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

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Major Problem: U.S. RTO/ISO-managed wholesale power markets are currently experiencing increasingly volatile and uncertain net load due to increasing reliance on renewable power and increasingly diverse types of market participants.

Major Concern: Three conceptually-problematic market-design aspects -- product definition & pricing, settlement timing, and supply-offer formulations -- are hindering attempts to remedy this major problem.

Possible Remedy:

- An alternative conceptually-consistent Linked Swing-Contract Market Design has been proposed, developed, and tested at Technology Readiness Level TRL-3.

- This alternative design is well-suited for scalable, efficient, & reliable support of increasingly decarbonized grid operations with increasingly diverse participants.

- Adoption of this alternative design by current RTO/ISO-managed markets would require changes in product definitions, settlement rules, and supply-offer forms, but not in real-time operations.

- Thus, adoption of this alternative design could proceed by gradual transition.

References
Overview: U.S. RTO/ISO-Managed Wholesale Power Markets

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

Fig. 1: Depiction of a U.S. Electric Power System as a linked T&D system

➢ This presentation focuses on critical issues currently facing U.S. electric power systems at the high-voltage transmission level.

➢ Attention is focused on market-design concerns arising for U.S. grid-supported wholesale power markets centrally managed by an Independent System Operator (ISO) or Regional Transmission Organization (RTO).

➢ 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 these markets.
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 Problem:

- 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*)

**Increasing Volatility and Uncertainty of Real-Time Net Load**

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

**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 Problem

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.

Market-Design Concerns

Conceptually-problematic legacy market-design features affecting operations in 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.

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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: Ref. [2]  
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 a market 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

This 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.
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:

$$ SC_m = \left( \alpha_m, T_m^{\text{ex}}, PP_m, \phi_m \right) $$

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** $T_m^{\text{ex}}$ 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 $T$. 

Second Key Design Innovation: Reserve Offers in 2-Part Pricing Swing-Contract Form
Reserve Offers in 2-Part Pricing Swing-Contract Form ... Continued

Power-Path Production Possibility Set $PP_m$:

- $PP_m$ characterizes the physical attributes of the power-paths $p_m$ that $m$ is offering in *advance* of operating period $T$ for possible RTO/ISO-dispatched delivery *during* $T$ at $m$’s grid location $b(m)$.

- $PP_m$ permits $m$ to specify with care the “*swing* (flexibility)” in the physical attributes of its offered power-paths.

The physical attributes of each power-path $p_m$ in $PP_m$ can include:

**Static Attributes:** Grid delivery location $b(m)$; grid-delivered energy (MWh) ...

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

Grid-delivered energy (MWh) is 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:

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

**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; ...

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

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

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

where:

\( \alpha \) = Offer price

\( PP = (b, t^s, p^s, RR(R1), t^{E1}, P(E1), t^{R2}, RR(R2), t^{E2}, P(E2), t^e) \)

\( b \) = Delivery location

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

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

\( RR(R1) \) = Set of feasible ramp-rates \( r(p^s, p_i(E1)) \) for R1

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

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

\( t^{R2} \) = Start-time for ramp interval R2

\( RR(R2) \) = Set of feasible ramp-rates \( r(p_i(E1), p_j(E2)) \) for R2

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

\( P(E2) \) = Set of feasible maintained power-steps \( p_j(E2) \) 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 \( p \in P(E1) \cup P(E2) \)
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 $D$. 

$g(t) - g^{\text{sync}}$ (MW)

$\theta$

$p^s = P^{\text{min}}$

$g^{\text{sync}}$

$\left[ t^{\text{su}}, t^{s}, t^{e}, t^{sd} \right]$ Day $D+1$

$\left[ t^{s}, t^{e} \right]$ MinRun

$\left[ t^{s}, t^{e} \right]$ NoLoad

$\left[ t^{s}, t^{e} \right]$ SD

$\left[ t^{s}, t^{e} \right]$ E1

$\left[ t^{s}, t^{e} \right]$ R1

$\left[ t^{s}, t^{e} \right]$ E2

$\left[ t^{s}, t^{e} \right]$ R2

$\left[ t^{s}, t^{e} \right]$ SU

$= \text{Dispatch Set Point}$
Example 3: A swing contract in firm form offering battery charge/discharge as an ancillary service

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

where:

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

\( b = \) Delivery location
\( ECap^{max} = \) 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 \( t^s \)
\( P = [P^{min}, P^{max}] = \) 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 $R^D = R^U =: R_{\text{max}}$. 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 $SC_m$ submitted to a swing-contract market $M(H)$ held in advance of $H$. 
Example 4: *Swing contract (firm) with flexible power & ramp*

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

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

where:

\[\alpha = \text{Offer price}\]
\[\mathbb{PP} = (b, t^s, p^s, \mathbb{P}, \mathbb{RR}, t^e)\]
\[b = \text{Delivery location}\]
\[t^s = \text{Start-time for power delivery}\]
\[p^s = \text{Initial power level at time } t^s\]
\[\mathbb{P} = [P_{\min}, P_{\max}] = \text{Range of feasible down/up power levels } p\]
\[\mathbb{RR} = [-R^D, R^U] = \text{Range of feasible down/up ramp-rates } r\]
\[t^e = \text{End-time for power delivery}\]
\[\phi = \text{Performance payment method for power-path delivery}\]
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 $D$. 

- **Detailed comparisons** of key design features and performance capabilities (with illustrative 5-118 bus test-case outcomes) for the Linked Swing-Contract Market Design and the design of current U.S. RTO/ISO-managed wholesale power markets are provided in Refs. [1-4] listed at the end of this presentation.

- **Illustrative comparisons** of key design features and optimization formulations for current and SC-proposed Day-Ahead Markets (DAMs) are provided in tables on the next two slides.
### DAM Design Comparisons: **Key Features**

<table>
<thead>
<tr>
<th>Similarities</th>
<th><strong>Current DAM</strong></th>
<th><strong>SC DAM</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Conducted day-ahead to plan for next-day operations</td>
<td>Optimal contract clearing</td>
</tr>
<tr>
<td></td>
<td>• RTO/ISO-managed</td>
<td>Swing contracts are two-part pricing contracts</td>
</tr>
<tr>
<td></td>
<td>• Market participants include LSEs, DPRs, &amp; IPRs</td>
<td>Payment for resource availability now &amp; resource performance ex post</td>
</tr>
<tr>
<td></td>
<td>• Same types of system constraints: Nodal power balance, zonal reserve requirements, line capacity limits, ...</td>
<td>No make-whole payments</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Differences</th>
<th><strong>Optimization form</strong></th>
<th><strong>Settlement</strong></th>
<th><strong>Market payments</strong></th>
<th><strong>OOM payments</strong></th>
<th><strong>Info released to participants</strong></th>
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<tbody>
<tr>
<td></td>
<td>SCUC &amp; SCED</td>
<td>Locational marginal prices</td>
<td>Payment for next-day energy before actual energy delivery</td>
<td>Make-whole payments</td>
<td>Unit commitments, LMPs, &amp; next-day dispatch schedule</td>
</tr>
<tr>
<td></td>
<td>Optimal contract clearing</td>
<td>Swing contracts are two-part pricing contracts</td>
<td>Payment for resource availability now &amp; resource performance ex post</td>
<td>No make-whole payments</td>
<td>Which swing contracts have been cleared</td>
</tr>
</tbody>
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**LSE =: Load Serving Entity; IPR =: Intermittent Power Resource; DPR =: Dispatchable Power Resource**
## DAM Design Comparisons: Optimization Formulations

<table>
<thead>
<tr>
<th>Similarities</th>
<th>Current DAM SCUC</th>
<th>Current DAM SCED</th>
<th>SC DAM Optimization</th>
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</thead>
<tbody>
<tr>
<td><strong>Objective</strong></td>
<td>Min [Start-up/shut-down costs + no-load costs + dispatch costs + reserve costs + constraint penalties]</td>
<td>Min [Dispatch costs + reserve costs + constraint penalties]</td>
<td>Min [Availability cost + performance cost + constraint penalties]</td>
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<tr>
<td><strong>Unit commitment constraints</strong></td>
<td>Yes</td>
<td>No</td>
<td>Each DPR includes its unit commitment constraints in its submitted swing contract</td>
</tr>
<tr>
<td><strong>Key RTO/ISO decision variables</strong></td>
<td>Unit commitments</td>
<td>Energy dispatch &amp; reserve levels</td>
<td>Which swing-contracts are cleared</td>
</tr>
<tr>
<td><strong>Settlement</strong></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>
</tr>
</tbody>
</table>

**DPR** = Dispatchable Power Resource
Conclusion

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

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

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

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