ON THE QUANTITY, QUALITY AND MEANING OF WIND CAPACITY

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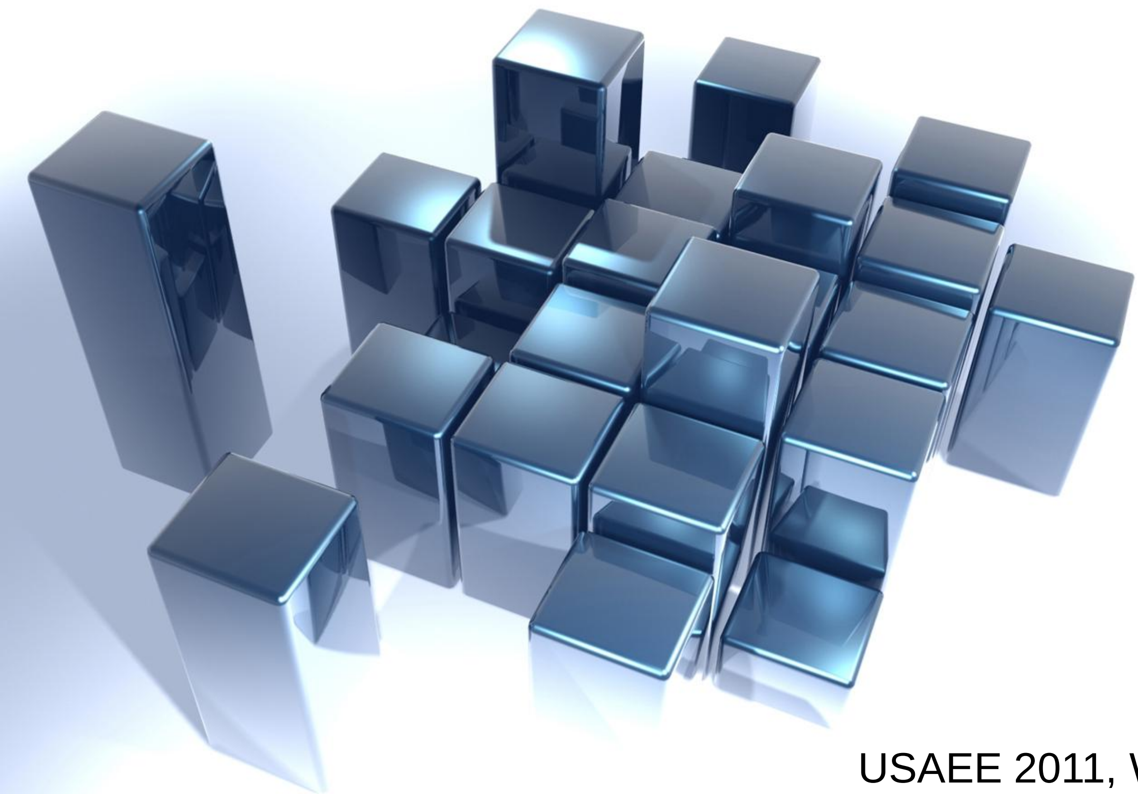

Tulane Energy Institute
Freeman School of Business
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USAEE 2011, Washington DC

Question: How to evaluate wind capacity?

How about

-- Installed Capacity (max)

-- Capacity Factor (average)

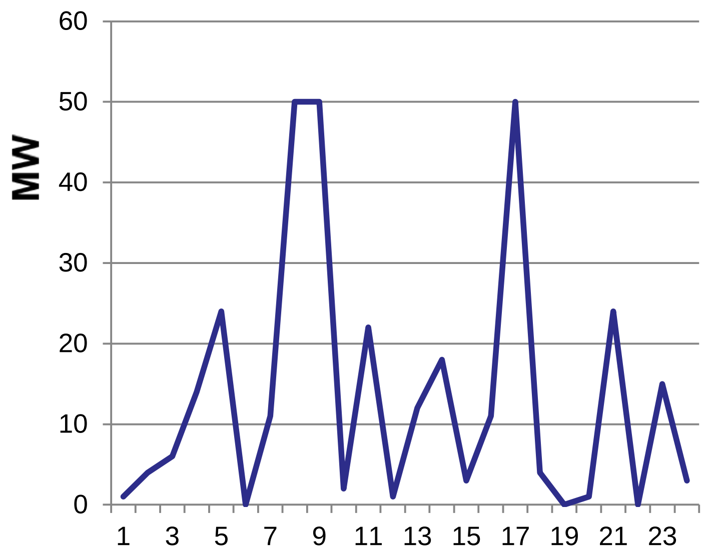
-- Guaranteed Capacity (min)

-- Capacity Credit (ELCC, Effective Load Carrying Capacity based on LOLP or LOLE)

- Non-intrinsic to wind itself
- Decreases as wind penetration increases as wind is taking advantage of the rest of the system to back it up
- It is a measure of best effort instead of the guaranteed service

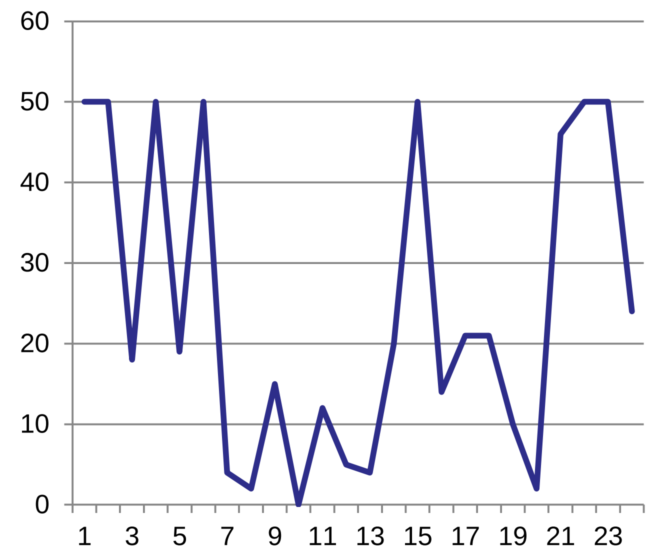
-- What is asked is to convert a stochastic process into a number.

