An End-to End Business Model for Retail Aggregation of Responsive Load to Produce Wholesale Demand Side Resources

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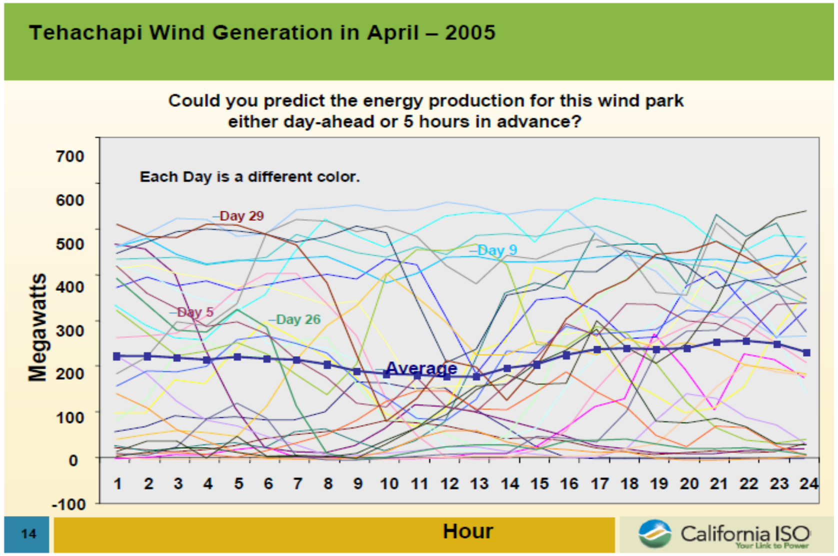
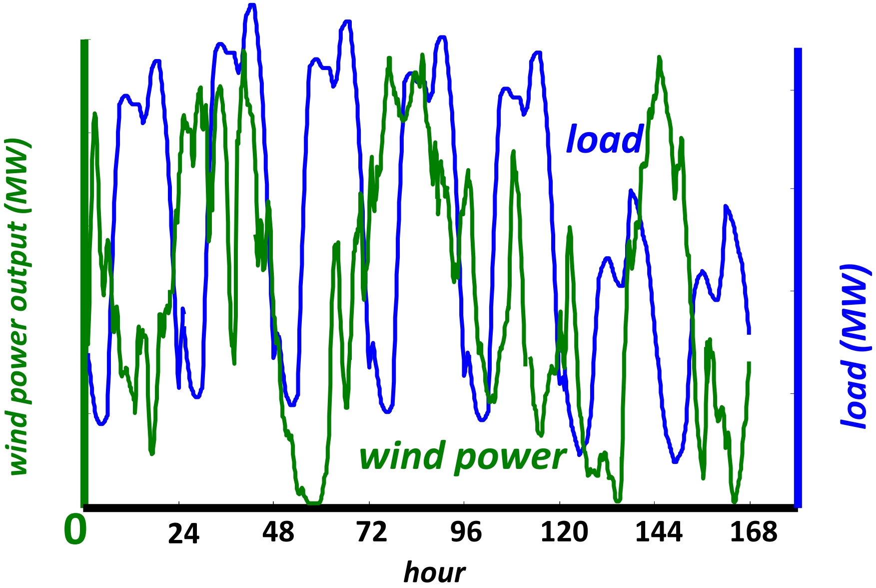
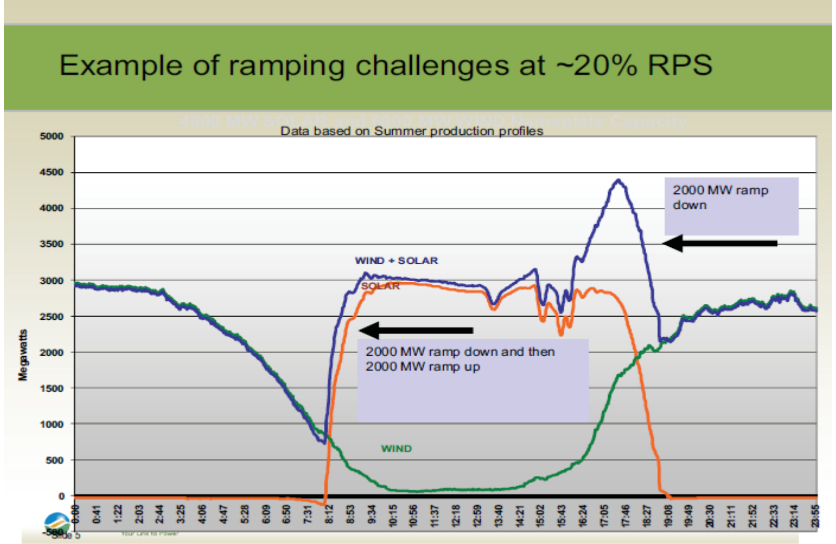
Drivers: Variability and Uncertainty of Renewables + Ramping Challenges



Tehachapi Wind Generation in April – 2005

Could you predict the energy production for this wind park either day-ahead or 5 hours in advance?





Example of ramping challenges at ~20% RPS

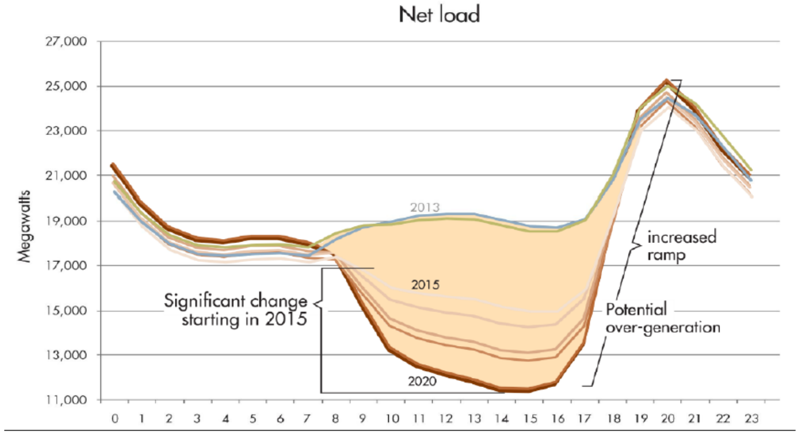
4000 MW SOLAR and 6000 MW WIND Nameplate Capacity

Data based on Summer production profiles

2000 MW ramp down

2000 MW ramp down and then 2000 MW ramp up

Chart 1: CAISO' Projected Net Load by Hour, using Avg. Projected Usage (aka "Duck Chart")



Source: CAISO

Challenges and Options

- ❑ Mobilize load flexibility and bring about a paradigm shift from “generation following load” to “load following available supply”
- ❑ Need business model and economic paradigm for a utility or third party aggregator to bridge the gap between wholesale commodity market and retail service
- ❑ Prices vs. Quantities
  - ➢ Treating retail electricity as a spot commodity: Provide real time wholesale prices to retail customers
  - ➢ Treating retail electricity as a subscribed service: Provide quality differentiated service based on contracted load control options
- ❑ Aggregated retail load control can be bid into the wholesale markets for balance energy and ancillary services.

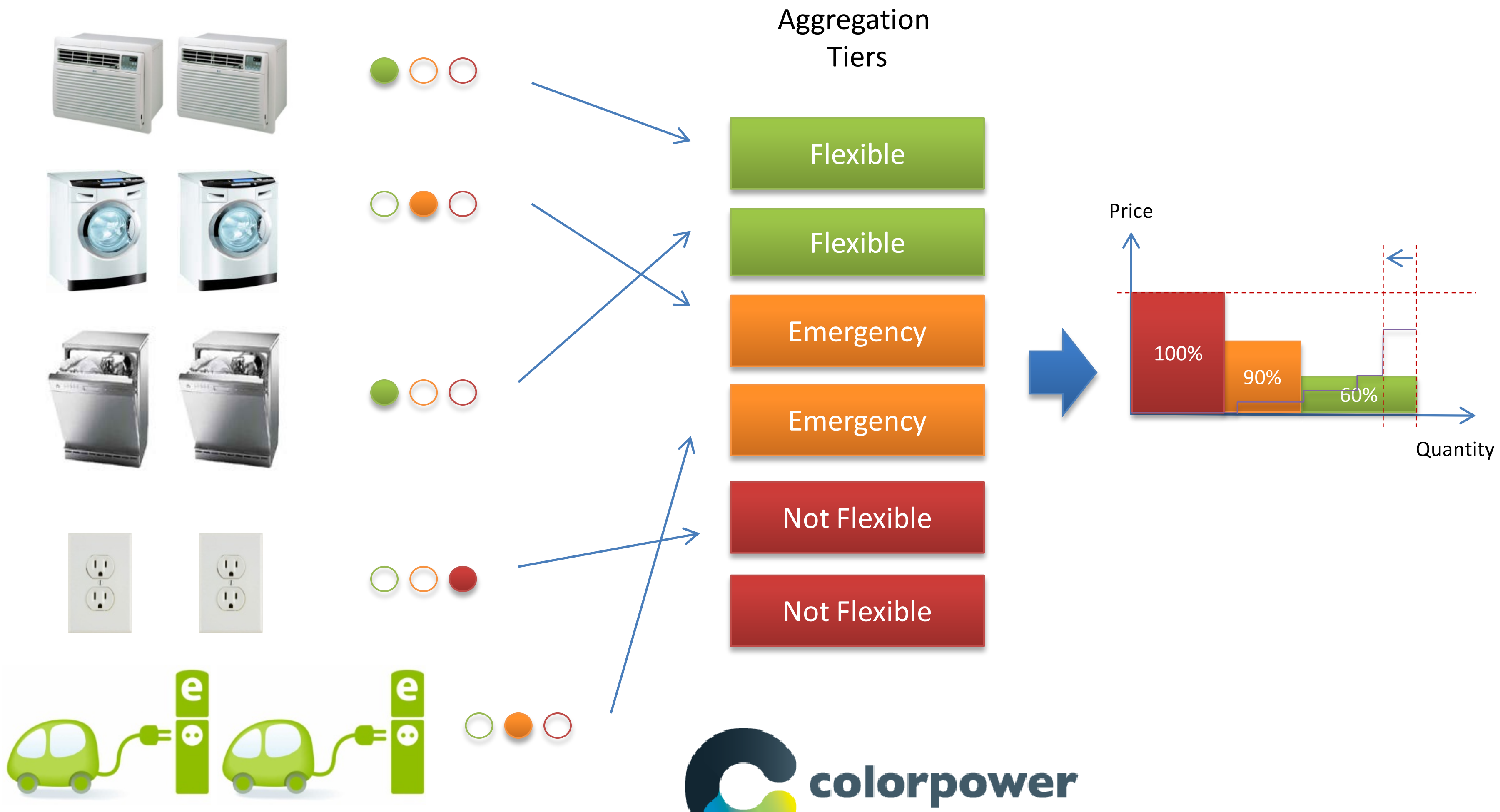
Rationale

- ❑ Treating electricity as a commodity works well at wholesale level but retail customers would rather think of electricity as a service.
- ❑ Quality differentiated service and optional price plans are common in other service industries (air transportation, cell phone, insurance)
  - ➢ Customers have experience with choosing between alternative service contracts
  - ➢ Conjecture: Customers prefer uncertainty in service rather than uncertain prices
- ❑ While RT price response can be automated it still puts the burden on the customer

Load Control Alternatives

- Nondisruptive device control (e.g. limited thermostat band control)
- Disruptive load control
  - Direct device control (thermostats, HVAC, water heaters, EV battery charge)
  - Fuse control: Control of power limits through the meter with customer dynamic allocation to devices in the home (manual or automated).
    - Maintain customer autonomy (watch super bawl or run dishwasher)
    - Performance guarantee (no customer override but there is still uncertainty in energy yield)

