTO/ISO can exercise \( SC_m \);

- **Power-Path Production Possibility Set** \( PP_m \), a digital twin characterization of the power-path production capabilities that \( m \) is offering for possible dispatch during \( T \);

- **Performance Payment Method** \( \phi_m \), a function mapping each power-path \( p \) in \( PP_m \) into \( m \)'s required dollar compensation \( \phi_m(p) \) if \( m \) is dispatched to deliver \( p \) during \( T \).
Reserve Offers in 2-Part Pricing Swing-Contract Form ... Continued

Power-Path Production Possibility Set $\text{PP}_m$:

— $\text{PP}_m$ characterizes the physical attributes of the power-paths $\text{p}_m$ that $m$ is offering in \textit{advance} of operating period $T$ for \textit{possible} RTO/ISO-dispatched delivery \textit{during} $T$ at $m$’s grid location $b(m)$.

— $\text{PP}_m$ permits $m$ to specify with care the “\textit{swing}” (\textit{flexibility}) in the physical attributes of its offered power-paths.

The physical attributes of each power-path $\text{p}_m$ in $\text{PP}_m$ can include:

\textbf{Static Attributes:} Grid delivery location $b(m)$; grid-delivered energy (MWh) ...

\textbf{Dynamic Attributes:} Power \textit{profile} for $T$; power-factor \textit{profile} for $T$; ramp-rate \textit{profile} for $T$; down-time/up-time \textit{profile} for $T$; power-path \textit{length} (“power mileage”) for $T$; ...

\textbf{Grid-delivered energy (MWh)} is \textbf{only one among many} potentially valuable power-path attributes that $m$ can seek to supply in return for appropriate compensation through submission of a swing-contract reserve offer.
Two-Part Pricing Form of Swing Contracts Permits Assured Revenue Sufficiency:

\[
\text{[Revenue]} \geq \text{[Avoidable Cost]} =: \text{[Avoidable Fixed Cost + Variable Cost]}
\]

**Offer Price:** \(\alpha_m\) (measured in $)

\(\alpha_m\) permits supplier \(m\) to receive compensation *ex ante* (i.e., before \(T\)) for any *avoidable fixed cost* that \(m\) must incur to guarantee the *advance availability* of the power-paths \(p\) in \(PP_m\) for *possible* RTO/ISO dispatch at \(m\)’s grid location \(b(m)\) during \(T\).

**Avoidable Fixed-Cost Examples:** Ref. [1, Appendix A.4]
Capital investment cost; Transaction cost (insurance, licensing,…); Unit commitment cost; Opportunity cost; …

**Performance Payment Method:** \(p \mapsto \varphi_m(p)\) (measured in $)

\(\varphi_m\) permits supplier \(m\) to receive compensation *ex post* (i.e., after \(T\)) for any *variable cost* \(\varphi_m(p')\) that \(m\) incurs for *verified actual period-\(T\) delivery of a power-path* \(p'\) in \(PP_m\) in accordance with RTO/ISO dispatch instructions (set-points) received during \(T\).

**Variable Cost Examples:** Ref. [1, Appendix A.4]
Fuel cost; Labor cost; Equipment wear & tear due to ramping; Transmission service charges; …
Two-Part Pricing Swing-Contract Reserve Offers ... Continued

➢ The performance payment method $\varphi_m$ should ideally be expressed in terms of **standardized performance metrics**.

➢ These metrics **should permit the RTO/ISO and** $m$: 

— to agree *ex ante* (i.e., *in advance of* $T$) on the nature of the power-path production *capabilities* that $m$ is offering for possible RTO/ISO-dispatched delivery *during* $T$; 

— to verify *ex post* (i.e., *after* $T$) the extent to which any *actual* delivery by $m$ of a power-path during $T$ deviates from admissible dispatch set-points that the RTO/ISO has communicated to $m$ during $T$.

**Example:**

Determine performance cost $\varphi_m(p)$ of each power-path $p$ in $PP_m$ as a linear combination of metrics that assign costs to various correlated (“jointly produced”) physical attributes of $p$, such as grid-delivered energy ($E$), ramp ($R$), and duration ($D$).

$$\varphi_m(p) = c^E(p) + c^R(p) + c^D(p) + ...$$

Costs assigned to **correlated** physical attributes of a **single** power-path $p$. 
Example 1: A simple energy-block swing contract in firm form

Note: As shown in Ref. [2], this type of swing contract can easily be modified to implement current types of supply offers, such as ERCOT’s three-part supply offer.

\[ SC_m = [\alpha, \mathbb{PP}, \phi] \]

where:

\( \alpha = \) Offer price
\[ \mathbb{PP} = (b, t^s, p^{\text{disp}}, t^e) \]
\( b = \) Delivery location
\( t^s = \) Start time for energy block E
\( p^{\text{disp}} = \) Maintained power injection for energy block E
\( t^e = \) End-time for energy block E
\( \phi = \) Pre-specified price \( \pi \) for delivered energy
Example 1: A simple energy-block swing contract ... Continued

**Fig. 4** Illustration of m’s energy requirements for delivery of energy-block “Dispatch” at m’s grid-location b(m) during operating period T: namely, the energy-block (“Dispatch”); start-up (“SU”); ramp-up (“RU”); no-load (“No-Load”), ramp-down (“RD”), and shut-down (“SD”).

