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

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Efficiency through Improved Software
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SC Book [1]: Preface

SC Book [1] L. Tesfatsion (2021), *A New Swing-Contract Design for Wholesale Power Markets*, 20 Chapters, 288pp., John Wiley & Sons, Inc. (IEEE Press Series on Power Engineering), Hoboken, New Jersey, USA.
https://www2.econ.iastate.edu/tesfatsi/ANewSwingContractDesign.Flyer.WileyIEEEPress.pdf

— 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.

➢ **SC Book [1] proposes a new Linked Swing-Contract Market Design, consistent with [MD1] – [MD4],** that could meet the needs of U.S. RTO/ISO-managed wholesale power markets better than currently implemented designs.

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")*

1. Current RTO/ISO-Managed Markets: Net-Zero 2050 Concerns

❑ 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

net load **=:** [Power withdrawals/losses] **–** [***non***-dispatched power injections]

≈ [***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 **T**ransactive **E**nergy **S**ystem (**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: **D**ay-**A**head **M**arket **DAM**(**D+1**) held during day **D** for operating day **D+1**;
Real-**T**ime **M**arket **RTM**(**H**) held during hour **H-1** for operating hour **H**.

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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).

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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

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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 =: Avoidable Fixed Cost + 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* π^{Ret} ($/battery) that covers wholesale production cost ("**W**") plus transport/damage cost ("**Trans**").

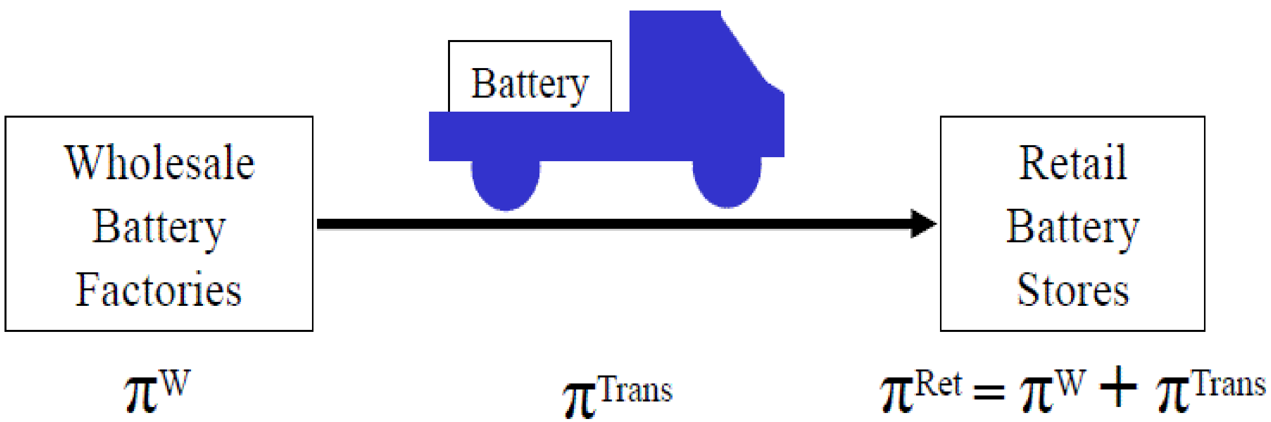

Fig. 1: *Energy (MWh) in uniform battery form can be transacted as a commodity.*

Note: The decomposition of the spot price π^{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.

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.

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

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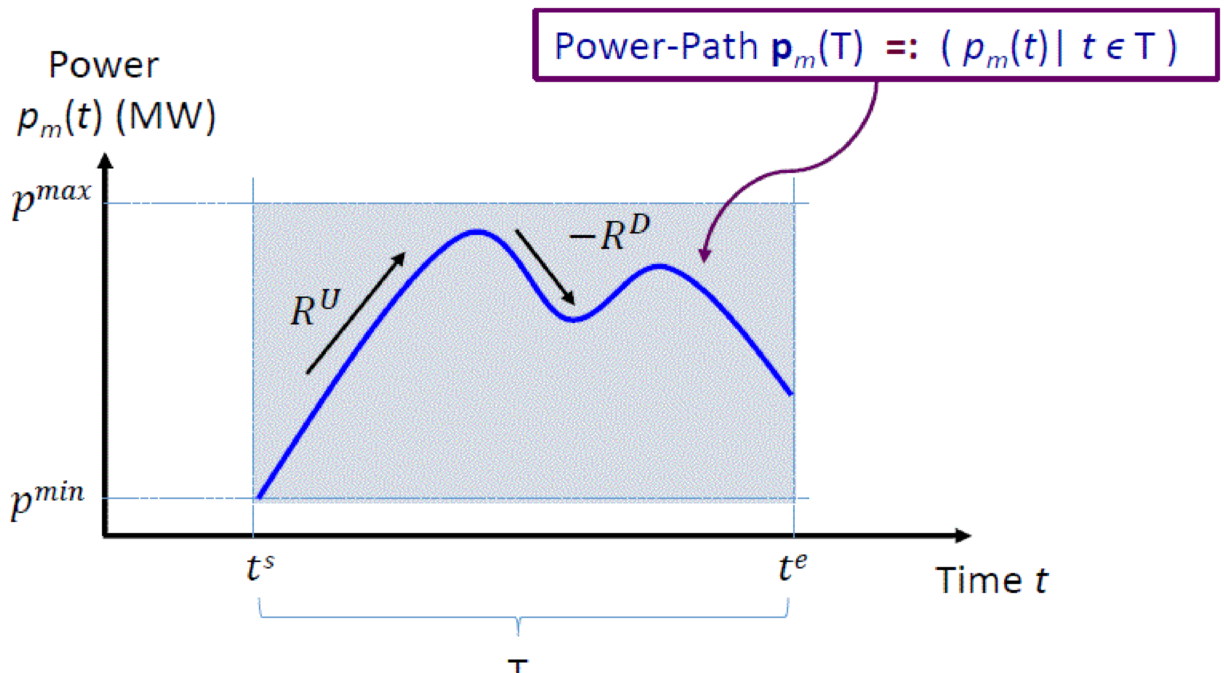


Fig. 2: *Illustrative depiction of a power-path* $\mathbf{p}_m$(T) *in a time-power plane provided by a dispatchable power resource m at its grid point-of-connection b(m) during an operating period T* **.**

Key Point (ii): U.S. RTO/ISO-managed wholesale power markets are ***forward power-path markets***

