U.S. RTO/ISO-Managed Wholesale Power Markets: A Fundamental Reconsideration

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Presentation Outline: Key Points

1. Current U.S. RTO/ISO-Managed Wholesale Power Markets [1, Sec. 1]

— **Key concern:** Increasing uncertainty and volatility of net load ⟶ need more flexible **power supply**

— **Potential remedy:** Increase the dependable availability of diverse dispatchable **power flows**

— **Design issues:** Conceptually-problematic *economic presumptions* ***(P1)-(P4)*** are **hindering remedy**

2. Essential Operating Characteristics of Grid-Based Centrally-Managed Wholesale Power Markets ⟶ *Counter-Claims (CC1)-(CC4)* to economic presumptions (P1)-(P4) [1, Secs.2-4]

3. Proposed Linked Swing-Contract Market Design [1, Sec. 5]; [2]

— **This design is consistent** with essential operating characteristics & counter-claims (CC1)-(CC4)

— **Design form:** *Linked RTO/ISO-managed forward reserve markets* ***M(T)*** *for future operating periods* ***T***

— **Reserve for T:** *Collections of diverse power flows* ***{ p(t) |t in T}*** *for possible RTO/ISO dispatch during T*

— **Form of reserve offers for T:** Two-part pricing *swing contracts* in firm or offer form, submitted by dispatchable power resources to markets M(T) for T with look-ahead horizons from years to minutes

— **Specific design purpose:** Facilitate dependable availability of diverse dispatchable **power flows**

References

[1] Leigh Tesfatsion (2022), **"Economics of Grid-Supported Electric Power Markets: A Fundamental Reconsideration,"** Economics Working Paper No. 22005, ISU Digital Repository, Iowa State University, Ames, Iowa, September.
https://www2.econ.iastate.edu/tesfatsi/EconomicsGridSupportedPowerMarkets.ISUDR22005.LTesfatsion.pdf

[2] 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., USA
http://www2.econ.iastate.edu/tesfatsi/ANewSwingContractDesign.Flyer.WileyIEEEPress.pdf

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

Basic Purpose:

— Maintain efficient production and transmission of bulk power to satisfy customer power demands, subject to reliable operation of supporting high-voltage AC transmission grid

Basic Reliability Requirement:

— Continual net-load balancing across the buses of the transmission grid, i.e.,

dispatched power injection $\cong$ net load

where:

net load $\equiv$ **[**power withdrawals & losses**]** **–** **[*****non*****-**dispatched power injection**]**

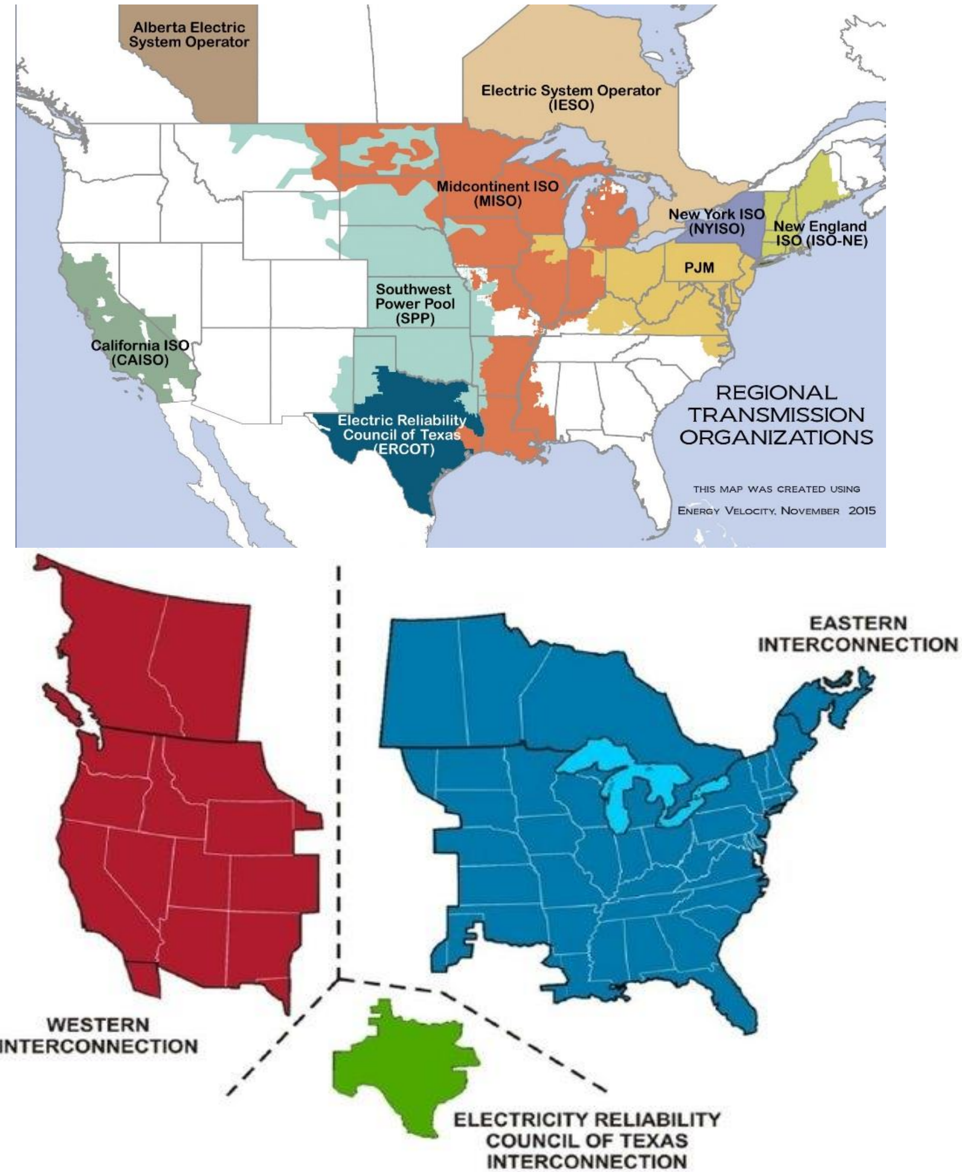

Fig. 1*: Seven North-American RTOs/ISOs operate over a high-voltage AC transmission grid consisting of three separately-synchronized parts.*