Hourly Wind Generation



I) January 1

Max=50
Min= 0
Ave=13.6

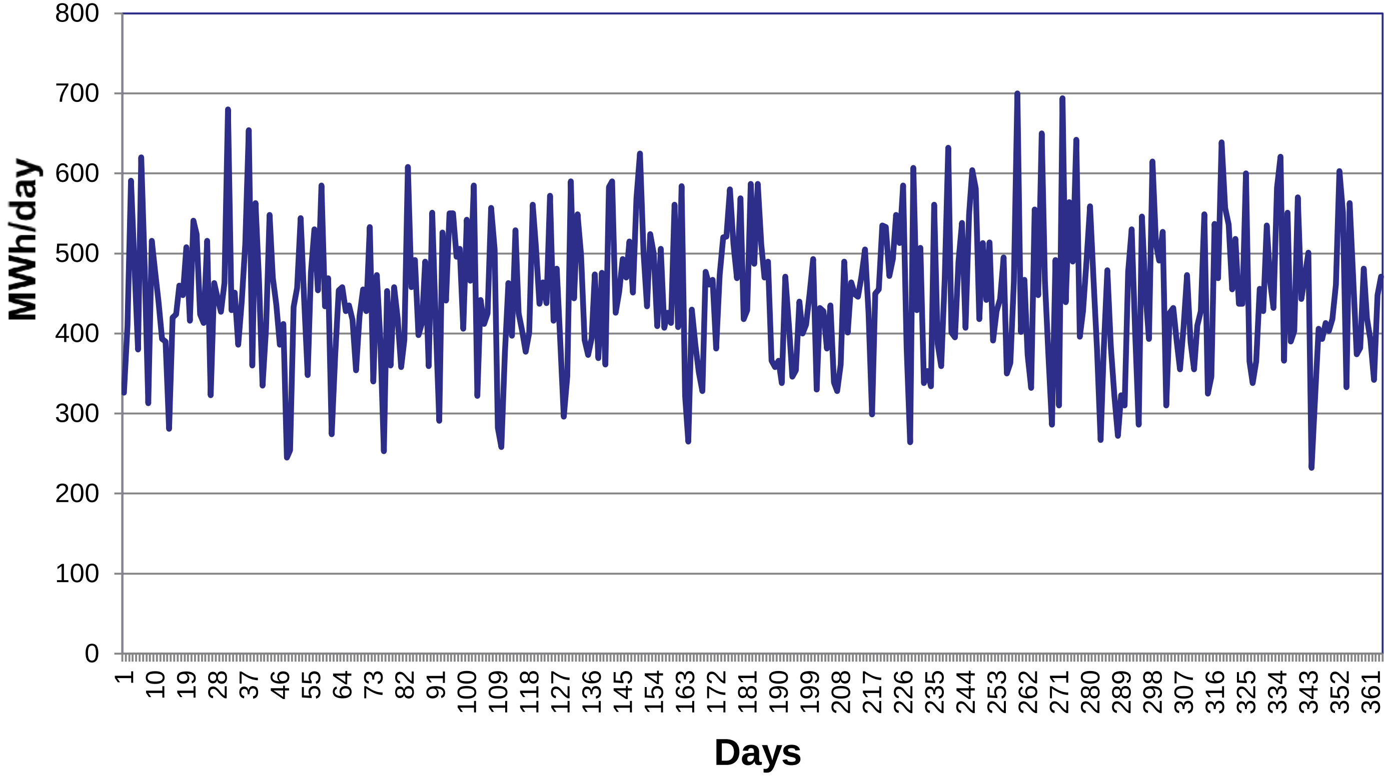


II) July 1

Max=50
Min= 0
Ave=24.5

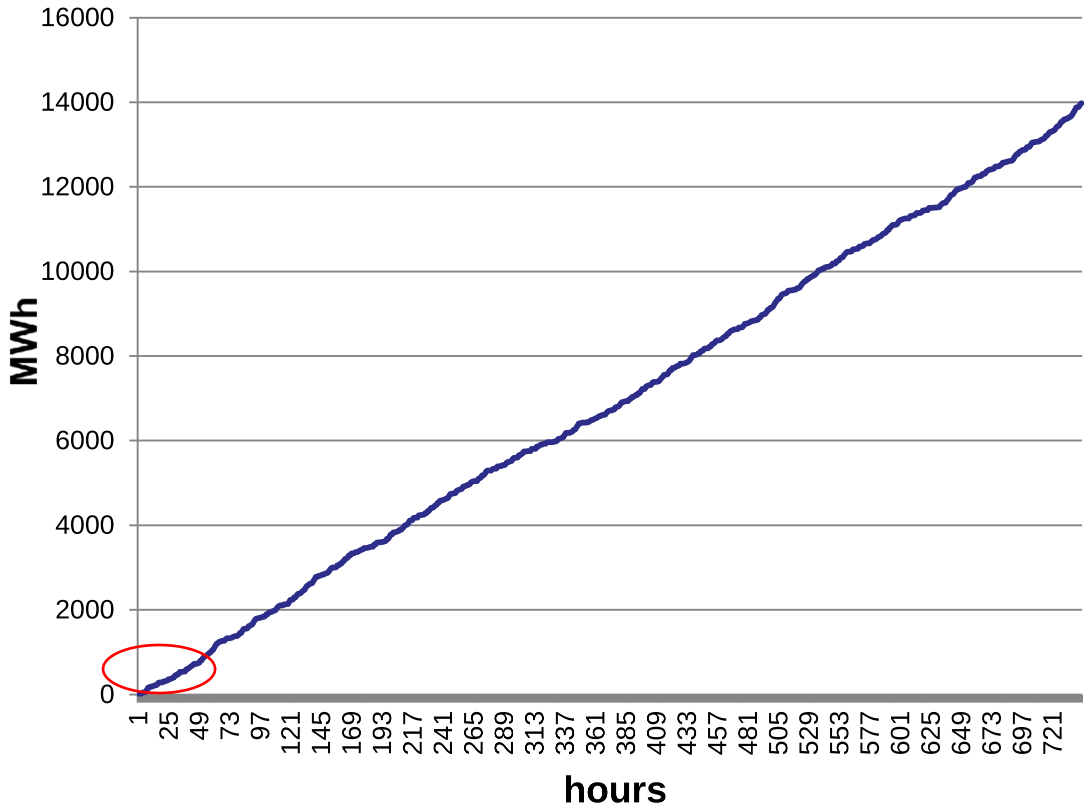
Data Source: Plexos Wind Profile 2005
I). January 1. II) July 1.

Daily Wind Generation



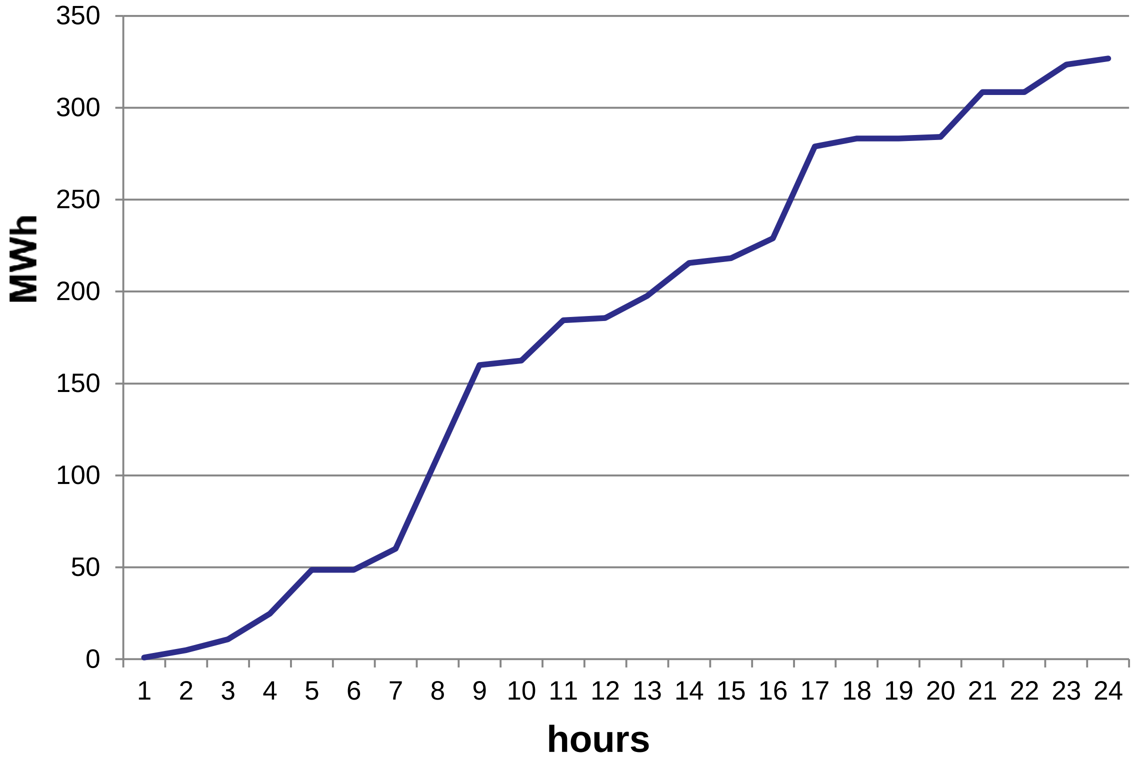
Data Source: Plexos Wind Profile 2005
Max: 700; Min=232; Average=447

Cumulative Hourly Wind Generation



Data Source: Plexos Wind Profile 2005
(Jan.1 -- Jan.31)

Cumulative Hourly Wind Generation (Cont'd)



Data Source: Plexos Wind Profile 2005 (Jan.1)

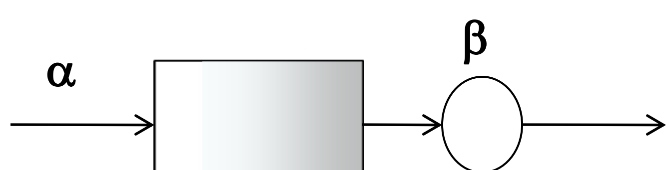
Network Calculus Approach
For Capacity Evaluation