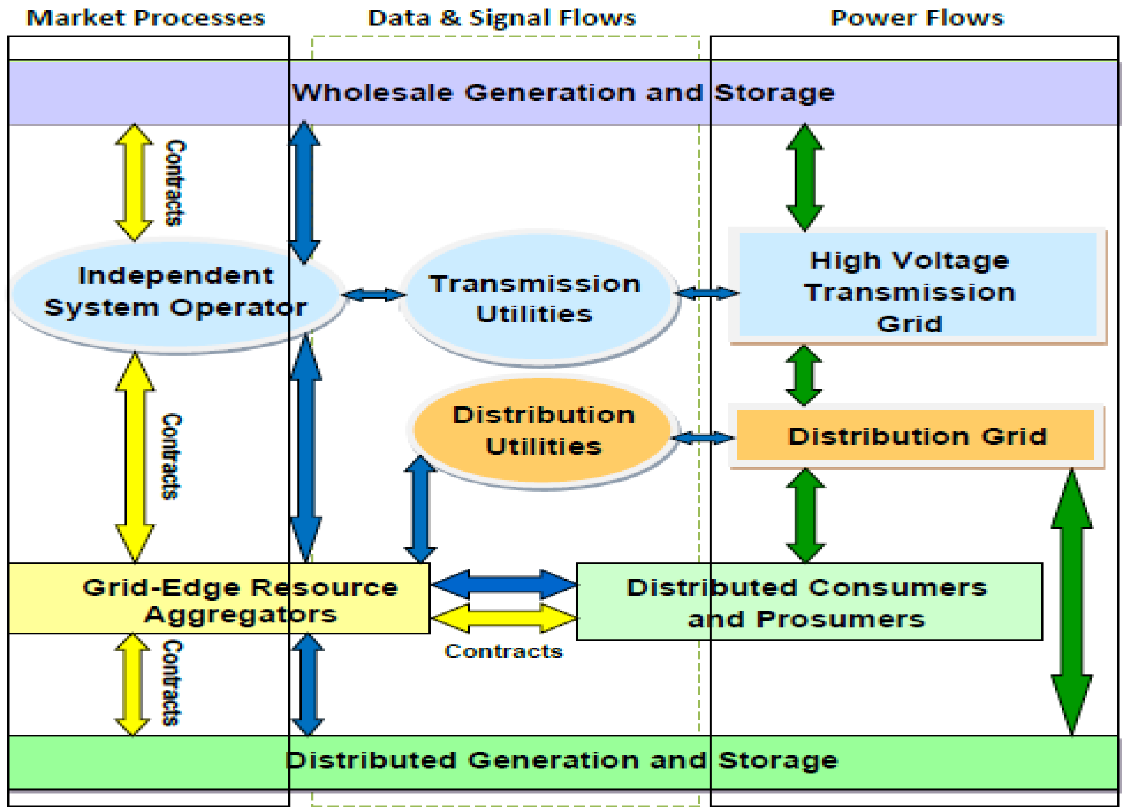


Fig. 3: *An RTO/ISO-managed wholesale power market is* ***a collection of forward markets for ensuring balanced power-path production and deliveries*** *for the transmission component of a T&D System.*

Grid-**E**dge **R**esource **(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.

SC Book [1] Leigh Tesfatsion (2021), *A New Swing-Contract Design for Wholesale Power Markets*, 20 Chapters, 288pp., John Wiley & Sons, Inc. (IEEE Press Series on Power Engineering), Hoboken, N.J.
https://www2.econ.iastate.edu/tesfatsi/ANewSwingContractDesign.Flyer.WileyIEEEPress.pdf

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.

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, *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:

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

  NetFixedLoad(***j***, M(T) **)**

  =: **Period-T net fixed load of an M(T)-participant *j***
  =: **[Fixed (*must-service*) power demand** by ***j*** during T**]** *minus* **[non-dispatched power injection** by ***j*** 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.

❑ Swing contract

$$\mathrm{SC}_m = \left(\alpha_m, \mathbb{T}^{\mathrm{ex}}_m, \mathbb{PP}_m, \phi_m\right)$$

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 $\boldsymbol{\alpha_m}$;

2) exercise set $\mathbf{T}^{\mathbf{ex}}_{\boldsymbol{m}}$ 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 $\boldsymbol{\varphi_m}$.

❑ Swing contract

$$\mathrm{SC}_m = \left(\alpha_m, \mathbb{T}_m^{\mathrm{ex}}, \mathbb{PP}_m, \phi_m\right)$$

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; …

Swing Contract: General Formulation … Continued

- In addition, swing contract SC_m permits *m*:

  - to request an **offer price α_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 φ_m** that maps each power-path $\mathbf{p} \in PP_m$ into a required performance payment $\varphi_m(\mathbf{p})$ (\$). 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 φ_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 $\varphi_m(\mathbf{p})$ of each power-path $\mathbf{p}$ in PP_m as a linear combination of metrics that separately assign costs to correlated attributes of $\mathbf{p}$, such as **delivered energy (*E*), power mileage (*PM*), duration (*D*)**, etc.

$$\varphi_m(\mathbf{p}) \;=\; \underbrace{c^E(\mathbf{p}) + c^{PM}(\mathbf{p}) + c^D(\mathbf{p}) + \ldots}_{\text{Costs assigned to correlated attributes of a single power-path } \mathbf{p}}$$

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.

$$\mathrm{SC}_m = [\alpha,\ \mathbb{PP},\ \phi]$$

where:

$$\alpha = \text{Offer price}$$

$$\mathbb{PP} = (b, t^{\mathsf{s}}, p^{\mathsf{disp}}, t^{\mathsf{e}})$$

$$b = \text{Delivery location}$$

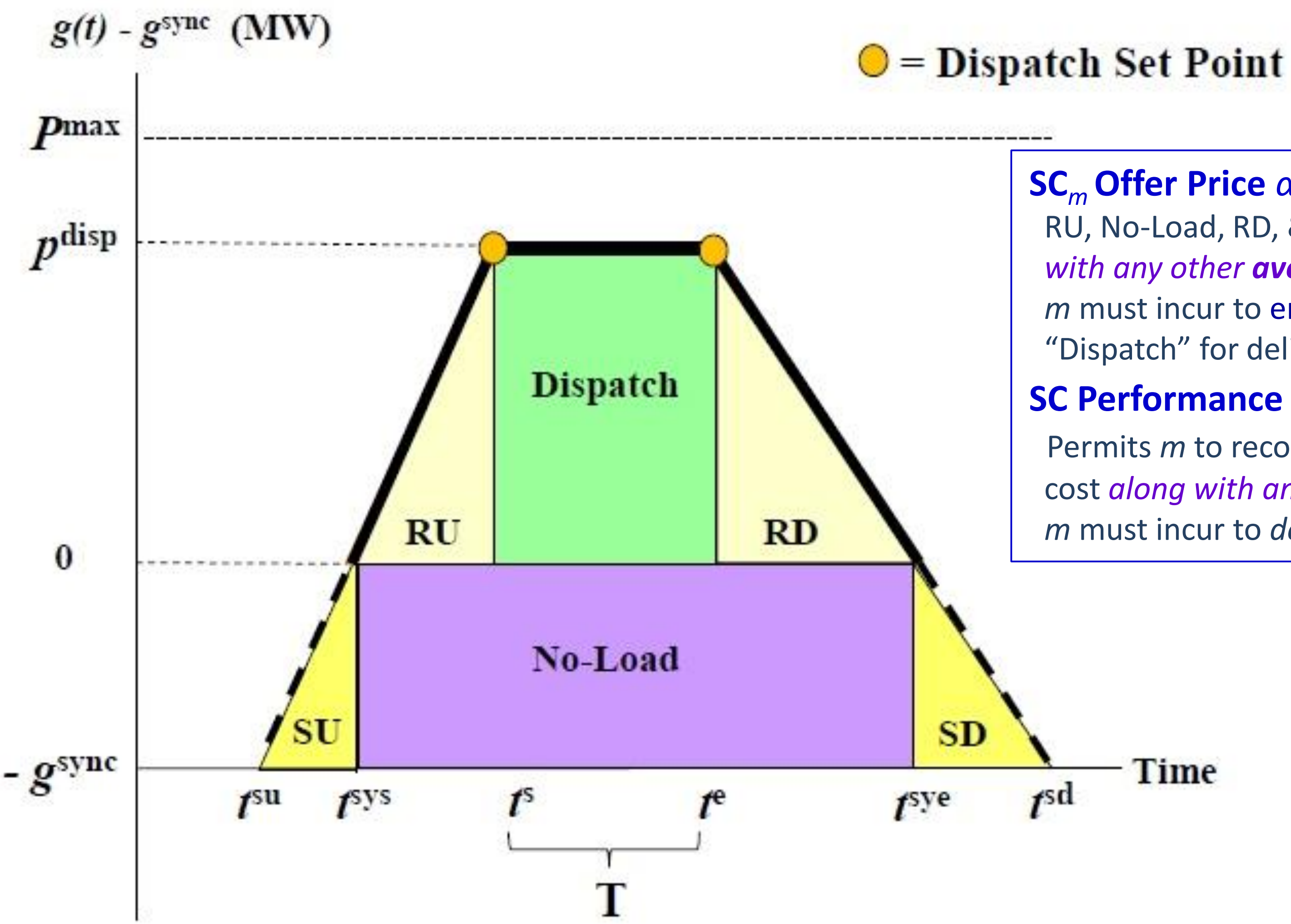
$$t^{\mathsf{s}} = \text{Start time for energy block E}$$

