

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

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Slide-Set Materials Summarizing Key Topics Addressed in:

***Supporting Document for e-filed “Comments”**

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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 market design by current RTO/ISO-managed markets would require changes in product definition and pricing, settlement timing, and supply-offer formulations, but not in real-time operations.
 - Thus, adoption of this design could be implemented through gradual transition.

Key References

Ref. [1] Leigh Tesfatsion (2023), "**Economics of Grid-Supported Electric Power Markets: A Fundamental Reconsideration,**" Econ WP #22005, ISU Digital Repository, Ames, IA, 65pp.
<https://www2.econ.iastate.edu/tesfatsi/EconomicsGridSupportedPowerMarkets.ISUDR22005.LTesfatsion.pdf>

NOTE: **Ref. [1]** is the Supporting Document ("Attachment A") for *Comments* (Accession No. 20230117-5051) e-filed in January 2023 to the U.S. Federal Energy Regulatory Commission (FERC) for Docket No. AD21-10-000 ("Modernizing Wholesale Electric Power Market Design").

Ref. [2] Leigh Tesfatsion (2023), "**Locational Marginal Pricing: When and Why Not,**" Economics Working Paper, Iowa State University, Ames, IA, April 17, 10pp.
<https://www2.econ.iastate.edu/tesfatsi/LMPWhenAndWhyNot.LTesfatsion.pdf>

Ref. [3] 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, New Jersey, USA. ([Wiley/IEEEPressBookFlyer.pdf](#)).

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

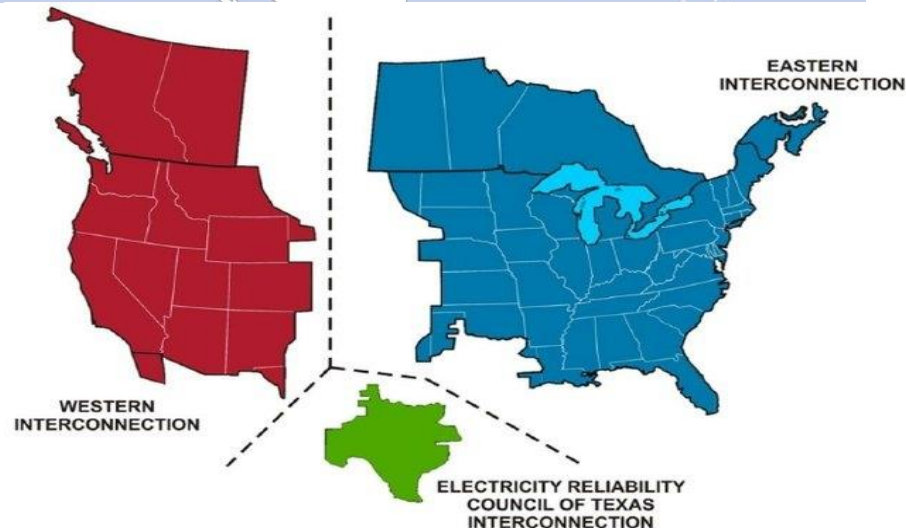
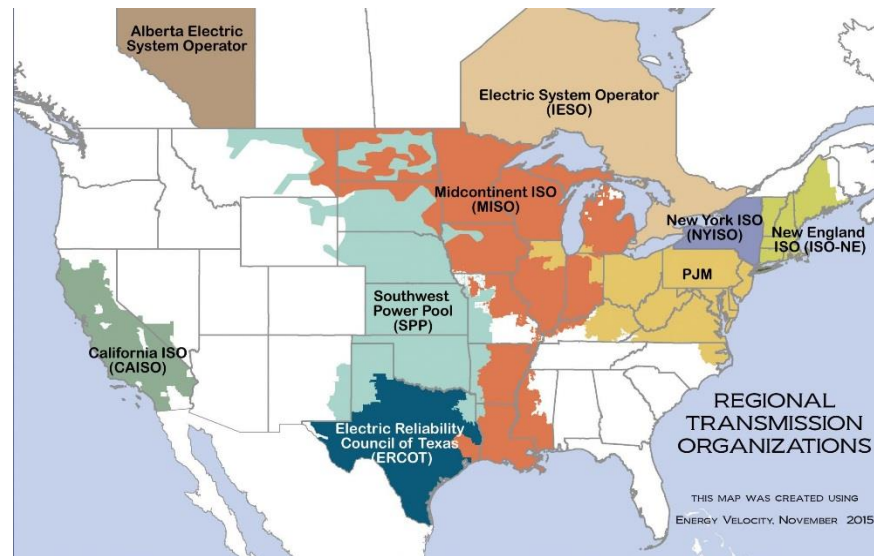


Fig. 1: Seven North-American RTO/ISO-managed wholesale power markets operate over a high-voltage AC transmission grid consisting of three separately-synchronized parts.

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

Major Problem:

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

➔ **Increasingly Volatile & Uncertain Net Load \cong [Load Minus 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 Problem (Net-Load Volatility & Uncertainty)

- **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 Power Resources (IPRs)*
 - 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 Energy System (TES) designs*.
- **Major Concern:**

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

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

- Grid-delivered energy, conditional on delivery location and time, strongly fails to satisfy a unit homogeneity property that is a necessary condition 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: $[earnings] \geq [variable\ costs + \textit{avoidable fixed costs}]$*

Fundamental Reconsideration of These Three Legacy Market-Design Aspects: Ref. [1]

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 Forms:

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 of Product Definition & Pricing: Essential Definitions

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, payment obligations for these transacted asset amounts, and deliveries of these transacted asset amounts *all occur at the same location and 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 available *A*-unit *u*’ by any other available *A*-unit *u*” 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 π^{Ret} (\$/battery)* that covers wholesale production cost (“**W**”) plus transport/damage cost (“**Trans**”).