Key Concern

Recent trends:

- increasingly diverse customers with just-in-time power demands
- increasing reliance on **I**ntermittent **P**ower **R**esources (**IPRs**)
  (e.g., wind farms & large solar PV panel arrays ***not*** fully firmed by storage)

➡ Increasingly volatile and uncertain net load

➡ RTOs/ISOs must function as ***"fiduciary conductors"*** tasked with orchestrating the availability and subsequent possible *just-in-time* dispatch of power resources to service increasing volatile and uncertain net load

➡ Grid-supported RTO/ISO-managed wholesale power markets must function as ***"flexibility-support mechanisms"***

Potential Remedy

- ***Increase the dependable availability of diverse dispatchable power flows*** to balance increasingly uncertain & volatile net load

  - **obtainable from *wholesale* power resources**
    - Firm up dispatchability of intermittent power via co-operated ***storage***.
  - **obtainable from *distributed* power resources**
    - 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 *__T__ransactive __E__nergy __S__ystem (__TES__) designs*. **(FERC Order 2222)**

- **Difficulty**

Legacy market design features of current U.S. RTO/ISO-managed wholesale power markets are ***hindering*** the pursuit of this potential remedy.

Conceptually-Problematic Aspects of Current Market Designs

- **Four conceptually-problematic economic presumptions (P1)-(P4)** implicit in core DAM/RTM two-settlement system for each U.S. RTO/ISO-managed wholesale power market *are hindering the ability to ensure increased dependable availability of diverse dispatchable power flows .*

Problematic Presumption (P1): The ***basic transacted product*** in grid-supported U.S. RTO/ISO-managed wholesale power markets is *delivered energy (MWh),* i.e., power (MW) accumulated at designated grid *delivery locations* during designated *delivery periods*.

Problematic Presumption (P2): It suffices to partition ***total supplier cost*** into:

(1) a ***variable*** component *determined by* supplier-delivered energy;
(2) a ***fixed*** component *independent of* supplier-delivered energy.

Problematic Presumption (P3): ***Energy*** conditional on delivery location & delivery period is a *commodity with perfectly substitutable units (MWh)* whose *uniform price ($/MWh)* and *transacted quantities* should be determined in a *competitive commodity spot market.*

Problematic Presumption (P4): ***Supplier revenue*** attained in these competitive commodity spot markets *will suffice over time to cover total supplier cost.*

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.

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

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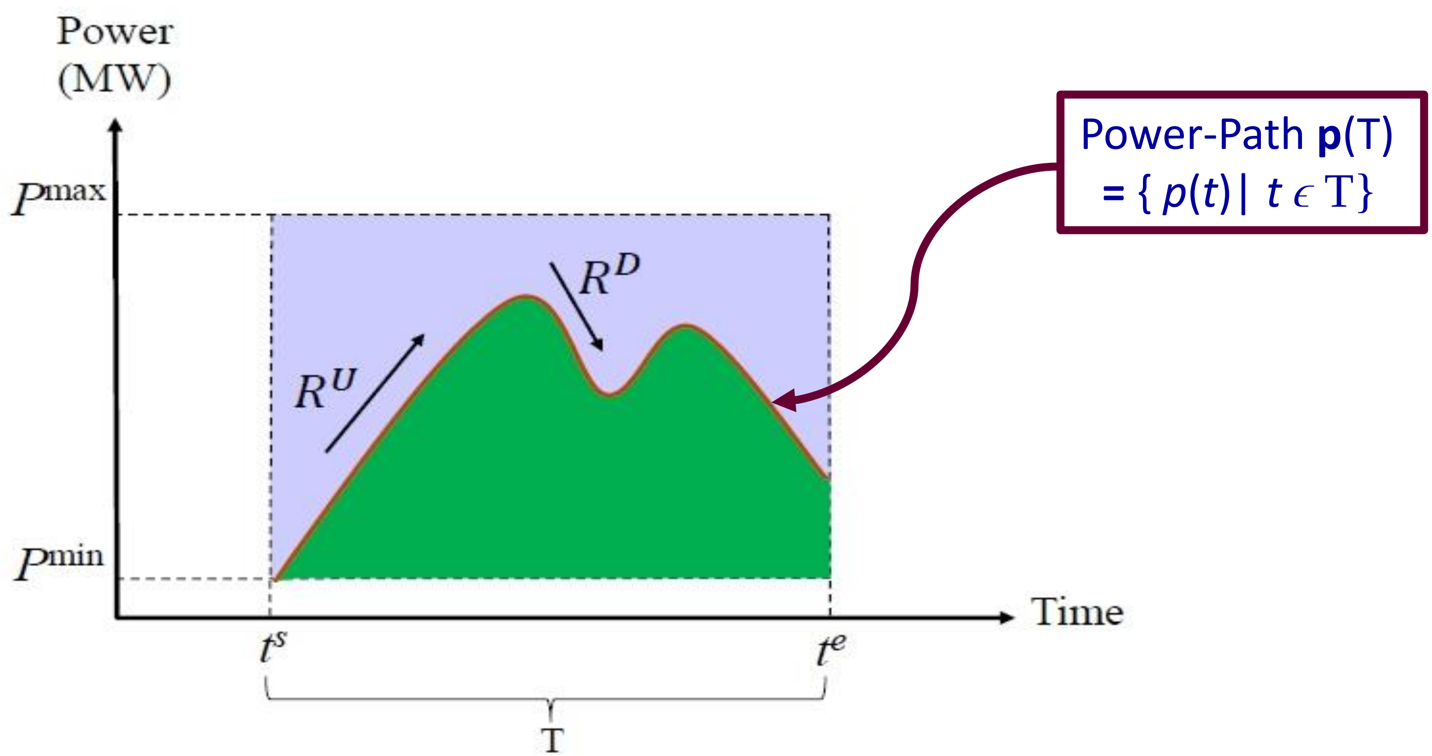


Fig. 2: *Depiction of a power-path in a time-power plane.*

2. Essential Operating Characteristics of a Grid-Supported Centrally-Managed Wholesale Power Market ➡ *Counter-Claims (CC1) – (CC4)* to *(P1) – (P4)*

(CC1): Energy conditional on delivery location & delivery period is ***not*** a commodity because *the units (MWh) of this energy are **not** perfectly substitutable.*

(CC2): ***Any*** market process carried out within such a context must necessarily be a ***forward*** market due to the speed of real-time grid operations.