$$p^{\mathsf{disp}} = \text{Maintained power injection for energy block E}$$

$$t^{\mathsf{e}} = \text{End-time for energy block E}$$

$$\phi = \text{Pre-specified price } \pi \text{ for delivered energy}$$

Example 1: *A simple energy-block swing contract … Continued*



SC_m Offer Price α: 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 φ: 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*

$$\mathrm{SC}_m = [\alpha, \mathbb{PP}, \phi]$$

where:

α = Offer price

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

b = Delivery location

t^{s} = Start-time for ramp interval R1

p^{s} = Power injection level at start-time t^{s}

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

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

$\mathbb{P}(\mathrm{E1})$ = Set of feasible maintained power-steps $p_i(\mathrm{E1})$ for E1

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

$\mathbb{RR}(\mathrm{R2})$ = Set of feasible ramp-rates $r(p_i(\mathrm{E1}), p_j(\mathrm{E2}))$ for R2

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

$\mathbb{P}(\mathrm{E2})$ = Set of feasible maintained power-steps $p_j(\mathrm{E2})$ for E2

t^{e} = End-time for E2

ϕ = Payment for ramp and delivered energy calculated by means of power-path mileage and a pre-specified price $\pi(p)$ for each $p \in \mathbb{P}(\mathrm{E1}) \cup \mathbb{P}(\mathrm{E2})$

Example 2: *A piecewise-linear swing contract … Continued*

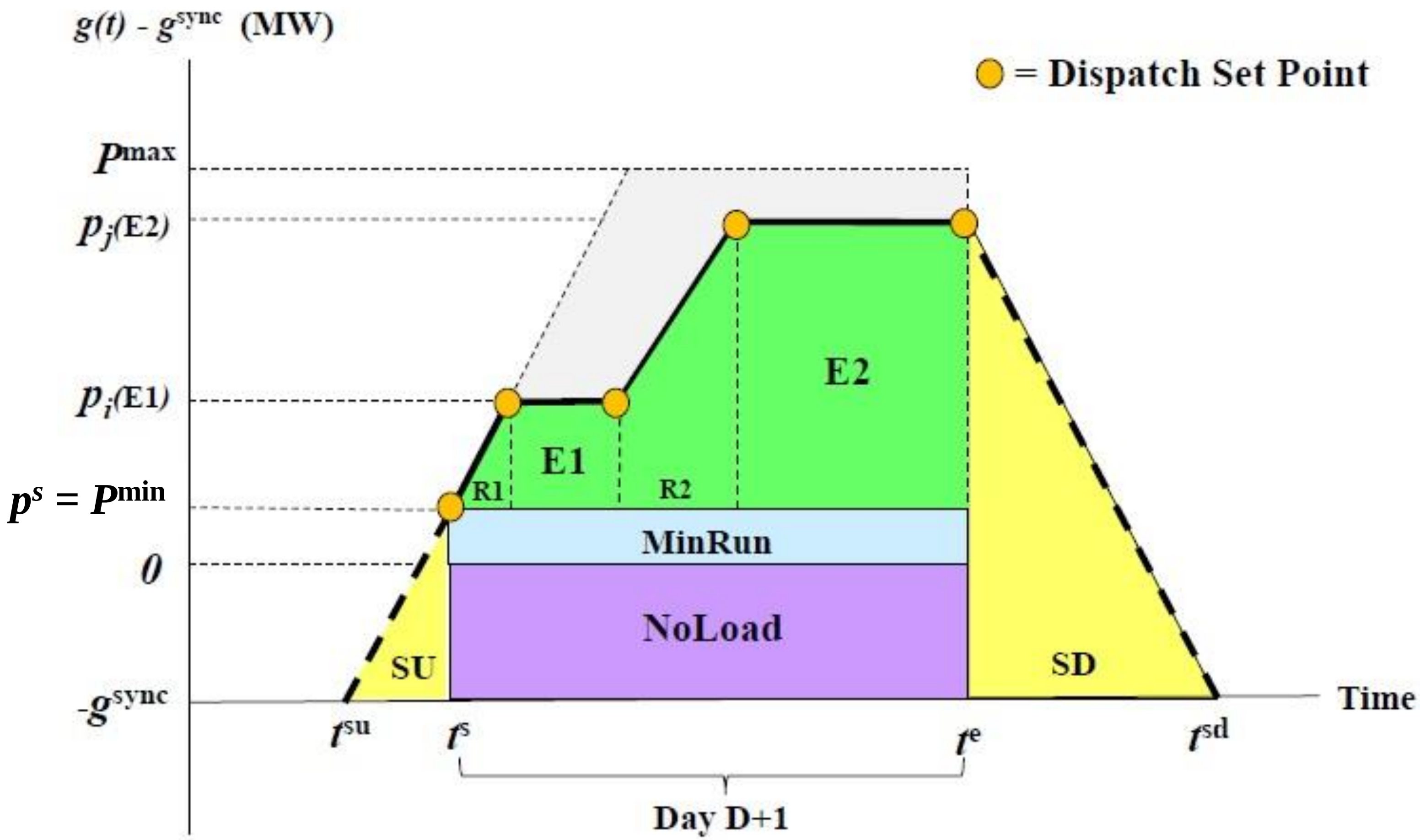


Fig. 5: ***One among many possible power-paths p*** *the RTO/ISO could dispatch m to deliver during operating day D+1 if the RTO/ISO clears m's piecewise-linear swing contract* SC_m *submitted to an SC day-ahead market M(D+1) held on day D.*