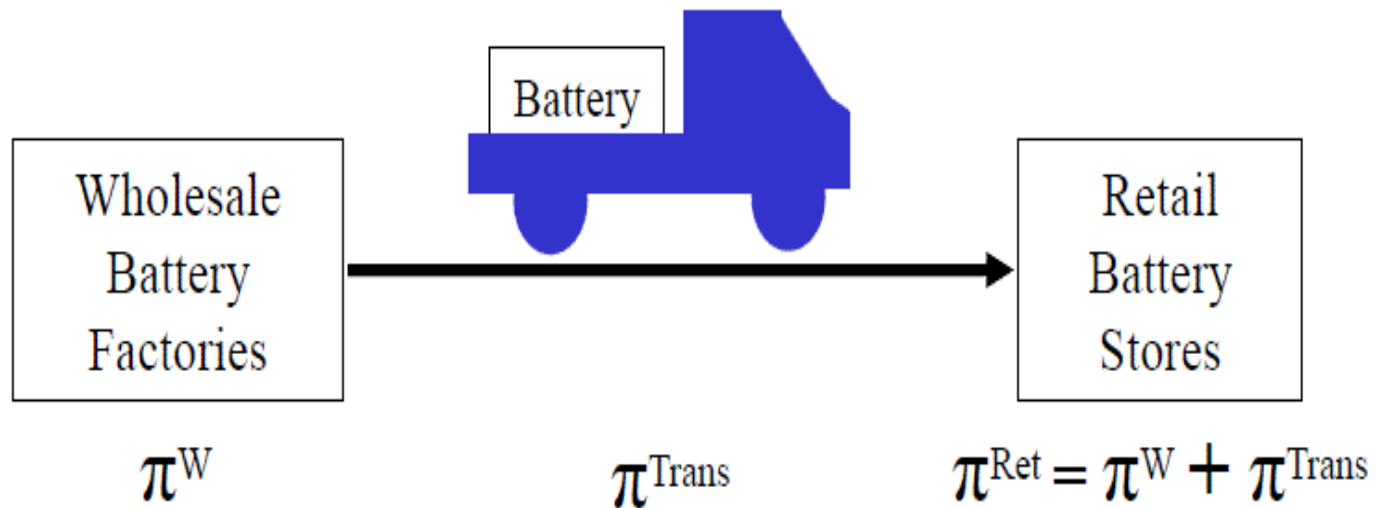


Fig. 3: Energy (MWh) in uniform battery form *can* be transacted as a commodity.

Note: The decomposition of the “spot price” π^{Ret} into “energy” and “transport/damage” components is analogous to the standard decomposition of LMPs into “energy,” “congestion,” and “loss” components. 11

Grid-delivered energy (MWh) is not a commodity

□ 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

Point 1:

The standard economic **competitive (marginal cost = marginal benefit) spot-pricing rule** requires the transacted asset to be a commodity. See Ref. [1, Sec. 3], Ref.[2] for rigorous proof.

Point 2:

Grid-delivered energy is an asset with a standard unit of measurement ($u = 1\text{MWh}$); 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: Refs. [1, 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

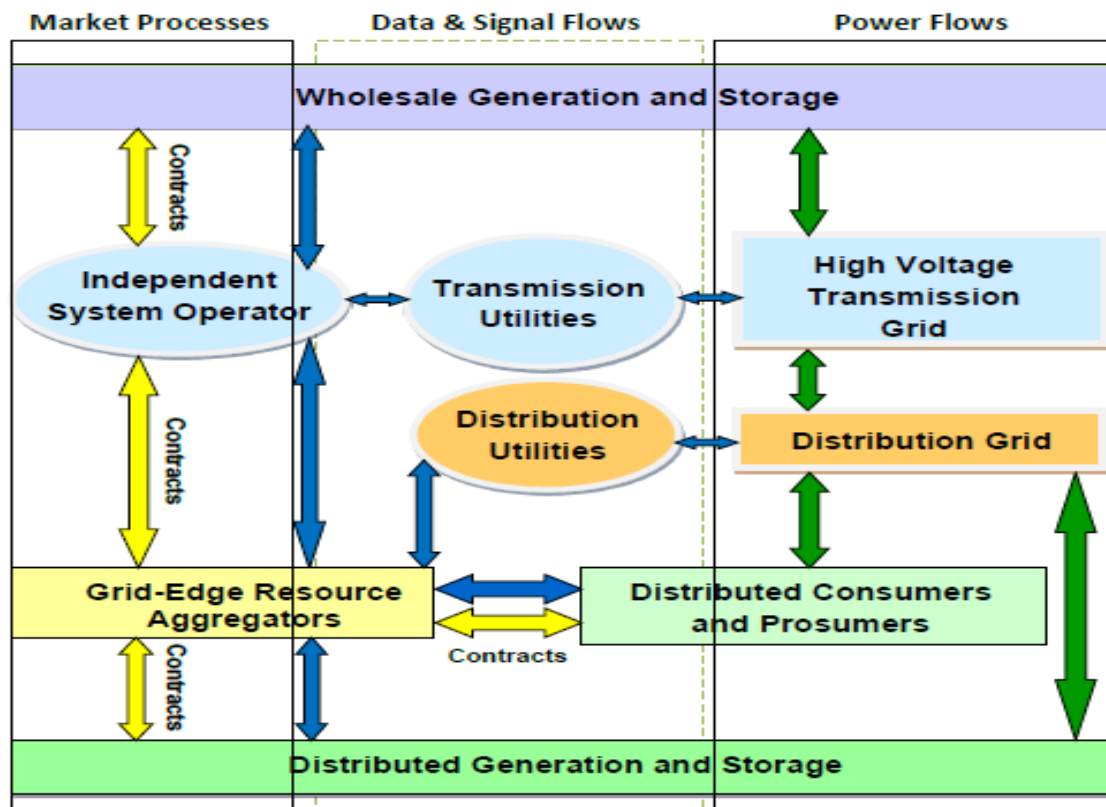


Fig. 4: The basic purpose of U.S. RTO/ISO-managed wholesale power markets is to support the efficient just-in-time production and transmission of bulk power to satisfy just-in-time customer power demands as well as just-in-time power requirements for reliable transmission-grid operation.

