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

Leigh Tesfatsion

Research Professor of Economics, Courtesy Research Professor of
Electrical & Computer Engineering, and Professor Emerita of Economics,
Iowa State University, Ames, IA 50011-1054
https://www2.econ.iastate.edu/tesfatsi/
tesfatsi@iastate.edu

Slide-Set Materials Summarizing Key Topics Addressed in:

***Supporting Document (Attachment A) for e-filed Comments:**
L. Tesfatsion, Accession No. 20230117-5051, U.S. Federal Energy Regulatory Commission,
Docket No. AD21-10-000 (“Modernizing Wholesale Electricity Market Design”)

Presentation Outline

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

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

- ☐ **Possible Remedy:**
  - — An alternative conceptually-consistent **Linked Swing-Contract Market Design** has been proposed, developed, and tested at Technology Readiness Level TRL-3.
  - — This alternative design is well-suited for scalable, efficient, & reliable support of increasingly decarbonized grid operations with increasingly diverse participants.
  - — Adoption of this alternative design by current RTO/ISO-managed markets would require changes in product definition, settlement rules, and supply-offer forms, but not in real-time operations.
  - — Thus, adoption of this design could be implemented through gradual transition.

- ☐ **References**

U.S. Wholesale Power Markets Centrally-Managed by a Regional Transmission Organization (RTO) or Independent System Operator (ISO)

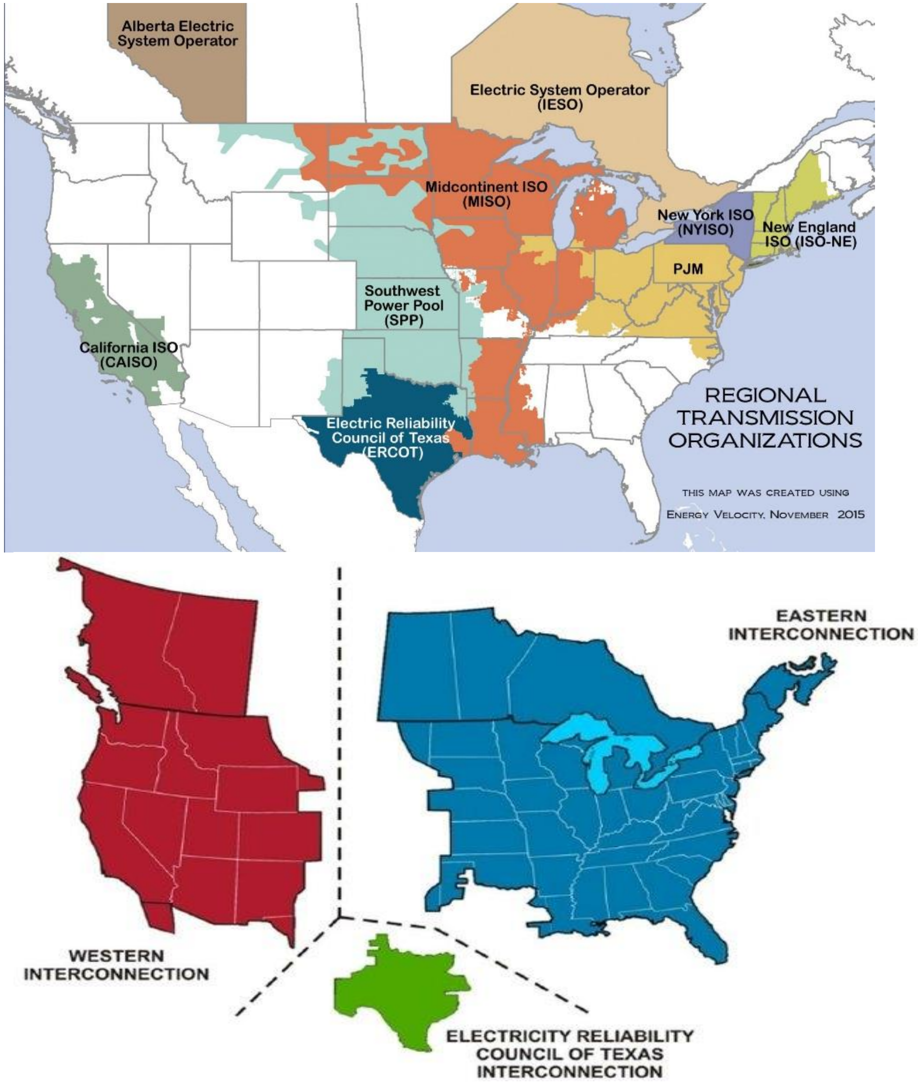


Fig. 1*: Seven North-American RTO/ISO-managed wholesale power markets operate over a high-voltage AC transmission grid consisting of three separately-synchronized parts.*

U.S. RTO/ISO-Managed Wholesale Power Markets

Major Concern:

- — Increasing reliance on *Intermittent Power Resources* ***(IPRs)***
  (e.g., wind farms & large solar PV panel arrays ***not*** fully firmed by storage)
- — Increasing encouragement of more active participation by *distribution-level* power resources and customers (*FERC Order 2222*, Final Rule, 17 September 2020)

➡ Increasing volatility & uncertainty of **Net Load ≅ [Load – Non-Dispatched Generation]**

➢ **RTOs/ISOs** must function as ***"fiduciary conductors"*** tasked with orchestrating:

- — availability & *just-in-time* dispatch of *increasingly diverse* dispatchable power resources
- — to service *just-in-time* power demands of *increasingly diverse* customers
- — while meeting *just-in-time* power requirements for grid reliability.

➢ **Grids** supporting RTO/ISO-managed wholesale power market operations must function as ***"flexibility-support mechanisms"***

Potential Remedy for Major Concern

- **Physically-Covered Insurance:** Increase the dependable advance availability of *flexible dispatchable power-production capabilities*

  - **from wholesale power resources**

    — Use storage to firm-up dispatchability of *Intermittent **P**ower **R**esources (**IPR**s)*

  - **from distributed power resources (FERC Order 2222)**

    — Permit aggregators (T&D linkage entities) to participate in wholesale power markets as suppliers of RTO/ISO-dispatchable power flows harnessed from ***diverse*** collections of ***distribution-level power resources*** by means of *Transactive **E**nergy **S**ystem (**TES**) designs*.

- **Difficulty:**

  Conceptually-problematic legacy market design aspects affecting the core operation of current grid-supported U.S. RTO/ISO-managed wholesale power markets are *hindering* the pursuit of this potential remedy.

Three Conceptually-Problematic Legacy Market Design Aspects: *Refs. [1,2]*

1) Product Definition and Pricing: *Static focus on grid-delivered energy (MWh), settled via conceptually ill-defined Locational Marginal Prices ($/MWh)*

— Grid-delivered energy, conditional on delivery location and time, **strongly** fails to satisfy a unit homogeneity property that is **necessary** for the conceptual coherency of Locational Marginal Pricing (LMP).

2) Settlement Timing: *Pay-for-performance in advance of actual performance*

— Sequential provisional forward-market determination of LMP settlements takes place in advance of final ex-post LMP settlements for actual real-time dispatched performance.

— This results in time-inconsistent settlements, hence in unnecessarily complex and confusing settlement rules.

3) Supply-Offer Forms: *Revenue Insufficiency & Reliance on Out-of-Market Payments*

— Suppliers are forced to express supply costs as functions of grid-delivered energy amounts.

— Suppliers are not required to distinguish between avoidable and non-avoidable fixed costs.