(CC3): ***Two*** distinct types of valued service can be provided by dispatchable power resources participating in a ***forward*** market*:*

(i) Volumetric risk reduction, i.e., *guaranteed availability* of power-paths for *possible* RTO/ISO-dispatched delivery during *future* operating periods T;

(ii) Power-path delivery, i.e., *real-time delivery* of power-paths *during* operating periods T in response to RTO/ISO dispatch instructions.

(CC4): Dispatchable power resources can use *supply offers taking a two-part pricing swing-contract form* -- based on a *three-part partition* of total supplier cost – that ensure they receive full compensation for:

(1) all avoidable fixed cost incurred to reduce volumetric risk for *future* operating periods T;

(2) any variable cost incurred for dispatched power-path delivery *during* operating periods T.

➡ ***Suppliers can ensure their revenue sufficiency.***

Justifications for Counter-Claims (CC1)—(CC4)

Four Needed Economic Definitions:

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

Commodity: Asset A with a standard unit of measurement such that, at any given location and time, the units of A are *perfect substitutes,* i.e., any unit of A can be substituted for any other unit of A *with no change in valuation*.

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 time* ("*on the spot*").

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.

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**") and transport/damage cost ("**Trans**").

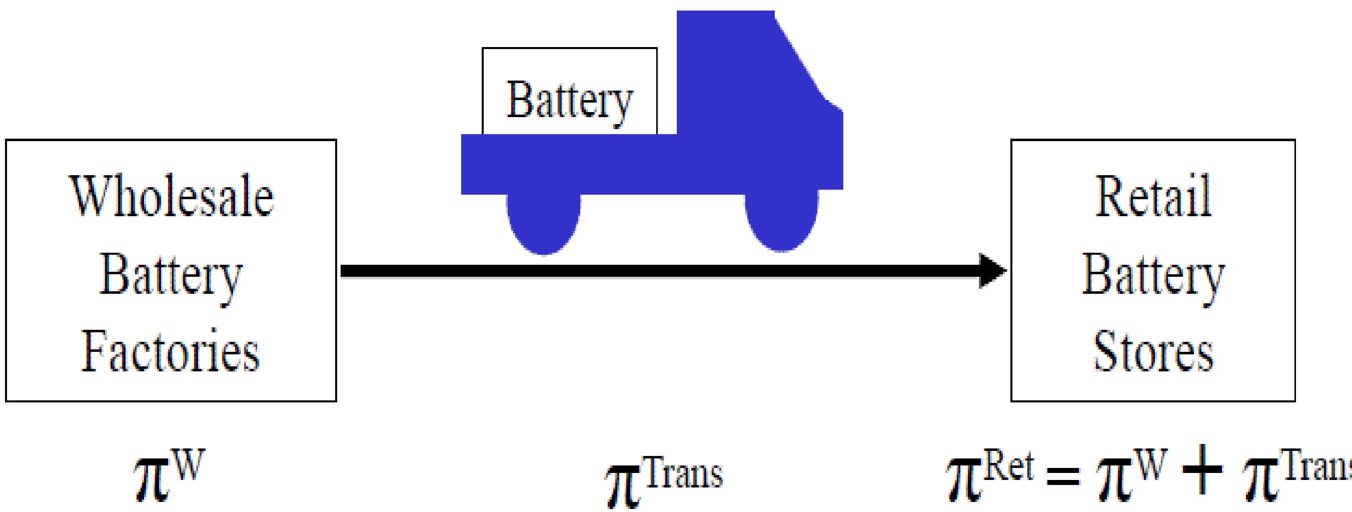


Fig. 3: *Energy (MWh) in uniform battery form* ***can*** *be transacted as a commodity.*

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.

Key Point (i): ***Energy (MWh) conditional on delivery location and delivery period*** is ***not*** a commodity for grid-supported centrally-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 the central manager.

- 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;

— Central manager, with fiduciary responsibility for grid reliability, benefits from flexible just-in-time availability of voltage-control support ***during*** T.

Key Point (ii): Grid-supported RTO/ISO-managed wholesale power markets are ***forward power-path markets***