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*.

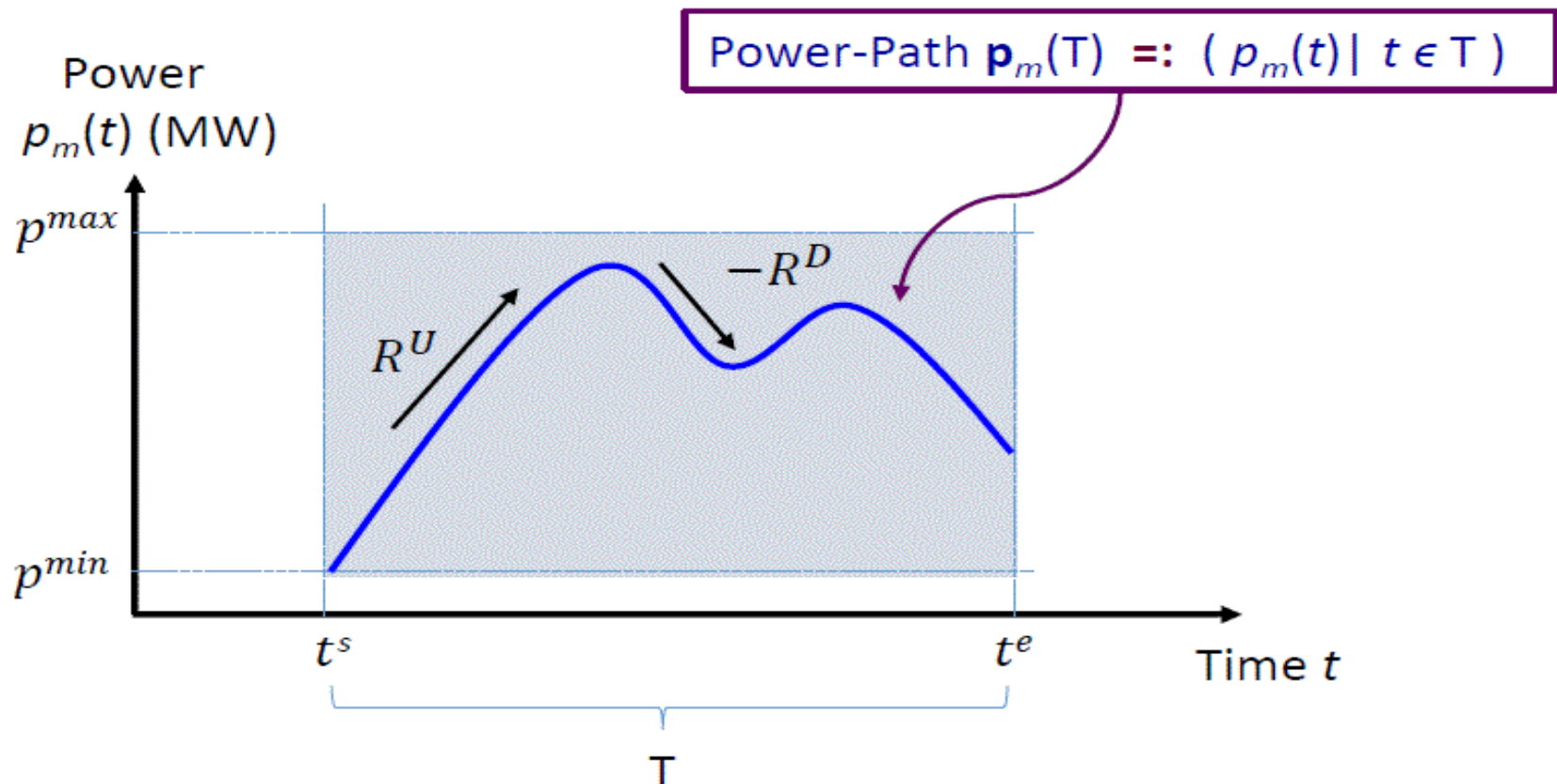


Fig. 2: One of multiple possible power-paths offered by a dispatchable power resource m for possible RTO/ISO dispatch at its grid location b_m during a future operating period T .

Power-paths are not a commodity for grid-supported power markets

□ 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**, as carefully analyzed in **Ref. [3]**, reviewed in **Ref. [1]**, outlined in **Ref. [2]**, & briefly discussed here in remaining slides, “**swing-contracts**” are well-suited for the support of power-path transactions in U.S. RTO/ISO-managed markets.

□ 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:

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

α_m =: Offer price (availability payment)

T_m^{ex} =: Set of RTO/ISO contract-exercise times

PP_m =: Power-path production possibility set

ϕ_m =: Performance payment method

- The swing contract SC_m permits dispatchable power resource m :
 - to offer the RTO/ISO a production possibility set 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 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 $SC_m = (\alpha_m, T_m^{\text{ex}}, PP_m, \phi_m)$

- permits m to request an **offer price α_m (\$)** 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 $\mathbf{p} \in PP_m$ into a required performance payment $\phi_m(\mathbf{p})$ (measured in \$). This allows m to recover ex post (i.e., after T) any **variable cost** that m incurs for actual period- T power-path delivery in accordance with RTO/ISO dispatch signals received by m 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 \mathbf{p} in \mathbf{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 (R)**, **duration (D)**, etc.

$$\varphi_m(\mathbf{p}) = \underbrace{c_m^E(\mathbf{p}) + c_m^R(\mathbf{p}) + c_m^D(\mathbf{p}) + \dots}$$