— Suppliers are unable to specify and submit their market supply offers in a manner that ensures *supplier revenue sufficiency: [revenue] ≥ [variable cost + avoidable fixed cost]*

Fundamental Reconsideration of These Legacy Market-Design Aspects

Product Definition and Pricing:

Two basic types of product are provided by dispatchable power resources:

- ***Reserve (physically-covered insurance) for future operating-periods T:*** Dependable advance availability of dispatchable power-production capabilities for possible RTO/ISO dispatch during a future operating-period T to protect against volumetric grid risk (net load imbalance);
- ***Real-time delivery of power during an operating period T*** in response to RTO/ISO dispatch signals.

Settlement Timing and Supply-Offer Formulations:

A **conceptually-sound definition** of revenue sufficiency for a supplier **requires**:

- Partitioning of the supplier's Total Cost into **three** components:

  Total Cost =: *Unavoidable ("Sunk") Fixed Cost + Avoidable Fixed Cost + Variable Cost*

- Use of this 3-part partitioning to define revenue sufficiency for this supplier as follows:

  Supplier Revenue Sufficiency =: [Market-Attained Revenue ≥ Market-Incurred Avoidable Cost]

where:

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

Time-consistent settlements that also assure supplier **revenue sufficiency** (as defined above) can be achieved in RTO/ISO-managed **forward** (e.g., day-ahead, hour-ahead) markets **without** resort to Out-of-Market (OOM) make-whole payments **if** suppliers are permitted to submit their supply offers in an appropriate **two-part pricing** form**.**

Fundamental Reconsideration: Essential Definitions *Refs. [1-2]*

DEF 1: Asset =: Anything in physical or financial form that can function as a store of value

Examples: Health; batteries; common stock shares, …

DEF 2: Spot Market for an Asset =: Transacted asset amounts, payments for these transacted asset amounts, and deliveries of these transacted asset amounts *all occur at the same time* ("*on the spot*").

Example: Asset Street-Vending. A person offers candy for sale to people who happen to pass by.

DEF 3: Forward Market for an Asset =: Transacted asset amounts and payment obligations for these transacted asset amounts *are determined in advance of the delivery* of these transacted asset amounts.

Example: Physically-Covered Insurance Market. In return for an up-front fee ("insurance premium"), a supplier *i* offers a buyer *j* *now* the guaranteed advance availability of production facilities for buyer *j*'s possible use at a designated location *b* during a designated *later* time-period T, where any actual use of these production facilities by buyer *j* at *b* during T is subject to an additional specified use-fee ("insurance co-payment").

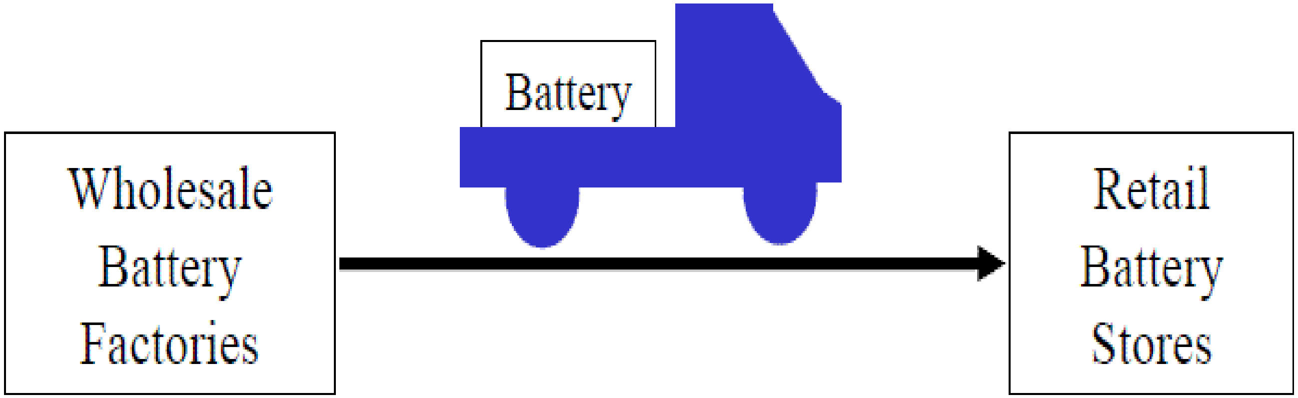
DEF 4: Commodity =: Physically-exchangeable asset *A* with standard unit of measurement *u* such that, conditional on location and time, each *A*-trader (supplier and/or buyer) considers all *A*-units *u* available for trade to be ***perfect substitutes*** ("economically equivalent''); that is, the substitution of ***any*** *A*-unit *u'* available for trade by ***any other*** *A*-unit *u'' available for trade* does **not** change the economic value that the *A*-trader assigns to this *A*-unit.

Example: Manufactured product such as DURACELL AA 1.5v batteries, with *u* = 1 Battery

Energy (MWh) as a Commodity -- A *Spot* Market Example

- Suppose energy (MWh) is produced and sold in the form of *identical units =: identical DURACELL AA 1.5v batteries.*

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



Wholesale Battery Factories

Battery

Retail Battery Stores

π^{W} $\qquad$ π^{Trans} $\qquad$ $\pi^{\text{Ret}} = \pi^{W} + \pi^{\text{Trans}}$

Fig. 3: *Energy (MWh) in uniform battery form* ***can*** *be transacted as a commodity.*

Note: The decomposition of the "spot price" $\boldsymbol{\pi}^{\text{Ret}}$ into "energy" and "transport/damage" components is analogous to the standard decomposition of LMPs into "energy," "congestion," and "loss" components.

Grid-delivered energy (MWh) is not a commodity *Refs. [1-3]*

☐ Why Not?

- Exact way that power (MW) injected at a grid-location *b* during an operating period T accumulates up into a grid-delivered energy amount E* (MWh) can matter greatly to producers, customers, and/or the RTO/ISO.
- That is, the dynamic attributes of the sequence of injections and/or withdrawals of power (MW) used to implement the delivery of E* at *b* during T typically matter, not simply the static amount E* (MWh) of grid-delivered energy.

Examples:

— Producers care about depreciation costs from ramping wear & tear ***during*** T;

— Customers benefit from flexible just-in-time power availability ***during*** T;

— RTO/ISO, with fiduciary responsibility for grid reliability, benefits from having flexible just-in-time availability of net-load balancing services ***during*** T.

LMP is Not Conceptually Well-Defined for Grid-Delivered Energy *Ref. [3]*

Point 1:

The standard economic **competitive (marginal cost = marginal benefit) spot-pricing rule** *requires* the transacted asset *to be a commodity*.

Point 2:

Grid-delivered energy is an asset with a standard unit of measurement (u = 1MWh); but grid-delivered energy is typically *not a commodity* because, conditional on location and time, each trader k (supplier or buyer) does *not* consider *all* "next" units u of grid-delivered energy available for trade to be perfect substitutes (economically equivalent). Thus:

(2.1) A *supplier* k of grid-delivered energy typically does *not* have a conceptually well-defined *marginal cost (MC)* function for grid-delivered energy, conditional on location and time;

(2.2) A *buyer* k of grid-delivered energy typically does *not* have a conceptually well-defined *marginal benefit (MB)* function for grid-delivered energy, conditional on location and time.

(2.3) Competitive (MC = MB) spot-pricing typically *cannot* be implemented in a *conceptually coherent manner* for *grid-delivered energy (MWh),* conditional on location and time.