Direct Device Control

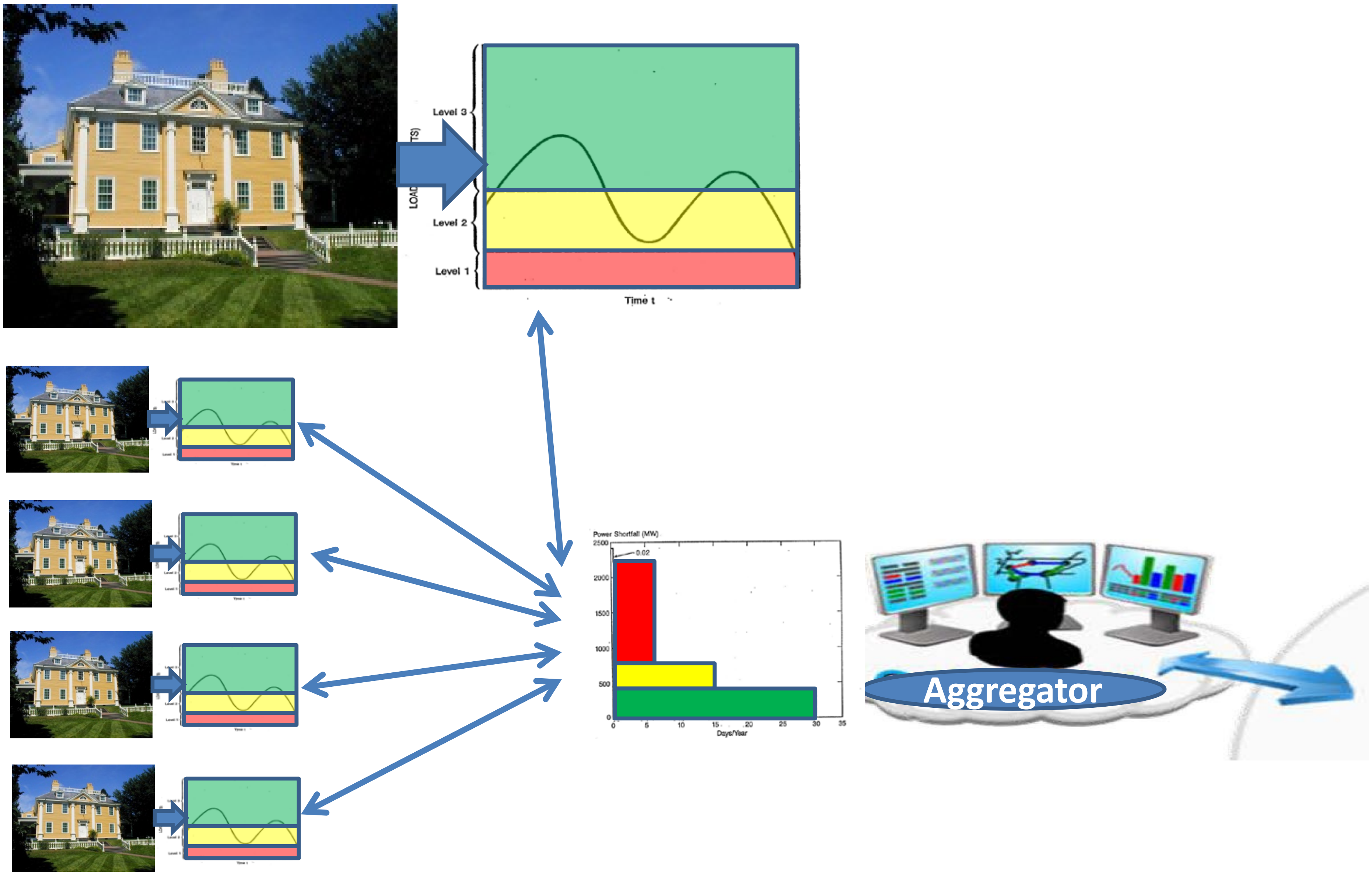


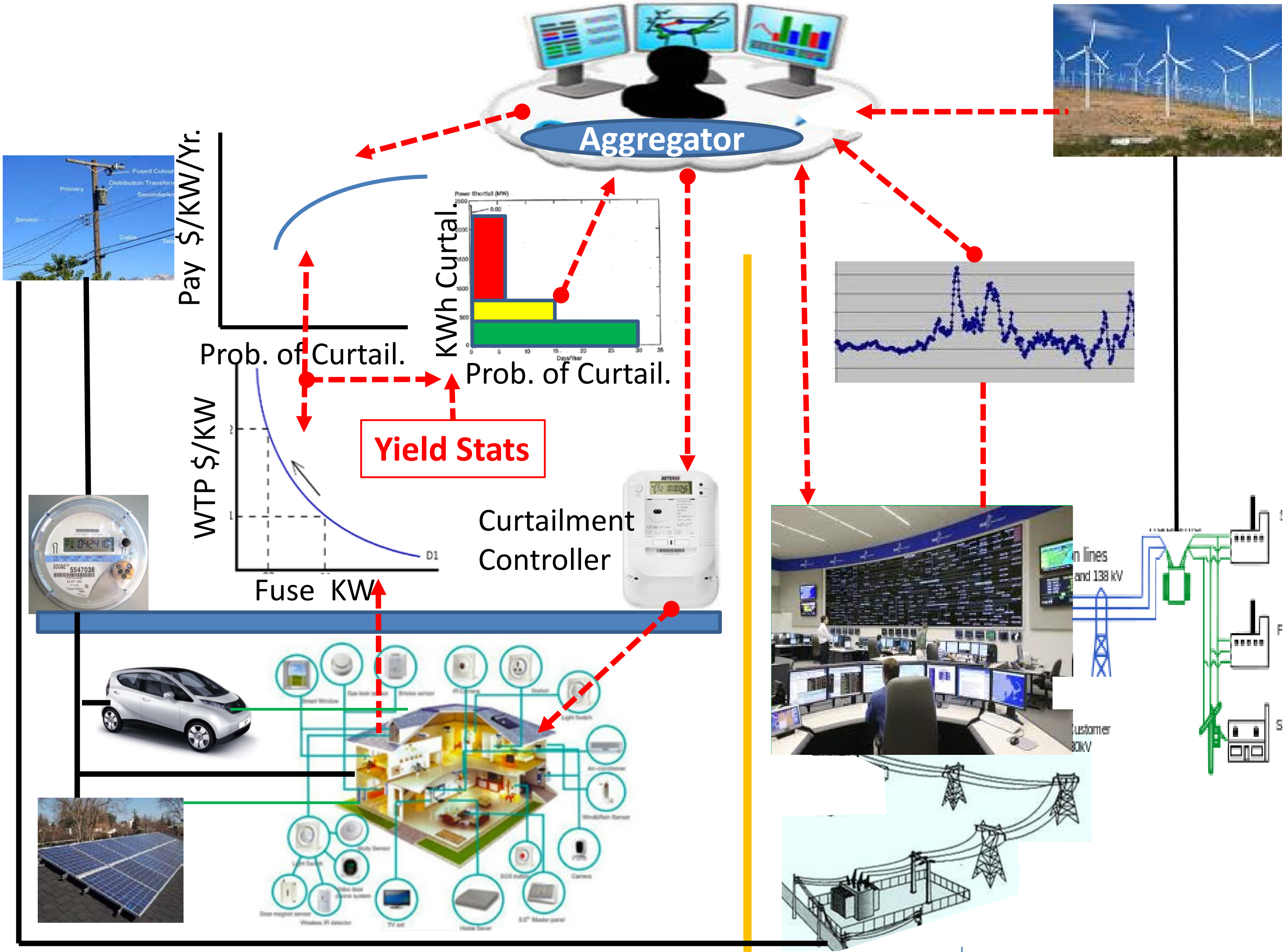
Aggregation Tiers

- 🟩 Flexible
- 🟩 Flexible
- 🟧 Emergency
- 🟧 Emergency
- 🟥 Not Flexible
- 🟥 Not Flexible

colorpower

Stratification of Demand into Service Priorities





Aggregator

Pay $/KW/Yr.

Prob. of Curtail.

KWh Curtal.

Prob. of Curtail.

WTP $/KW

Fuse KW

Yield Stats

Curtailment Controller

Road Map

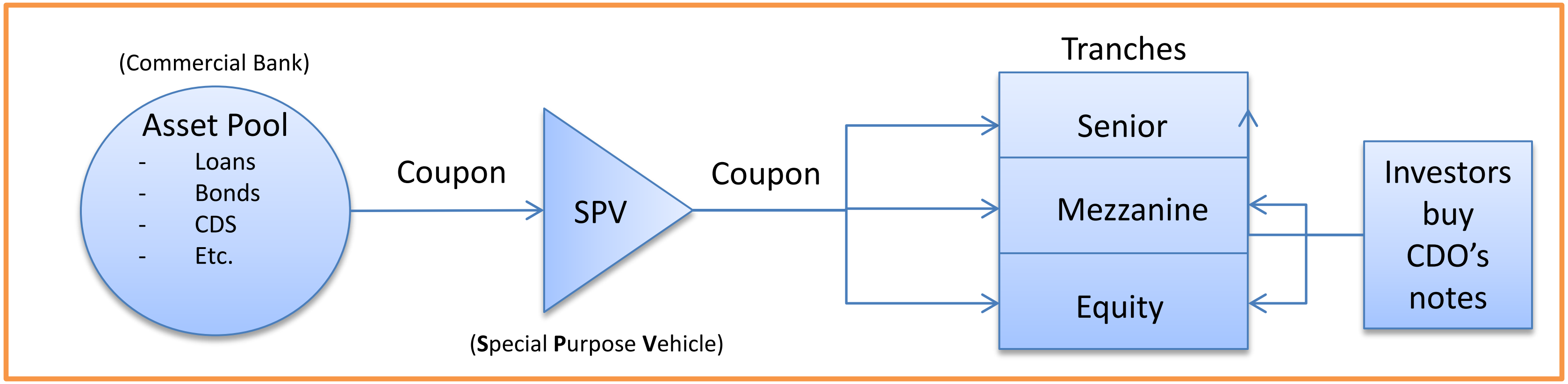
- ☐ Theoretical framework for contract design and pricing of load control options at the retail level
    - Priority service
    - CDO analogy
- ☐ Optimization of device management on the customer side in response to load control options.
- ☐ Characterization and calibration of retail supply function for load control options
- ☐ Characterization of wind uncertainty
    - Copula distributions
- ☐ Optimization of aggregator's load control and renewables portfolio
- ☐ Algorithms for exercise of load control options
- ☐ Design of wholesale electricity products (and pricing) backed by aggregator portfolios.
- ☐ Simulation studies of unit commitment and real time markets with load control products
- ☐ Planning tools for electricity systems with ubiquitous load control.

Bringing Financial Concepts to the Electricity Markets

FINANCIAL ANALOGY

Collateralized Default Obligations (CDO’s)

- A CDO is an asset backed security (ABS) that issues categorized claims against the revenue stream generated by a pool of debt obligations.



- A theoretical discussion about the rational behind the specific structure of these instruments as well as under which circumstances such a structure is effective can be found in Boot and Thakor (1993) and DeMarzo (2005). In the papers the authors explain that
  - Pooling imply economic gains by diversifying the risks of the collateral assets and allowing the creation of higher rated instruments.
  - Tranching allows improving the issuer’s returns in imperfect markets where investors have different levels of information.
- Choudry (2005) and Bluhm and Overbeck (2007) identify four main drivers behind the issuance of CDO’s.
  - Risk transfer.
  - Regulatory capital relief.
  - Funding.
  - Spread and rating arbitrage.
- A market overview on structured credit products including CDOs can be found in Choudry (2004).