Costs assigned by m to *correlated* attributes of a *single* power-path \mathbf{p}

Swing Contract Illustrative Examples: *Key Source: SC Book, Ref. [3, 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, e.g., ERCOT's three-part supply offer.

$$SC_m = [\alpha, \text{PP}, \phi]$$

where:

α = Offer price

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

b = Delivery location

t^s = Start time for energy block E

p^{disp} = Maintained power injection for energy block E

t^e = End-time for energy block E

ϕ = Pre-specified price π for delivered energy

Example 1: A simple energy-block swing contract ... Continued

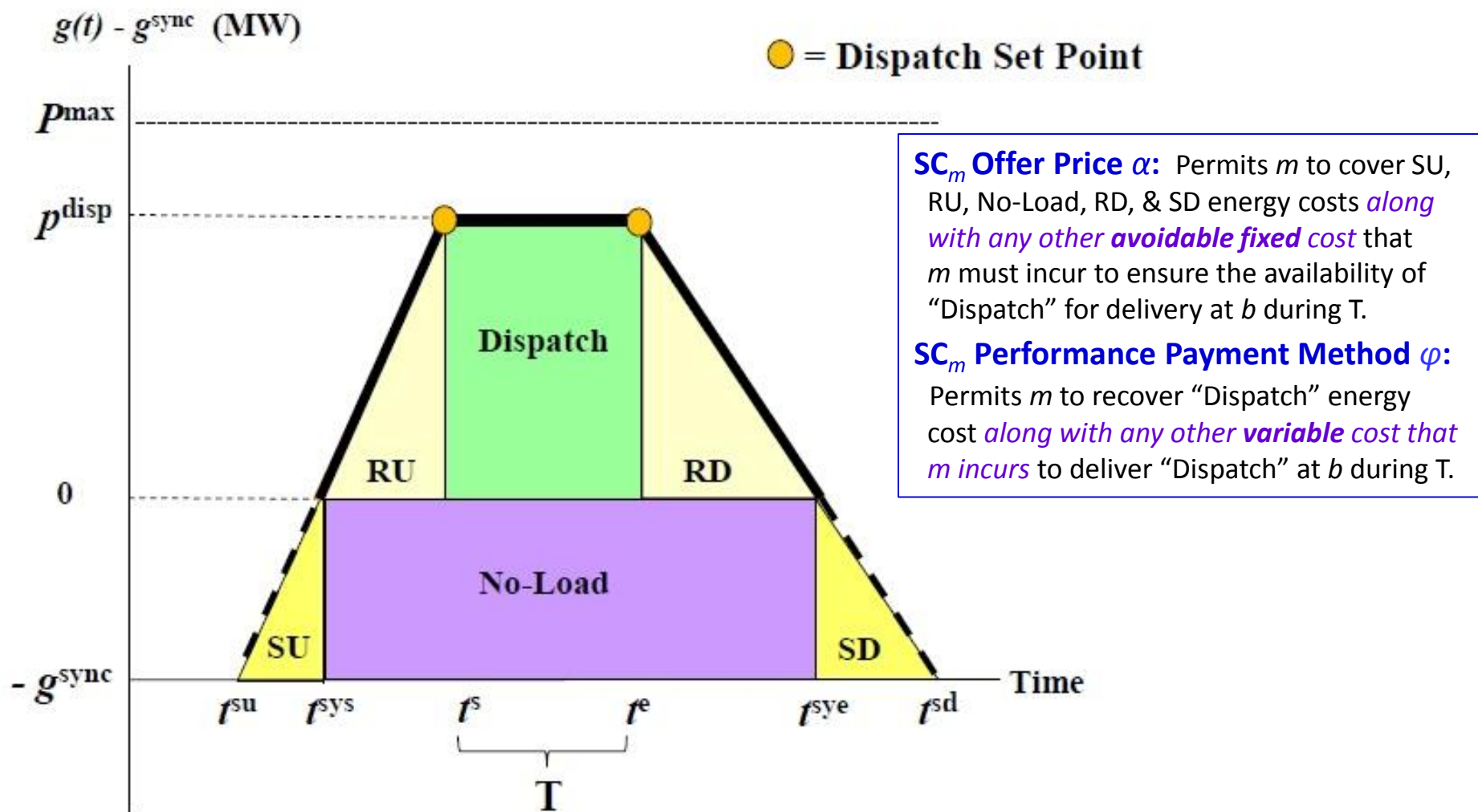


Fig. 5: Illustration of m 's **energy** requirements for delivery of energy-block “Dispatch” at m 's grid-location b during operating period T : namely, the energy block (“Dispatch”); start-up (“SU”); ramp-up (“RU”); no-load (“No-Load”), ramp-down (“RD”), and shut-down (“SD”).

Example 2: A piecewise-linear swing contract in firm form

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

where:

α = Offer price

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

b = Delivery location

t^s = Start-time for ramp interval R1

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

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

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

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

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

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

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

$\mathbb{P}(\text{E2})$ = Set of feasible maintained power-steps $p_j(\text{E2})$ 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 $p \in \mathbb{P}(\text{E1}) \cup \mathbb{P}(\text{E2})$