Major Implication of Points 1 and 2:

The justification commonly asserted for use of ***Locational Marginal Pricing (LMP)*** for price-settlement of grid-delivered energy in U.S. RTO/ISO-managed wholesale power markets – namely, the efficiency and optimality properties of competitive (MC = MB) spot-pricing -- ***is not conceptually supportable.***

U.S. RTO/ISO-managed wholesale power markets are forward "power-path" markets

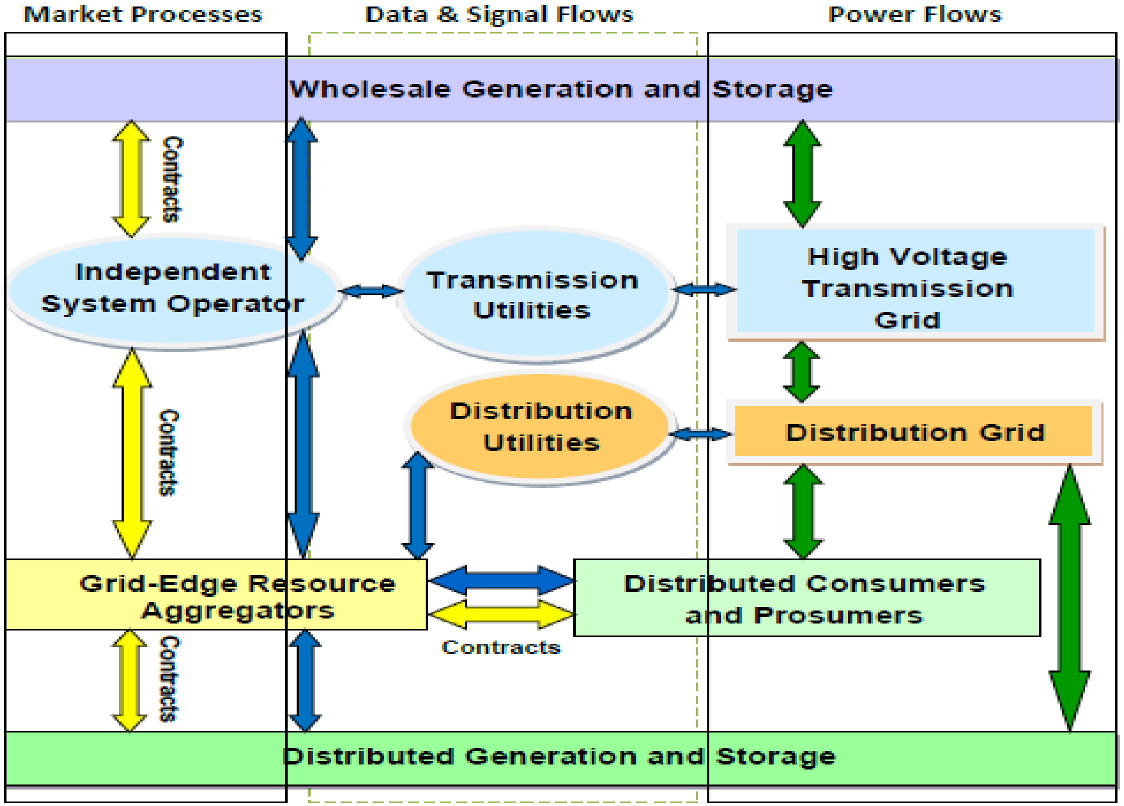


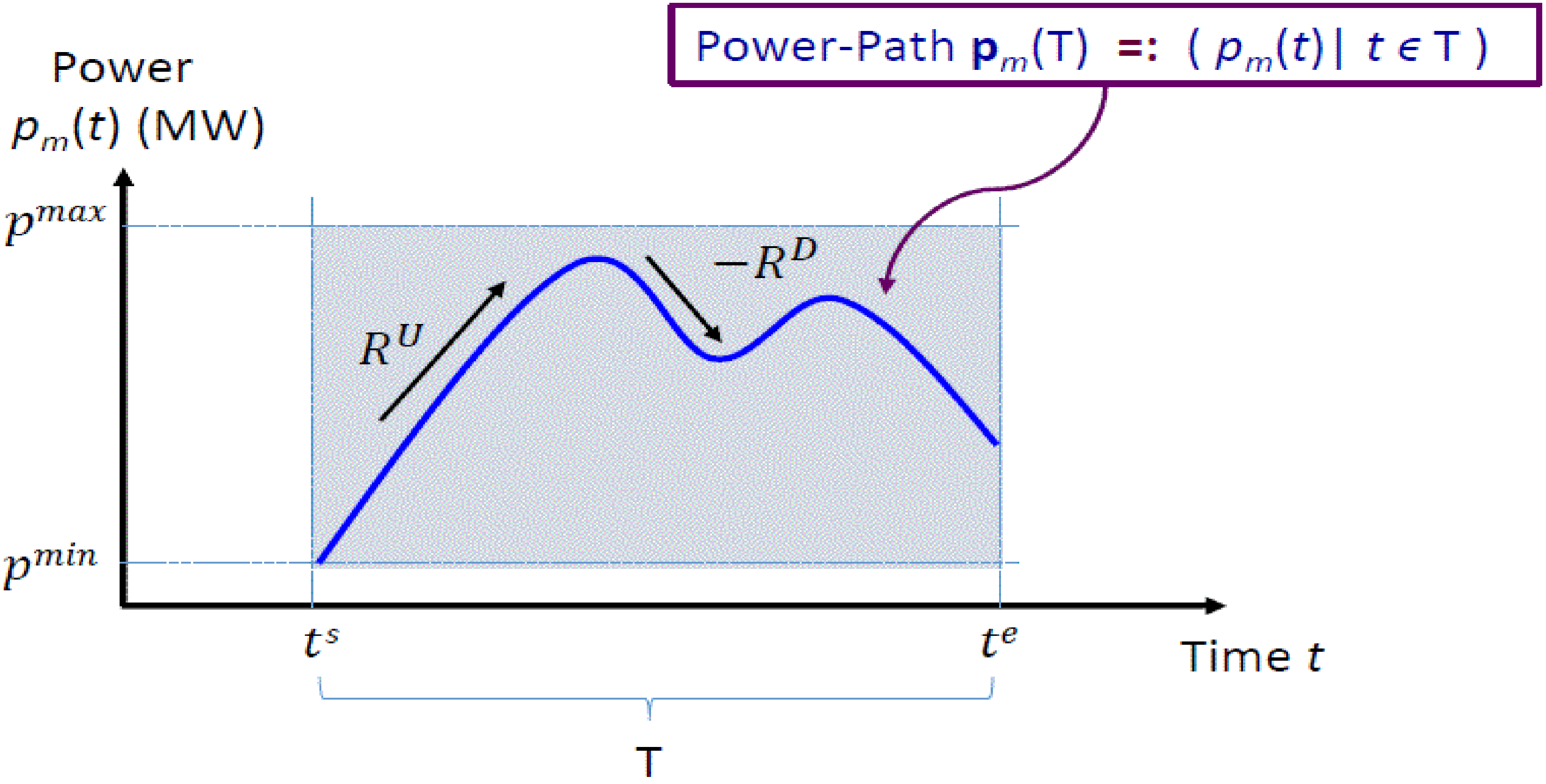
Fig. 4: *The basic purpose of U.S. RTO/ISO-managed wholesale power markets is to support the efficient just-in-time production and transmission of bulk power to satisfy just-in-time customer power demands as well as just-in-time power requirements for reliable transmission-grid operation.*

Grid-Edge Resource (GER) **=:** Any entity capable of power usage and/or power output that has a *direct* electrical point-of-connection to a *distribution* grid.

Def. 5: Power-path 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.***



Power-Path $\mathbf{p}_m(\mathrm{T})$ **=:** $(p_m(t) \mid t \in \mathrm{T})$

Fig. 2: *One of multiple possible power-paths offered by a dispatchable power resource m for possible RTO/ISO dispatch at its grid location b(m) during a future operating period T.*

Power-paths are *not a commodity* for grid-supported power markets *Ref. [3]*

☐ Why Not?

- **Power-paths** have multiple types of dynamic and static attributes that affect how they are evaluated by power producers, power customers, and the RTO/ISO itself.
- Thus, power-paths do not have a standard unit of measurement *u* such that, conditional on location and start-time for an operating period T, each trader (supplier or buyer) considers any unit *u′* available for period-T trade to be a perfect substitute for any other unit *u′′* available for period-T trade.