Example 3: *A swing contract in firm form offering battery charge/discharge as an ancillary service*

$$\mathrm{SC}_m = [\alpha, \mathbb{PP}, \phi]$$

where:

$\alpha =$ Offer price

$\mathbb{PP} = (b, ECap^{\mathsf{max}}, \eta, t^{\mathsf{s}}, \mathbb{SOC}^{\mathsf{s}}, \mathbb{RR}, \mathbb{P}, t^{\mathsf{e}}, \mathbb{SOC}^{\mathsf{e}})$

$b =$ Delivery location

$ECap^{\mathsf{max}} =$ Maximum energy storage capacity

$\eta =$ Round-trip efficiency

$t^{\mathsf{s}} =$ Start-time for power discharge/charge

$\mathbb{SOC}^{\mathsf{s}} =$ Set of feasible state-of-charge percentages at t^{s}

$\mathbb{P} = [P^{\mathsf{min}}, P^{\mathsf{max}}] =$ Range of feasible discharge/charge levels p

$\mathbb{RR} = [-R^{\mathsf{D}}, R^{\mathsf{U}}] =$ Range of feasible ramp-rates r

$t^{\mathsf{e}} =$ End-time for power discharge/charge

$\mathbb{SOC}^{\mathsf{e}} =$ 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*

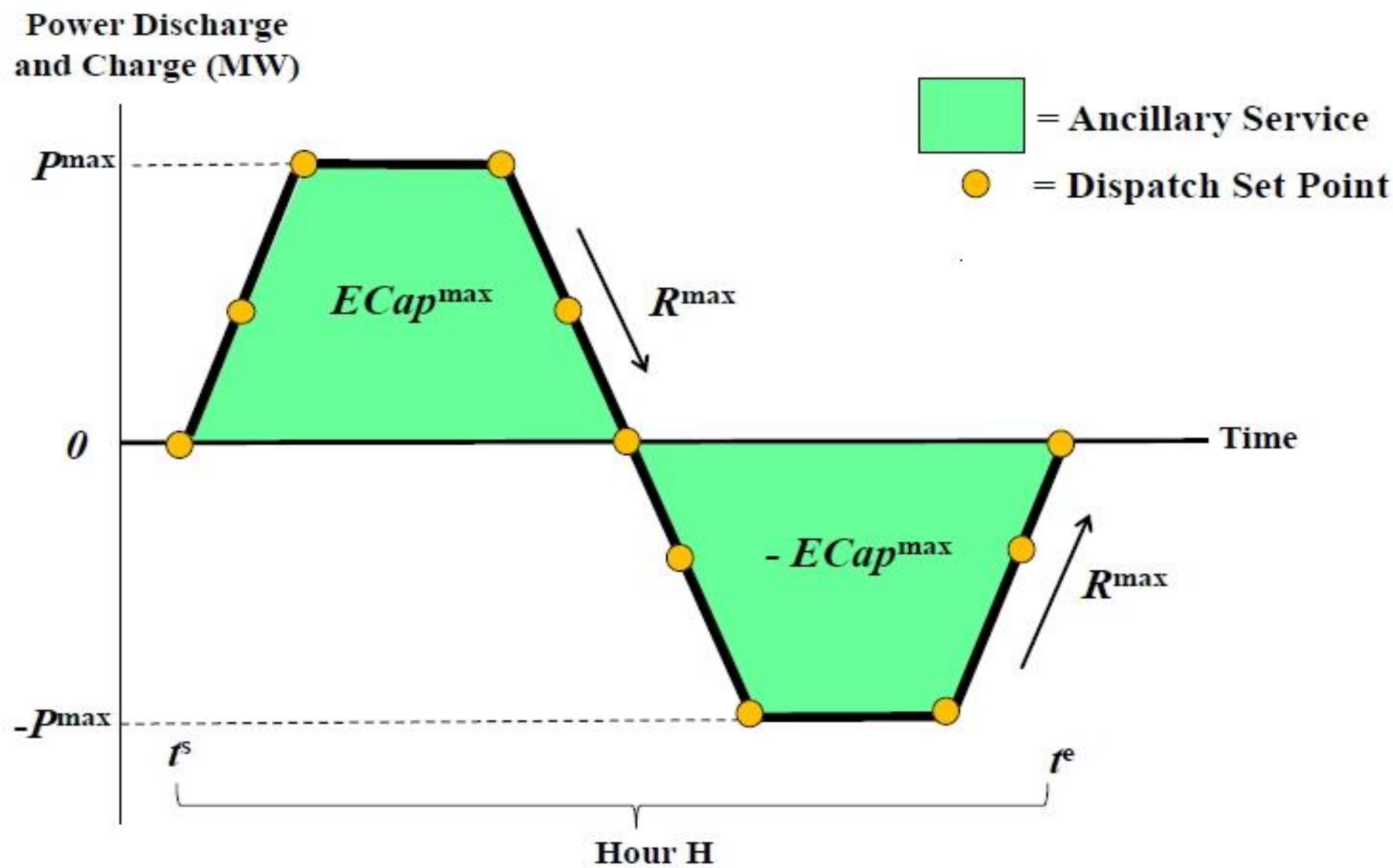


Fig. 6: *Suppose* **SOC^s = SOC^e** *= {**100%**}, and* **P^{min}** *=* **- P^{max}**. *Then the depicted dispatched power-path is* ***one among many possible power-paths p*** *the RTO/ISO could dispatch m to deliver during operating hour H = [t^s, t^e) if the RTO/ISO clears m's battery service swing 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]

$$\mathrm{SC}_m = [\alpha, \mathbb{PP}, \phi]$$

where:

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

Example 4: *Swing contract (firm) with flexible power & ramp … Continued*

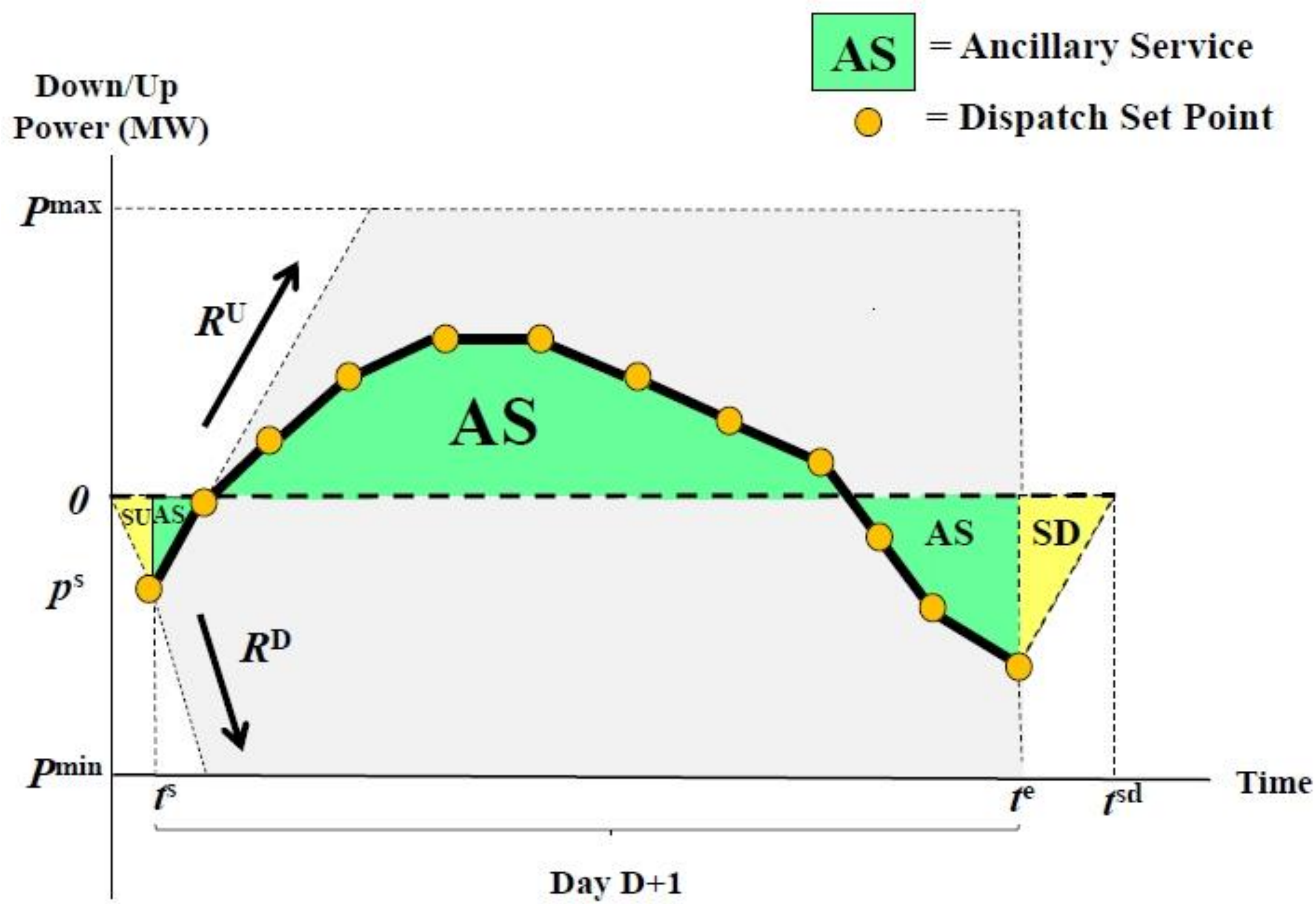
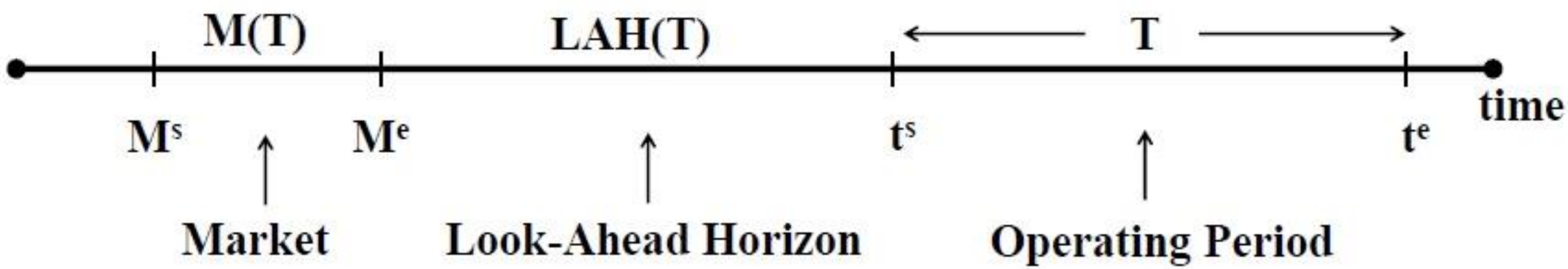


Fig. 7: ***One among many possible power-paths p*** *the RTO/ISO could dispatch m to deliver during operating day D+1 if the RTO/ISO clears m's flexible power/ramp SC submitted to an SC day-ahead market M(D+1) held on day D.*

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 **L**ook-**A**head-**H**orizon **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).

Swing-Contract Market: Key Features … Participants

- **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

$$\mathbf{SC}_m = (\,SC_{m1}, \ldots, SC_{mN}\,)$$

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:

  Total Net Benefit **=:** [Reserve Benefit **–** Reserve Cost]

  Reserve Benefit **=:** [Customer benefit expressed by their reserve bids]

  Reserve Cost **=:** [Offer Cost (OC) **+** Performance Cost (PC) **+** 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, …)

Swing-Contract Market: Key Features … Optimization Continued

- 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.

Swing-Contract Market: Key Features … Optimization Continued

- 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

[2] Shanshan Ma, Zhaoyu Wang, and Leigh Tesfatsion (2019), "Swing Contracts with Dynamic Reserves for Flexible Service Management," *IEEE Trans. on Power Systems*, 34(5), 4024-4037.