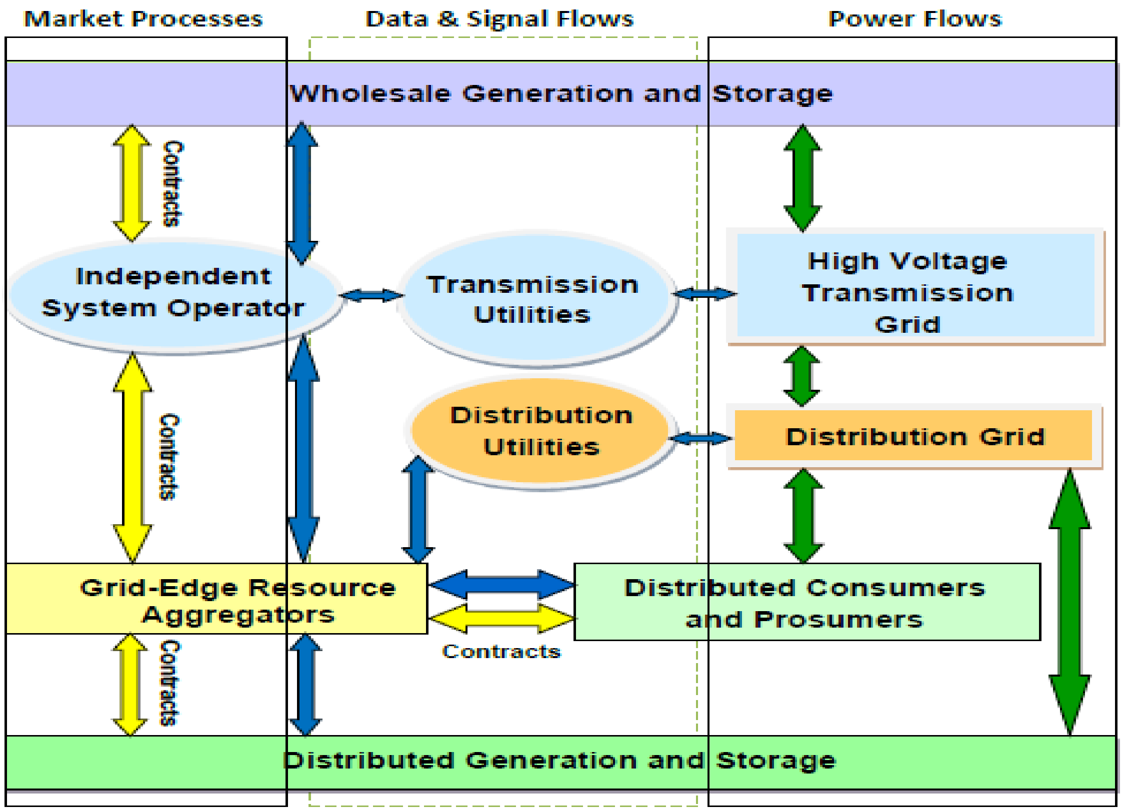


Fig. 4: *An RTO/ISO-managed wholesale power market is a collection of forward power-path markets operating over a high-voltage AC transmission grid electrically connected to one or more lower-voltage distribution grids. The purpose of these markets is to support the efficient, reliable, just-in-time production and transmission of bulk power to facilitate the just-in-time continual balancing of customer power demands at designated transmission-grid locations.*

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.

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, a power-path can have ***diverse correlated attributes*** that lead producers, customers, and RTO/ISO to assign ***diverse valuations*** to this power-path.

Examples:

— Down/up ramp (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/MVA) ***profile*** during T can affect power system reliability during T,

where:

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

❑ **However …**

- As will be shown in next Section 3, ***"swing-contracts"*** *are well-suited for support of power-path transactions in RTO/ISO-managed wholesale power markets.*

3. Proposed Linked Swing-Contract Market Design Ref. [2]

- **Design Overview:** The *Linked Swing-Contract Market Design* facilitates flexible dependable availability of reserve in RTO/ISO-managed wholesale power markets.

— **A swing-contract (SC) 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.*

— **A reserve offer** submitted by a dispatchable resource *m* to a swing-contract market M(T) for a future operating period T is *a portfolio of one or more swing contracts offering power-path availability for T.*

— **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 taking a price-sensitive and/or fixed (must-service non-dis.) form.*

— **Linkages** are established among the SC markets M(T) by the RTO/ISO's successive contract-clearing and dispatch decisions. *The RTO/ISO keeps track of these market linkages by carrying forward on its books an adaptively updated record of its cleared reserve bids/offers and dispatch decisions.*

General Swing-Contract Form of Reserve Offers

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

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

- **The swing contract $\mathbf{SC}_m$ permits** ***m*****:**

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

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

- **The physical attributes of each offered 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, 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** $\boldsymbol{\alpha_m}$ ($) in lump-sum or amortized form that covers *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 during T.

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

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

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

Swing Contract: General 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 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 **p** in PP_m as a linear combination of metrics that separately assign costs to correlated attributes of **p**, such as **delivered energy (*E*), power mileage (*R*), duration (*D*)**, etc.

$$\varphi_m(\mathbf{p}) \quad = \quad \underbrace{c^E(\mathbf{p}) \; + \; c^R(\mathbf{p}) \; + \; c^D(\mathbf{p}) \; + \; \ldots}$$

Costs assigned to ***correlated*** attributes of a ***single*** power-path **p**

❑ Swing Contract: Illustrative Examples [2, Ch. 5]

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

Remark: This type of swing contract is easily modified to handle current types of supply offers, such as ERCOT's three-part supply offer.

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

where:

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

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

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

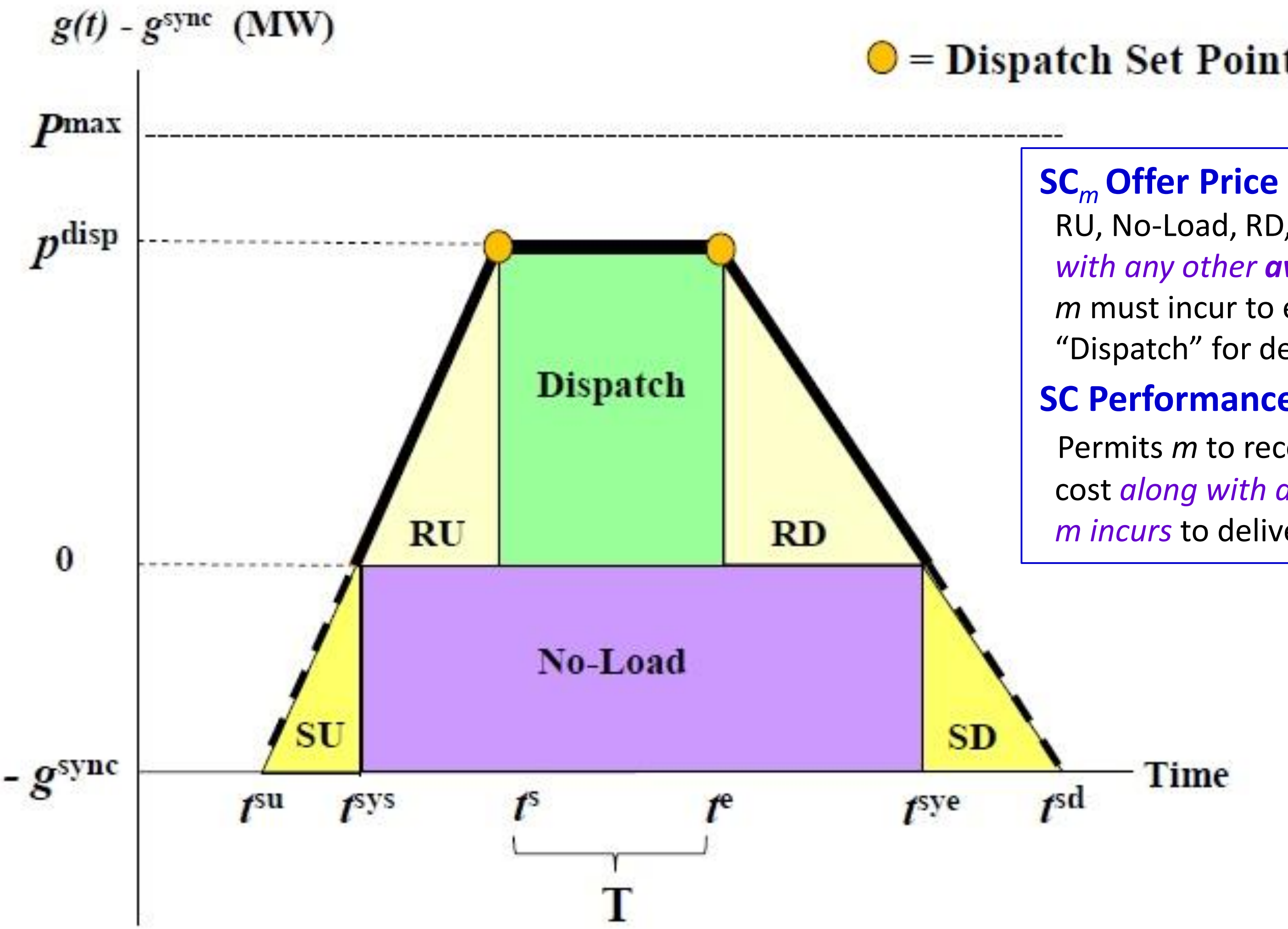
$$t^{\mathrm{s}} = \text{Start time for energy block E}$$

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

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

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

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 during **T**.

SC Performance Payment Method φ: Permits *m* to recover "Dispatch" energy cost *along with any other* ***variable*** *cost m incurs* to deliver "Dispatch" during **T**.

Fig. 5: *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

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

b = Delivery location

t^{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 $r(p^{\mathsf{s}}, p_i(\mathrm{E1}))$ 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*

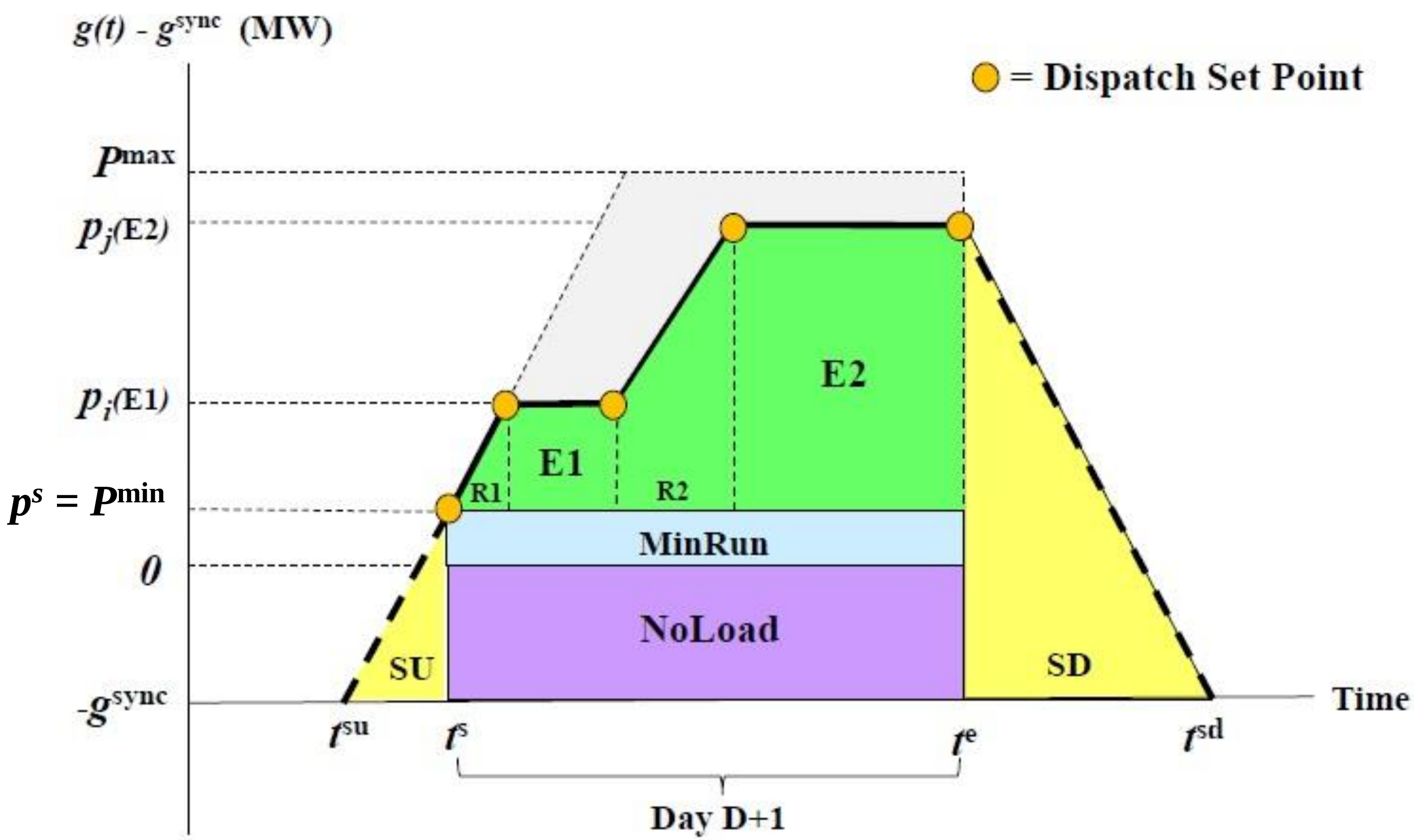


Fig. 6: ***One among many possible power-paths p*** *the RTO/ISO could dispatch m to deliver during operating day D+1 if the RTO/ISO clears m's piecewise-linear swing contract SC_m submitted to an SC day-ahead market M(D+1) held on day D.*