Examples of Dynamic Attributes:

- Down/up ramp-rate (MW/min) ***profile*** during T can affect producer cost (wear & tear) during T;
- Active power (MW) ***profile*** during T can affect customer benefit during T;
- Power factor (MW/MVAR) ***profile*** during T can affect power system reliability during T,

where:

profile during T =: *Form that some measured attribute takes **during** operating period T.*

☐ **However,** for reasons carefully analyzed in *Refs. [1,2],* summarized in *Ref. [3],* and reviewed here in remaining slides, **swing contracts** are well-suited for the support of power-path transactions in U.S. RTO/ISO-managed markets.

Linked Swing-Contract Market Design: Basic Features

- ☐ Design Purpose
  - Facilitate balancing of increasingly volatile & uncertain net load in grid-supported centrally-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.*

General Swing-Contract Reserve Offer Formulation

- **The general form of a swing contract** submitted by a dispatchable power resource *m* to a swing-contract market M(T) for a future operating period T consists of four components:

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

$\boldsymbol{\alpha}_m$ =: offer price (insurance premium)

$\mathbf{T}^{\mathrm{ex}}_m$ =: Set of RTO/ISO exercise times

$\mathbf{PP}_m$ =: Power-path production possibility set

$\boldsymbol{\varphi}_m$ =: Performance payment method

- **The swing contract $\mathbf{SC}_m$ permits dispatchable power resource *m*:**
  - to offer the RTO/ISO a *production-possibility set* $\mathbf{PP}_m$ consisting of reserve (power-paths **p**) for possible RTO/ISO-dispatched delivery during T at *m*'s grid location *b(m)*;
  - to specify with care the *swing* (*flexibility*) in the physical attributes of the offered power-paths **p** in $\mathbf{PP}_m$.

- **The physical attributes of each offered power-path p** can include:

static attributes: grid delivery location *b(m)*; grid-delivered energy amount (MWh) …

dynamic attributes: power level *profile*; power-factor *profile*; ramp-rate *profile*; power-path *length* (*mileage*); …

General Swing-Contract Reserve Offer Formulation … *Continued*

- In addition, the swing contract $\mathrm{SC}_m = \left(\alpha_m, \mathbb{T}^{\text{ex}}_m, \mathbb{PP}_m, \phi_m\right)$

— permits *m* to request an **offer price *α*$_m$ ($) --** i.e., an insurance premium – that is sufficient to cover *ex ante* (i.e., in advance of T) any **avoidable fixed cost ($)** that *m* must incur in order to guarantee the availability of the power-paths in **PP**$_m$ for possible RTO/ISO dispatch at *m*'s grid location *b(m)* during T.

Avoidable fixed cost examples: Capital investment cost; transaction cost (insurance, licensing, …); unit commitment cost; opportunity cost; … *Ref. [1, Appendix A.4]*

— permits *m* to specify a **performance payment method *φ*$_m$** that maps each power-path **p** ϵ **PP**$_m$ into a required performance payment ***φ***$_m$(**p**) (measured in $). This allows *m* to recover *ex post* (i.e., after T) any **variable cost** that m incurs for verified period-T power-path delivery in accordance with RTO/ISO dispatch signals received during T.

Variable cost examples: Fuel cost; labor cost; transmission service charges; equipment wear and tear due to ramping; … *Ref. [1, Appendix A.4]*

General Swing-Contract Reserve Offer Formulation … *Continued*

- The performance payment method φ_m should be explicitly expressed in terms of **performance metrics**.

- These performance metrics **should permit the RTO/ISO and *m*:**
  - to agree *ex ante* (i.e., *in advance of T*) on nature of *m*'s *offered* power-path production *capabilities* for *possible* RTO/ISO-dispatched delivery *during* T;
  - 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 **p** in $\mathbf{PP}_m$ as a linear combination of metrics that separately assign costs to correlated attributes of **p**, such as **delivered energy (*E*), ramp (*R*), duration (*D*)**, etc.

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

Swing Contract Illustrative Examples *Ref. [2, Chapter 5]*

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

Remark: This simple type of swing contract can easily be modified to express current types of supply offers, such as ERCOT’s three-part supply offer.

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

where:

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

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

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

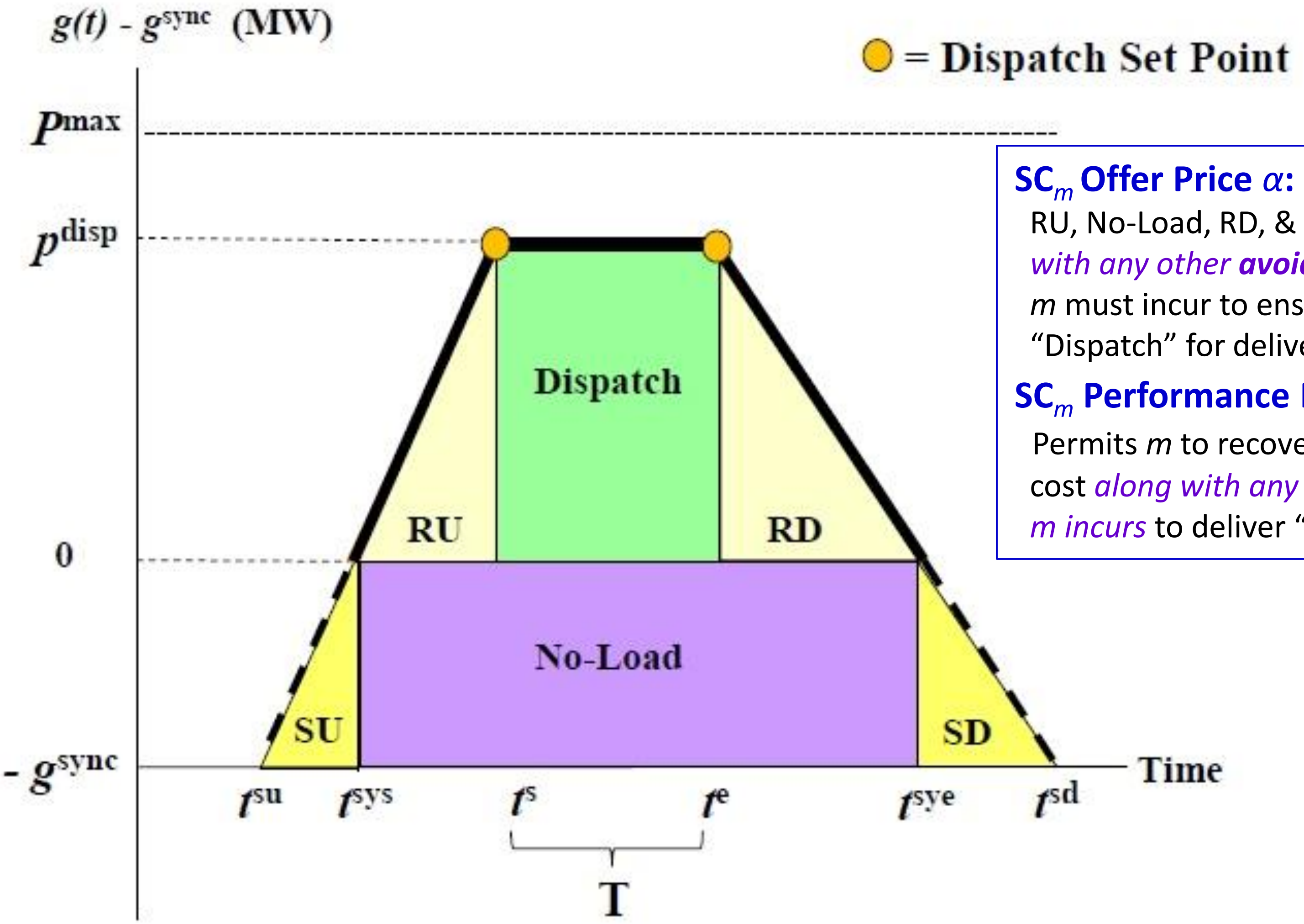
$$t^{\mathrm{s}} = \text{Start time for energy block E}$$

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

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

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

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 at *b(m)* during T.