- Chang, Cheng-Shang (2000)
- Le Boudec and Thiran (2001)

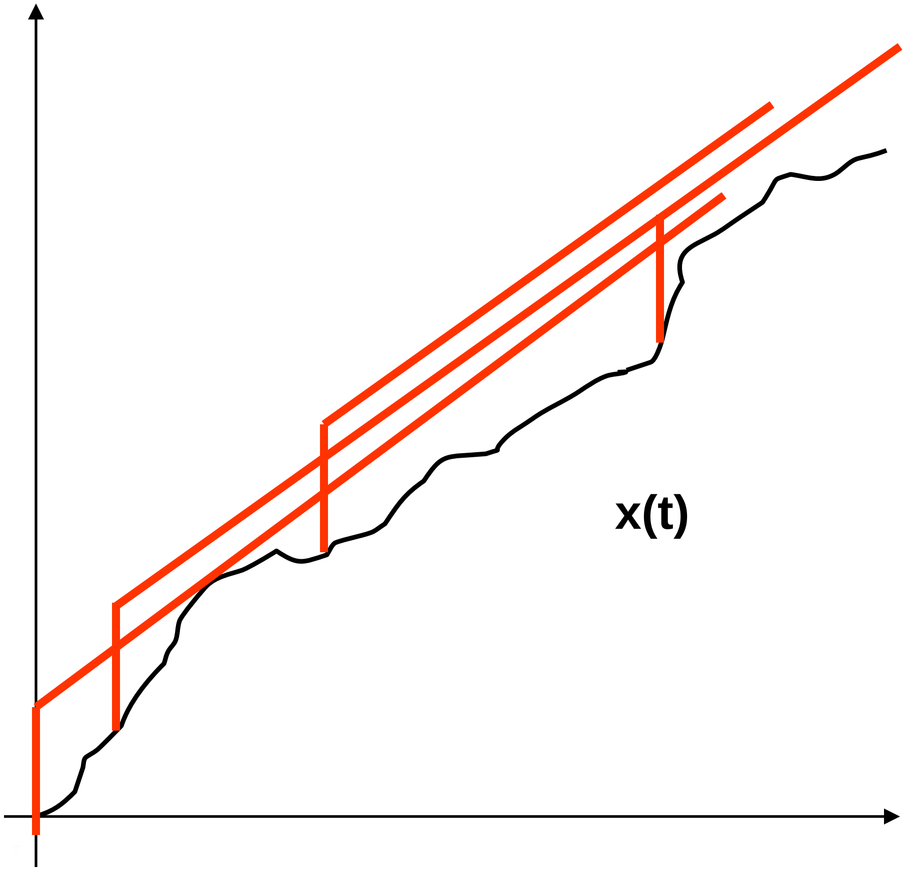
Arrival Curve: α for characterizing demand

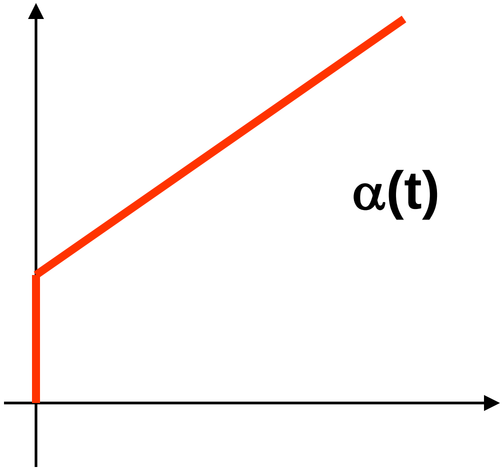
Service Curve: β for characterizing supply

Purpose: to characterize the level of QoS can be guaranteed by the supply-demand pair (α,β)



Arrival Curves: Illustration





x(s)+ α(t-s) is the upper envelop of x(t) for all t ≥ s,
i.e., x=α⊗x

Arrival Curves: Definition

Definition (Arrival Curve). Given a non-decreasing function α defined for $t \geq 0$, we say that a flow x is constrained by α if and only if for all

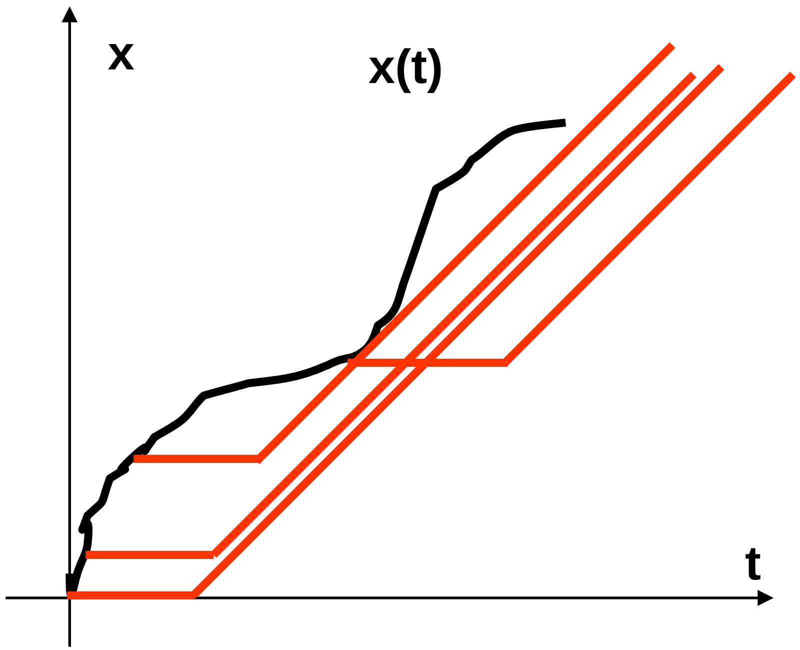
$s \leq t$: $\qquad x(t)-x(s) \leq \alpha(t-s)$.