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*

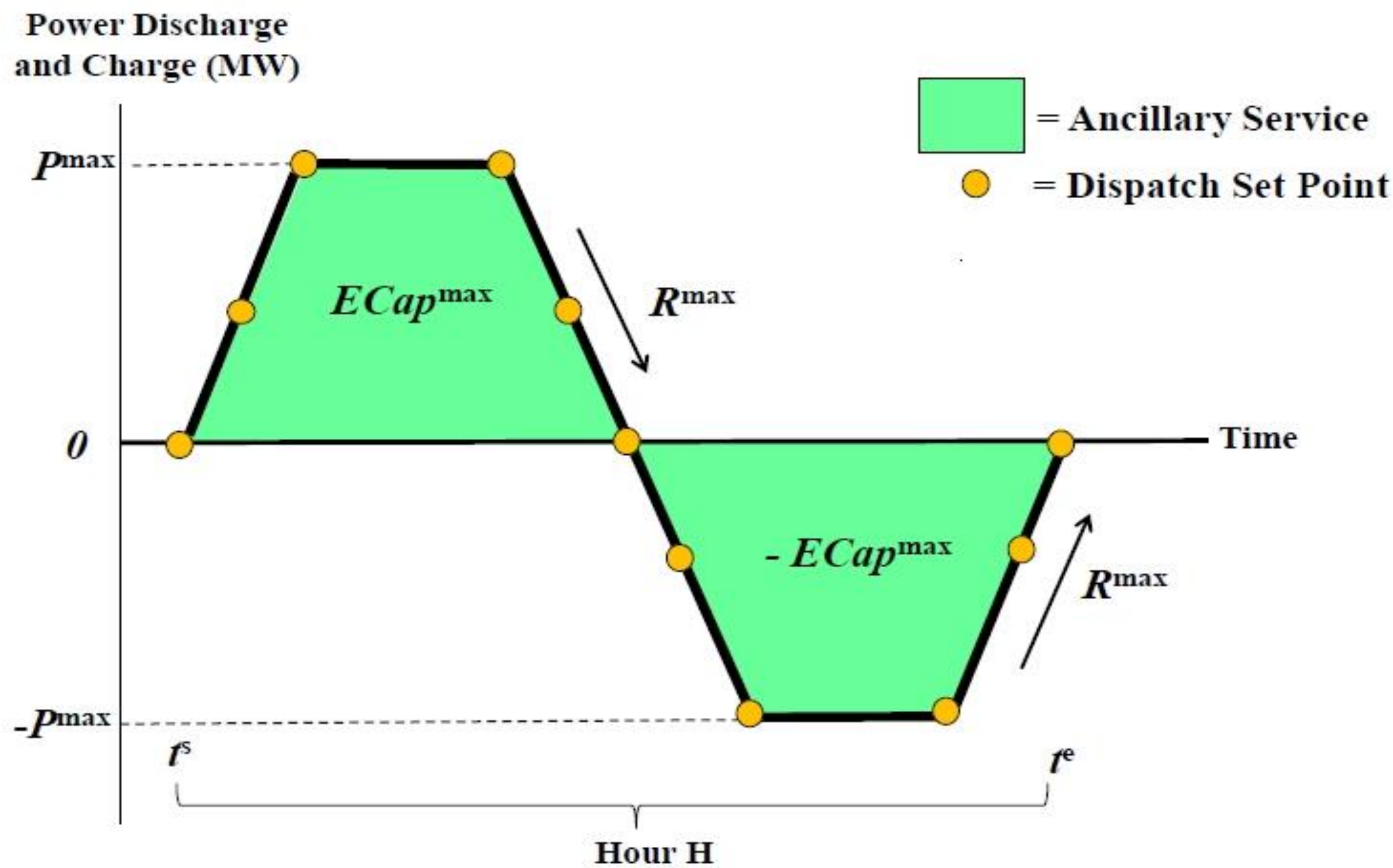


Fig. 7: *Suppose* ***SOC^s = SOC^e*** *= {**100%**}, and* ***P^{min} = - P^{max}****. Then the depicted dispatched power-path is* ***one among many possible power-paths p*** *the RTO/ISO could dispatch m to deliver during operating hour H = [t^s, t^e) if the RTO/ISO clears m's battery service swing contract 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:

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

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

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

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

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

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

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

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

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

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

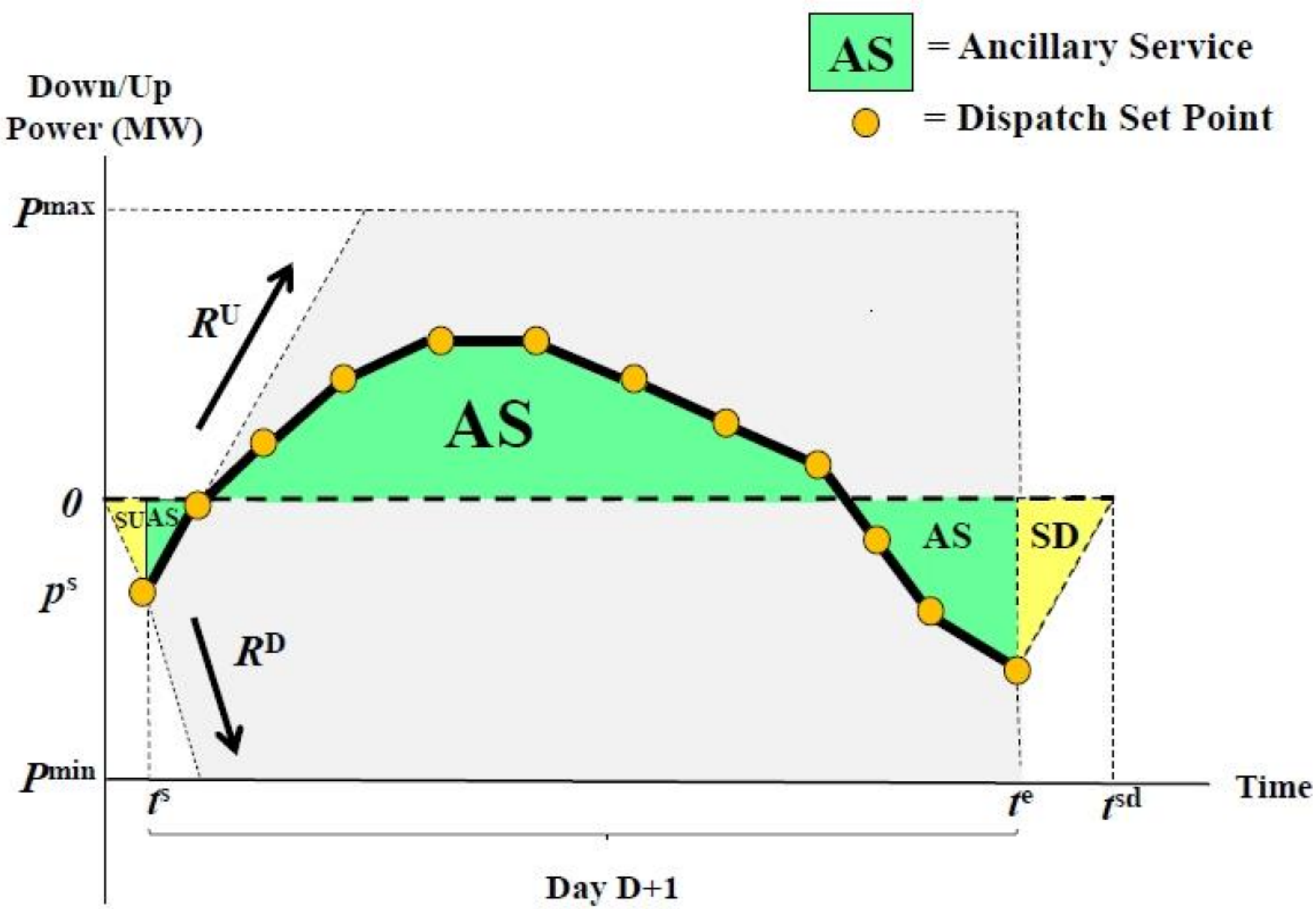
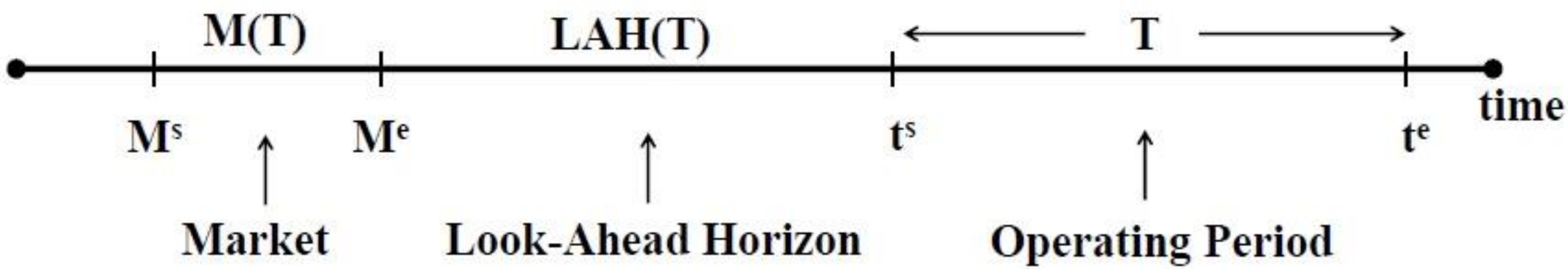


Fig. 8: ***One among many possible power-paths p*** *the RTO/ISO could dispatch m to deliver during operating day D+1 if the RTO/ISO clears m's flexible power/ramp SC submitted to an SC day-ahead market M(D+1) held on day D.*

❑ Swing-Contract Market M(T): Key Features [1, Sec. 5], [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 $m \in M$

— 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_{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., 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 M(T)-participant *j* during T

  =: [Fixed (*non-dispatched 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 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 [2, Chs. 10-11]