**SC}_m\text{ Offer Price } \alpha: \text{ Permits } m \text{ to cover SU, RU, No-Load, RD, } & \text{SD energy costs } \text{along with any other avoidable fixed cost } \text{that } m \text{ must incur to ensure the availability of “Dispatch” for delivery at } b(m) \text{ during } T. 

**SC}_m\text{ Performance Payment Method } \varphi: \text{ Permits } m \text{ to recover the cost of the energy amount “Dispatch” delivered at } b(m) \text{ during } T \text{ along with any other variable cost that } m \text{ incurs to deliver “Dispatch” at } b(m) \text{ during } T.
Example 2: A piecewise-linear swing contract in firm form

\[ S_{Cm} = [\alpha, P^P, \phi] \]

where:

\( \alpha \) = Offer price

\( P^P = (b, t^s, p^s, RR(R_1), t^{E_1}, P(E_1), t^{R_2}, RR(R_2), t^{E_2}, P(E_2), t^e) \)

\( b \) = Delivery location

\( t^s \) = Start-time for ramp interval R1

\( p^s \) = Power injection level at start-time \( t^s \)

\( RR(R_1) \) = Set of feasible ramp-rates \( r(p^s, p_i(E_1)) \) for R1

\( t^{E_1} \) = Start-time for energy block E1

\( P(E_1) \) = Set of feasible maintained power-steps \( p_i(E_1) \) for E1

\( t^{R_2} \) = Start-time for ramp interval \( R_2 \)

\( RR(R_2) \) = Set of feasible ramp-rates \( r(p_i(E_1), p_j(E_2)) \) for R2

\( t^{E_2} \) = Start-time for energy block E2

\( P(E_2) \) = Set of feasible maintained power-steps \( p_j(E_2) \) for E2

\( t^e \) = End-time for E2

\( \phi \) = Payment for ramp and delivered energy calculated by means of power-path mileage and a pre-specified price \( \pi(p) \) for each \( p \in P(E_1) \cup P(E_2) \)
Example 2: A piecewise-linear swing contract ... Continued

Fig. 5: One among multiple possible power-paths $p$ the RTO/ISO could dispatch $m$ to deliver at $m$’s grid-location $b(m)$ during operating day $D+1$ if the RTO/ISO clears $m$’s piecewise-linear swing-contract $SC_m$ submitted to a swing-contract day-ahead market $M(D+1)$ held on day $D$. 
Example 3: A swing contract in firm form offering battery charge/discharge as an ancillary service

\[ SC_m = [\alpha, PP, \phi] \]

where:

\[ \alpha = \text{Offer price} \]
\[ PP = (b, ECap_{\text{max}}, \eta, t^s, SOC^s, RR, P, t^e, SOC^e) \]

- \( b \) = Delivery location
- \( ECap_{\text{max}} \) = Maximum energy storage capacity
- \( \eta \) = Round-trip efficiency
- \( t^s \) = Start-time for power discharge/charge
- \( SOC^s \) = Set of feasible state-of-charge percentages at \( t^s \)
- \( P = [P_{\text{min}}, P_{\text{max}}] \) = Range of feasible discharge/charge levels \( p \)
- \( RR = [-R^D, R^U] \) = Range of feasible ramp-rates \( r \)
- \( t^e \) = End-time for power discharge/charge
- \( SOC^e \) = Set of feasible state-of-charge percentages at \( t^e \)
- \( \phi \) = Performance payment method for down/up power-path delivery
Example 3: Swing contract in firm form offering battery service... Continued

Fig. 6: Suppose $\text{SOC}^s = \text{SOC}^e = \{100\%\}$, $P^\text{min} = -P^\text{max}$, and $R^\text{D} = R^\text{U} =: R^\text{max}$. Then the depicted dispatched power-path is one among multiple power-paths $p$ the RTO/ISO could dispatch $m$ to deliver at $m$’s grid-location $b(m)$ during hour $H = [t^s, t^e)$ if the RTO/ISO clears $m$’s battery service swing-contract $\text{SC}_m$ submitted to a swing-contract market $M(H)$ held in advance of $H$. 

- $P^\text{max}$
- $E\text{Cap}^\text{max}$
- $-R^\text{max}$
- $R^\text{max}$
- $f^s$
- $f^e$
- $0$
**Example 4: Swing contract (firm) with flexible power & ramp**

*Note:* Proposed for Integrated T&D support (FERC Order No. 2222) in *SC book, Ref. [2, Ch. 5]*

\[
SC_m = [\alpha, PP, \phi]
\]

where:

- \( \alpha \) = Offer price
- \( PP = (b, t^s, p^s, P, RR, t^e) \)
  - \( b \) = Delivery location
  - \( t^s \) = Start-time for power delivery
  - \( p^s \) = Initial power level at time \( t^s \)
  - \( P = [p_{\text{min}}, p_{\text{max}}] \) = Range of feasible down/up power levels \( p \)
  - \( RR = [-R^D, R^U] \) = Range of feasible down/up ramp-rates \( r \)
  - \( t^e \) = End-time for power delivery
- \( \phi \) = Performance payment method for power-path delivery
**Example 4:** Swing contract (firm) with flexible power & ramp ... Continued