Example 2: A piecewise-linear swing contract ... Continued

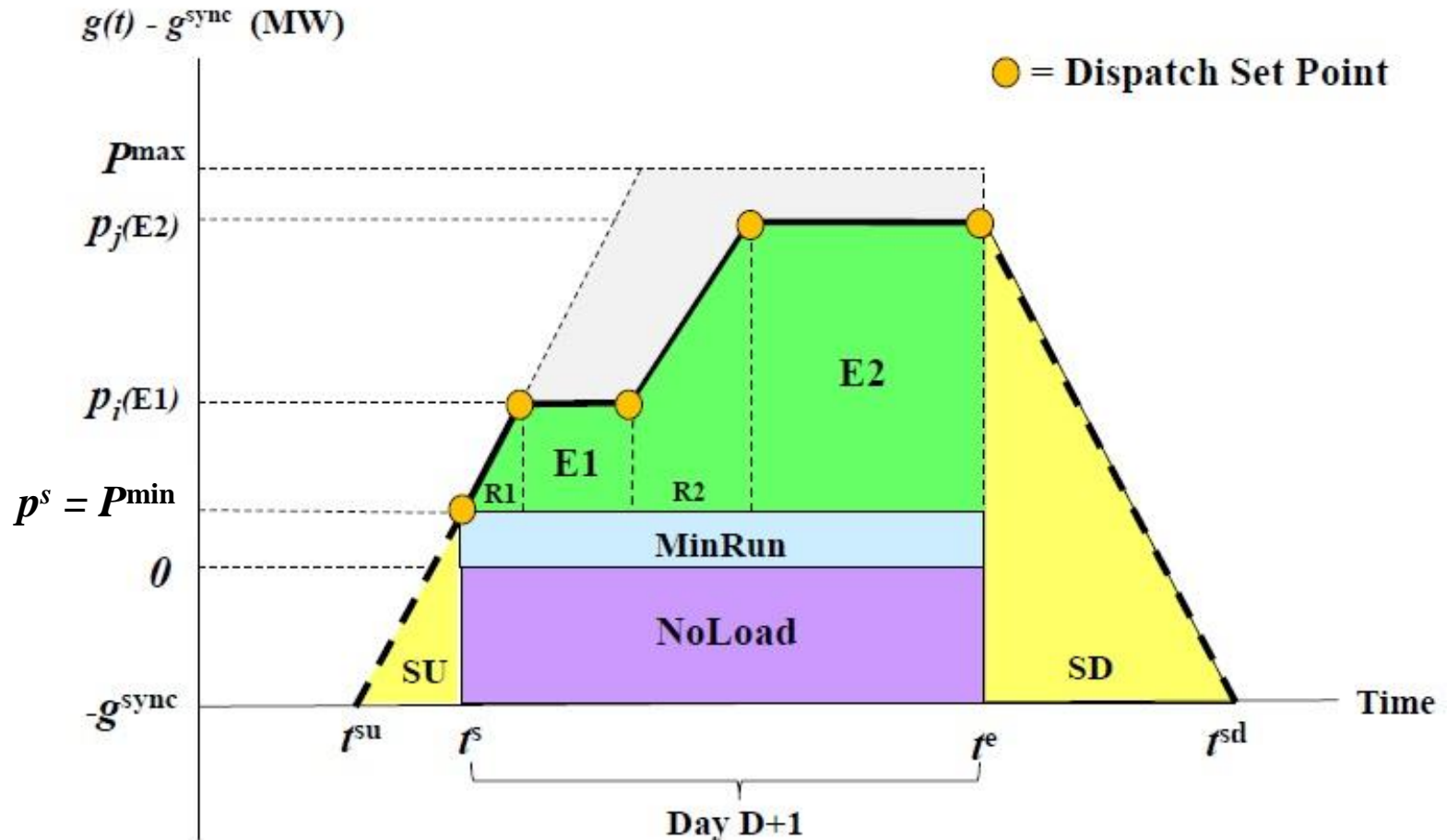


Fig. 6: One among multiple possible power-paths p the RTO/ISO could dispatch m to deliver at m 's grid-location b during operating day $D+1$ if the RTO/ISO clears m 's piecewise-linear swing-contract SC_m submitted to a swing-contract day-ahead market $M(D+1)$ held on day D .

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

$$SC_m = [\alpha, \mathbb{P}\mathbb{P}, \phi]$$

where:

α = Offer price

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

b = Delivery location

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

η = Round-trip efficiency

t^s = Start-time for power discharge/charge

SOC^s = Set of feasible state-of-charge percentages at t^s

$\mathbb{P} = [P^{\min}, P^{\max}]$ = 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