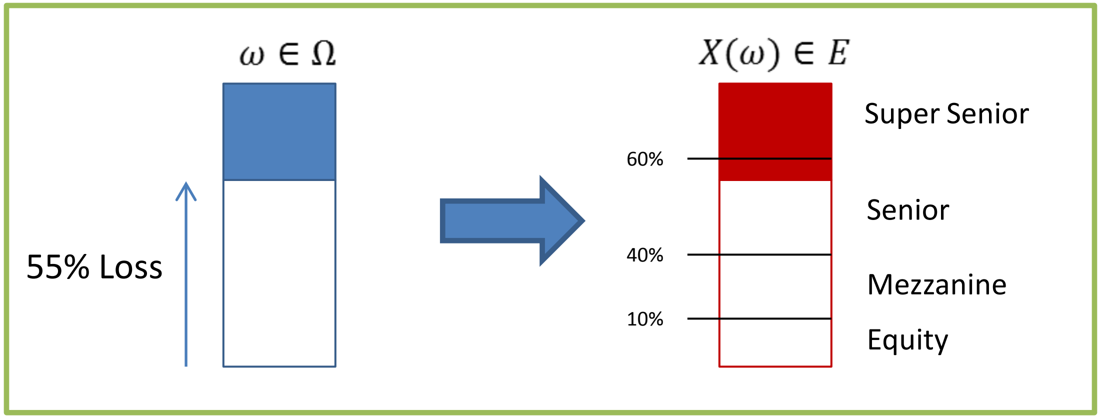
CDO Modeling*: Conceptual Framework

- The dynamics of the CDO are mainly determined by the behavior of the collateral pool of assets.

- Events in the asset pool translate into events in the CDO's securities.

- Mathematically, in modeling a CDO we consider the following elements:
  - A probability space $(\Omega, \mathcal{F}, \mathbb{P})$ to model the dynamics of the collateral pool.
  - An induced probability space $(E, \mathcal{E}, \mathbb{P}_X)$ to model the dynamics of the cash flows in each tranche.
  - A random vector $X: \Omega \rightarrow E$, representing the cash flows scenarios per tranche.

- X is determined by the **waterfall payment rule** and the definitions of the **attachment and detachments points** of the CDO.



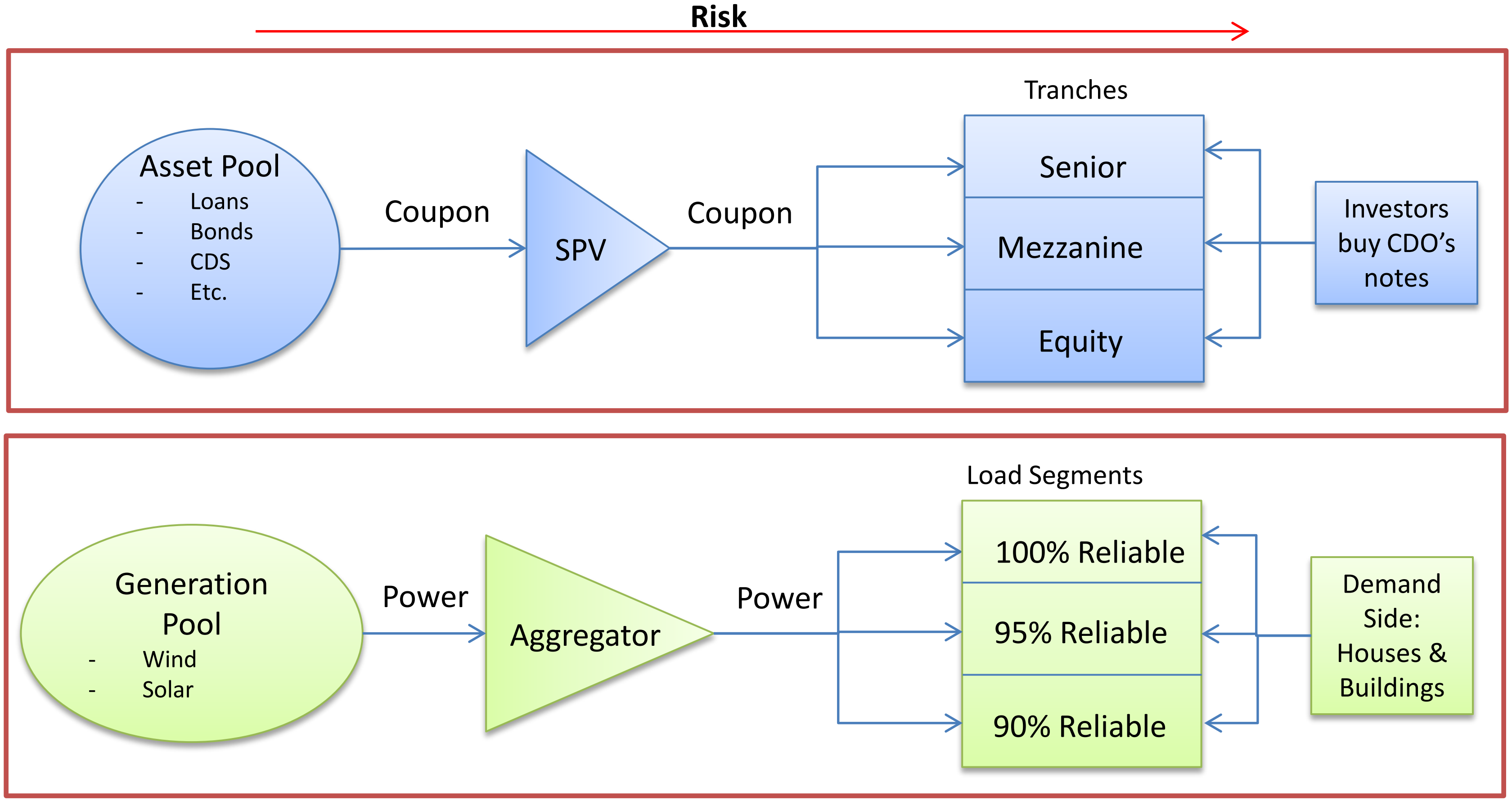
In this example, we have that the collateral pool has suffered a 55% loss on its notional . Given the CDO structure and the waterfall payment rule, that lost is translated into:

- A 100% loss in the notional of the Equity and Mezzanine securities.
- A 75% loss in the notional of the Senior tranche.
- The Super Senior tranche remains intact.

*This section is based on Bluhm and Overbeck (2007) and O'Kane (2008).

The Analogy

- Parallel structural elements:
  - Pool of assets – pool of intermittent generation resources
  - the risk transfer from the originator to the investors – risk transfer from generators to load
  - the segmentation of notes – load segmentation
  - the cash flow dynamics – service rules



Collateral Losses Modeling

- Notation:
  - We index the assets in the collateral pool indexed by $d \in \{1, \dots, D\}$
  - Default Times $\tau = (\tau_1, \dots, \tau_D)$.
  - R_d: Recovery rate of asset d.
  - T: maturity of the instrument.

- By time t the losses in the portfolio will be:

$$C_t = \frac{1}{D} \sum_{d=1}^{D} (1 - R_d) 1_{\{\tau_d \leq t\}} \ \forall t \in [0, T]$$

- In order to characterize the behavior of C_t, we describe τ probabilistically.

- There are two types of models:
  - Static models:
    - Direct estimation of $F_\tau(t) = P\left(\tau \leq \vec{t}\right)$.
    - One period dependency.
  - Multi-period models: (for details see Finger (2000) and Morokoff (2003))
    - There is an underlying time-series model used to characterize the lengths of the default times.
    - Dependencies are estimated for each of the relevant periods.
    - For instance:

$$\tau_d = \inf\{t \geq 0: B_d(t) \leq b_d\}$$

Static Models and Copulas

The most common static models are based on copulas*.

Subcopulas: Let $\{0,1\} \subset A_i \subset [0,1]$ $\forall 1 \leq \mathrm{i} \leq \mathrm{n}$. A subcopula is a function $\mathcal{C}:\times_{i=1}^{n} A_i \to \mathbb{R}$ that satisfies:

- $\mathcal{C}$ is grounded.
- $\mathcal{C}_i(u) = u \quad \forall i \in \{1, \dots, n\}$.
- $\mathcal{C}$ is n-increasing, i.e., the $\mathcal{C}$-volume of any n-box $[\boldsymbol{a}, \boldsymbol{b}]$ defined as $\Delta_{\boldsymbol{a}}^{\boldsymbol{b}} \mathcal{C}(\boldsymbol{t}) \geq 0$.

Copula: is a function $C: [0,1]^n \to \Re$ such that it is a subcopula.

The fundamental result in Copula Theory is Sklar's Theorem in Sklar (1959).

Let $\{F_i(x_i)\}_{i=1}^{n}$ be a set of m.d.f., then, $\forall \boldsymbol{x} \in \mathbb{R}^{\boldsymbol{n}}$

- $\forall \mathcal{C}$ such that $\times_{i=1}^{n}$ Ran $F_i \subset$ Dom $\mathcal{C}$, $\boldsymbol{H}(\boldsymbol{x}) = \boldsymbol{\mathcal{C}}(\boldsymbol{F_1}(\boldsymbol{x_1}), \dots, \boldsymbol{F_n}(\boldsymbol{x_n}))$ is a j.d.f. with margins $F_1(x_1), \dots, F_n(x_n)$.
- Conversely, if F is a j.d.f. with margins $F_1(x_1), \dots, F_n(x_n)$, then $\exists! \mathcal{C}\ s.t.$ $\boldsymbol{F}(\boldsymbol{x}) = \boldsymbol{\mathcal{C}}(\boldsymbol{F_1}(\boldsymbol{x_1}), \dots, \boldsymbol{F_n}(\boldsymbol{x_n}))$.

  If $F_i' s$ are continuous then $\mathcal{C}$ is copula; if not, then there is a copula such that $C(\boldsymbol{u}) = \mathcal{C}(\boldsymbol{u})\ \ \forall \boldsymbol{u} \times_{i=1}^{n}$ Ran F_i

Usually, in static modeling a model for the marginals and a copula is calibrated with the data.

- For each τ_d find $F_d(\cdot)$.
- Select a copula model so that $F_{\tau}(\vec{t}) = P\ (\tau_1 \leq t_1, \dots, \tau_D \leq t_D) = C(F_1(t_1), \dots, F_D(t_d))$.

*For an introduction on the subject see Nielsen (1999). For implementation techniques and applications see Cherubini et al. (2005).

Applying Copula Models to Describe Wind Power Production

CALIBRATION EXERCISE

Description

- We compare the empirical distribution to four time series models:
  - Papavasiliou and Oren (2011) Model without spatial correlation (PO).
  - Papavasiliou and Oren (2011) Model with spatial correlation (POC).
  - Variation of POC with Gaussian Copula (GC).
  - Variation of POC with Student t Copula (TC).

- We compare the goodness of fit per location and the goodness of fit of the sum across all locations.