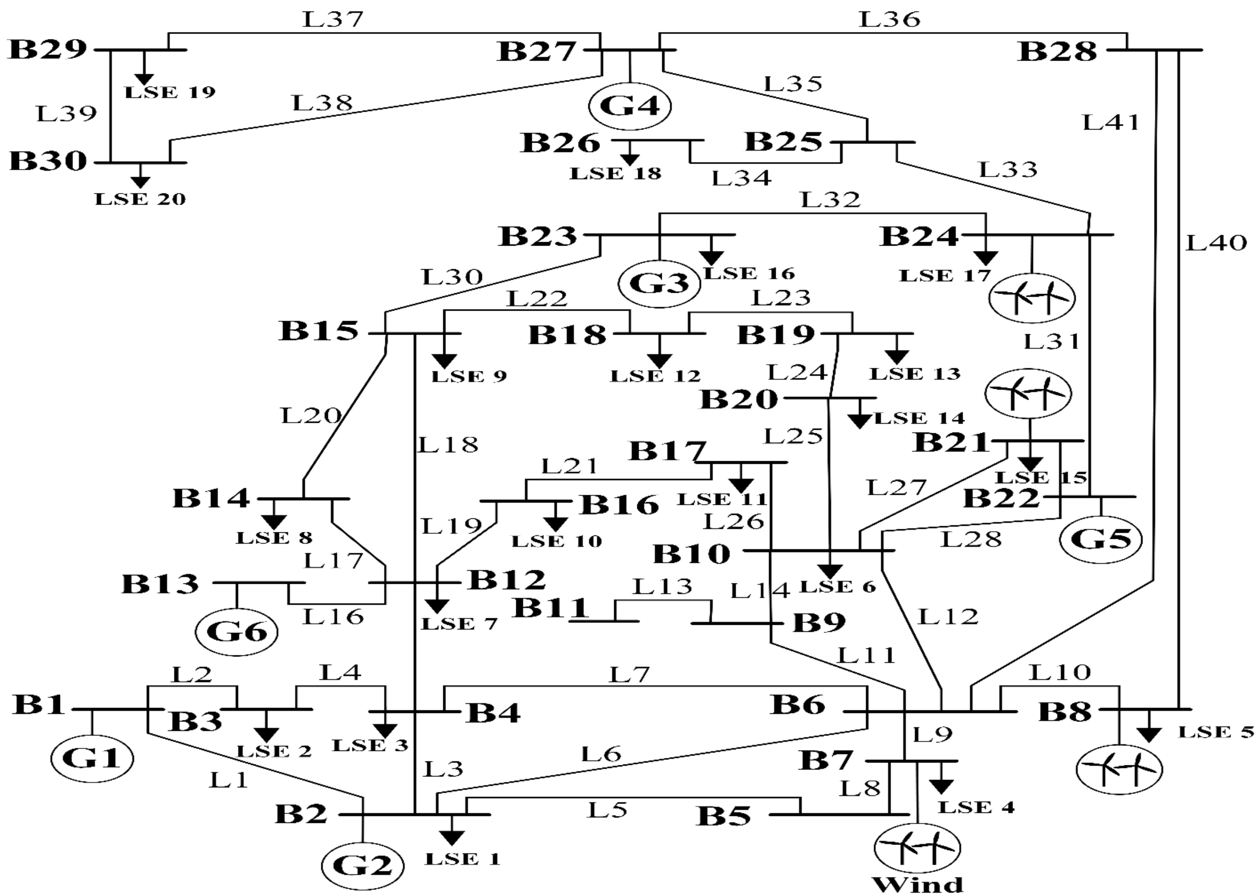


Fig. 8: Grid for 30-Bus Test Case. *30 buses B1-B30; 41 transmission lines L1-L41; 6 dispatchable thermal generators G1-G6; 4 non-dispatchable wind farms located at buses B7, B8, B21, and B24; and 20 LSEs servicing fixed load at 20 different buses.*

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** ⟶ [*Max* Expected Net Benefit] ≡ [*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:

$$\widehat{C}(T) = \underbrace{\sum_{m\in\mathbb{M}} [c_m\alpha_m}_{\text{Offer Cost (OC)}} + \underbrace{\phi_m(\mathbf{p}_m)]}_{\text{Performance Cost (PC)}} + \underbrace{\sum_{b\in\mathbb{B}}\sum_{k\in\mathbb{K}} [\Lambda^-\beta_b^-(k) \ + \ \Lambda^+\beta_b^+(k)]\Delta t}_{\text{Imbalance Cost (IC)}}$$

Imbalance Cost (IC) = "Canary in the Coal Mine"

RTO/ISO Binary Decision Variables:

- Contract clearing indicators: $c_m \in \{0,1\}, \ \forall m \in \mathbb{M}$

RTO/ISO Continuously-Valued Decision Variables:

- Power dispatch levels: $p_m(k), \ \forall m \in \mathbb{M}, \ k \in \mathbb{K}$
- Bus voltage angles: $\theta_b(k), \ \forall b \in \mathbb{B}/\{1\}, \ k \in \mathbb{K}$

Variables determined by RTO/ISO Decisions and System Constraints:

- Run-time minimum power levels: $\underline{p}_m(k), \ \forall m \in \mathbb{M}, \ k \in \mathbb{K}$
- Run-time maximum power levels: $\overline{p}_m(k), \ \forall m \in \mathbb{M}, \ k \in \mathbb{K}$
- Unit availability indicators: $v_m(k) \in \{0,1\}, \ \forall m \in \mathbb{M}, \ k \in \mathbb{K}$
- Transmission line power flows: $w_\ell(k), \ \forall \ell \in \mathbb{L}, \ k \in \mathbb{K}$
- Power balance slack variables: $\beta_b(k), \beta_b^-(k), \beta_b^+(k), \ \forall b \in \mathbb{B}, \ k \in \mathbb{K}$ ⟵ (Imbalance Cost)
- Bus voltage angle for reference bus 1: $\theta_1(k), \ \forall k \in \mathbb{K}$

SC DAM 30-Bus Test Case … Continued

Outcomes for Offer Cost (OC); Performance Cost (PC); and Imbalance Cost (IC)

Table 6.6 Thirty-bus SC DAM performance over three successive days for two different reserve zone treatments

Day D_j	Treatment	Reserve Zones zj	Contract Clearing $c_{G1}, c_{G2}, c_{G3}, c_{G4}, c_{G5}, c_{G6}$	$OC(Z,D_j)$	$E^{xp}[PC(Z,D_j)]$	$E^{xp}[IC(Z,D_j)]$
D_0	Proposed	$z1$: Bus 23 $z2$: Bus 27 29 30 $z3$: Bus 1-22 24 25 26 28	[1,1,1,1,1,1]	\$10,750	\$100,555.65	\$194.22
	Single Zone	$z1$: Bus 1-30	[1,1,1,1,0,1]	\$8,750	\$106,420.12	\$5,371.73
D_1	Proposed	$z1$: Bus 23 $z2$: Bus 21 22 24-27 29 30 $z3$: Bus 1-20 28	[1,1,1,1,1,1]	\$10,700	\$98,012.73	\$10,359.74
	Single Zone	$z1$: Bus 1-30	[1,1,1,1,0,1]	\$9,100	\$99,996.96	\$13,990.73
D_2	Proposed	$z1$: Bus 23 24 25 26 $z2$: Bus 27 29 30 $z3$: Bus 1-22 28	[1,1,1,1,1,1]	\$9,410	\$104,494.04	\$10,597.97
	Single Zone	$z1$: Bus 1-30	[1,1,1,1,0,1]	\$7,810	\$105,077.11	\$13,282.30