SC$_m$ Performance Payment Method φ: Permits *m* to recover "Dispatch" energy cost *along with any other **variable** cost that m incurs* to deliver "Dispatch" at *b(m)* during T.

Fig. 5: *Illustration of m's **energy** requirements for delivery of energy-block "Dispatch" at m's grid-location b(m) during operating period T: the energy block ("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*

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

where:

$\alpha =$ Offer price

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

$b =$ Delivery location

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

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

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

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

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

$t^{\mathsf{R2}} =$ 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

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

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

$t^{\mathsf{e}} =$ 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 $p \in \mathbb{P}(\mathrm{E1}) \cup \mathbb{P}(\mathrm{E2})$

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

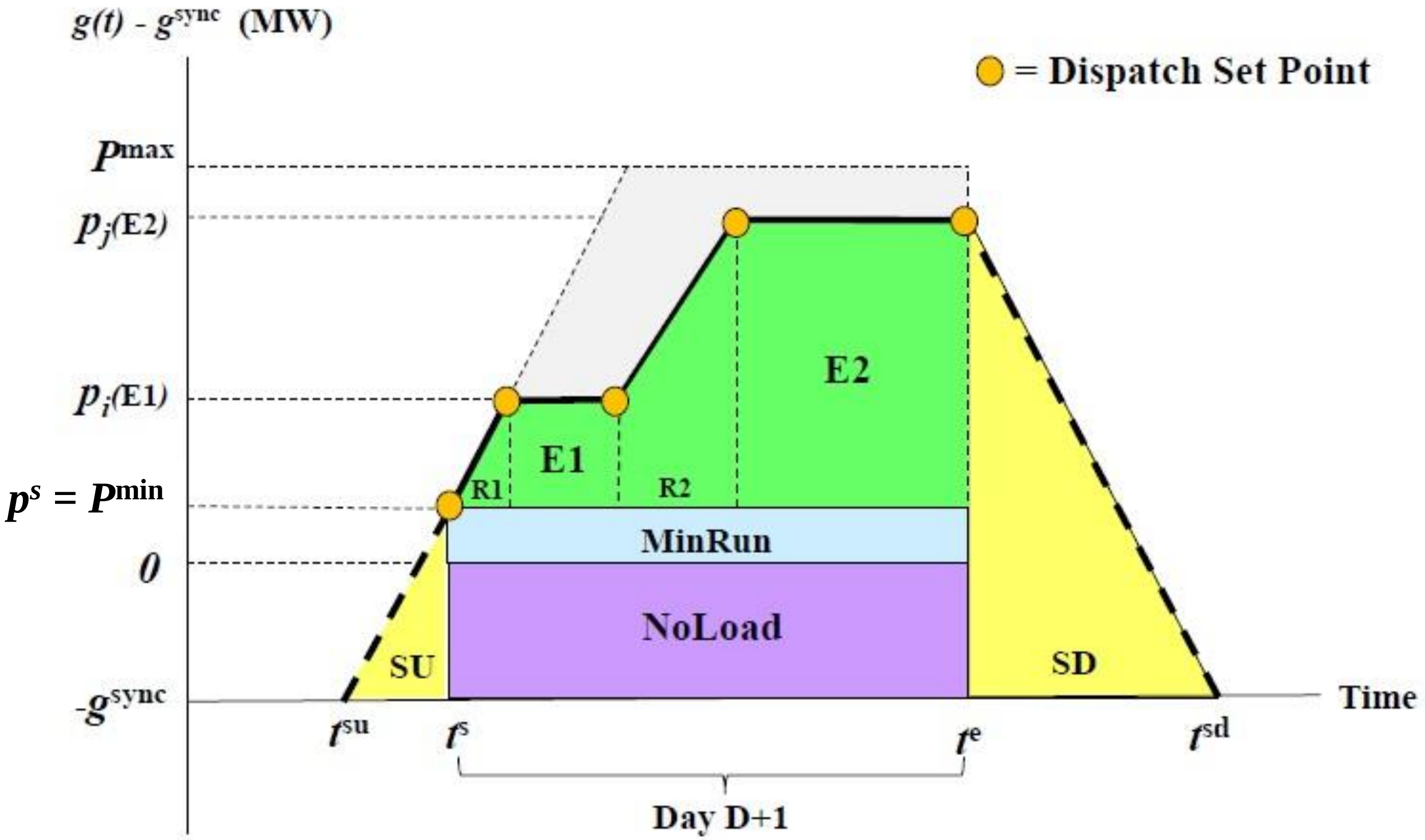


Fig. 6: ***One among multiple possible power-paths p*** *the RTO/ISO could dispatch m to deliver at m's grid-location b(m) during operating day D+1 if the RTO/ISO clears m's piecewise-linear swing-contract SC_m submitted to a swing-contract day-ahead market M(D+1) held on day D.*

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

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

where:

$\alpha =$ Offer price

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

$b =$ Delivery location

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

$\eta =$ Round-trip efficiency

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

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

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

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

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

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

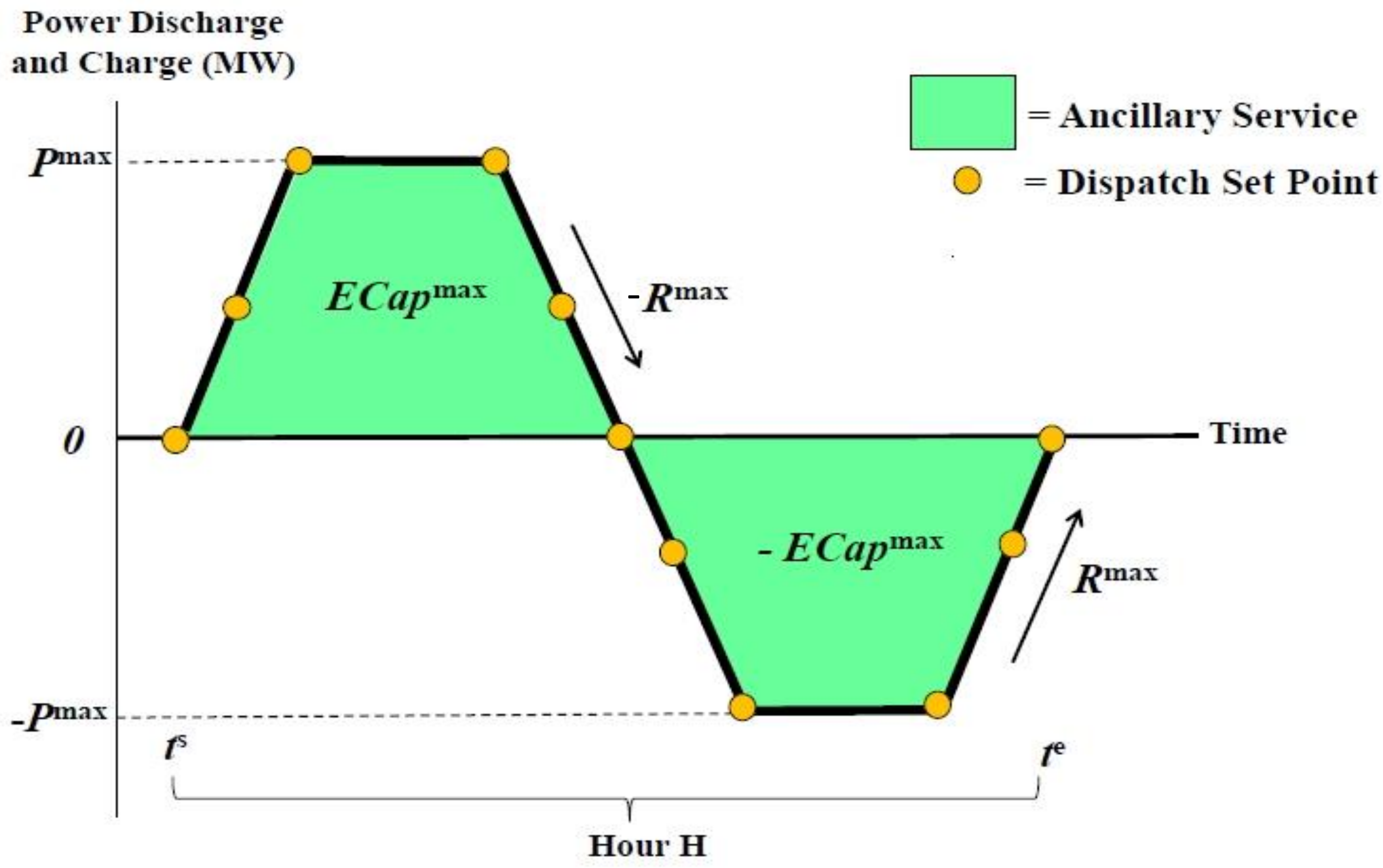


Fig. 7: *Suppose* **SOC^s = SOC^e = {100%}**, **P^{min} = - P^{max}**, *and* $R^D = R^U =: R^{max}$. *Then the depicted dispatched power-path is* ***one among multiple power-paths p*** *the RTO/ISO could dispatch m to deliver at m's grid-location b(m) during hour H = [t^s, t^e) if the RTO/ISO clears m's battery service swing-contract SC_m submitted to a swing-contract market M(H) held in advance of H.*

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

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

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

where:

$\alpha = $ Offer price

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

$b = $ Delivery location

$t^{\mathsf{s}} = $ Start-time for power delivery

$p^{\mathsf{s}} = $ Initial power level at time t^{s}

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

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

$t^{\mathsf{e}} = $ End-time for power delivery

$\phi = $ Performance payment method for power-path delivery

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

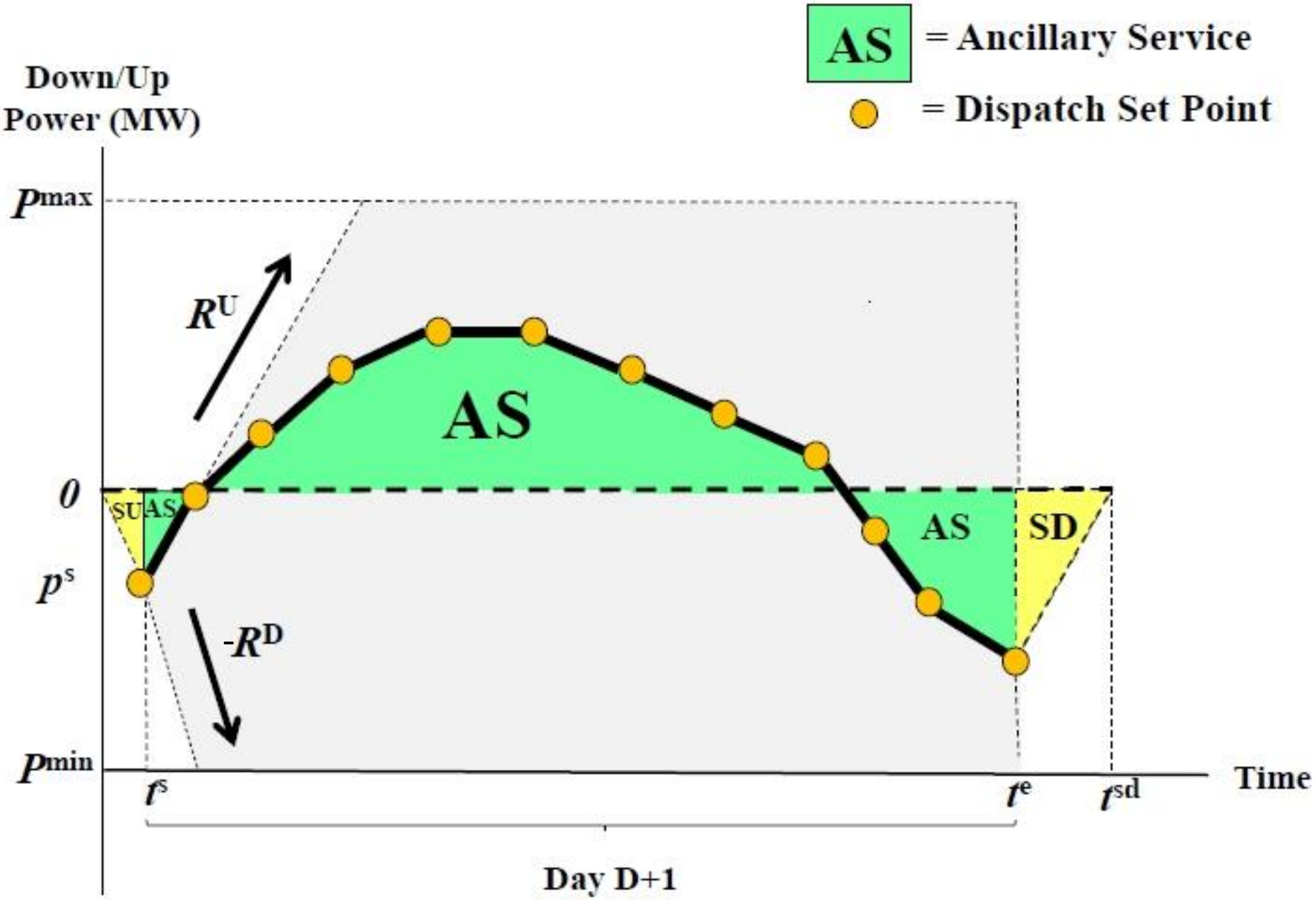
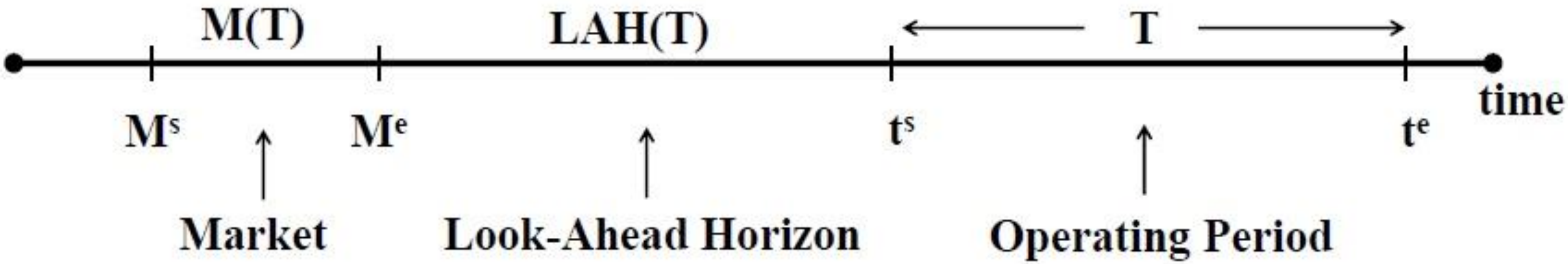


Fig. 8: ***One among many possible power-paths p*** *the RTO/ISO could dispatch m to deliver at m's grid-location b(m) during operating day D+1 if the RTO/ISO clears m's flexible power/ramp swing-contract SC_m submitted to a swing-contract day-ahead market M(D+1) held on day D.*

Swing-Contract Market M(T): Key Features *[Ref. 1, Sec. 6],[Ref. 2, Ch. 6]*

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

- *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 M(T): 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 price-sensitive and/or *fixed* (*non-dispatched must-service*) form.

