Transitioning to Linked Swing-Contract
Wholesale Power Markets for Net-Zero 2050

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Presentation Slide-Set (Longer Form for Posting)

Session W2, Wednesday, June 22, 12:30pm EDT
FERC Technical Conference (Virtual)
Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software
21-23 June 2022
Growing reliance of U.S. RTO/ISO-managed wholesale power markets on renewable power resources and demand-side participation have led to greater uncertainty and volatility of net load.

RTOs/ISOs are finding it harder to secure reserve with sufficient flexibility and dependability to permit the continual balancing of net load, a basic requirement for power system reliability.

SC Book [1] reconsiders the design of these markets, stressing four market design principles:

[MD1] Wholesale power markets must necessarily be forward markets due to the speed of real-time operations;

[MD2] Only one type of product can effectively be offered: reserve, an insurance product offering the availability of net-load balancing services for future real-time operations;

[MD3] Net load balancing services primarily take the form of power-paths that can be RTO/ISO-dispatched at specific grid locations over time;

[MD4] All dispatchable power resources should be permitted to compete for the provision of power-paths without regard for irrelevant underlying technological differences.

If principles [MD1] – [MD4] are accepted, trade and settlement arrangements in U.S. RTO/ISO managed wholesale power markets will need to be fundamentally altered.

Presentation Outline

1. U.S. RTO/ISO-managed markets: Net-Zero 2050 Concerns [1, Chapters 2-3]

2. A linked swing-contract market design [1, Chapters 1, 4-11]
   2.1 Design overview
   2.2 Swing contract: General formulation and examples
   2.3 Swing-contract market: Key features
   2.4 Swing-contract day-ahead market: 30-bus test case
   2.5 Linked swing-contract markets

3. Comparisons with current U.S. RTO/ISO-managed markets [1, Chapters 12-16]
   3.1 Comparison of basic features
   3.2 Comparison of optimization formulations

4. Support for integrated T&D system operations [1, Chapters 1, 17-18]

5. Conclusion

6. References

Appendix: *Ptolemaic Epicycle Conundrum for Market Design* (“Onion Problem”)

- **U.S. RTO/ISO-managed wholesale power markets**
  - **Basic Purpose:** Ensure production & transmission of bulk power efficiently and reliably over time, for ultimate distribution to end-use customers.
  
  - **Reliability Requirement:** Continual net-load balancing across the grid
    
    \[
    \text{net load} = [\text{Power withdrawals/losses}] - [\text{non-dispatched power injections}] 
    \approx [\text{dispatched power injections}]
    \]

  U.S. RTOs/ISOs are finding it harder to maintain continual net-load balancing as the electric power industry increasingly moves towards power-grid decarbonization, consistent with **UN Net-Zero 2050 Goal:** Net-zero greenhouse gas emissions by 2050.

- **Key Concern:** Increasingly volatile and uncertain net load due to
  
  - increased reliance on intermittent non-dispatchable renewable power resources connected to the *transmission grid* (wind farms, large solar PV panel arrays, ...);
  
  - more active power trading among entities connected to the *distribution grid* (producers, prosumers, & consumers).
Three Potential Remedies

• **Hybrid Power Resources**
  Firm up *non*-dispatchable power resources with jointly-operated *storage*.

• **Increased Power-Supply Flexibility**
  Provide more opportunities/incentives for diverse RTO/ISO-dispatchable wholesale power resources able to provide *just-in-time power supply* to service *just-in-time net-load demand*.

• **FERC Order No. 2222 Initiatives**
  Permit T&D linkage entities to participate in wholesale power markets as suppliers of RTO/ISO-dispatchable power and/or ancillary services harnessed from *diverse* collections of *distribution-level power resources* voluntarily participating in distribution-level Transactive Energy System (TES) designs.

➢ **Difficulty**
  Conceptually problematic aspects of current U.S. RTO/ISO-managed wholesale power markets are impeding the implementation of these remedies.
Four Conceptually-Problematic Aspects of U.S. RTO/ISO-Managed Markets

1. Artificial Distinction Between “Energy” and “Reserve”

A wholesale power market $M(T)$ for a future operating period $T$ is a forward market for which only one type of product can effectively be offered: namely, net-load balancing services for $T$.

Examples: Day-Ahead Market $DAM(D+1)$ held during day $D$ for operating day $D+1$; Real-Time Market $RTM(H)$ held during hour $H-1$ for operating hour $H$.

2. “Product” Proliferation

Problematic treatment of highly correlated attributes of a resource’s power output over time as independent products that can be separately transacted at separately determined prices.

Example: Max energy capacity (MWh), power cap range (MW), feasible ramp-rate range (MW/min) of a single generator $G$ treated as independent products: ENERGY (MWh); CAPACITY (MW); RAMP (MW/min).