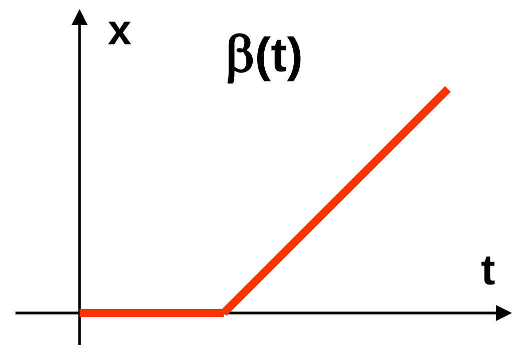
Equivalently, for all $t \geq 0$,

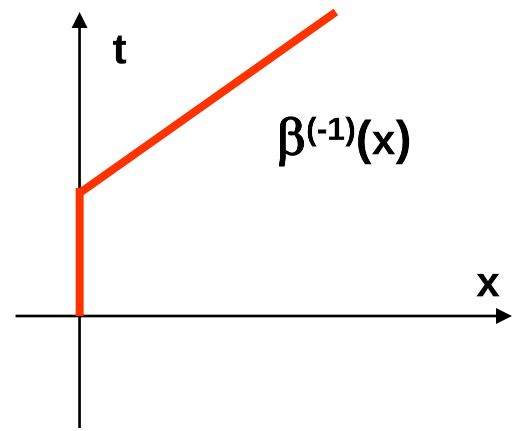
$$x(t) \leq \inf_{0 \leq s \leq t} \{x(s)+ \alpha(t-s)\} = (x \otimes \alpha)(t) \leq x(t).$$

We have $x=x \otimes \alpha$. Here $\otimes$ is the (min-plus) convolution.

Service Curves: Illustration







$x(s)+\beta(t-s)$ is the lower envelop of $x(t)$ for all $t \geq s$,
i.e., $x^{(-1)} = x^{(-1)} \otimes \beta^{(-1)}$.

Service Curves: Definition

Definition (Strict Service Curve) We say that system S offers a strict service curve β iff during any “busy” period of duration u, the output is at least $\beta(u)$, i.e., for all $s \leq t$: $x(t)-x(s) \geq \beta(t-s)$.

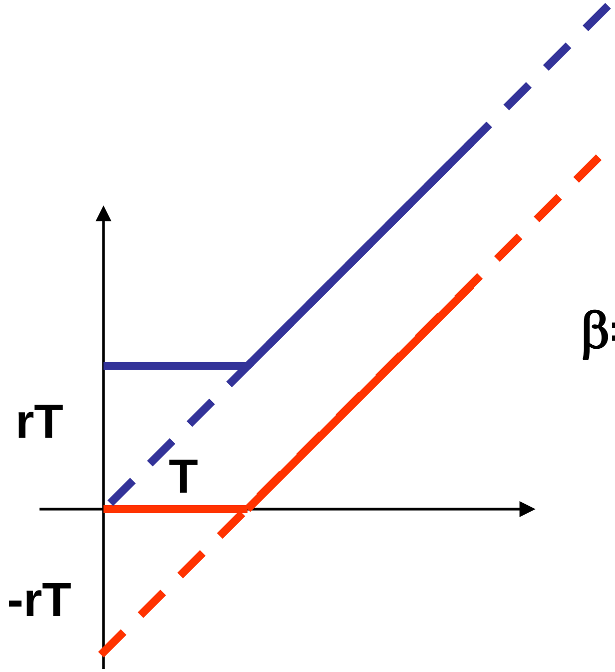
Equivalently, for any function h, define

$$h^{(-1)}(u)=\sup(t\geq 0 | h(t)\leq u).$$

System S offers a strict service curve β iff

$$x^{(-1)} = x^{(-1)} \otimes \beta^{(-1)} .$$

Interpretation of Service Curves



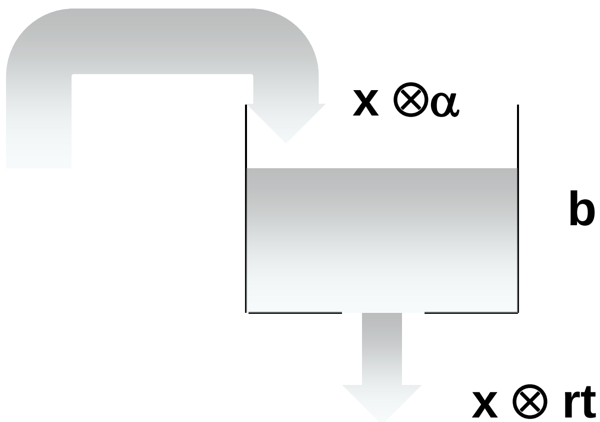
$\beta = \alpha^{(-1)}$

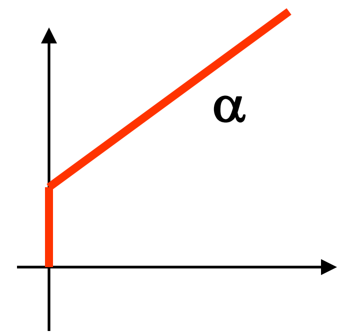
$= r(t-T)^{+}$

Interpretation: the wind capacity can be rated at r if the system has tolerance for net cumulative deficit up to rT MWh.