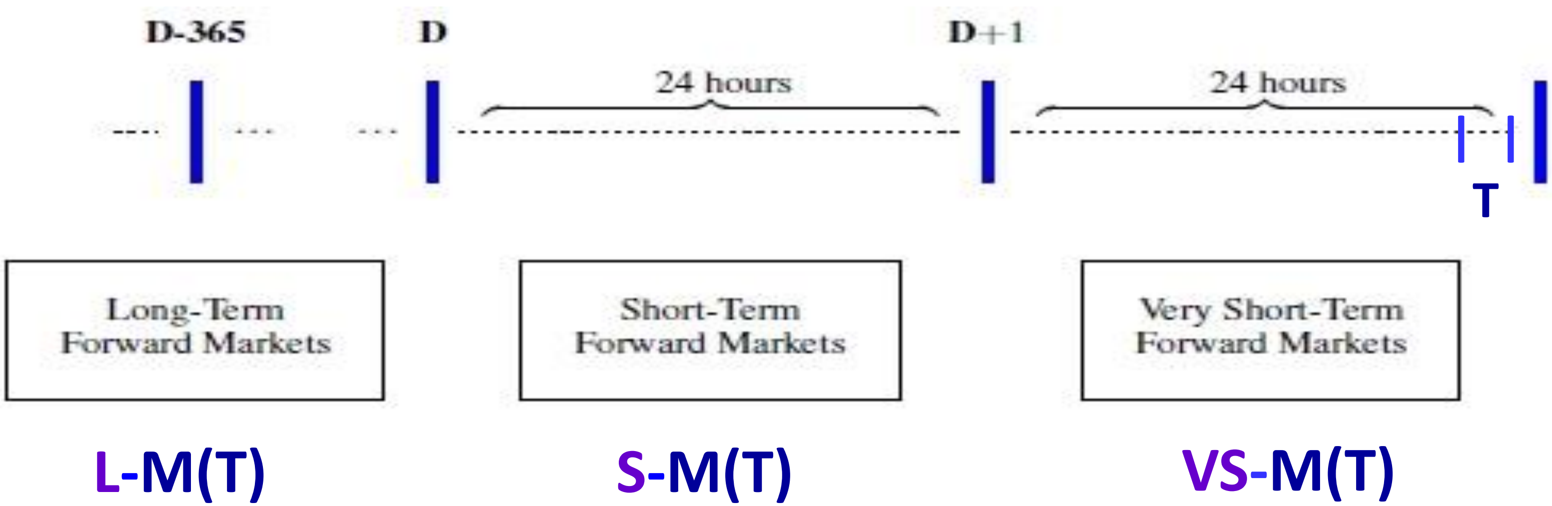
Example 1: Intertemporal Linkages for Given Operating Period T

— Linked SC markets **M(T)** for a *given* future operating period **T** with **L**ook-**A**head **H**orizons **LAH**(**T**) ranging from *L*ong (*L*) to *S*hort *(S)* to *V*ery *S*hort *(VS).*

— Linkage is established among the successive markets **M(T)** for the given **T** by

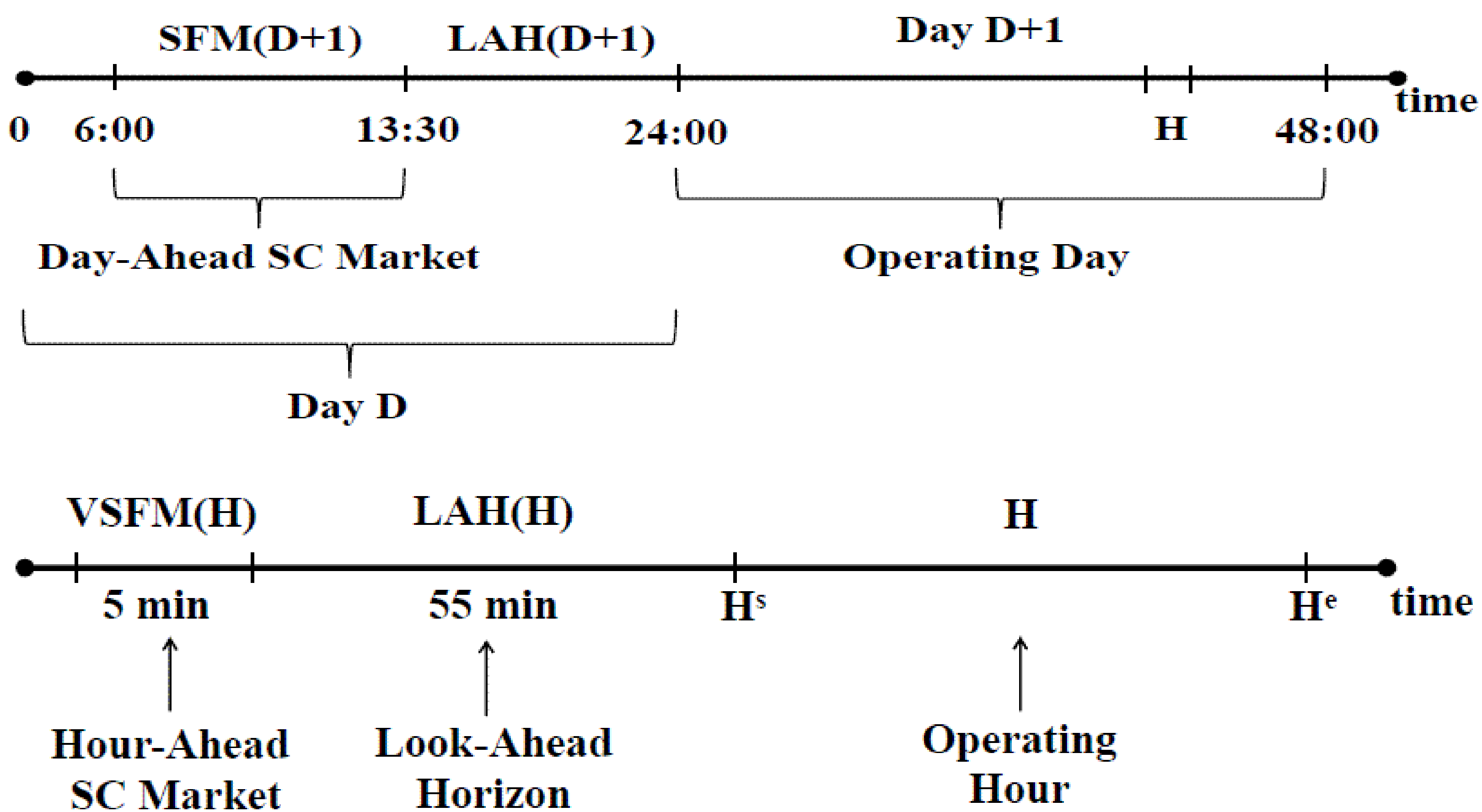
ISOPort(T) =: Portfolio of reserve bids and reserve offers cleared for **T** that the RTO/ISO carries forward through time for use during **T**.

— The RTO/ISO *updates* **ISOPort(T)** in *successive* SC markets **M(T)** held *prior to* **T** to include any *newly-cleared* contracts for **T**.



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 **D**ay-**A**head **M**arket (**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

		Current DAM	SC DAM
Similarities		• Conducted day-ahead to plan for next-day operations • RTO/ISO-managed • Participants include LSEs, dispatchable resources, & VERs • Same types of system constraints (line capacity limits; power balance; gen attributes; reserve requirements; …)	
Differences	Optimization formulation	SCUC & SCED	Swing-contract clearing
	Settlement	Locational marginal prices	Contract-determined prices
	Payment	Payment for next-day energy before energy delivery	Payment for reserve availability now & reserve performance ex post
	Out-of-market payments	Make-whole payments (e.g., for unit commitment)	No out-of-market payments
	Info released to participants	Unit commitments, LMPs, & next-day dispatch schedule	Which swing-contracts have been cleared