3. “Participation Model” Proliferation

Growing taxonomy of power-resource types based in part on irrelevant distinctions, each type with special market eligibility rules & performance requirements.

Example: “Energy” participant vs. “Reserve” participant

4. Revenue Insufficiency (Avoidable Cost > Market-Based Revenue)

Incorrect presumption that compensation of power resources for scheduled “energy deliveries” (MWh) at grid locations $b$ during standardized operating periods $T$ solely by locational marginal prices $LMP(b,T)$ ($/MWh$) will necessarily result in revenue that fully covers all incurred

Avoidable Cost $=\text{ Avoidable Fixed Cost} + \text{Variable Cost}$ (See appendix for cost definitions)
Fundamental Issue Underlying Conceptual Concerns 1. – 4.

➢ The **Standard Market Design** *(DAM/RTM two-settlement system)* at the core of all seven current U.S. RTO/ISO-managed wholesale power markets *incorrectly presumes these markets are “commodity” markets.*

Review of Four Important Economic Definitions [1, Appendix, Table A.3]:

**Asset:** Anything in physical or financial form that can function as a store of value over time.

**Commodity:** Asset with a *standard unit of measurement* for which units at any given time and location can be *substituted* for each other *with no change in valuation.*

**Spot Market for an Asset:** Delivery and payment for the asset are determined *at the same time* (“*on the spot*”).

**Forward Market for an Asset:** The asset payment method is contractually decided *in advance* of the asset delivery date.
Energy (MWh) as a Commodity: \textit{Spot Market Example}

- Suppose energy (MWh) is produced and sold in the form of \textit{uniformly packaged batteries}.

- At any given time and retail location, each battery sells at a \textit{common retail price} $\pi^{\text{Ret}} (\$/\text{battery})$ that covers wholesale production cost ("$W$") plus transport/damage cost ("$\text{Trans}$").

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Energy (MWh) in uniform battery form can be transacted as a commodity.}
\end{figure}

\textbf{Note:} The decomposition of the spot price $\pi^{\text{Ret}}$ into "$W$" and "$\text{Trans}$" components is analogous to the decomposition of a locational marginal price $\text{LMP}(b,T)$ into "energy," "congestion," & "loss" components.
Key Point (i): *Energy (MWh)* typically is *not* a commodity in U.S. RTO/ISO-managed wholesale power markets

☐ Why Not?

- *Exact way* that power (MW) injected *at* a grid-location *b during* an operating period T *accumulates up* into energy (MWh) can matter greatly to producers, customers, and/or RTOs/ISOs.

- That is, the “power-path” *typically matters*, not simply the static amount of delivered energy (MWh).

**Examples:**
- Producers care about depreciation costs from ramping wear & tear *during T*;
- Customers benefit from flexible just-in-time power availability *during T*;
- RTOs/ISOs care about flexible voltage control support *during T*.
Key Definition from Swing-Contract Book [1]

Power-path $p(T)$ for an operating period $T$:

Sequence of injections and/or withdrawals of power (MW) that take place at a single grid location during operating period $T$.

*Important*: a power-path is a path through time taking place at a fixed location.

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**Fig. 2:** Illustrative depiction of a power-path $p_m(T)$ in a time-power plane provided by a dispatchable power resource $m$ at its grid point-of-connection $b(m)$ during an operating period $T$.
Key Point (ii): U.S. RTO/ISO-managed wholesale power markets are *forward power-path markets*

**Fig. 3:** An RTO/ISO-managed wholesale power market is a collection of forward markets for ensuring balanced power-path production and deliveries for the transmission component of a T&D System.

**Grid-Edge Resource (GER) =:** Any entity capable of power usage and/or power output that has a *direct* electrical point-of-connection to the *distribution* grid.
Key Point (iii): *Power-paths* are **not** a commodity in current U.S. RTO/ISO-managed wholesale power markets

คำถามที่ท้าทาย: ทำไม?

- **Power-paths** ไม่มี **standard unit of measurement** ที่เป็นมาตรฐาน ทำให้การส่งผ่าน หรือ "unit" ที่มีอยู่ในเส้นทางที่กำหนด สามารถส่งผ่านกันไปได้ ที่สถานีใดก็ได้ ไม่มีการเปลี่ยนแปลงในมูลค่า.

- แต่ตรงข้ามกัน ที่ไม่เหมือนกัน ส่งผ่าน สามารถมีการเปลี่ยนแปลงที่มีความหมายต่างๆ ซึ่งนำไปสู่การมีความมูลค่าที่มีความแตกต่างกัน.