Leaky Buckets for Affine Arrival Curve

Let a leaky bucket has leaking rate r and bucket size b. Then the input that does not overflow this leaky bucket has arrival curve $\alpha(t) = rt + b$.



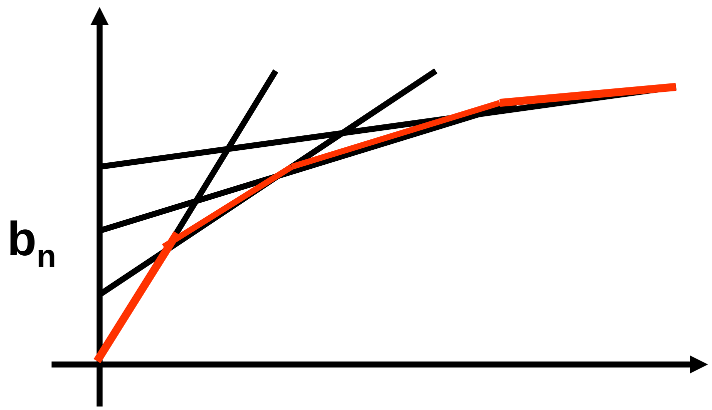


Interpretation: a generator with capacity r can serve this load if the system tolerates net cumulative deficit up to b (MWh).

Demand of Capacity and Its QoS Implication

The arrival curve of N parallel leaky bucket α_n is

$$\alpha(t) = \min_n \alpha_n(t).$$



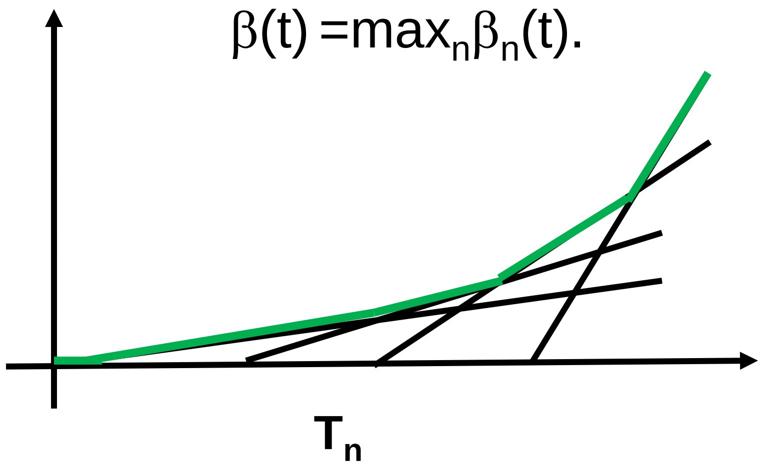
$$\boldsymbol{\alpha_n(t) = r_n(t) + b_n}$$

Interpretation: a generator with capacity r_n can serve this demand if the system tolerates maximum net cumulative deficit b_n (MWh).

Supply of Capacity and Its QoS Implication

The service curve of a generator that conforms to N Rate-Latency curve is

$$\beta(t) = \max_n \beta_n(t).$$



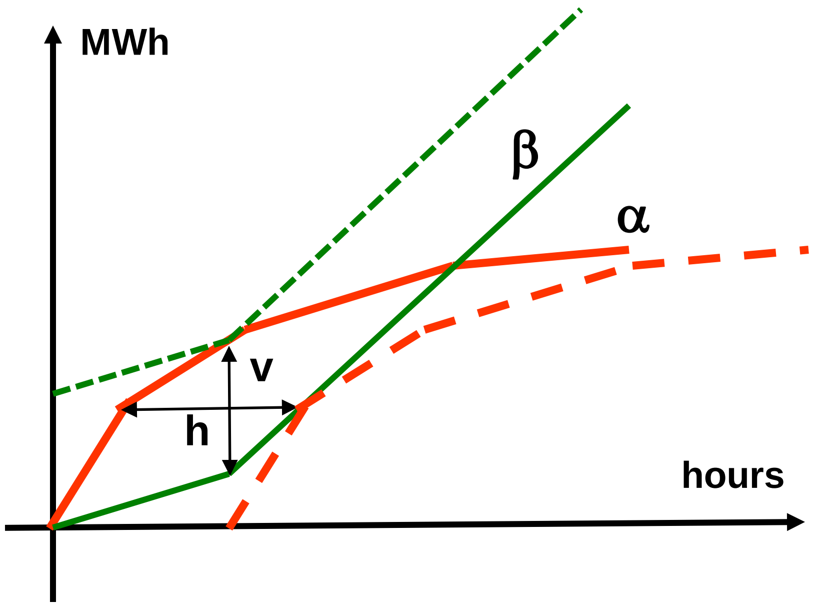
$$\beta_n(t) = r_n(t - T_n)^+$$

Interpretation: this generator can serve a constant load at the level of $\mathbf{r_n}$ MW if the system allows deficit to be repaid in $\mathbf{T_n}$ hours.

Quality-of-Service Bounds v & h

- **v**

Supported by a storage with energy content v (MWh), a generator with a service curve β is adequate to serve a demand of a arrival curve α.