- **Dispatchable Power Resources (DPRs) denoted $m \in M$**

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

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

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

- **Intermittent Power Resources (IPRs)**

— The RTO/ISO inputs into M(T) a ***forecast*** for IPR power-path at each transmission grid bus during period T.

Swing-Contract Market M(T): Key Features … Contract-Clearing Optimization

❑ **Contract-Clearing Optimization Problem for RTO/ISO Managing 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 state conditions ***plus*** information extracted from submitted reserve offers and reserve bids
- ***and subject to*** the usual types of SCED system constraints (e.g., nodal power-balance, transmission capacity limits, reserve uncertainty sets, …)

Swing-Contract Market M(T): Key Features … RTO/ISO Cost Allocation Rules

- Allocate **M(T) net reserve cost** across M(T) participants based on *anticipated volatility/size* and *ex-post realization* of their **net fixed load during T**, where:

M(T) Net Reserve Cost

=: RTO/ISO ***net*** reserve procurement cost from M(T) operations

=: [Offer cost] ***plus*** [performance cost] ***minus*** [revenue from price-sensitive demand]

Net Fixed Load of an M(T)-participant *j* during T

=: [**Fixed** (*non-dispatched must-service)* power **demand** by *j* during T]
minus **Fixed** *(non-dispatched must-service)* power **supply** by *j* during T]

- Allocate **M(T) transmission service cost** across M(T) participants based on:

— 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.

Linked Swing-Contract Markets *Ref. [2, Chapters 10-11]*

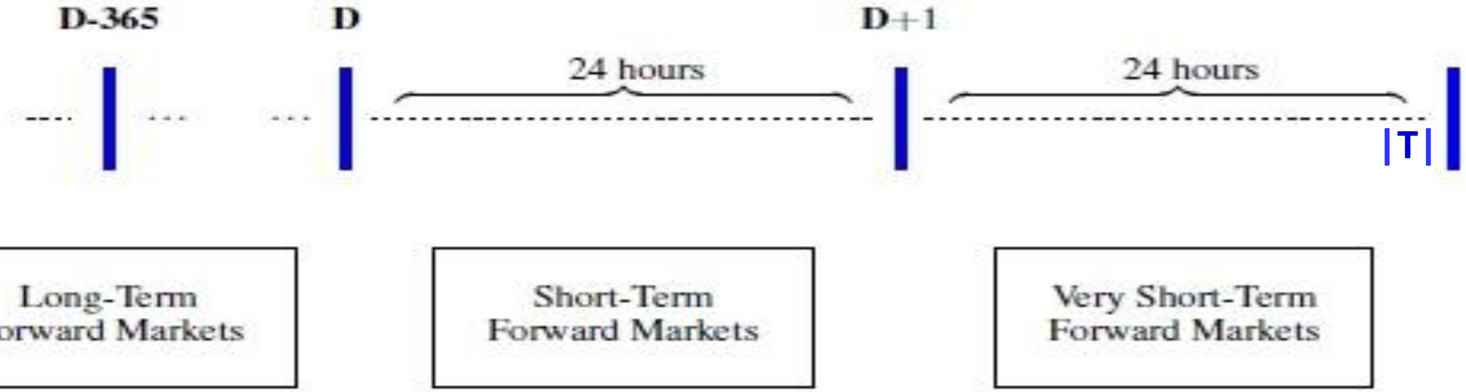
Example 1: Intertemporal Linkages for a Given Operating Period T

Linked SC markets **M(T)** for a *given* future operating period **T** with **L**ook-**A**head **H**orizons **LAH**(**T**) ranging from *long* (**L**) to *short* (**S**) to *very short* (**VS**)

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

ISOPort(T) **=:** Portfolio of RTO/ISO-cleared reserve offers and reserve bids for **T,** plus past RTO/ISO-signaled dispatch set-points**,** 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* swing contracts for **T** and/or any *newly-signaled* dispatch set-points.

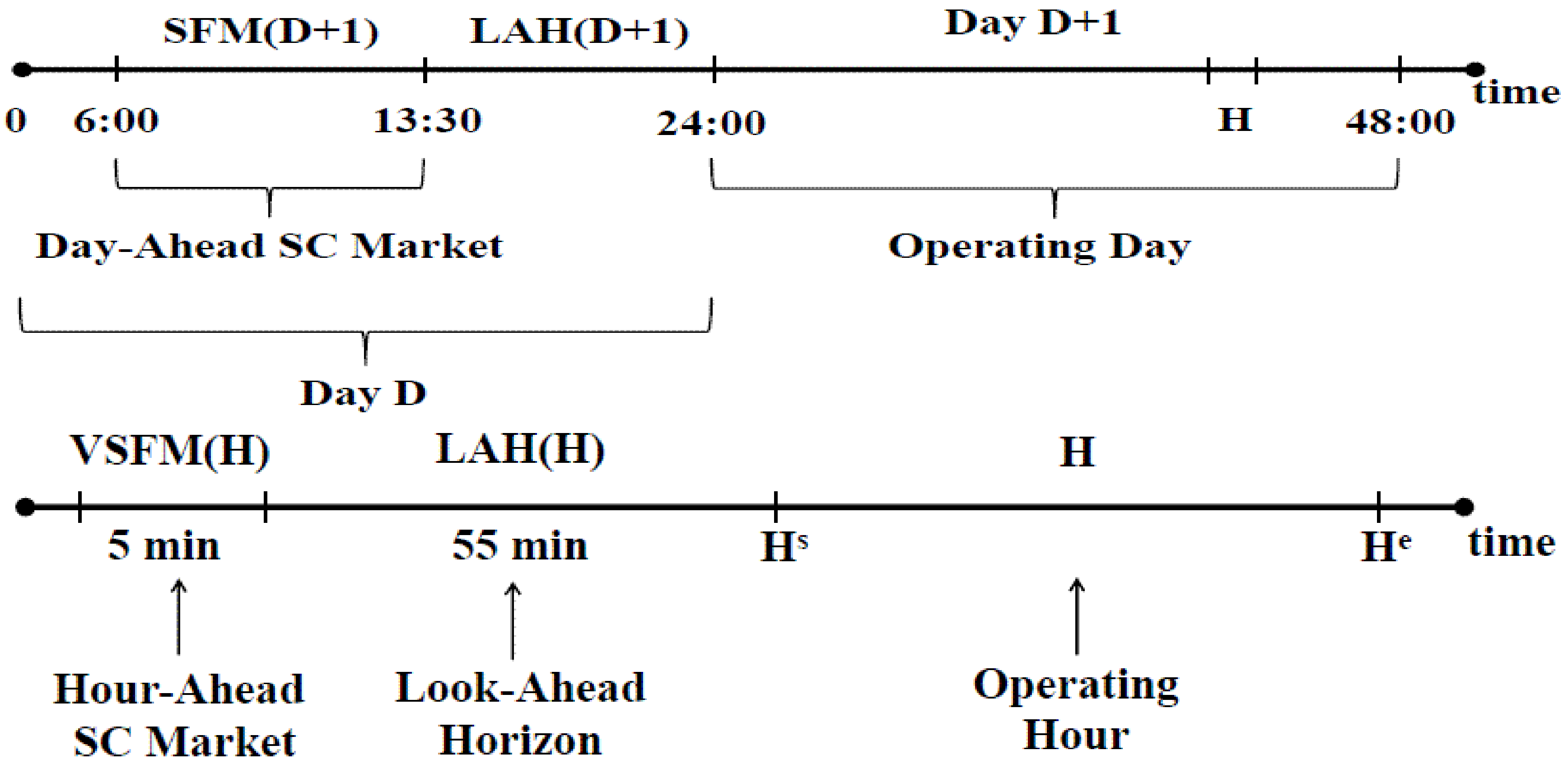


L-M(T) **S-M(T)** **VS-M(T)**

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**



Comparisons with Current U.S. RTO/ISO-Managed Markets

- Detailed comparisons with current RTO/ISO-managed wholesale power market designs are given in *Ref. [2, Chps. 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**).