**Examples:**

- รูปแบบขึ้นลง ramping **profile** ของ T สามารถมีผลกระทบต่อมูลค่าการผลิต (การใช้ทรัพยากร) ของ T;
- รูปแบบการเปลี่ยนแปลงของ **profile** ของ Active power ใน T สามารถมีผลกระทบต่อมูลค่าการผลิตของ T;
- รูปแบบการเปลี่ยนแปลงของ **profile** ของ Reactive power ใน T สามารถมีผลกระทบต่อมูลค่าการผลิตของ T,

โดย:

**profile during T** คือ: *Form that some attribute takes during operating period T.*
**Key Point (iv):** Swing contracts are well-suited for the support of *power-path transactions* in RTO/ISO-managed wholesale power markets.

**Why?**

The **general swing-contract formulation** defined in SC Book [1] permits a dispatchable power resource to:

- offer *availability* of power-paths with diverse attributes for possible RTO/ISO-dispatched delivery *during a future operating period T*;

- ensure receipt of *full compensation ex ante* (i.e., *in advance of T*) for the systemic risk reduction provided by this *period-T availability*;

- ensure receipt of *full compensation ex post* (i.e., *after T*) for any *verified period-T delivery* of one of these offered power-paths in response to dispatch set-points received from the RTO/ISO.
2. Linked Swing-Contract Market Design

2.1 Design Overview

Purpose: The intended purpose of the Linked Swing-Contract Market Design developed in SC Book [1] is to facilitate the flexible dependable availability of reserve in RTO/ISO-managed wholesale power markets.

— A swing-contract market M(T) for a future operating period T is an RTO/ISO-managed forward reserve market for T.

— Reserve for T consists of RTO/ISO-dispatchable power-paths for T.

— A power-path for T is a sequence of injections and/or withdrawals of power (MW) at a single grid location during T.

Design Overview: Reserve Offers & Reserve Bids

- A reserve offer submitted by a dispatchable power resource $m$ to a swing-contract market $M(T)$ for a future operating period $T$ is an offer to ensure availability of power-paths for possible RTO/ISO-dispatched delivery during $T$.
  
  - A reserve offer is thus a physically-covered insurance product.
  
  - Each reserve offer is a portfolio of one or more swing contracts in firm or option form.
  
  - Swing-contract portfolios permit dispatchable power resources to express the swing (flexibility) in the attributes of their offered power-paths in a clear and comprehensive manner.

- A reserve bid submitted to a swing-contract market $M(T)$ for a future operating period $T$ is a demand for power-path delivery during $T$.
  
  - Reserve bids can take a price-sensitive and/or fixed (must-service) form.
Design Overview: Swing Contracts

- A swing contract $SC_m$ submitted by a dispatchable power resource $m$ to an RTO/ISO-managed swing-contract market $M(T)$ for a future operating period $T$ is a two-part pricing contract.

  - The offer price that $m$ includes in $SC_m$ permits $m$ to ensure full compensation in advance of $T$ for any avoidable fixed cost that $m$ must incur to guarantee the availability of power-paths for possible RTO/ISO dispatch during $T$.

  - The performance payment method that $m$ includes in $SC_m$ permits $m$ to ensure full compensation after $T$ for any variable cost that $m$ incurs for verified delivery of a power-path during $T$ in accordance with dispatch set-points received from the RTO/ISO.
RTO/ISO goal for a swing-contract market M(T) for a future operating period T

Maximize Expected Total Net Benefit of M(T) participants, conditional on initial state conditions and subject to system constraints.

RTO/ISO cost allocation rules to ensure RTO/ISO independence, i.e., no ownership/financial stake in market participants or power system operations

Allocate M(T) net reserve procurement cost across M(T) participants in accordance with anticipated volatility/size and ex-post realization of their net fixed load during T, where:

\[ \text{NetReserveCost}(\text{M(T)}) = \text{RTO/ISO net reserve procurement cost from M(T) operations} = [\text{Offer cost}] \text{ plus } [\text{performance cost}] \text{ minus } [\text{revenues from price-sensitive demand}] \]

\[ \text{NetFixedLoad}(j, \text{M(T)}) = \text{Period-T net fixed load of an M(T)-participant } j = [\text{Fixed (must-service) power demand by } j \text{ during T}] \text{ minus } [\text{non-dispatched power injection by } j \text{ during T}] \]

Allocate M(T) transmission service cost across M(T) participants in accordance with:

- relative power imbalance \( RPI(b,T) \) recorded at each grid location b during T; and
- relative contribution of each M(T)-participant \( j \) to \( RPI(b(j),T) \), where \( b(j) = j's \ grid location. \)
2.2 Swing Contract: General Formulation and Examples

☐ Swing contract

\[
SC_m = (\alpha_m, T_m^{ex}, PP_m, \phi_m)
\]

submitted by a dispatchable resource \( m \) to an RTO/ISO-managed SC market \( M(T) \) for a future operating-period \( T \) consists of:

1) offer price \( \alpha_m \);

2) exercise set \( T_m^{ex} \) of possible contract exercise times;

3) power-path set \( PP_m \) providing a “digital twin” representation of an offered collection of power-paths that \( m \) is physically capable of delivering at some designated grid location during the future operating period \( T \) in response to received RTO/ISO dispatch set-points;

4) performance payment method \( \phi_m \).
Swing Contract: General Formulation ... Continued

Swing contract

\[ SC_m = (\alpha_m, T_m^{ex}, PP_m, \phi_m) \]

submitted by a dispatchable resource \( m \) to a swing-contract market \( M(T) \) for a future operating period \( T \) permits \( m \):

— to offer the RTO/ISO a choice set \( PP_m \) of reserve (power-paths) \( p \) for possible RTO/ISO-dispatched delivery during operating period \( T \);

— to specify with care the swing (flexibility) in the offered power-paths \( p \) in terms of both physical attributes and exercise times.

The physical attributes of each power-path \( p \) can include:

static attributes: delivery time/place; delivered energy (MWh) ...

dynamic attributes: power profile; power-factor profile; ramp-rate profile; power mileage; down-time/up-time profile; ...
In addition, swing contract SC\(_m\) permits \(m\):

- to request an **offer price** \(\alpha_m\) ($) that covers **ex ante** (i.e., in advance of \(T\)) any **avoidable fixed cost** that \(m\) would have to incur in order to ensure the **availability** of the power-paths in PP\(_m\) for **possible** RTO/ISO dispatch during \(T\).

**Avoidable fixed cost examples:** Capital investment cost; transaction cost (insurance, licensing, ...); unit commitment cost; opportunity cost; ...

- to specify a **performance payment method** \(\varphi_m\) that maps each power-path \(p \in \text{PP}_m\) into a required performance payment \(\varphi_m(p)\) ($). This permits \(m\) to ensure **recovery ex post** (i.e., after \(T\)) for any **variable cost** that \(m\) incurs **for verified delivery of a power-path during** \(T\) in accordance with dispatch set-points received from the RTO/ISO.

**Variable cost examples:** Fuel cost; labor cost; transmission service charges; equipment wear and tear due to fast ramping; ...
Swing Contract: General Formulation ... Continued

- The performance payment method $\phi_m$ should be explicitly expressed in terms of standardized performance metrics.

- These performance metrics should permit the RTO/ISO and $m$:
  - to agree \textit{ex ante} (i.e., \textit{in advance} of $T$) on the nature of $m$’s \textit{offered} period-$T$ power-path delivery;
  - to verify \textit{ex post} (i.e., \textit{after} $T$) the extent to which $m$’s \textit{actual} period-$T$ power-path delivery deviates from admissible dispatch set-points that the RTO/ISO has communicated to $m$ during $T$ (if any).

\textbf{Example:}

Determine performance cost $\phi_m(p)$ of each power-path $p$ in $PP_m$ as a linear combination of metrics that separately assign costs to correlated attributes of $p$, such as \textbf{delivered energy} ($E$), \textbf{power mileage} ($PM$), \textbf{duration} ($D$), etc.

$$\phi_m(p) = c^E(p) + c^{PM}(p) + c^D(p) + \ldots$$

Costs assigned to \textit{correlated} attributes of a \textit{single} power-path $p$.
Swing Contract: Examples

Example 1: A simple energy-block swing contract in firm form

Remark: As shown in [1, Sect. 5.4], this form of swing contract can easily be modified to represent current RTO/ISO supply-offer forms, 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

**SC\(_m\) 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 during \(T\).

**SC Performance Payment Method \(\varphi\):** Permits \(m\) to recover “Dispatch” energy cost along with any other variable cost that \(m\) must incur to deliver “Dispatch” during \(T\).

**Fig. 4:** Illustrative depiction of \(m\)’s energy requirements for delivery of energy-block “Dispatch” during operating period \(T\): namely, the energy block itself (“Dispatch”); start-up (“SU”); ramp-up (“RU”); no-load (“No-Load”), ramp-down (“RD”), and shut-down (“SD”).
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 many possible power-paths $p$ the RTO/ISO could dispatch $m$ to deliver during operating day $D+1$ if the RTO/ISO clears $m$’s piecewise-linear swing contract $SC_m$ submitted to an SC 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:

- \(\alpha\) = 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
Fig. 6: Suppose $SOC^s = SOC^e = \{100\%\}$, and $P^{min} = -P^{max}$. Then the depicted dispatched power-path is one among many possible power-paths $p$ the RTO/ISO could dispatch $m$ to deliver during operating hour $H = [t^s, t^e)$ if the RTO/ISO clears $m$’s battery service swing contract $SC_m$ submitted to an SC market $M(H)$ held in advance of hour $H$. 
Example 4: *Swing contract (firm) with flexible power & ramp*

