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

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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.
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

$$\text{Avoidable Cost} = \text{Avoidable Fixed Cost} + \text{Variable Cost}$$

(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: *Spot Market Example*

- Suppose energy (MWh) is produced and sold in the form of *uniformly packaged batteries*.
- At any given time and retail location, each battery sells at a *common retail price* $\pi_{\text{Ret}} (\$/battery)$ that covers wholesale production cost (“$W$”) plus transport/damage cost (“Trans”).

**Fig. 1:** *Energy (MWh) in uniform battery form can be transacted as a commodity.*

**Note:** The decomposition of the spot price $\pi_{\text{Ret}}$ into “$W$” and “Trans” components is analogous to the decomposition of a locational marginal price 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 \( p(T) \) in a time-power plane.*
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

Why Not?

- **Power-paths** do *not* have a *standard unit of measurement* such that power-path “units” available for delivery at a grid-location b during an operating period T can be substituted for each other with *no* change in valuation.

- To the contrary, power-paths can have *diverse attributes* that result in *diverse valuations* by producers, customers, and/or RTOs/ISOs.

Examples:

- Down/up ramping *profile* during T can affect producer cost (wear & tear) during T;
- Active power *profile* during T can affect customer benefit during T;
- Reactive power *profile* during T can affect power system reliability during T,

where:

  profile during T =: *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 $T$.

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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 $\text{SC}_m$ 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 $\text{SC}_m$ 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 $\text{SC}_m$ 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.
Design Overview: RTO/ISO Management

☐ 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, \textit{conditional on} initial state conditions \textit{and subject to} system constraints.

☐ RTO/ISO cost allocation rules to ensure \textit{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 \textit{anticipated volatility/size} and \textit{ex-post realization} of their \textit{net fixed load during T}, where:

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

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

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

— \textit{relative power imbalance \textit{RPI}(b,T)} recorded at each grid location \textit{b} during \textit{T}; and

— \textit{relative contribution of each M(T)-participant } j \text{ to \textit{RPI}(b(j),T), where } b(j) =: j’s grid location.
Swing contract

![Swing contract formula](image)

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 \(p \in PP_m\) 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 ex ante (i.e., in advance of $T$) on the nature of $m$'s offered period-T power-path delivery;
- to verify ex post (i.e., after $T$) the extent to which $m$'s actual period-T power-path delivery deviates from admissible dispatch set-points that the RTO/ISO has communicated to $m$ during $T$ (if any).

**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 delivered energy ($E$), power mileage ($PM$), duration ($D$), etc.

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

Costs assigned to correlated attributes of a 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.

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

where:

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

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

- **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
Example 3: A swing contract in firm form offering battery...Continued

Fig. 6: Suppose $SOC^s = SOC^e = \{100\%\}$, and $P_{\text{min}} = -P_{\text{max}}$. 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]

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

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 \(t^s\)

\(P = [p_{min}, p_{max}] = \) 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 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 M(T): 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 M(T): 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, ...)

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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.
SC DAM 30-Bus Test Case: Contract-clearing optimization in an analytical Mixed Integer Linear Programming (MILP) Form

**Note:** The operating day D+1 is discretized into time-steps \( k \) in \( K \), and all load is assumed to be fixed.

**RTO/ISO Objective:** All load fixed \( \rightarrow \) [Max Expected Net Benefit] \( \equiv \) [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:

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

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

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

**Variables determined by RTO/ISO Decisions and System Constraints:**
- Run-time minimum power levels: \( \underline{p}_m(k) \), \( \forall m \in \mathcal{M} \), \( k \in K \)
- Run-time maximum power levels: \( \overline{p}_m(k) \), \( \forall m \in \mathcal{M} \), \( k \in K \)
- Unit availability indicators: \( \nu_m(k) \in \{0, 1\} \), \( \forall m \in \mathcal{M} \), \( k \in K \)
- Transmission line power flows: \( w_\ell(k) \), \( \forall \ell \in \mathcal{L} \), \( k \in K \)
- Power balance slack variables: \( \beta_b(k), \beta_b^-(k), \beta_b^+(k) \), \( \forall b \in \mathcal{B} \), \( k \in K \)
- Bus voltage angle for reference bus 1: \( \theta_1(k) \), \( \forall k \in K \)
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</th>
<th>OC(Z,Dj)</th>
<th>E^(PC(Z,Dj))</th>
<th>E^(IC(Z,Dj))</th>
</tr>
</thead>
<tbody>
<tr>
<td>D₀</td>
<td>Proposed</td>
<td>z₁: 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>z₂: Bus 27 29 30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>z₃: Bus 1-22 24 25 26 28</td>
<td>[1, 1, 1, 1, 1, 1]</td>
<td>$8,750</td>
<td>$106,420.12</td>
<td>$5,371.73</td>
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<tr>
<td></td>
<td>Single Zone</td>
<td>z₁: Bus 1-30</td>
<td>[1, 1, 1, 1, 1, 0, 1]</td>
<td>$8,750</td>
<td>$107,670.78</td>
<td>$5,371.73</td>
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<tr>
<td>D₁</td>
<td>Proposed</td>
<td>z₁: 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>
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<td></td>
<td></td>
<td>z₂: Bus 21 22 24-27 29 30</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>z₃: Bus 1-20 28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single Zone</td>
<td>z₁: Bus 1-30</td>
<td>[1, 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>z₁: Bus 23 24 25 26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>z₂: Bus 27 29 30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>z₃: Bus 1-22 28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single Zone</td>
<td>z₁: Bus 1-30</td>
<td>[1, 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 a Given Operating Period T**

- Linked SC markets $M(T)$ 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 $M(T)$ 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 ISOPort(T)* in successive SC markets $M(T)$ held *prior to T* to include any *newly-cleared* contracts for $T$.

![Diagram showing time periods D-365, D, D+1 with linkages between Long, Short, Very Short Term Forward Markets](image)

<table>
<thead>
<tr>
<th>D-365</th>
<th>D</th>
<th>D+1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Long-Term</strong></td>
<td><strong>Short-Term</strong></td>
<td><strong>Very Short-Term</strong></td>
</tr>
<tr>
<td>Forward Markets</td>
<td>Forward Markets</td>
<td>Forward Markets</td>
</tr>
</tbody>
</table>

$L-M(T)$  $S-M(T)$  $VS-M(T)$
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).

### 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&lt;br&gt;• RTO/ISO-managed&lt;br&gt;• Participants include LSEs, dispatchable resources, &amp; VERs&lt;br&gt;• Same types of system constraints (line capacity limits; power balance; gen attributes; reserve requirements; ... )</td>
<td>SCUC &amp; SCED</td>
<td>Swing-contract clearing</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Differences</th>
<th>Current DAM SCUC</th>
<th>Current DAM SCED</th>
<th>SC DAM Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similarities</td>
<td>Both SCUC and swing-contract (SC) clearing are solved as mixed integer linear programming (MILP) optimization problems subject to system constraints</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Objective</td>
<td>Min [Start-up/shut-down costs + no-load costs + dispatch costs + reserve costs]</td>
<td>Min [Dispatch costs + reserve costs]</td>
<td>Min [Offer cost + expected performance cost + expected imbalance cost]</td>
</tr>
<tr>
<td>Unit commitment</td>
<td>Yes</td>
<td>No</td>
<td>Unit commitment constraints are implicit in submitted swing-contracts</td>
</tr>
<tr>
<td>constraints</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Key ISO decision</td>
<td>Unit commitments</td>
<td>Energy dispatch &amp; reserve levels</td>
<td>Which swing-contracts are cleared</td>
</tr>
<tr>
<td>variables</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Settlement</td>
<td>No</td>
<td>LMPs calculated as SCED dual variables</td>
<td>Offer prices paid for cleared swing-contracts</td>
</tr>
</tbody>
</table>

**Fig. 9:** An ITD System with IDSO linkage agents, implemented by the ITD TES Platform V2.

See: ITD Project Homepage, [https://www2.econ.iastate.edu/tesfatsi/ITDProjectHome.htm](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 permits 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/SCBookReview.IEEEPESMag2022.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 whether or not the DM commits at time $t$ to undertaking action $A$ at time $t+1$;

(ii) does not depend on the 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 if and only if the DM commits at time $t$ to undertaking action $A$ at time $t+1$;

(ii) does not depend on the specific form of $A$.

$$\text{Variable Cost} =: \text{Cost } C(A) \text{ that:}$$

(i) the DM incurs if and only if the DM commits at time $t$ to undertaking action $A$ at time $t+1$;

(ii) does depend on the specific form of $A$.
Appendix: Ptolemaic Epicycle Conundrum for Market Design ... Continued

(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 \( p(T) = \{ p(t) \mid t \text{ in } T \} \) 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 to be too costly to undertake.