Data Set

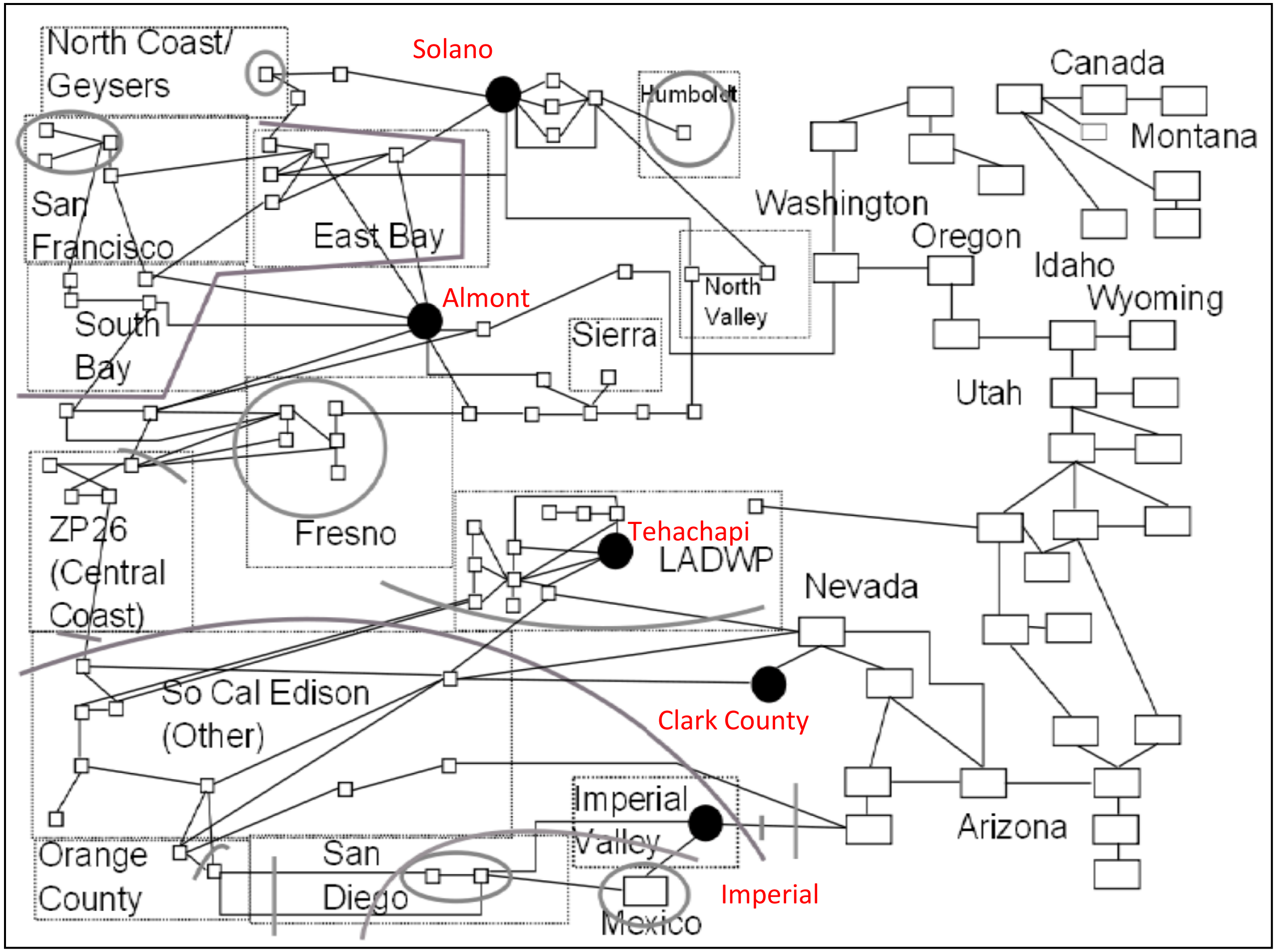
- Wind data collected from the National Renewable Energy Laboratory (NREL) Western Wind and Solar Integration Study (WWSIS) database.

- The study contains three years of wind speed and power production samples.

- As an starting point, we focus on the year 2006 and on locations in the WECC interconnection.

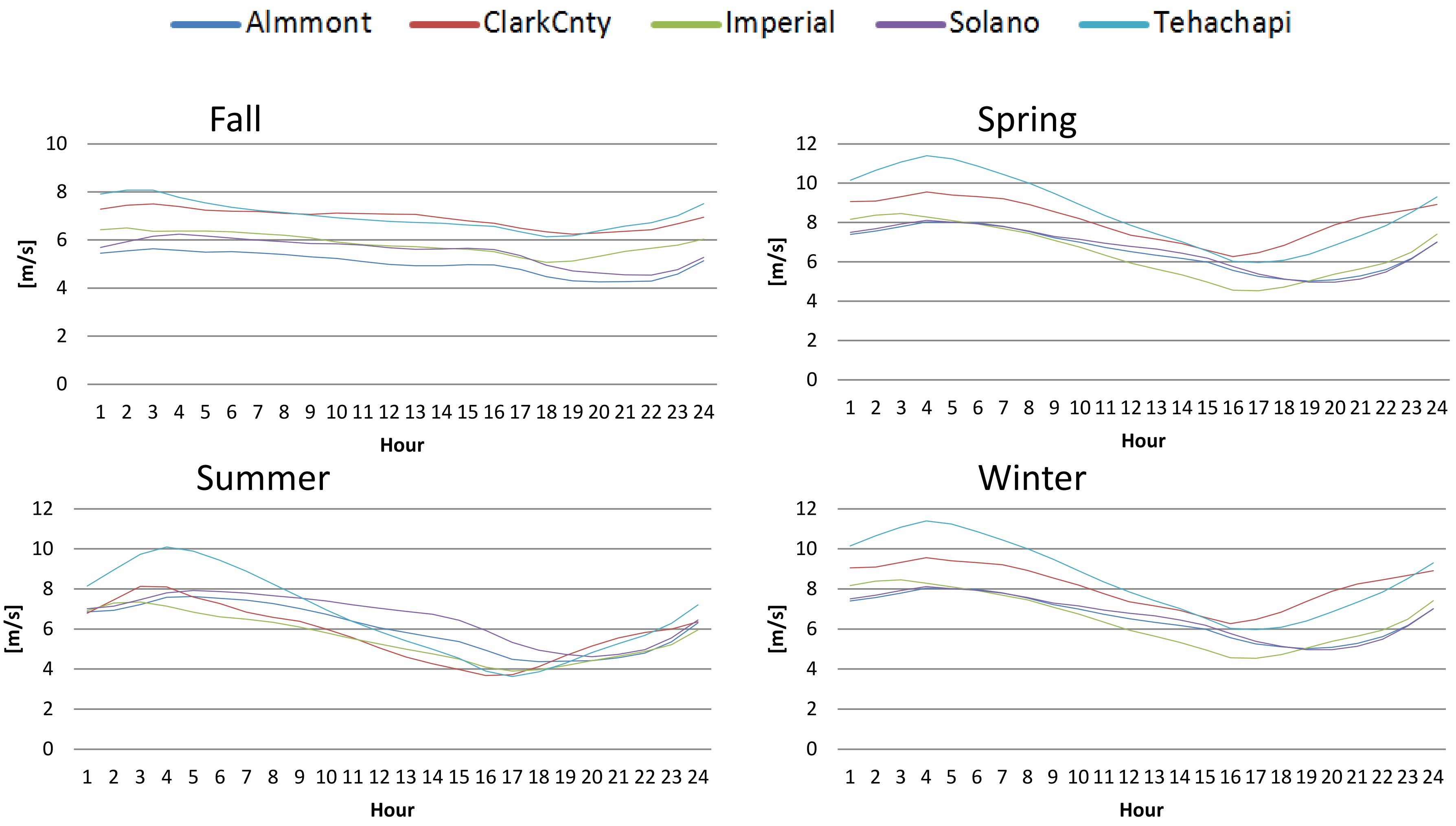
- We model the stochastic generation of five different locations in the WECC area.

Schematic of WECC Interconnection

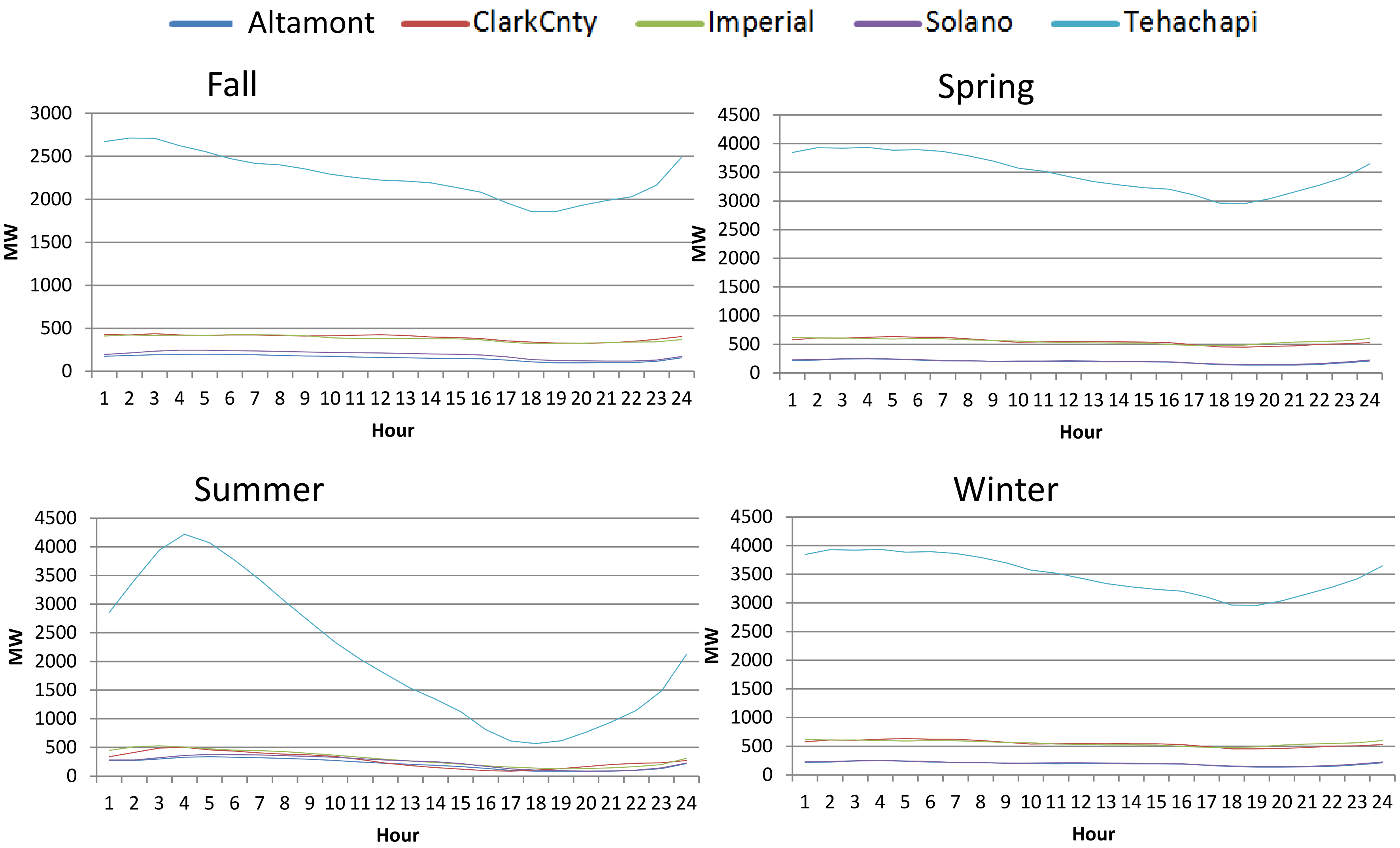


Source: Papavasiliou and Oren (2011).