*Note:* Proposed for Integrated T&D support (FERC Order No. 2222) in SC book [1]

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

where:

\[ \alpha = \text{Offer price} \]
\[ \mathbb{PP} = (b, t^s, p^s, \mathbb{P}, \mathbb{RR}, t^e) \]
\[ b = \text{Delivery location} \]
\[ t^s = \text{Start-time for power delivery} \]
\[ p^s = \text{Initial power level at time } t^s \]
\[ \mathbb{P} = [p^{\text{min}}, p^{\text{max}}] = \text{Range of feasible down/up power levels } p \]
\[ \mathbb{RR} = [-R^D, R^U] = \text{Range of feasible down/up ramp-rates } r \]
\[ t^e = \text{End-time for power delivery} \]
\[ \phi = \text{Performance payment method for power-path delivery} \]
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 during operating day \( D+1 \) if the RTO/ISO clears \( m \)'s flexible power/ramp SC submitted to an SC day-ahead market \( M(D+1) \) held on day \( D \).
2.3 Swing-Contract Market: Key Features

- A swing-contract market $M(T)$ for a future operating period $T$ is an RTO/ISO-managed forward reserve market.

- General time-line for $M(T)$:

- The Look-Ahead-Horizon $\text{LAH}(T)$ can range from very long (multiple years) to very short (minutes);

- The operating period $T$ can range from very long (multiple years) to very short (minutes).
Load-Serving Entities (LSEs)

Each LSE submits to M(T) a reserve bid, i.e., a request for power-path delivery during T in fixed (must-service) and/or price-sensitive form.

Dispatchable power resources \( m \in M \)

Each \( m \) submits to M(T) a reserve offer consisting of a portfolio

\[ SC_m = ( SC_{m1}, ..., SC_{mN} ) \]

of \( N \geq 1 \) swing contracts \( SC_{mj} \), each offering a physically characterized collection of power-paths for possible RTO/ISO dispatched delivery during T.

Non-dispatchable Variable Energy Resources (VERs)

The RTO/ISO inputs into M(T) a forecast for non-dispatchable VER generation at each transmission grid bus during period T.
Swing-Contract Market: Key Features ... Contract-Clearing Optimization

- **Contract-Clearing Optimization Problem for the RTO/ISO that Manages M(T)**
  - Which price-sensitive reserve bids to clear for T?
  - Which reserve offers to clear for T?

- **Objective function:** *Expected Total Net Benefit* of the M(T) participants from period-T operations, where:
  
  \[ \text{Total Net Benefit} =: [ \text{Reserve Benefit} - \text{Reserve Cost} ] \]
  
  \[ \text{Reserve Benefit} =: [ \text{Customer benefit expressed by their reserve bids} ] \]
  
  \[ \text{Reserve Cost} =: [ \text{Offer Cost (OC)} + \text{Performance Cost (PC)} + \text{Imbalance Cost (IC)} ] \]

- **Optimization:** *Select* contract-clearing binary (yes/no) decisions *that*
  
  maximize Expected Total Net Benefit
  
  -- *conditional on* initial conditions *plus* information automatically extracted from submitted reserve offers and reserve bids
  
  -- *and subject to* the usual types of SCED system constraints (e.g., power-balance, transmission capacity limits, reserve uncertainty sets, ...)
The RTO/ISO’s contract-clearing optimization problem for M(T) is conditioned on the following types of initial conditions:

- Forecasted/calculated *down/up-time status* and *power level* of each dispatchable power resource *m* at the *start* of operating period *T*;
- Bid/forecasted *fixed (must-service) load* at each grid bus during *T*;
- Forecasted *non-dispatchable VER generation* at each grid bus during *T*. 
The RTO/ISO’s contract-clearing optimization problem for M(T) is subject to the following types of SCED system constraints:

- transmission line constraints;
- power balance constraints (with slack variables);
- dispatchable resource capacity constraints;
- dispatchable resource ramping constraints (start-up, normal, and shut-down);
- dispatchable resource minimum up-time/down-time constraints;
- dispatchable resource hot-start constraints;
- dispatchable resource start-up/shut-down cost constraints;
- system-wide and zonal down/up reserve requirement constraints;
- bus voltage angle constraints.
2.4 Swing-contract day-ahead market (SC DAM): 30-bus test case


Fig. 8: Grid for 30-Bus Test Case. 30 buses B1-B30; 41 transmission lines L1-L41; 6 dispatchable thermal generators G1-G6; 4 non-dispatchable wind farms located at buses B7, B8, B21, and B24; and 20 LSEs servicing fixed load at 20 different buses.
RTO/ISO Objective: All load fixed \[\text{Max Expected Net Benefit} \equiv \text{Min Expected Avoidable Cost}\]