Important Remarks:

— The ***essential differences*** between current U.S. RTO/ISO-managed DAM designs and the swing-contract DAM design proposed in *Ref. [2]* are differences in **product definition**, **contractual forms**, **settlement rules, and RTO/ISO management practices** **---** ***not*** differences in real-time operations.

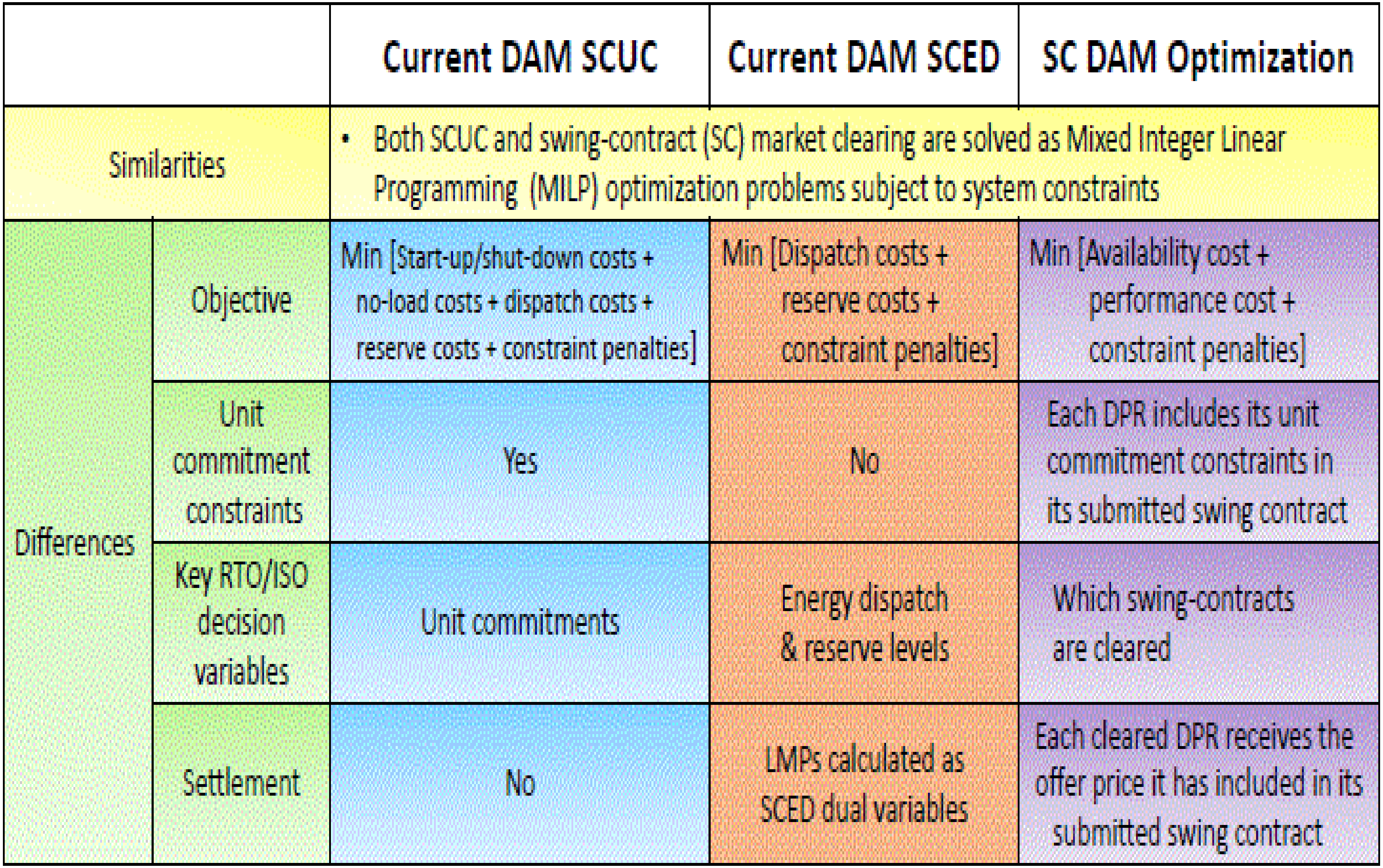
— ***These essential differences can be introduced gradually*** into current RTO/ISO-managed wholesale power markets; see *Ref. [2, Ch. 16]* for a "Transitional DAM" example.

Illustrative DAM Comparisons: Basic Features

		Current DAM	SC DAM
Similarities		• Conducted day-ahead to plan for next-day operations • RTO/ISO-managed • Market participants include LSEs, DPRs, & IPRs • Same types of system constraints: Nodal power balance, zonal reserve requirements, line capacity limits, …	
Differences	Optimization form	SCUC & SCED	Optimal contract clearing
	Settlement	Locational marginal prices	Swing contracts are two-part pricing contracts
	Market payments	Payment for next-day energy before actual energy delivery	Payment for resource availability now & resource performance ex post
	OOM payments	Make-whole payments	No make-whole payments
	Info released to participants	Unit commitments, LMPs, & next-day dispatch schedule	Which swing contracts have been cleared

LSE =: Load Serving Entity; IPR =: Intermittent Power Resource; DPR =: Dispatchable Power Resource

Illustrative DAM Comparisons: Optimization Formulations



		Current DAM SCUC	Current DAM SCED	SC DAM Optimization
Similarities		• Both SCUC and swing-contract (SC) market 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 + constraint penalties]	Min [Dispatch costs + reserve costs + constraint penalties]	Min [Availability cost + performance cost + constraint penalties]
	Unit commitment constraints	Yes	No	Each DPR includes its unit commitment constraints in its submitted swing contract
	Key RTO/ISO decision variables	Unit commitments	Energy dispatch & reserve levels	Which swing-contracts are cleared
	Settlement	No	LMPs calculated as SCED dual variables	Each cleared DPR receives the offer price it has included in its submitted swing contract

DPR =: Dispatchable Power Resource

Conclusion: Key Points

- ☐ This presentation first identified three conceptually-problematic aspects of current U.S. RTO/ISO-managed wholesale power markets that are hindering their smooth transition to decarbonized grid operations with diverse participants: product definitions; settlement rules; and supply-offer formulations.

- ☐ Attention next focused on product definition and settlement-rule concerns:

- — Static focus on grid-delivered energy (MWh) as the basic transacted product.

- — Failure of grid-delivered energy to satisfy a fundamental unit homogeneity property necessary for Locational Marginal Pricing (LMP) to provide a conceptually-coherent settlement process for grid-delivered energy transactions

- ☐ Key features of a new Linked Swing-Contract Market Design were then briefly reviewed.

- — This design provides proof-of-concept (at TRL-3) that alternative conceptually-consistent designs can be developed for grid-supported centrally-managed wholesale power markets that are well-suited for decarbonized grid operations with diverse market participants.

- — Adoption of this design would require changes in current U.S. RTO/ISO-managed market product definition, settlement rules, and supply-offer forms; however, it would *not* require changes in real-time operations. Thus, the adoption could proceed gradually, without disruption of real-time operations.

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