Wind Speed Profiles per Season



Wind Power Profiles per Season



Calibration Methodology

- Remove seasonal and diurnal effects: Let $\overline{w}_l$ be the wind speed measurements taken at site l and μ_{lt}^m, σ_{lt}^m be the mean and standard deviación of the wind speed meassured at time t, in location l during the season m.

$$\overline{w}_{lt}^S = \frac{y_{lt} - \mu_{lt}^m}{\sigma_{lt}^m}$$

- *Estimate marginal distributions for the data* $\left(\overline{w}_1^S, \dots, \overline{w}_L^S\right)$.

- *Normalize the historical time serie:* Define

$$z_{lt} = \Phi^{-1}\left(\widehat{F}_l\left(y_{lt}^S\right)\right) \quad \textit{(transform to Gaussian)}$$

- *Fit AR(P) model:* Per each location find the coefficients of

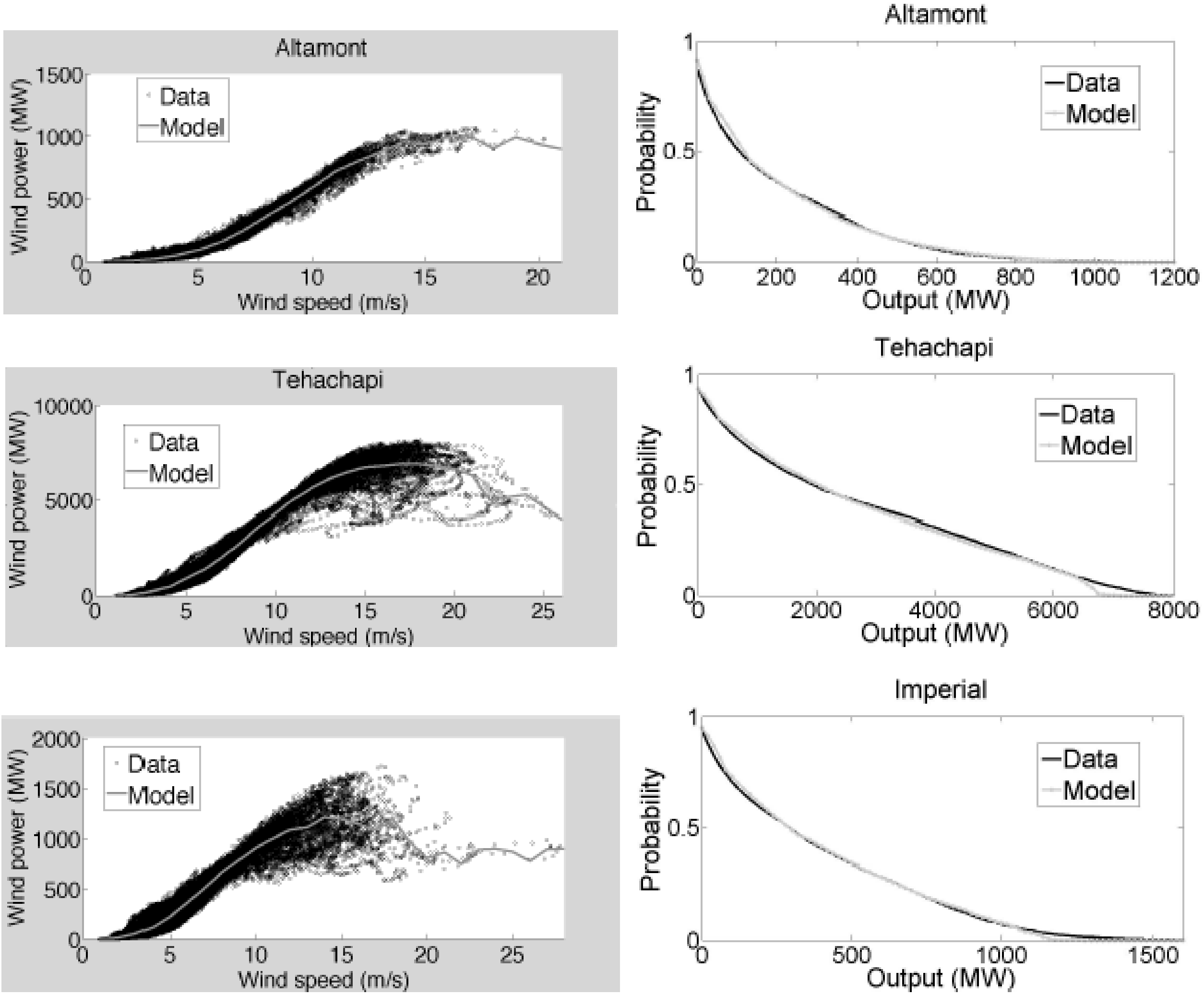
$$z_{lt} = \sum_{j=1}^{p} \hat{\phi}_{lj}\, z_{lt-j} + \varepsilon_{lt} \quad \textit{(Yule Walker equations)}$$

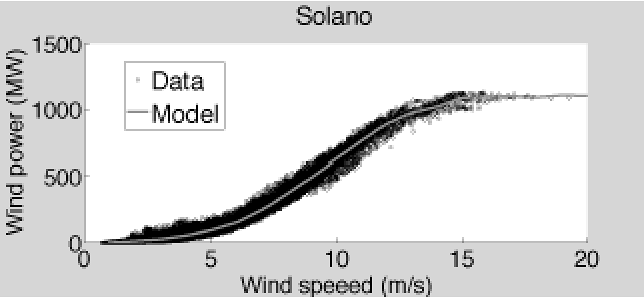
- *Fit a joint distribution model to the white noise* $(\varepsilon_1, \dots, \varepsilon_L)$, *where*

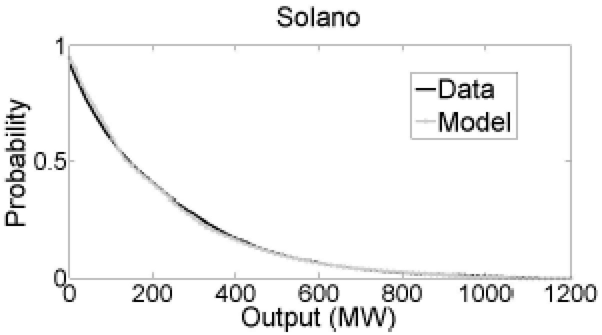
$$\varepsilon_{lt} = z_{lt} - \sum_{j=1}^{p} \hat{\phi}_{lj}\, z_{lt-j}$$

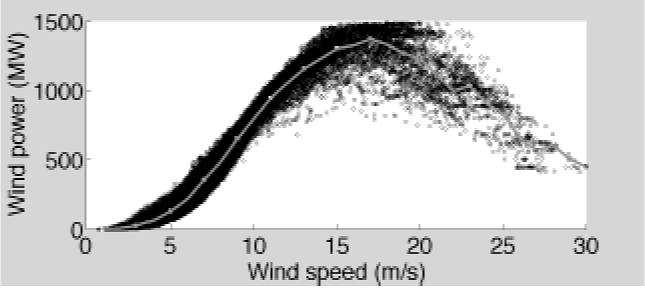
Results Based on Multi-area Gaussian Model:

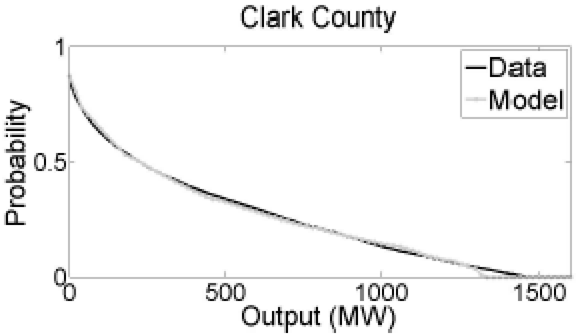
Power curves and complementary cdf of wind output




Solano
Data
Model
1500
1000
500
0
0
5
10
15
20
Wind power (MW)
Wind speeed (m/s)


Solano
Data
Model
1
0.5
0
0
200
400
600
800
1000
1200
Probability
Output (MW)


1500
1000
500
0
0
5
10
15
20
25
30
Wind power (MW)
Wind speed (m/s)


Clark County
Data
Model
1
0.5
0
0
500
1000
1500
Probability
Output (MW)

Copulas Estimation

We use the Inference for the Margins (IFM) method.

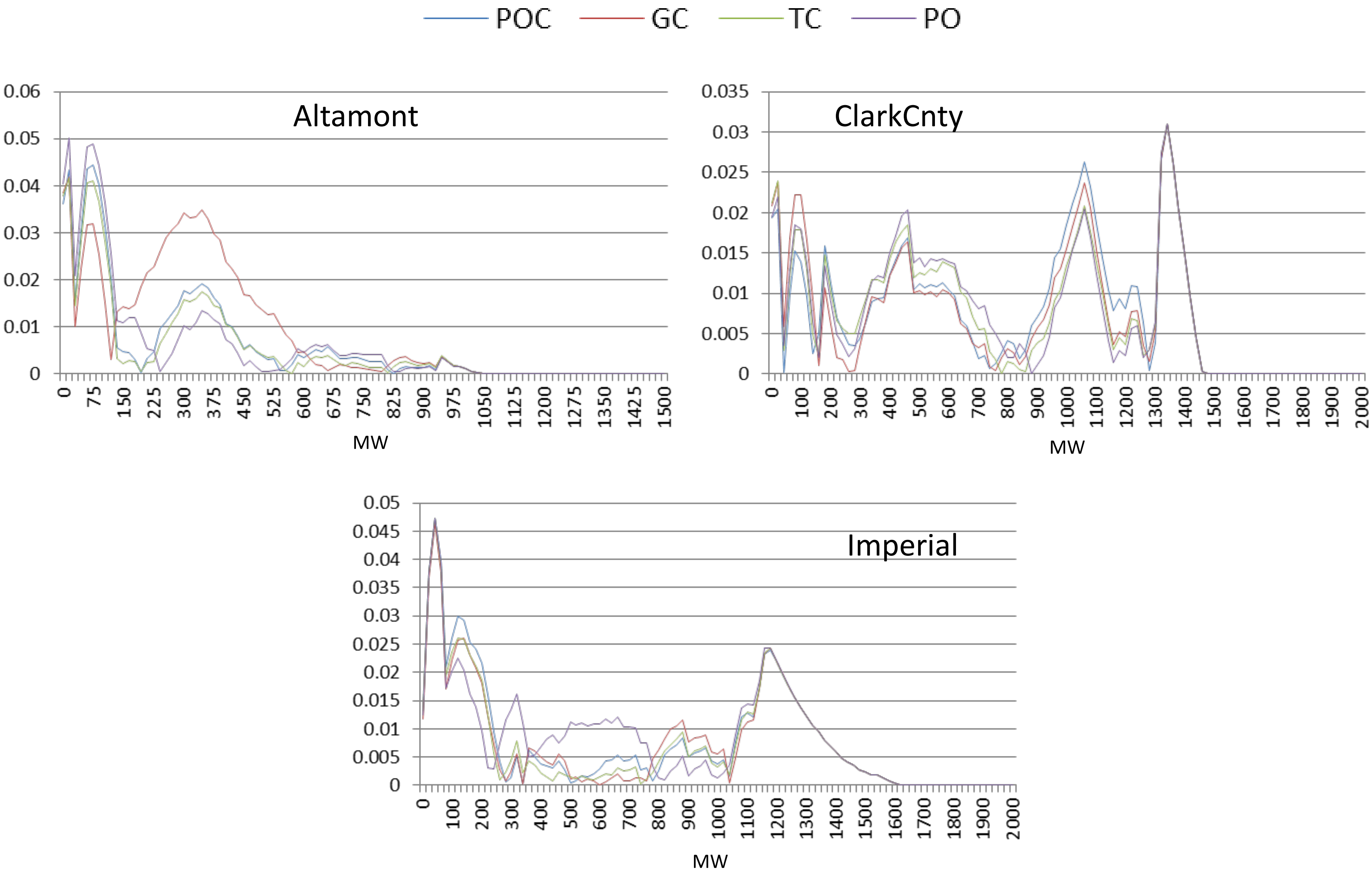
- *Estimation of marginal's parameters:*

$$\hat{\theta}_1 = \underset{\theta_1}{\operatorname{argmax}} \sum_{t=1}^{T} \sum_{j=1}^{n} \ln f_j(x_{jt}; \theta_1)$$