Select decision variables to minimize forecasted total avoidable cost, subject to system constraints, where forecasted total avoidable cost is given by:

\[
\widehat{C}(T) = \sum_{m \in M} [c_m \alpha_m + \phi_m(p_m)] + \sum_{b \in B} \sum_{k \in K} [\Lambda - \beta_b^- (k) + \Lambda + \beta_b^+ (k)] \Delta t
\]

RTO/ISO Binary Decision Variables:
- Contract clearing indicators: \( c_m \in \{0, 1\}, \forall m \in M \)

RTO/ISO Continuously-Valued Decision Variables:
- Power dispatch levels: \( p_m(k), \forall m \in M, k \in K \)
- Bus voltage angles: \( \theta_b(k), \forall b \in B \setminus \{1\}, k \in K \)

Variables determined by RTO/ISO Decisions and System Constraints:
- Run-time minimum power levels: \( \underline{p}_m(k), \forall m \in M, k \in K \)
- Run-time maximum power levels: \( \bar{p}_m(k), \forall m \in M, k \in K \)
- Unit availability indicators: \( v_m(k) \in \{0, 1\}, \forall m \in M, k \in K \)
- Transmission line power flows: \( w_{\ell}(k), \forall \ell \in L, k \in K \)
- Power balance slack variables: \( \beta_b(k), \beta_b^-(k), \beta_b^+(k), \forall b \in B, k \in K \)
- Bus voltage angle for reference bus 1: \( \theta_1(k), \forall k \in K \)

Note: The operating day D+1 is discretized into time-steps \( k \) in \( K \), and all load is assumed to be fixed.
Table 6.6 Thirty-bus SC DAM performance over three successive days for two different reserve zone treatments

<table>
<thead>
<tr>
<th>Day</th>
<th>Treatment</th>
<th>Reserve Zones</th>
<th>Contract Clearing $c_{G_1},c_{G_2},c_{G_3},c_{G_4},c_{G_5},c_{G_6}$</th>
<th>OC(Z,$D_j$)</th>
<th>$E^{xp}[PC(Z,D_j)]$</th>
<th>$E^{xp}[IC(Z,D_j)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D₀</td>
<td>Proposed</td>
<td>$z_1$: Bus 23</td>
<td>[1, 1, 1, 1, 1, 1]</td>
<td>$10,750</td>
<td>$100,555.65</td>
<td>$194.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$z_2$: Bus 27 29 30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$z_3$: Bus 1-22 24 25 26 28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single Zone</td>
<td>$z_1$: Bus 1-30</td>
<td>[1, 1, 1, 1, 0, 1]</td>
<td>$8,750</td>
<td>$106,420.12</td>
<td>$5,371.73</td>
</tr>
<tr>
<td>D₁</td>
<td>Proposed</td>
<td>$z_1$: Bus 23</td>
<td>[1, 1, 1, 1, 1, 1]</td>
<td>$10,700</td>
<td>$98,012.73</td>
<td>$10,359.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$z_2$: Bus 21 22 24-27 29 30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$z_3$: Bus 1-20 28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single Zone</td>
<td>$z_1$: Bus 1-30</td>
<td>[1, 1, 1, 1, 0, 1]</td>
<td>$9,100</td>
<td>$99,996.96</td>
<td>$13,990.73</td>
</tr>
<tr>
<td>D₂</td>
<td>Proposed</td>
<td>$z_1$: Bus 23 24 25 26</td>
<td>[1, 1, 1, 1, 1, 1]</td>
<td>$9,410</td>
<td>$104,494.04</td>
<td>$10,597.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$z_2$: Bus 27 29 30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$z_3$: Bus 1-22 28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single Zone</td>
<td>$z_1$: Bus 1-30</td>
<td>[1, 1, 1, 1, 0, 1]</td>
<td>$7,810</td>
<td>$105,077.11</td>
<td>$13,282.30</td>
</tr>
</tbody>
</table>
2.5 Linked Swing-Contract Markets

Example 1: Intertemporal Linkages for Given Operating Period T

- Linked SC markets $\mathbf{M(T)}$ for a given future operating period $T$ with Look-Ahead Horizons $\text{LAH(T)}$ ranging from Long ($L$) to Short ($S$) to Very Short ($VS$).

- Linkage is established among the successive markets $\mathbf{M(T)}$ for the given $T$ by $\text{ISOPort}(T) =: \text{Portfolio of reserve bids and reserve offers cleared for } T \text{ that the RTO/ISO carries forward through time for use during } T.$

- The RTO/ISO updates $\text{ISOPort}(T)$ in successive SC markets $\mathbf{M(T)}$ held prior to $T$ to include any newly-cleared contracts for $T$. 