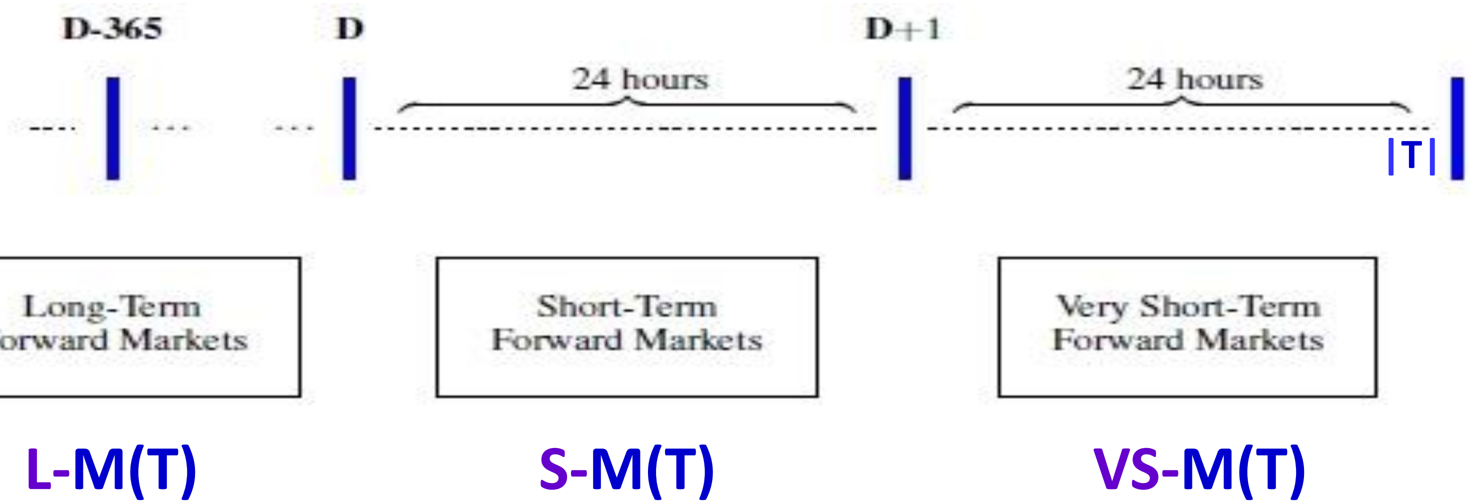
Example 1: Intertemporal Linkages for a Given Operating Period T

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** that the RTO/ISO carries forward through time for use during **T**.

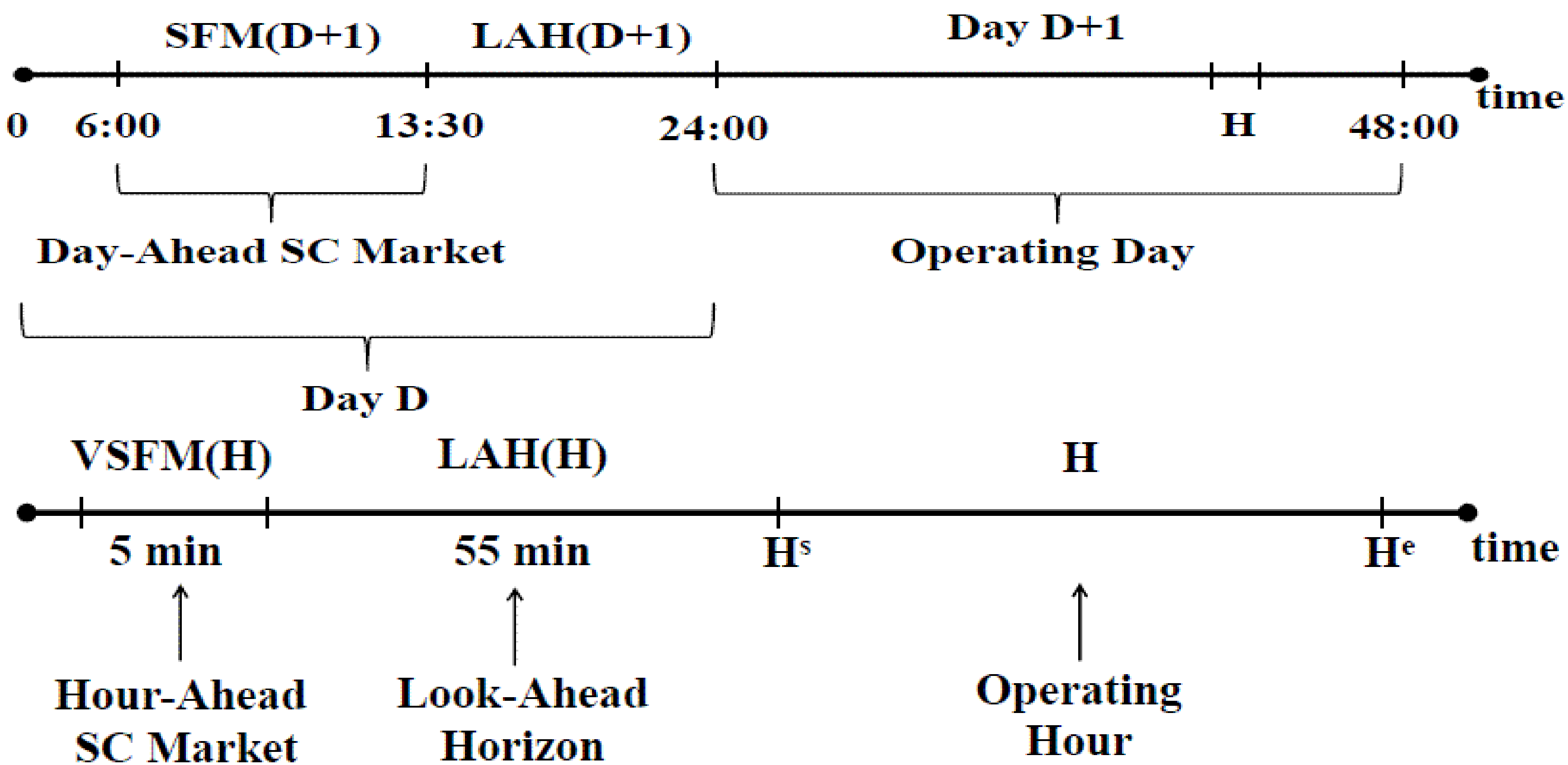
— The RTO/ISO *updates* **ISOPort(T)** in *successive* SC markets **M**(**T**) held *prior to* **T** to include any *newly-cleared* swing contracts for **T**.



❑ 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, 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**).

Important Notes:

— 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,** ***not*** differences in real-time operations.

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

Illustrative DAM Comparisons: Basic Features

		Current DAM	SC DAM
Similarities		• Conducted day-ahead to plan for next-day operations • RTO/ISO-managed • Participants include LSEs, DPRs, & IPRs • Same system constraint types: e.g., power balance, line capacity limits, reserve requirements, resource attributes.	
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		• 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

Conclusion

- Linked Swing-Contract Market 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.*