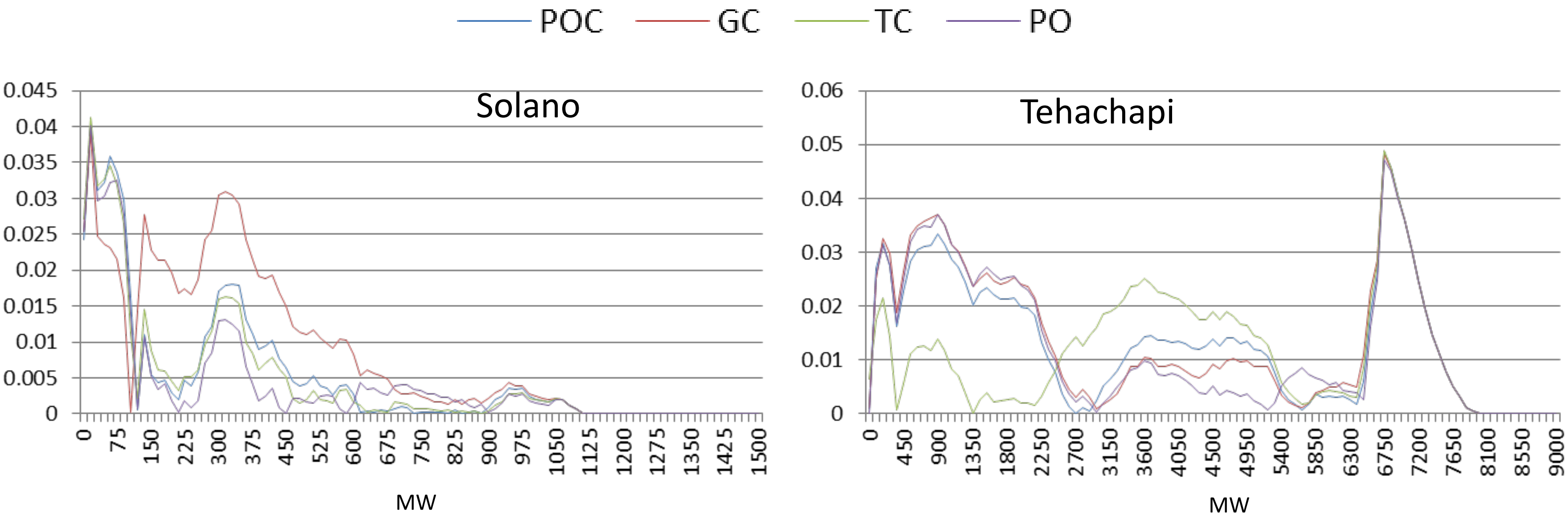
- *Estimation of copula's parameters:*

$$\hat{\theta}_2 = \underset{\theta_2}{\operatorname{argmax}} \sum_{t=1}^{T} \ln c(F_1(x_{1t}), F_2(x_{2t}), \dots, F_n(x_{nt})); \hat{\theta}_1, \theta_2)$$

Differences per Location: $\left|\hat{F}_s(x_i) - \hat{F}_d(x_i)\right|$



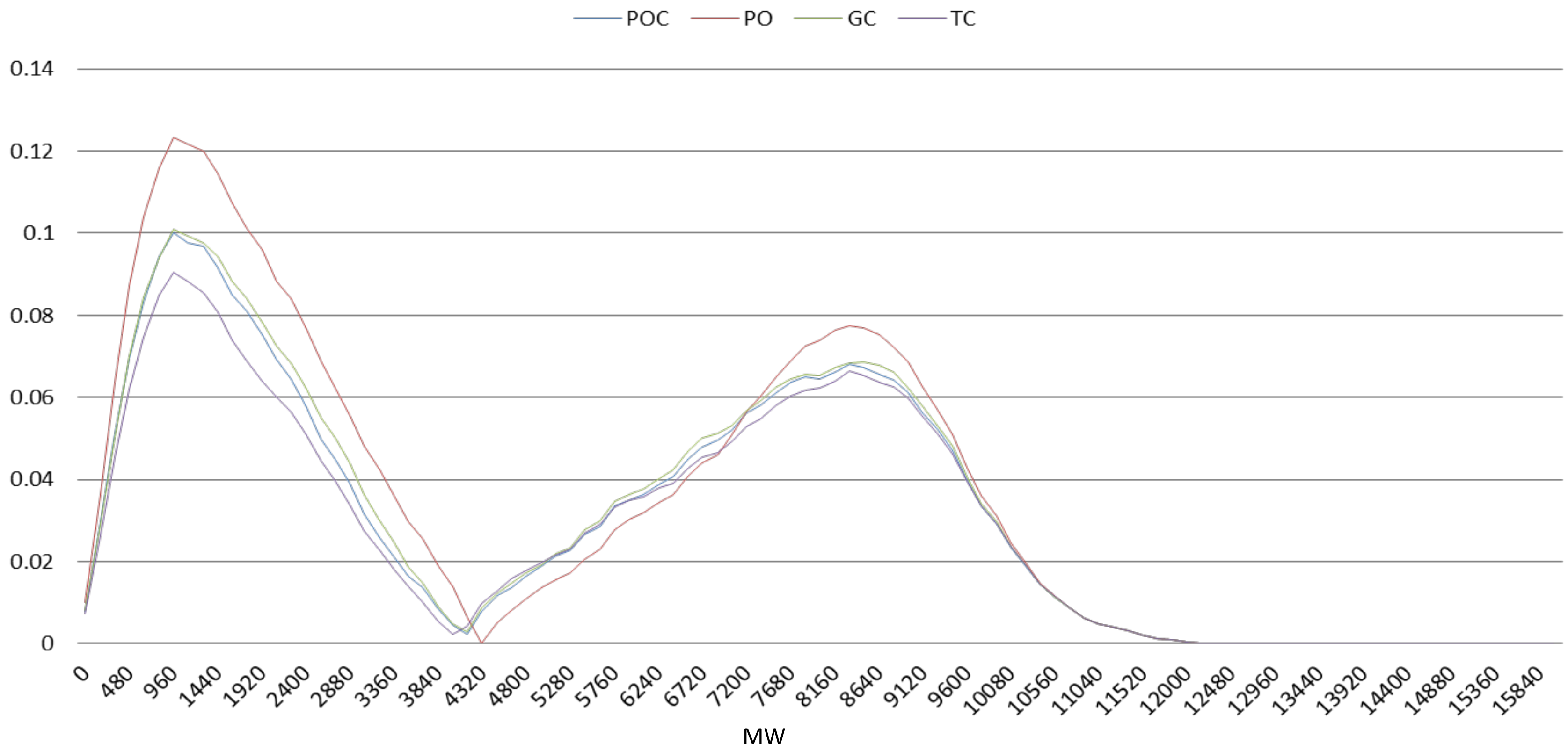
Differences per Location and Summary



Locations	POC	PO	GC	TC
Alatmont	0.6392	0.6364	0.9259	0.5762
ClarkCnty	0.7744	0.7574	0.7264	0.7532
Imperial	0.7702	0.8442	0.7405	0.7237
Solano	0.5257	0.4405	0.8750	0.4958
Tehachapi	1.3276	1.2594	1.3457	1.1660
Total	4.0371	3.9378	4.6135	3.7149

Table 1: Summation of Differences per Location and Model

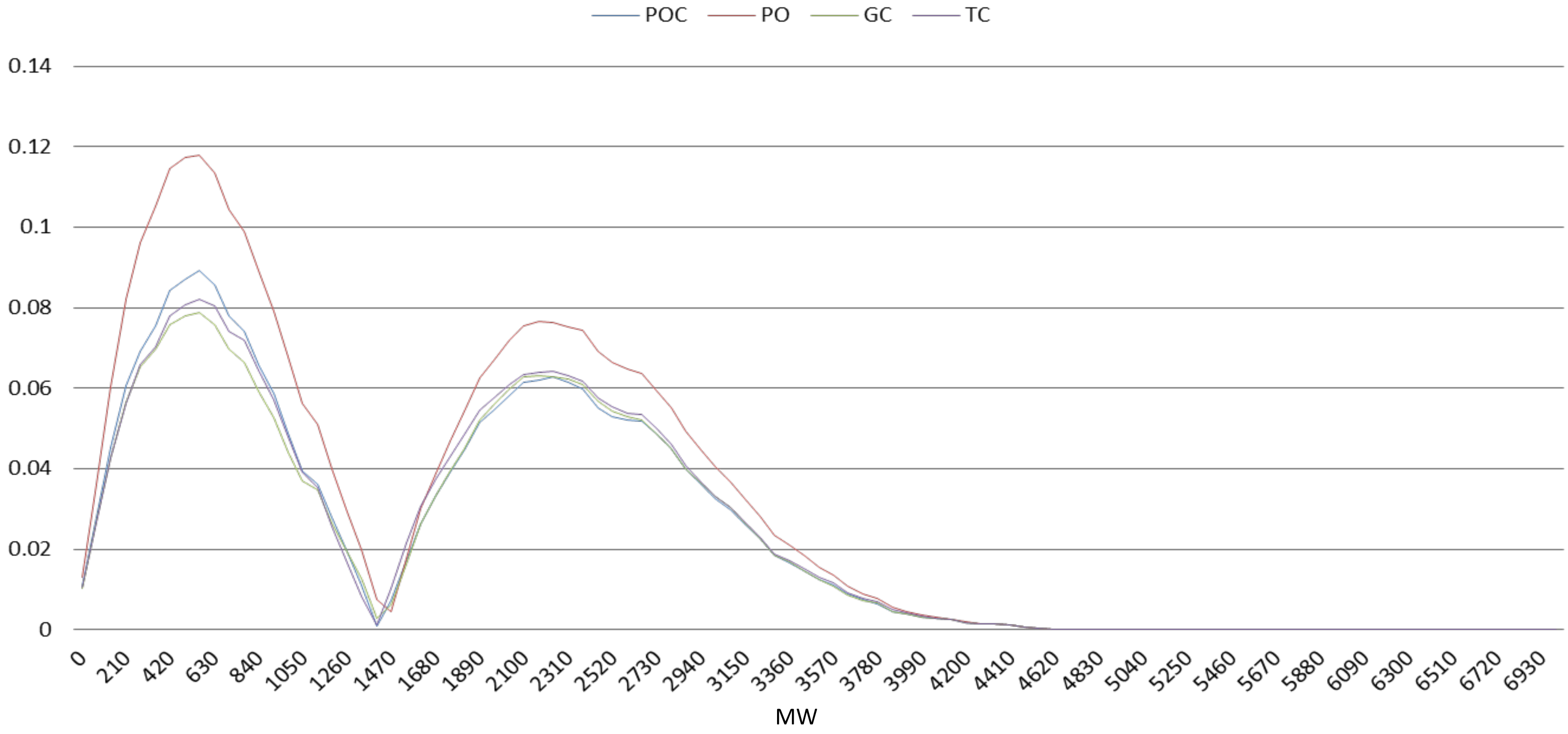
Diff. Between Estimated C.D.F. of Summation