*Fig. 7:* One among many possible power-paths $p$ the RTO/ISO could dispatch $m$ to deliver at $m$’s grid-location $b(m)$ during operating day $D+1$ if the RTO/ISO clears $m$’s flexible power/ramp swing-contract $SC_m$ submitted to a swing-contract day-ahead market $M(D+1)$ held on day $D$. 
Comparisons with Current U.S. RTO/ISO-Managed Markets

➢ Detailed comparisons (with 5-118 bus test-case illustrations) of key features and optimization formulations for the Linked Swing-Contract Market Design and current U.S. RTO/ISO-managed wholesale power markets are provided in:

https://www2.econ.iastate.edu/tesfatsi/SCBookReview.IEEEPESMag2022.pdf  

https://www2.econ.iastate.edu/tesfatsi/LMPWhenAndWhyNot.LTesfatsion.pdf

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10122700

➢ Illustrative Day-Ahead Market (DAM) comparisons of key features and optimization formulations are provided in tables on the next two slides.
# DAM Design Comparisons: Key Features

**Similarities**

- Conducted day-ahead to plan for next-day operations
- RTO/ISO-managed
- Market participants include LSEs, DPRs, & IPRs
- Same types of system constraints: Nodal power balance, zonal reserve requirements, line capacity limits, ...

## Differences

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<tr>
<th>Optimization form</th>
<th>Current DAM</th>
<th>SC DAM</th>
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<tbody>
<tr>
<td></td>
<td>SCUC &amp; SCED</td>
<td>Optimal contract clearing</td>
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<th>Settlement</th>
<th>Current DAM</th>
<th>SC DAM</th>
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<td></td>
<td>Locational marginal prices</td>
<td>Swing contracts are two-part pricing contracts</td>
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<th>Market payments</th>
<th>Current DAM</th>
<th>SC DAM</th>
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<tr>
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<td>Payment for next-day energy before actual energy delivery</td>
<td>Payment for resource availability now &amp; resource performance ex post</td>
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<th>OOM payments</th>
<th>Current DAM</th>
<th>SC DAM</th>
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<tr>
<td></td>
<td>Make-whole payments</td>
<td>No make-whole payments</td>
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<tr>
<th>Info released to participants</th>
<th>Current DAM</th>
<th>SC DAM</th>
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<tr>
<td></td>
<td>Unit commitments, LMPs, &amp; next-day dispatch schedule</td>
<td>Which swing contracts have been cleared</td>
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</tbody>
</table>

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LSE =: Load Serving Entity; IPR =: Intermittent Power Resource; DPR =: Dispatchable Power Resource
# DAM Design Comparisons: Optimization Formulations

<table>
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<th>Current DAM SCUC</th>
<th>Current DAM SCED</th>
<th>SC DAM Optimization</th>
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<tr>
<td>Similarities</td>
<td>• Both SCUC and swing-contract (SC) market clearing are solved as Mixed Integer Linear Programming (MILP) optimization problems subject to system constraints</td>
<td></td>
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</tr>
<tr>
<td>Objective</td>
<td>Min $\left[\text{Start-up/shut-down costs + no-load costs + dispatch costs + reserve costs + constraint penalties}\right]$</td>
<td>Min $\left[\text{Dispatch costs + reserve costs + constraint penalties}\right]$</td>
<td>Min $\left[\text{Availability cost + performance cost + constraint penalties}\right]$</td>
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<tr>
<td>Unit commitment</td>
<td>Yes</td>
<td>No</td>
<td>Each DPR includes its unit commitment constraints in its submitted swing contract</td>
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<td>constraints</td>
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<tr>
<td>Key RTO/ISO decision</td>
<td>Unit commitments</td>
<td>Energy dispatch &amp; reserve levels</td>
<td>Which swing-contracts are cleared</td>
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<tr>
<td>Settlement</td>
<td>No</td>
<td>LMPs calculated as SCED dual variables</td>
<td>Each cleared DPR receives the offer price it has included in its submitted swing contract</td>
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DPR  =:  Dispatchable Power Resource
U.S. RTO/ISO-managed wholesale power markets are currently attempting to decarbonize their grid operations and to diversify their market participants.

This presentation first identified three conceptually-problematic design aspects of these markets that are hindering these attempts:

- Product definition and pricing issues;
- Settlement-timing issues;
- Supply-offer formulation issues.

The Linked Swing-Contract Market Design – an alternative RTO/ISO-managed wholesale power market design developed and tested at Technology Readiness Level TRL-3 in Refs. [2-4] -- was then briefly reviewed.

This alternative design appears well-suited for the support of decarbonized grid operations with diverse market participants.

Adoption of this alternative design would require changes in product definitions, settlement rules, and supply-offer forms, but not in real-time operations.

Thus, as illustrated in Refs. [2, Ch. 16] & [4], adoption of this alternative design could proceed by gradual transition, without disruption of real-time operations.