ϕ = Performance payment method for down/up power-path delivery

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

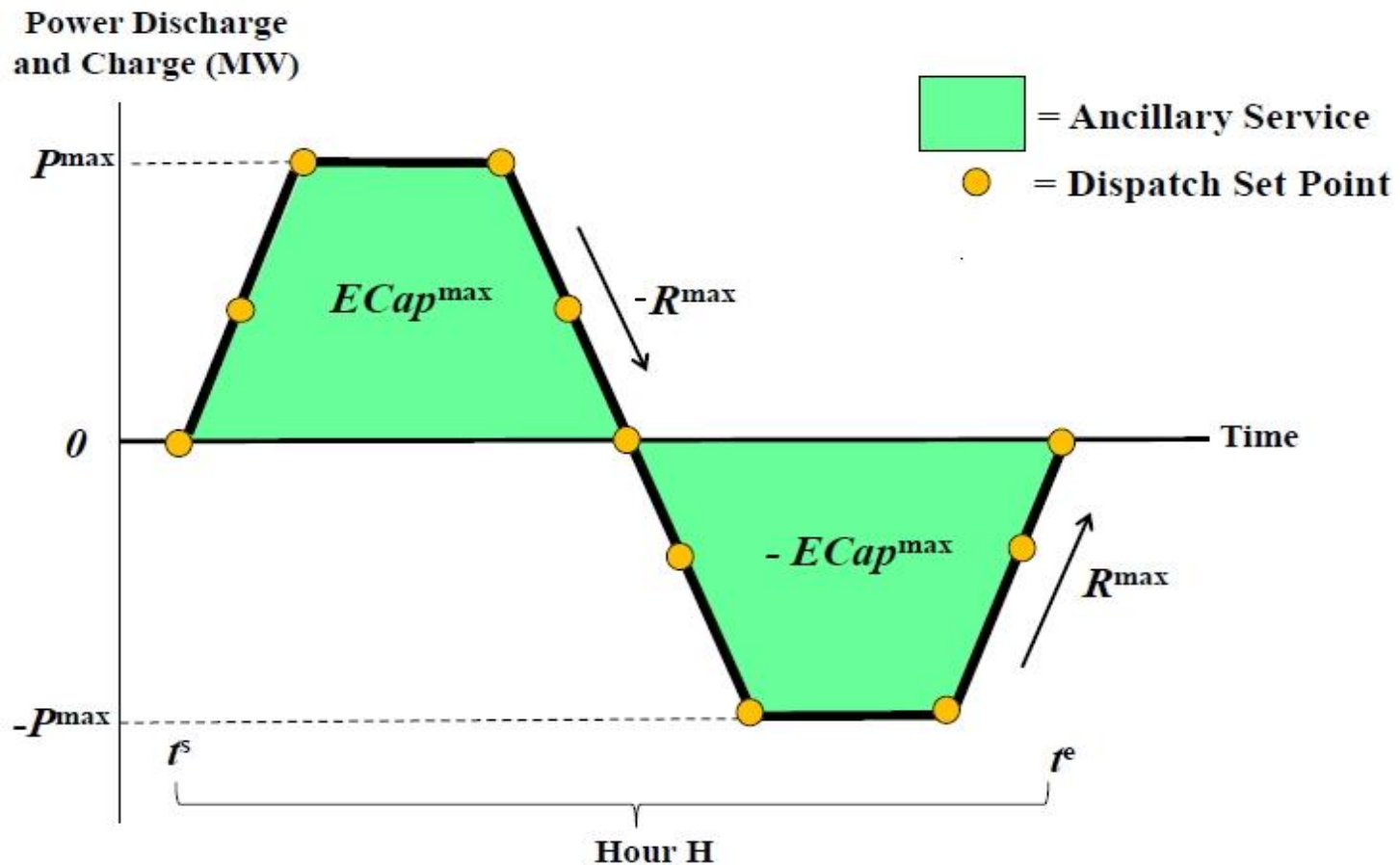


Fig. 7: Suppose $SOC^s = SOC^e = \{100\%$, $P^{min} = -P^{max}$, and $R^D = R^U =: R^{\max}$. Then the depicted dispatched power-path is **one among multiple power-paths p** the RTO/ISO could dispatch m to deliver at m 's grid-location b during hour $H = [t^s, t^e)$ if the RTO/ISO clears m 's battery 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. [3]*

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

where:

α = Offer price

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

b = Delivery location

t^s = Start-time for power delivery

p^s = Initial power level at time t^s

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

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

t^e = End-time for power delivery

ϕ = Performance payment method for power-path delivery

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

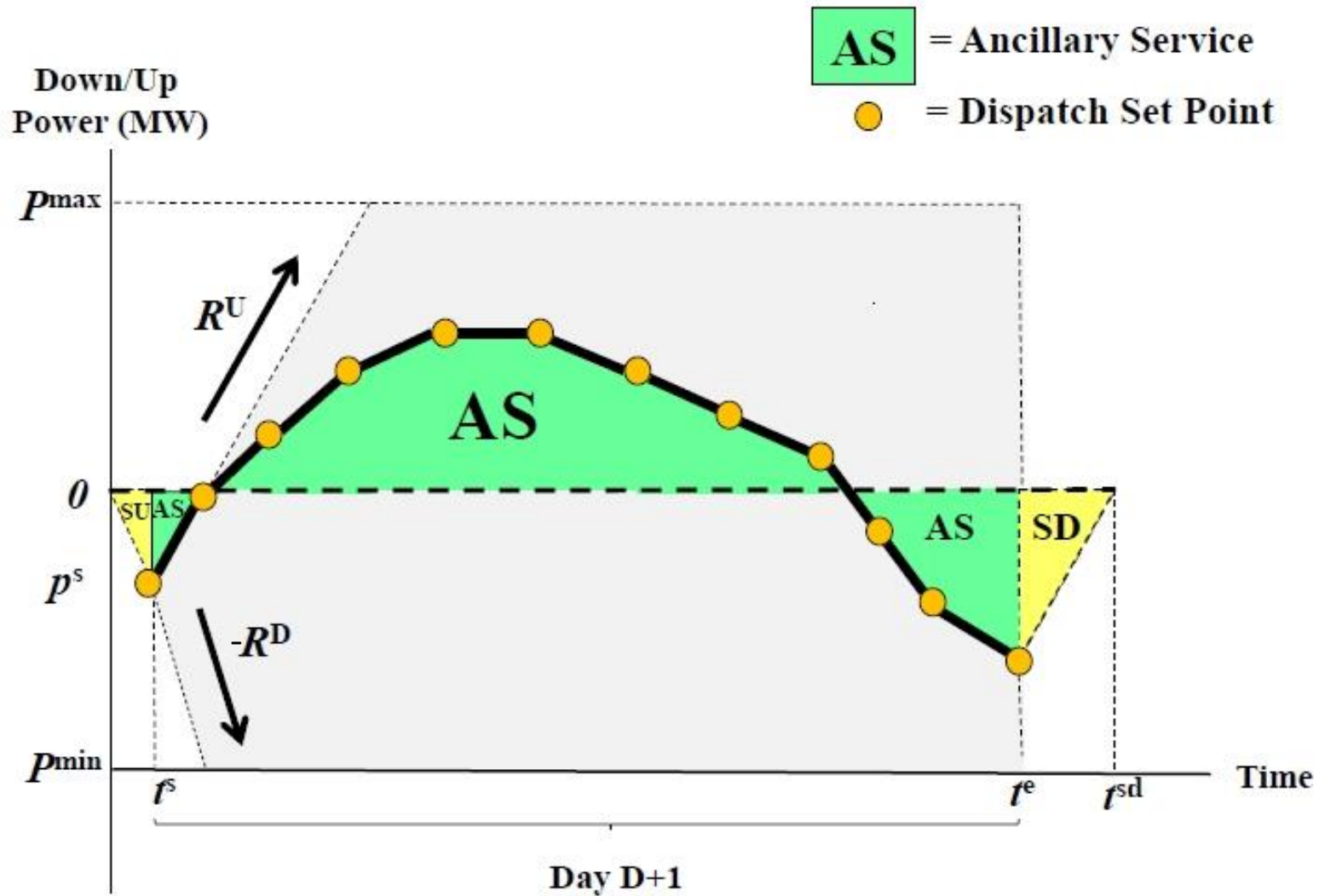
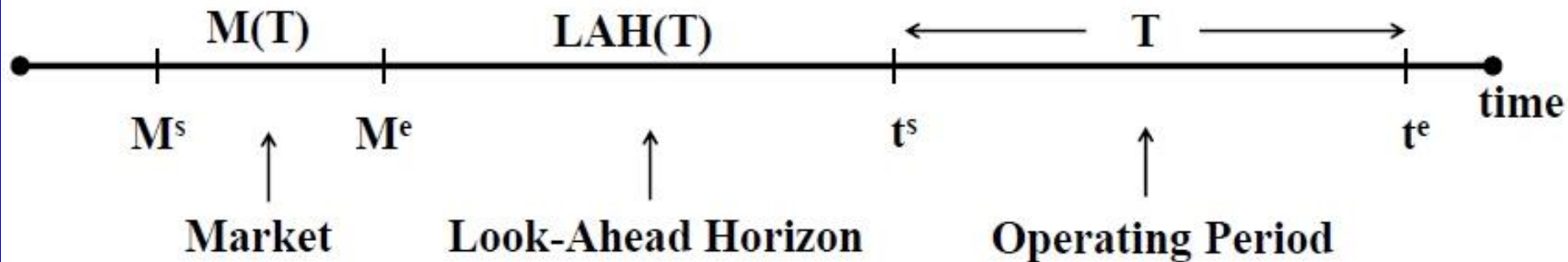