POC	PO	GC	TC
3.0767	3.5409	3.1756	2.8706

Table 2: Summation of Differences per Model

Diff. Between Estimated C.D.F. of Summation without Tehachapi



POC	PO	GC	TC
2.3489	3.0291	2.2700	2.3486

Table 3: Summation of Differences per Model

RETAIL CONTRACT DESIGN

Demand Resource

- For the demand resource, we depart from the setting proposed by Chao and Wilson (1987).
- Consumption segments (describing fuse capacity) are characterized by the their expected net valuation per unit capacity of, $v \in [0, V]$. (v accounts for optimal reallocation within the customer premises and variation in energy use and is net of the retail energy cost)
- The complimentary cumulative distribution of consumption segments in the population is given by the normalized demand function $D(v)$
- A demand response provider will offer a menu $M = \{(t, r)\}$ to the consumers, where t is a compensation and r is a reliability.
- If a segment is not curtailed it gains $(v - p^R)^+$, the net expected consumer surplus after paying the retail demand charge.
- Under contract *(t,r)* the expected gain per unit of a segment with valuation *v* will be:

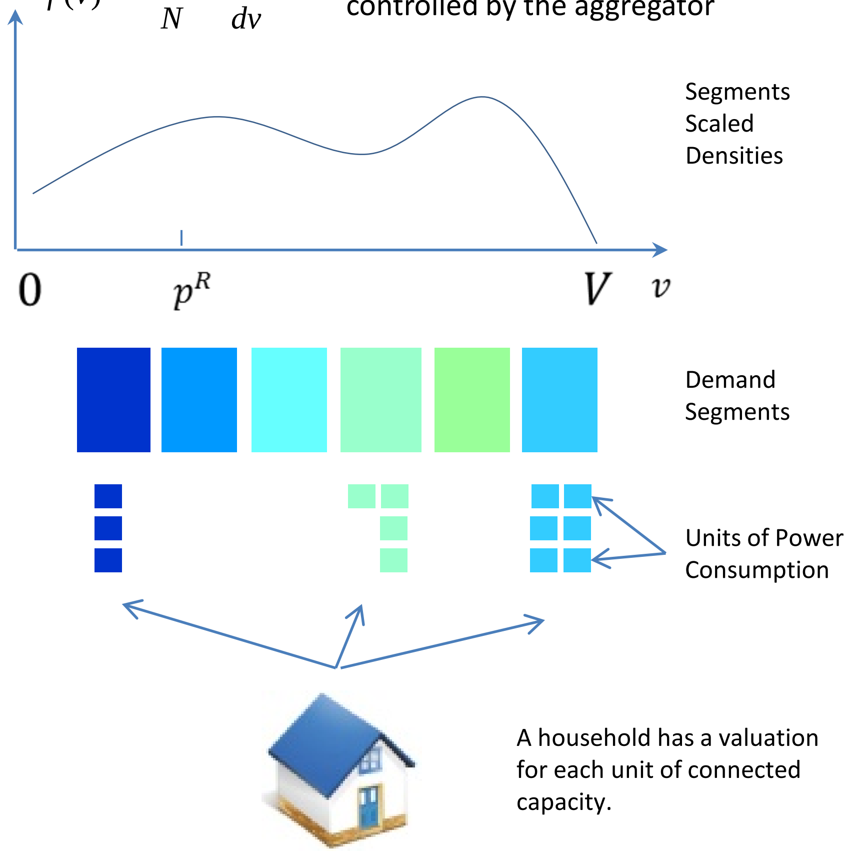
$$t + r(v - p^R)^+$$

Note : It is reasonable to assume that only segments with positive net gains are candidates for subscribing to a contract but this restriction is not imposed.

Schematic

$$f(v) = -\frac{1}{N} \cdot \frac{dD(v)}{dv}$$

N is the total connected capacity controlled by the aggregator



Segments Scaled Densities

Demand Segments

Units of Power Consumption

A household has a valuation for each unit of connected capacity.

Feasible Contract Menu

We consider the feasible region of a typical mechanism design problem, however, we constraint the problem further in order to leave segments outside of the service. The relevant segments will be those in $[\underline{v}, \overline{v}]$.

Feasible Region

- $t(v) + r(v)(v - p^R)^+ \geq (v - p^R)^+ \qquad \forall v \in [\underline{v}, \overline{v}] \quad (IR).$
- $t(v) + r(v)(v - p^R)^+ < (v - p^R)^+ \qquad \forall v \in [\overline{v}, V] \quad (IR^C).$
- $t(v) + r(v)(v - p^R)^+ \geq t(v') + r(v')(v - p^R)^+ \quad \forall v \in [\underline{v}, V] \quad (IC).$

Necessary conditions for a menu satisfying the above set of constraints (incentive compatibility).

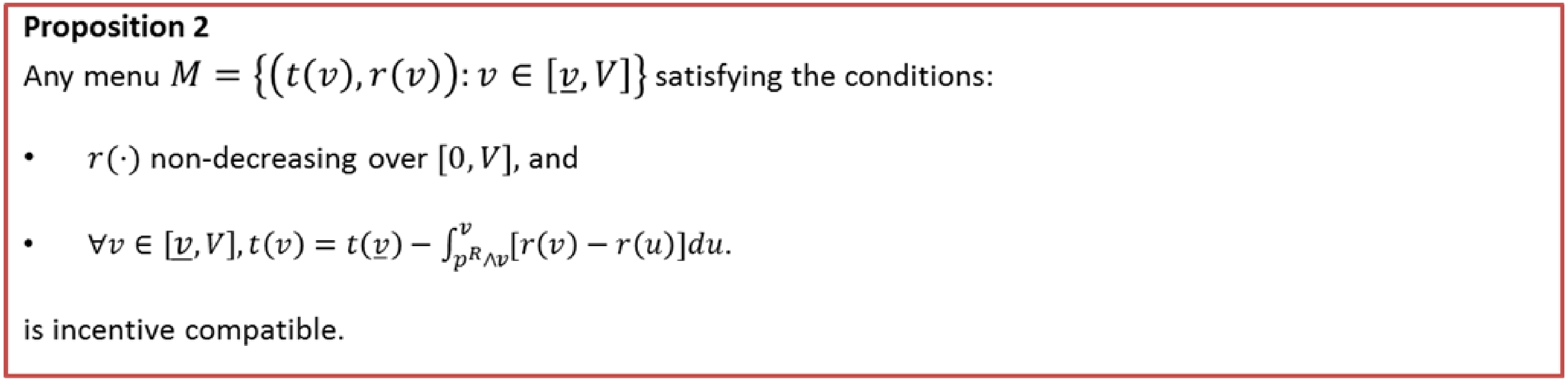
Proposition 1

Any incentive compatible menu $M = \{(t(v), r(v)) : v \in [0, V]\}$ will meet the following conditions:

- $r(\cdot)$ non-decreasing over $[p^R, V]$,
- $t(\cdot)$ constant over $[\underline{v}, p^R]$ and non-increasing over $[p^R, V]$, and
- $\forall v \in [\underline{v}, V], t(v) = t(\underline{v}) - \int_{p^R \wedge v}^{v} [r(v) - r(u)] du.$ (*t(v)* decreases and *r(v)* increases in *v)*

More Characterizations

Additionally, we also find sufficient conditions for satisfying the incentive compatible set of constraints.



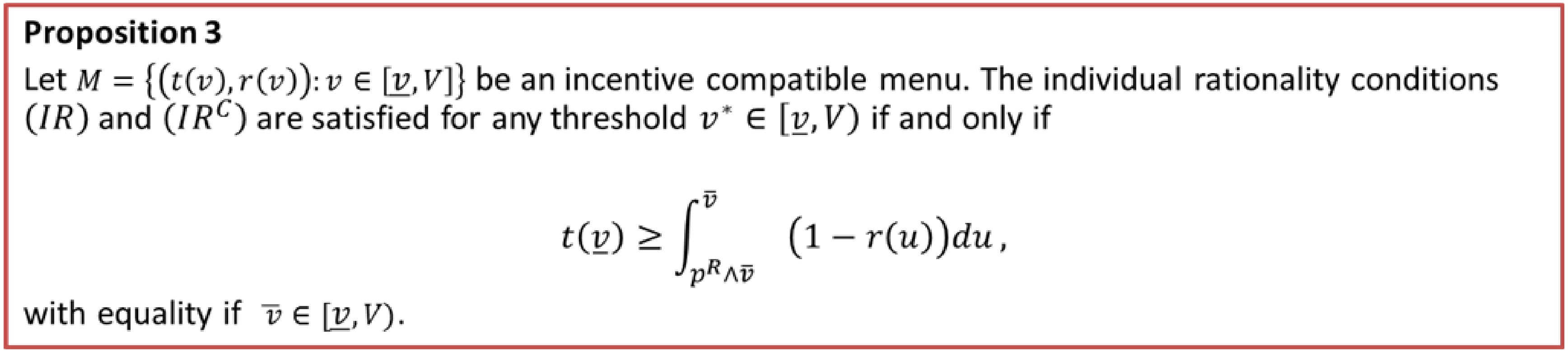
Proposition 2

Any menu $M = \{(t(v), r(v)) : v \in [\underline{v}, V]\}$ satisfying the conditions:

- $r(\cdot)$ non-decreasing over $[0, V]$, and
- $\forall v \in [\underline{v}, V], t(v) = t(\underline{v}) - \int_{p^R \wedge v}^{v} [r(v) - r(u)]du.$

is incentive compatible.

Finally, in the region of incentive compatible menus, it is possible to characterize menus which satisfies the individual rationality constraints (IR) and (IR^C).



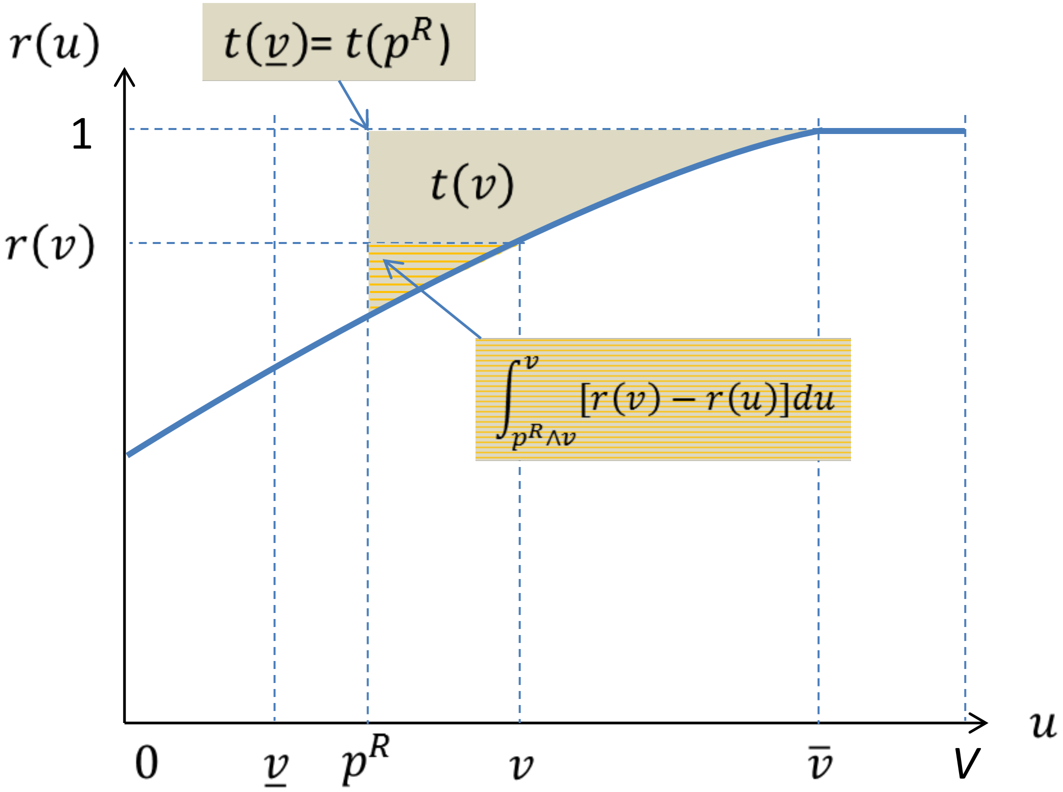
Proposition 3

Let $M = \{(t(v), r(v)) : v \in [\underline{v}, V]\}$ be an incentive compatible menu. The individual rationality conditions (IR) and (IR^C) are satisfied for any threshold $v^* \in [\underline{v}, V)$ if and only if