Interpretation via an ideal storage

- **h**

After feeding a storage for h hours, a supplier with service curve curve β can serve a demand of arrival curve α.

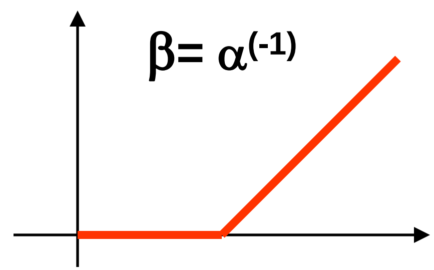
Capacity Evaluation Approach I: Leaky Bucket Inversion

Denote

$w(t)$	wind power in MW
$W(t)=\int_0^t w(s)ds$	wind energy in MWh
$C_r(t)= rt$	constant supply or demand of rate r

For $W(t)$, find the affine arrival curve for $W^{(-1)}$. If $W^{(-1)}$ conforms to an arrival curve α, then the service curve of W is given by

$$\beta= \alpha^{(-1)} .$$

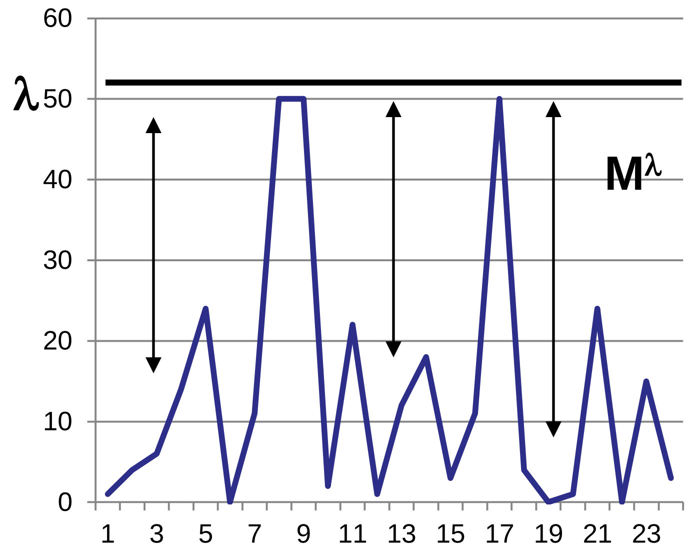


Capacity Evaluation Approach II: Negative Load

Let $\lambda \geq \max_{0 \leq s \leq t} w(s)$. Define

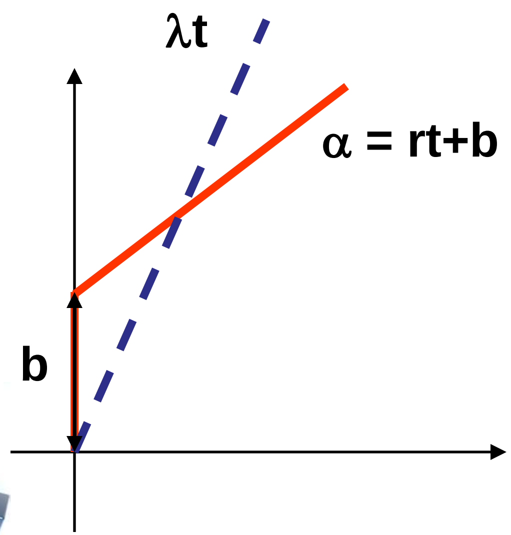
$$M^{\lambda}(t) = \lambda t - W(t)$$

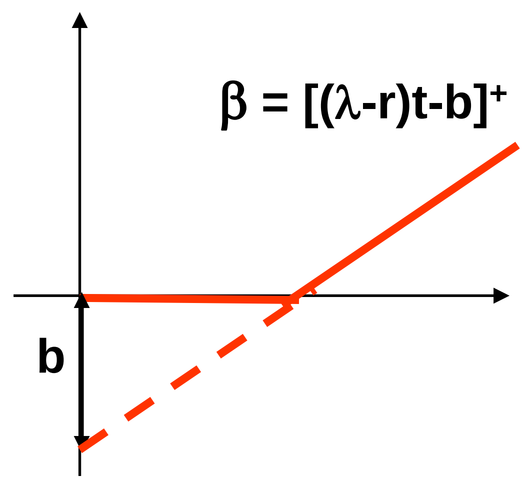
$M^{\lambda}(t)$ can be interpreted as the reduction of constant load at level λ. In short, it is the negative load.



Capacity for Negative Load

Now, pass the "negative load" to a leaky bucket with rate r, the maximum backlog b can be determined. Thus, the load flow $M^{\lambda}(t)$ conforms to arrival curve $\alpha(t)= rt+b$. This implies, when the generator's capacity is rated at $(\lambda-r)$, the system has to tolerate deficit up to b MWh.