3.2 Illustrative DAM Comparison … Optimization

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

4. Swing-Contract Support for Integrated Transmission and Distribution (ITD) Systems

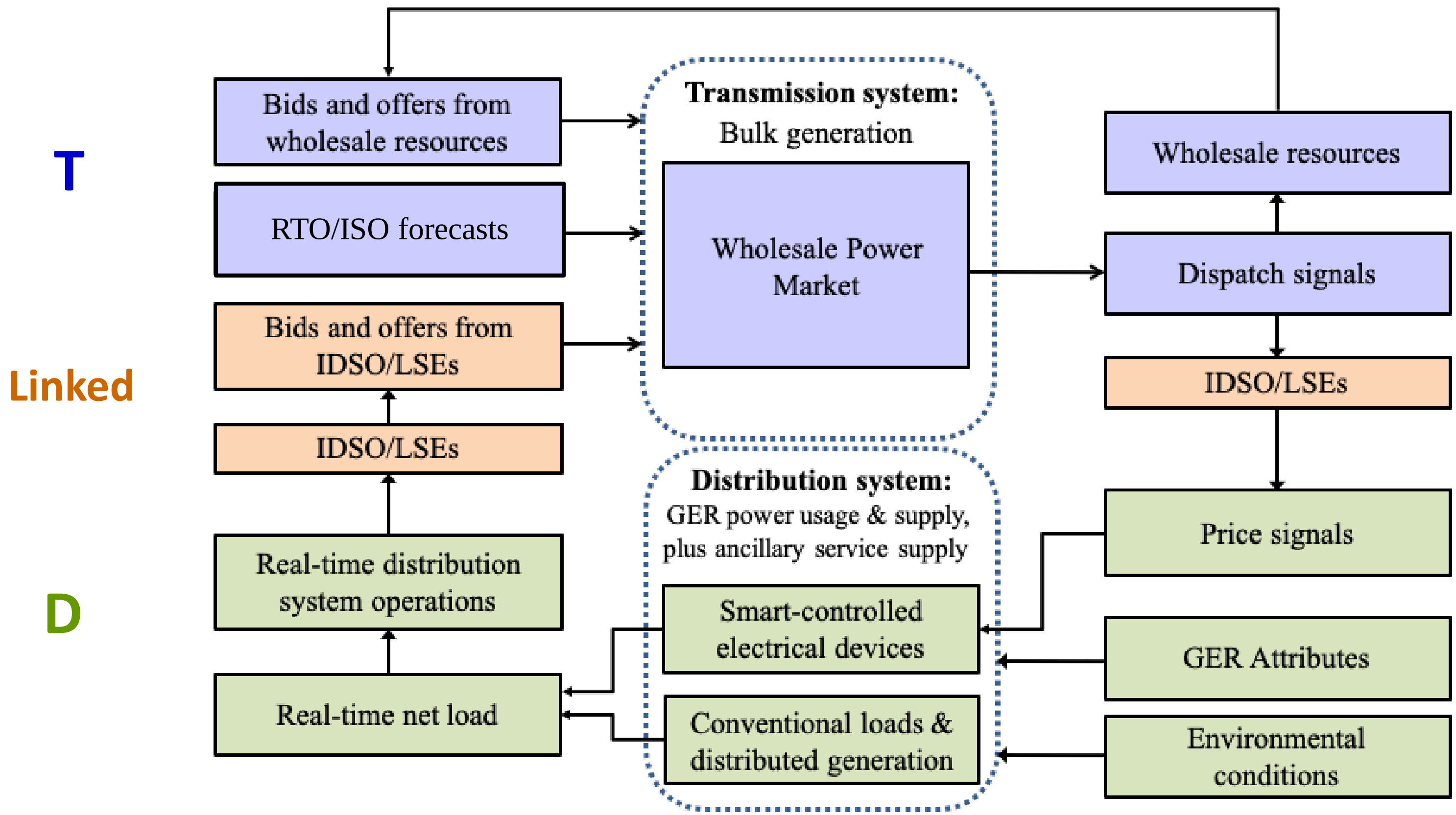


Fig. 9: *An ITD System with IDSO linkage agents, implemented by the ITD TES Platform V2.*

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 **I**ndependent **D**istribution **S**ystem **O**perators (**IDSO**s) in RTO/ISO-managed wholesale power markets as providers of ancillary services harnessed from **G**rid-**E**dge **R**esources (**GER**s), 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 = (α, PP, ϕ) 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 α; and the **RTO/ISO *is obligated to select*** some power-path **p*** ϵ 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 **T**ransactive **E**nergy **S**ystem (**TES**) design to determine these retail price signals during day D+1: namely, the bid-based **Five-Step TES Design** developed in:

➡ [5] Swathi Battula, Leigh Tesfatsion, and Zhaoyu Wang (2020), **"A Customer-Centric Approach to Bid-Based Transactive Energy System Design"** (**IEEEPreprint,1.2MB**), *IEEE Trans. on Smart Grid* 11(6), pp. 4996-5008.

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.*

Conclusion … Continued

- 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 D**ay-**A**head **M**arket (**DAM**) [1, Ch. 16]

  — Potential future research directions [1, Ch. 19]

6. References

[1] Leigh Tesfatsion (2021), *A New Swing-Contract Design for Wholesale Power Markets*, 20 Chapters, 288pp., Wiley (IEEE Press Series on Power Engineering), Hoboken, New Jersey.

https://www2.econ.iastate.edu/tesfatsi/SwingContractMonograph.TOCIntro.LTesfatsion.pdf
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[2] Shanshan Ma, Zhaoyu Wang, and Leigh Tesfatsion (2019), "Swing Contracts with Dynamic Reserves for Flexible Service Management," *IEEE Trans. on Power Systems*, 34(5), 4024-4037.

https://www2.econ.iastate.edu/tesfatsi/SwingContractsWithDynamicReserves.PreprintIEEETPWRS.pdf

[3] Wanning Li and Leigh Tesfatsion (2018), "A Swing-Contract Market Design for Flexible Service Provision in Electric Power Systems," Chapter 5 (pp. 105-127) in: Sean Meyn, Tariq Samad, Ian Hiskens, and Jakob Stoustrup (Eds.), *Energy Markets and Responsive Grids: Modeling, Control, and Optimization,* The IMA Volumes in Mathematics and its Applications Series, Springer.

https://www2.econ.iastate.edu/tesfatsi/SwingContractMarketDesign.LiTesfatsion.WP17020.pdf

[4] Leigh Tesfatsion, César A. Silva-Monroy, Vernon W. Loose, James F. Ellison, Ryan T. Elliott, Raymond H. Byrne, and Ross T. Guttromson (2013), *A New Wholesale Power Market Design Using Linked Forward Markets: A Study for the DOE Energy Storage Systems Program*, Sandia Report, SAND2013-2789, Unlimited Release, April.

https://www2.econ.iastate.edu/tesfatsi/MarketDesignSAND2013-2789.LTEtAl.pdf

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

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

A **D**ecision-**M**aker (**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:

Sunk Cost =: **Non-Avoidable Fixed Cost**

=: **Cost C^o 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 **D**ecision-**M**aker (**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:

Net Benefit =: **[Benefit] - [Avoidable Cost]**

Avoidable Cost =: **[Avoidable Fixed Cost] + [Variable Cost]**

Avoidable Fixed Cost =: **Cost C^o 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.***

Variable Cost =: **Cost *C(A)* 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

SC book [1, Secs. 14.2-14.4]

— 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)* | *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.