Fig. 8: One among many possible power-paths p the RTO/ISO could dispatch m to deliver at m 's grid-location b during operating day $D+1$ if the RTO/ISO clears m 's flexible power/ramp swing-contract SC_m submitted to a swing-contract day-ahead market $M(D+1)$ held on day D .

□ Swing-Contract Market $M(T)$: Key Features [Ref. 1, Sec. 6], [Ref. 3, Chapter 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 **Look-Ahead-Horizon** $LAH(T)$ 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 *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

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

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 an 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 (including forecasts) **plus** information extracted from submitted reserve offers & 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 *k* during T

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

minus **Fixed** (*non-dispatched must-service*) power **supply** by *k* during T]

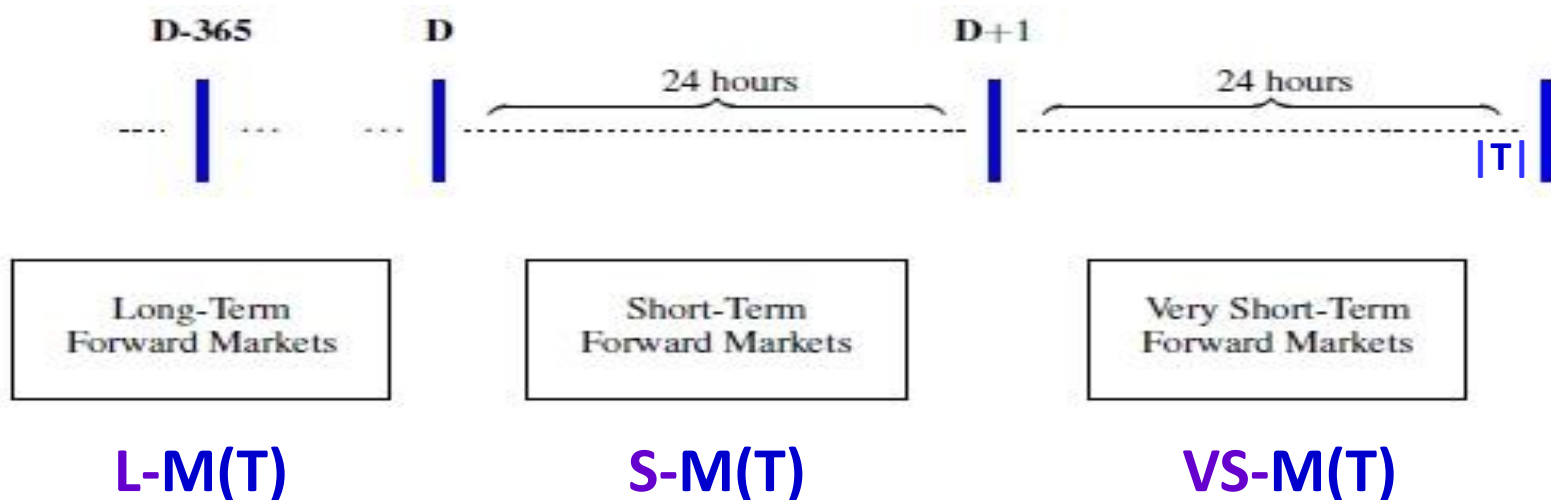
- Allocate **M(T) transmission service cost** across M(T) participants based on:
 - relative power imbalance **RPI(b,T)** recorded at each grid location *b* during T; and
 - relative contribution of each M(T)-participant *k* to **RPI(b(k),T)**, where *b(k)* =: *k*'s grid location.