---

**Diagram:**

D-365  

\[
\begin{array}{c}
\text{D} \\
\text{24 hours} \\
\text{D+1} \\
\text{24 hours} \\
T
\end{array}
\]

- **Long-Term Forward Markets**: $L-M(T)$
- **Short-Term Forward Markets**: $S-M(T)$
- **Very Short-Term Forward Markets**: $VS-M(T)$
2.5 Linked Swing-Contract Markets ... Continued

Example 2: Nested Operating Periods

— Linked *day-ahead & hour-ahead* SC markets for a *given* operating hour $H$ during a *given* operating day $D+1$
3. Comparisons with Current U.S. RTO/ISO-Managed Markets

- Key features of the proposed Linked Swing-Contract Market Design are described in previous slides and throughout SC book [1].

- Detailed comparisons with current RTO/ISO-managed wholesale power market designs are given in SC book [1, Chapters 2-3, 12-15].

- The next two tables outline key similarities & differences between the two designs for the special case of a **Day-Ahead Market (DAM)**.

**Note:** The essential differences between current U.S. RTO/ISO-managed DAM designs and the swing-contract DAM design proposed in SC Book [1] are differences in **product definition, contractual forms, & settlement rules**.
# 3.1 Illustrative DAM Comparison … Basic Features

<table>
<thead>
<tr>
<th>Similarities</th>
<th>Current DAM</th>
<th>SC DAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conducted day-ahead to plan for next-day operations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTO/ISO-managed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Participants include LSEs, dispatchable resources, &amp; VERs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same types of system constraints (line capacity limits; power balance; gen attributes; reserve requirements; … )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Differences</th>
<th>Optimization formulation</th>
<th>Settlement</th>
<th>Payment</th>
<th>Out-of-market payments</th>
<th>Info released to participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCUC &amp; SCED</td>
<td>Locational marginal prices</td>
<td>Payment for next-day energy before energy delivery</td>
<td>Make-whole payments (e.g., for unit commitment)</td>
<td>Unit commitments, LMPs, &amp; next-day dispatch schedule</td>
<td>Unit commitments, LMPs, &amp; next-day dispatch schedule</td>
</tr>
<tr>
<td>Swing-contract clearing</td>
<td>Contract-determined prices</td>
<td>Payment for reserve availability now &amp; reserve performance ex post</td>
<td>No out-of-market payments</td>
<td>Which swing-contracts have been cleared</td>
<td></td>
</tr>
</tbody>
</table>
### 3.2 Illustrative DAM Comparison ... Optimization

<table>
<thead>
<tr>
<th>Similarities</th>
<th>Current DAM SCUC</th>
<th>Current DAM SCED</th>
<th>SC DAM Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objective</strong></td>
<td>Min ([\text{Start-up/shut-down costs} + \text{no-load costs} + \text{dispatch costs} + \text{reserve costs}])</td>
<td>Min ([\text{Dispatch costs} + \text{reserve costs}])</td>
<td>Min ([\text{Offer cost} + \text{expected performance cost} + \text{expected imbalance cost}])</td>
</tr>
<tr>
<td><strong>Unit commitment constraints</strong></td>
<td>Yes</td>
<td>No</td>
<td>Unit commitment constraints are implicit in submitted swing-contracts</td>
</tr>
<tr>
<td><strong>Key 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>Offer prices paid for cleared swing-contracts</td>
</tr>
</tbody>
</table>

- Both SCUC and swing-contract (SC) clearing are solved as mixed integer linear programming (MILP) optimization problems subject to system constraints.

Fig. 9: An ITD System with IDSO linkage agents, implemented by the ITD TES Platform V2. ITD Project Homepage, https://www2.econ.iastate.edu/tesfatsi/ITDProjectHome.htm

Grid-Edge Resource (GER) =: Any entity capable of power usage and/or power output with a direct electrical point-of-connection to the distribution grid.
SC support for ITD operations ... Continued

- **Swing contracts** can facilitate participation of Independent Distribution System Operators (IDSOs) in RTO/ISO-managed wholesale power markets as providers of ancillary services harnessed from Grid-Edge Resources (GERs), in accordance with FERC Order No. 2222 objectives.

**Example:** Consider an IDSO that operates at a T-D linkage bus $B_L$ for an Integrated Transmission and Distribution (ITD) system.

- Suppose the **IDSO submits** a swing-contract $SC = (\alpha, PP, \phi)$ into an RTO/ISO-managed day-ahead market DAM(D+1) held on day D for real-time operations on D+1.

- Suppose the **RTO/ISO clears** the swing-contract SC. Then the **IDSO receives** its offer price $\alpha$; and the **RTO/ISO is obligated to select** some power-path $p^* \in PP$ and to communicate suitable dispatch set-points to the IDSO during D+1 to ensure the delivery of $p^*$ at $B_L$ during D+1.