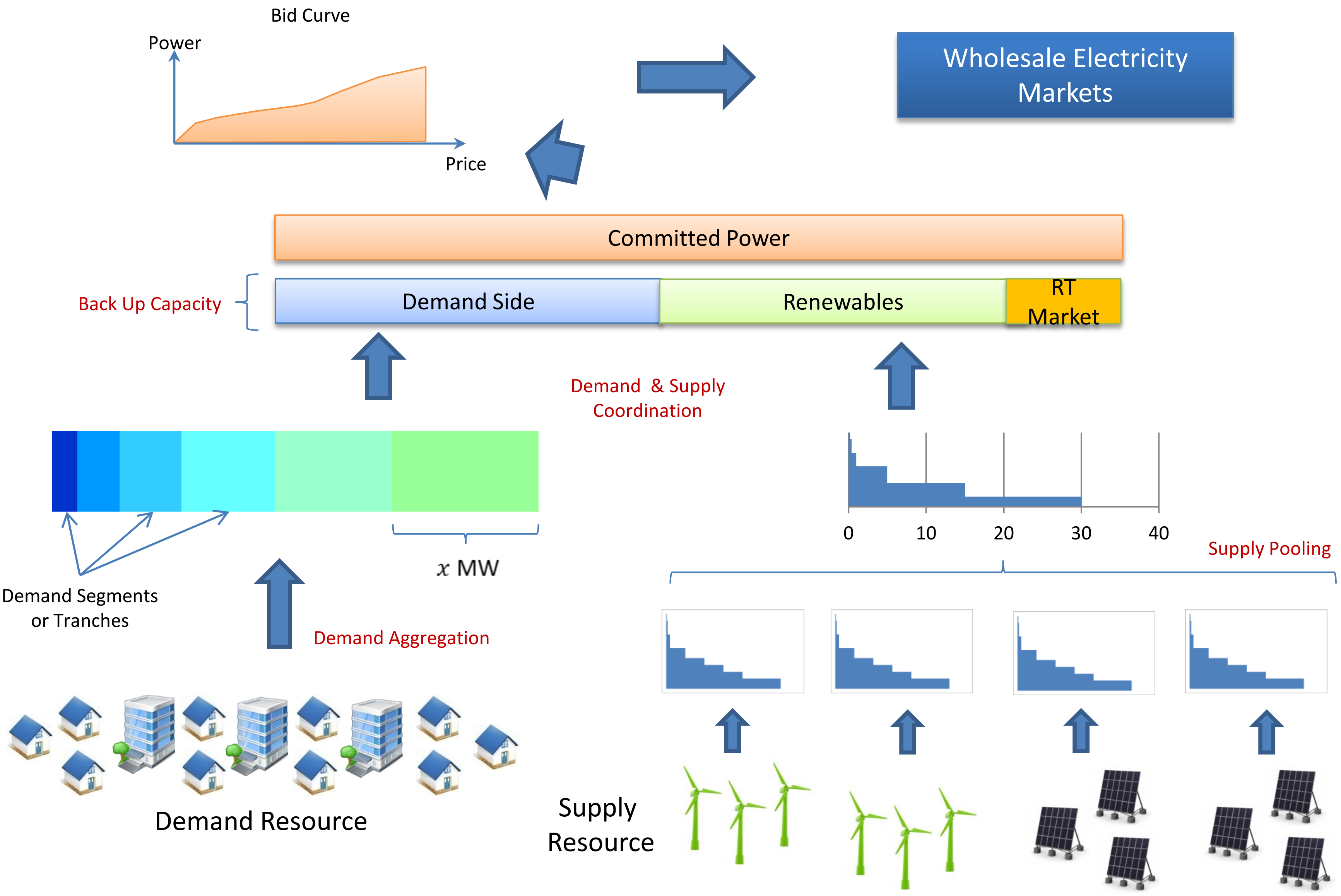
$$t(\underline{v}) \geq \int_{p^R \wedge \bar{v}}^{\bar{v}} (1 - r(u))du\,,$$

with equality if $\bar{v} \in [\underline{v}, V)$.

Geometric Interpretation of payment



The Wholesale Product Offered by the Aggregator



Bid Curve

Wholesale Electricity Markets

Committed Power

Back Up Capacity

Demand Side

Renewables

RT Market

Demand & Supply Coordination

Supply Pooling

x MW

Demand Segments or Tranches

Demand Aggregation

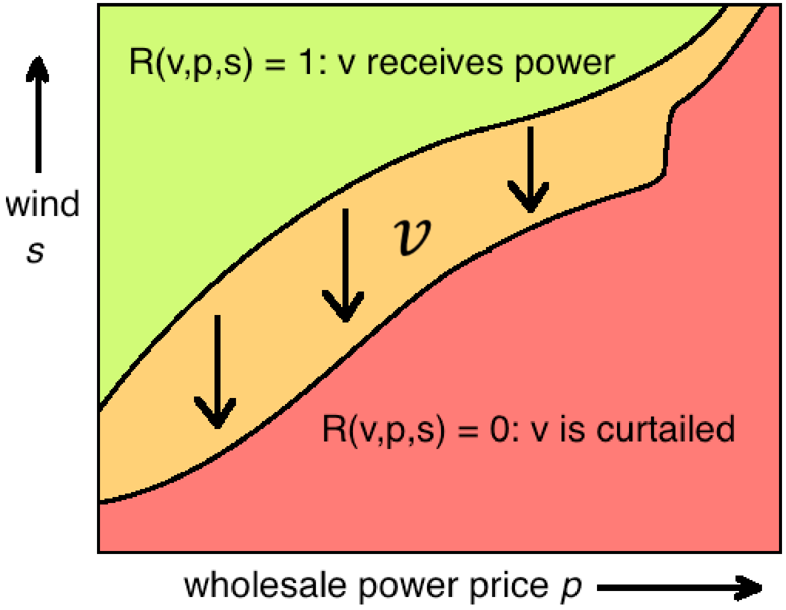
Demand Resource

Supply Resource

Curtailment Policy

- The policy $R_{N,S}(v, p^w, s)$ assigns an on/off value to valuation given Day-Ahead price p^w and wind availability s (as a fraction of the contracted nameplate capacity *S*)

Change in Policy as *v* increases



Reliability *r(v)*

- Given a curtailment policy, $R_{N,S}(v, p^w, s)$, a segment of type v has reliability *r*(v):

$$r(v) = \int R_{N,S}(v, p^W(\omega), s(\omega))dP(\omega)$$

$P(\omega)$ is a probability measure over the state of the system

- Suppose the joint density of DA price p^w and wind power availability *s* is $h(p^w, s)$. Then

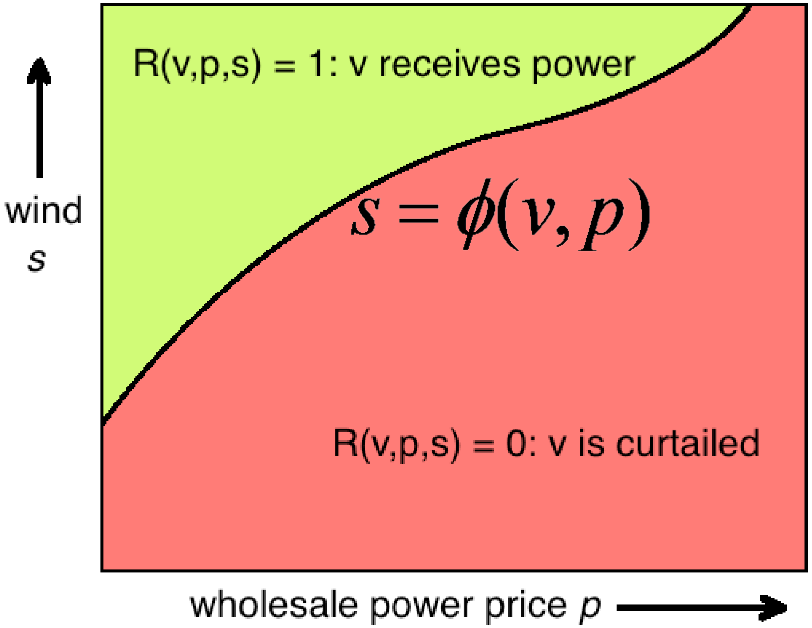
$$r(v) = \iint R_{N,S}(v, p, s)h(p, s)dpds$$

Policy Notation

- Assuming *efficient rationing*, the policy $R_{N,S}(v, p^w, s)$ can be expressed equivalently in terms of two functions:
- $\xi(p,s)$: the minimum valuation served (max curtailed) given wholesale price *p* and wind availability s.
- $\phi(v,p)$: the minimum wind level needed for valuation v to get service at wholesale price *p.*
- $\phi(v, p) = s \text{ s.t. } \xi(p,s) = v$
- Both $\xi(p,s)$ and $\phi(v,p)$ depend on the connected demand capacity *N* and the contracted wind capacity *S*

The Curtailment Function

- The graph of $\phi(v,\cdot)$ over the price domain represents the policy $R_{N,S}(v, p^w, s)$
- Segment reliability: $r(v) = \int_0^{Pcap} \int_{\phi(v,p)}^1 h(p,s)\,ds\,dp$



The Aggregator’s Wholesale Problem

1: DA price in a particular hour p^w is realized.

2: commitment $Q(p^w)$ becomes financially binding.

3: s is realized.

4: Excess wind beyond commitment is spilled and shortfalls are covered by curtailment policy or RT market/penalty at expected price c. (assuming RT price is independent of the day ahead price and wind realization)

Expected Profit:

$$\mathrm{E}_{p,s}\{p^w \cdot Q(p^w) - c \cdot [Q(p^w) - S \cdot s - N \cdot (F(\xi(p,s)) - F(p^R))]^+\}$$

$$-N \cdot \int_{\underline{v}}^{\overline{v}} t(v) f(v) dv$$

Re-writing the Payment

$$\int_{\underline{v}}^{\overline{v}} t(v)dv = \int_{p^R}^{\overline{v}} \left[\frac{F(v)}{f(v)} + (v - p^R)^+ \right] \underbrace{\left(\int_0^{Pcap} \int_0^{\phi(v,p)} h(s,p)\,ds\,dp \right)}_{1-r(v)} f(v)dv$$

Further change of variables enables simplification of expected profit function

Aggregator's Optimization

Maximize expected net profit with respect to wholesale offer function $Q(p^W)/S$
The ratio of connected demand to wind contracted capacity N/S and the curtailable valuation threshold $\overline{v}$ (for which $t(\overline{v})=0$).
Subject to efficient rationing , incentive compatibility and individual rationality constraints

Extensions

- Account for yield factor in curtailment (curtailed kW yields some expected fraction $q(v)$ of energy reduction)
- Demand recruitment policies to shape demand function
- Allow customer valuations to vary with state of the system ω

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