Linked Swing-Contract Markets *Key Source: Ref. [3, 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 Look-Ahead Horizons $LAH(T)$ ranging from *long* (L) to *short* (S) to *very short* (VS)

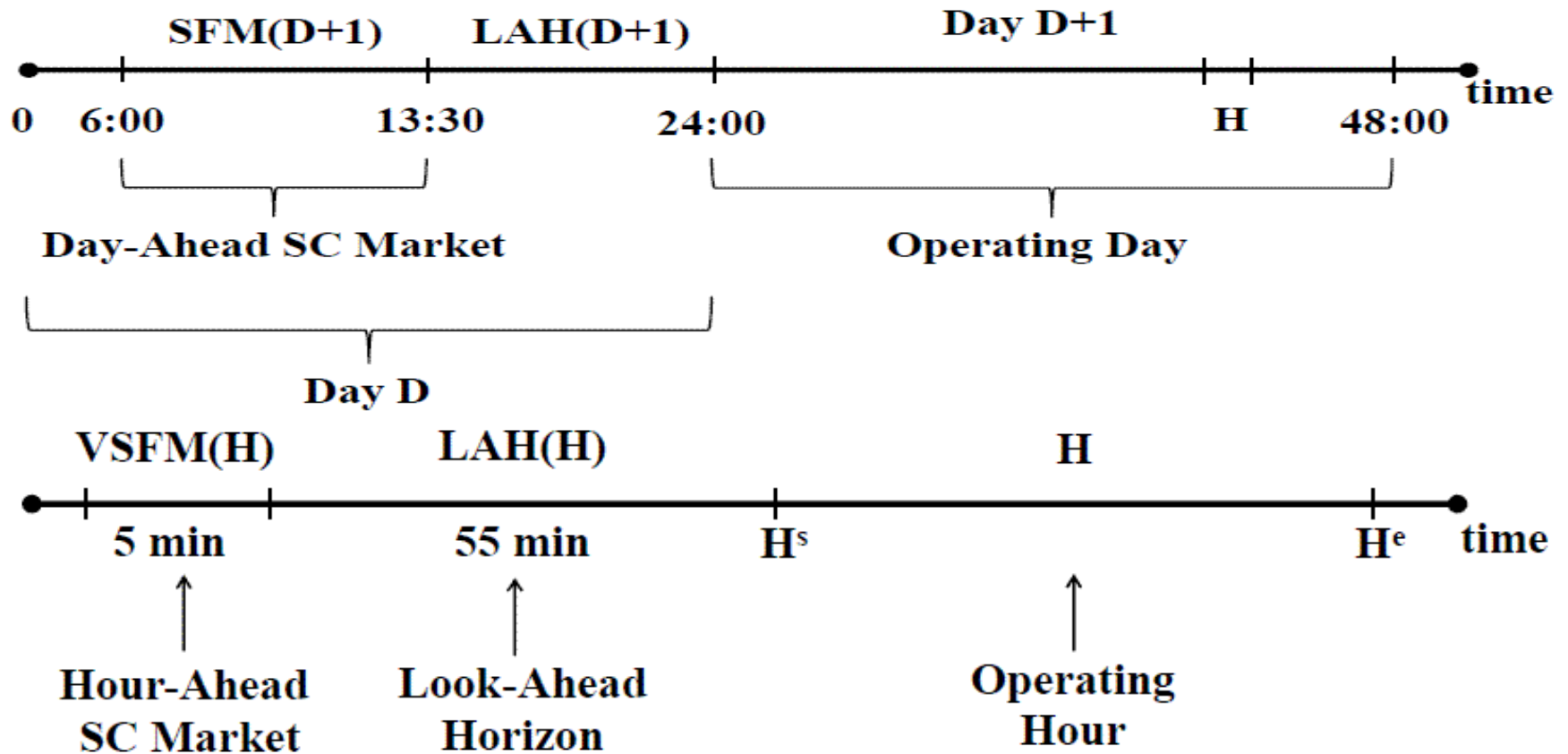
- *Linkage* is established among the *successive* SC markets $M(T)$ for the *given* T by **ISOPort(T)** =: Portfolio the RTO/ISO carries forward through time for use during T , where this portfolio includes: { all RTO/ISO-cleared reserve offers and reserve bids for T , plus all past RTO/ISO-signaled dispatch set-points }
- The RTO/ISO *updates* **ISOPort(T)** in *successive* SC markets $M(T)$ held *prior to* T to include any *newly-cleared* reserve offers/bids for T and/or any *newly-signaled* dispatch set-points.



Linked Swing-Contract Markets ... Continued

Example 2: Nested Day-Ahead and Hour-Ahead Operating Periods

- *Linked day-ahead & hour-ahead SC markets for a designated operating hour $H = [H^s, H^e)$ that takes place during a designated 24-hour operating day $D+1$*



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

- Detailed comparisons with current RTO/ISO-managed market designs and operations are given in *Ref. [3, Chps. 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)**.

Important Note:

- The ***essential differences*** between the design of current U.S. RTO/ISO-managed wholesale power markets and the Linked Swing-Contract Market Design proposed in *Ref. [3]* are differences in **product definition & pricing, settlement timing, and supply offer formulations** --- ***not*** differences in real-time operations.
- ***These differences can be introduced gradually*** into current RTO/ISO-managed wholesale power markets; see *Ref. [3, Ch. 16]* for a “Transitional DAM” example.

Illustrative DAM Comparisons: Basic Features

		Current DAM	SC DAM
Similarities		<ul style="list-style-type: none"> • 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

Illustrative DAM Comparisons: Optimization Formulations

		Current DAM SCUC	Current DAM SCED	SC DAM Optimization
Similarities		<ul style="list-style-type: none"> 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

Conclusion

- ❑ 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 definition and pricing; settlement timing; and supply-offer formulations.
- ❑ Attention was then focused on the following product definition and pricing 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 new design – proposed, developed, & tested in *Ref. [3]* -- provides proof-of-concept (at Technology Readiness Level 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 and pricing, settlement timing, and supply-offer formulations, but *not* in real-time operations. Thus, the adoption could proceed gradually, without disruption of real-time operations.