- The **IDSO implements** these dispatch set-points during D+1 by sending suitable retail price signals to distribution-system GERs whose electrical devices have smart (price sensitive) controllers.

- The **IDSO uses** a bid-based Transactive Energy System (TES) design to determine these retail price signals during day D+1: namely, the bid-based **Five-Step TES Design** developed in:

5. Conclusion

Linked Swing-Contract Market Design: Purpose

Facilitate efficient reliable balancing of increasingly volatile and uncertain net load in RTO/ISO-managed wholesale power markets.

Key Novel Design Aspects

- Each swing-contract market is a forward reserve market;
- Reserve consists of RTO/ISO-dispatchable power-paths;
- Reserve offers take the form of swing contracts;
- Each swing contract is a physically-covered insurance contract with two-part pricing.
- This two-part pricing permit reserve suppliers to guarantee their revenue sufficiency.
Design Features Stressed in This Slide-Set

- swing contract
- swing-contract market
- collection of linked swing-contract markets
- support for integrated T&D operations (FERC Order No. 2222)
Conclusion ... Continued

- Additional Topics Covered in Swing Contract book [1]
  - LSE reserve bids expressed via benefit functions [1, Ch. 9]
  - Gradual transition to swing-contract markets: An illustrative Transitional Day-Ahead Market (DAM) [1, Ch. 16]
  - Potential future research directions [1, Ch. 19]
6. References

https://www2.econ.iastate.edu/tesfatsi/SwingContractMonograph.TOCIntro.LTesfatsion.pdf


https://www2.econ.iastate.edu/tesfatsi/MarketDesignSAND2013-2789.LTEtAl.pdf
Appendix: Ptolemaic Epicycle Conundrum for Market Design ("Onion Problem")

(1) "Sunk Cost is Sunk" Dictum: Swing-contract book [1, Sec. 3.2.7]

A Decision-Maker (DM) must decide at some time \( t \) whether to commit to undertaking an action \( A \) at a future time \( t+1 \). In making this decision, the DM should ignore sunk cost, where:

\[
\text{Sunk Cost} =: \text{Non-Avoidable Fixed Cost}
\]

\[
=: \text{Cost } C^o \text{ that:}
\]
(i) the DM incurs \textit{whether or not} the DM commits at time \( t \) to undertaking action \( A \) at time \( t+1 \);
(ii) \textit{does not} depend on the \textit{specific} form of \( A \).

(2) Action Optimization Principle: Swing-contract book [1, Sec. 3.2.7]

A risk-averse Decision-Maker (DM) must decide at some time \( t \) whether to commit to undertaking an action \( A \) at a future time \( t+1 \). The DM should make this commitment at time \( t \) only if the DM expects to attain a non-negative net benefit from doing so, where:

\[
\text{Net Benefit} =: [\text{Benefit}] - [\text{Avoidable Cost}]
\]

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

\[
\text{Avoidable Fixed Cost} =: \text{Cost } C^o \text{ that:}
\]
(i) the DM incurs \textit{if and only if} the DM commits at time \( t \) to undertaking action \( A \) at time \( t+1 \);
(ii) \textit{does not} depend on the \textit{specific} form of \( A \).

\[
\text{Variable Cost} =: \text{Cost } C(A) \text{ that:}
\]
(i) the DM incurs \textit{if and only if} the DM commits at time \( t \) to undertaking action \( A \) at time \( t+1 \);
(ii) \textit{does} depend on the \textit{specific} form of \( A \).
(3) Fundamental Product Definition Problem in U.S. RTO/ISO-Managed Markets


— To guarantee net-load balancing during a future operating period $T$, attention in forward markets for $T$ should be switched

from a deterministic focus on:

scheduling now the energy amounts (MWh) for later RTO/ISO-dispatched delivery at designated grid locations during $T$

to a risk-aware focus on:

securing now the availability of suitably diverse collections of power-paths for possible later RTO/ISO-dispatched delivery at designated grid locations during $T$

where:

a power-path for $T$ is a sequence $p(T) = \{ p(t) \mid t \in T \}$ of power injections/withdrawals $p(t) \, (MW)$ at a single grid location during $T$.

(4) Ptolemaic Epicycle Conundrum for Market Design (“Onion Problem”)

— A fundamental conceptual problem with an initial core rule-set specified for a market design results in operational problems.

— These operational problems are addressed by instituting a layer of new rules (“epicycle”) around the initial core rule-set, which results in additional operational problems.

— Rule-layer accretion then continues to occur because, ignoring the “Sunk Cost is Sunk” Dictum (1), correction of the initial fundamental conceptual problem always seems too costly to undertake.