Backlog b

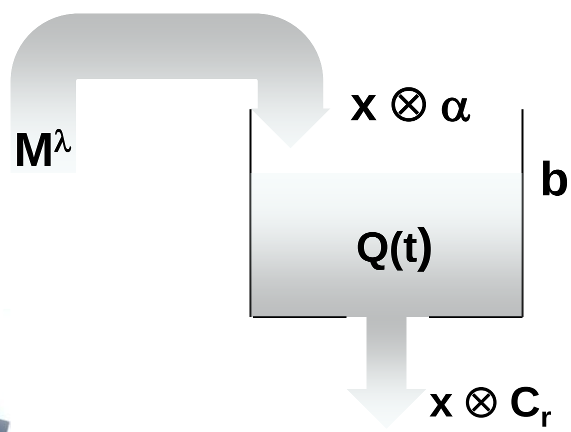
Given capacity r,

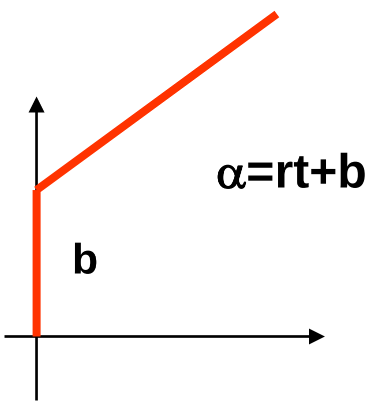
Q(0)=0;

$Q(t) = \max(0, Q(t-1)+M^{\lambda}(t)-M^{\lambda}(t-1)-r);\ t \geq 1$

$b = \max_t Q(t)$

Service Curve: $\beta = [(\lambda - r)t - b]^{+}$





A Numerical Example

Real Wind Data

Start: 1/1/2008

End: 12/31/2008

Interval: I hour

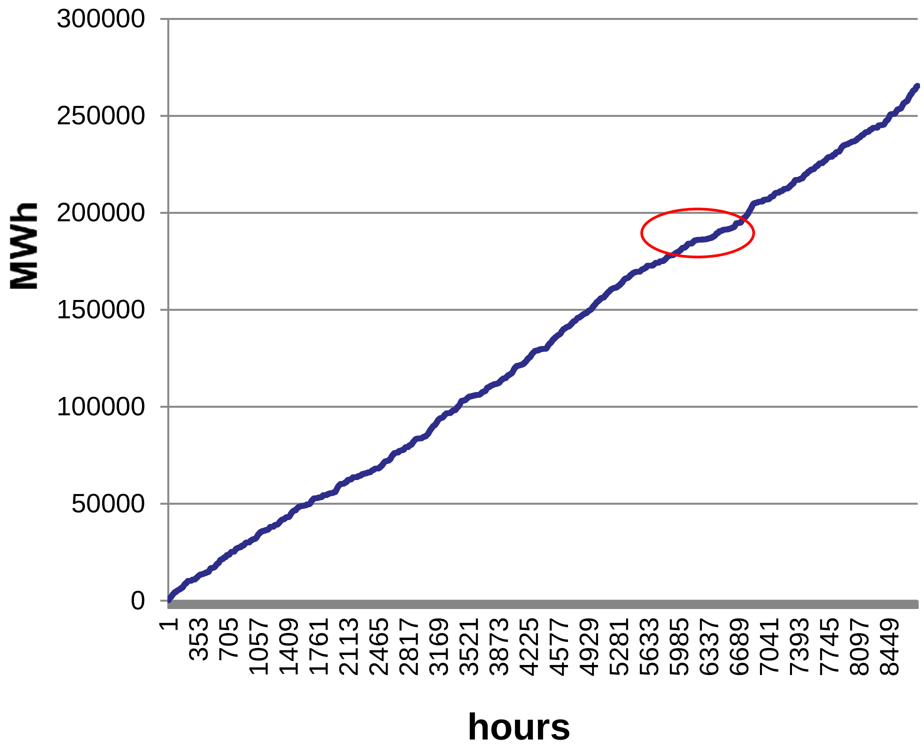
Basic Stats (Unit: MW)

Max: 98.77

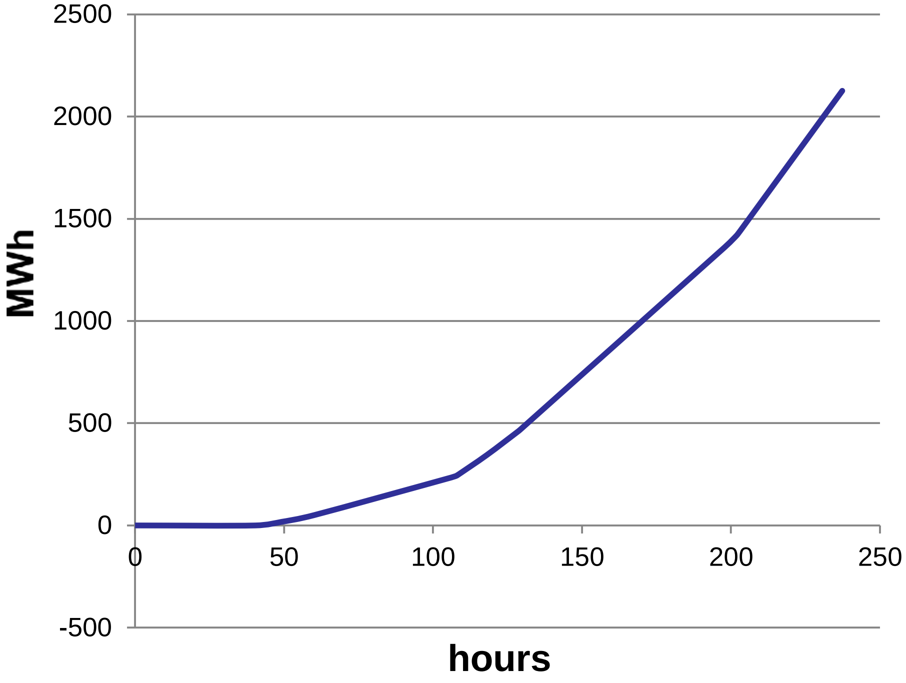
Min: -0.70

Ave: 32.97

Std: 31.34

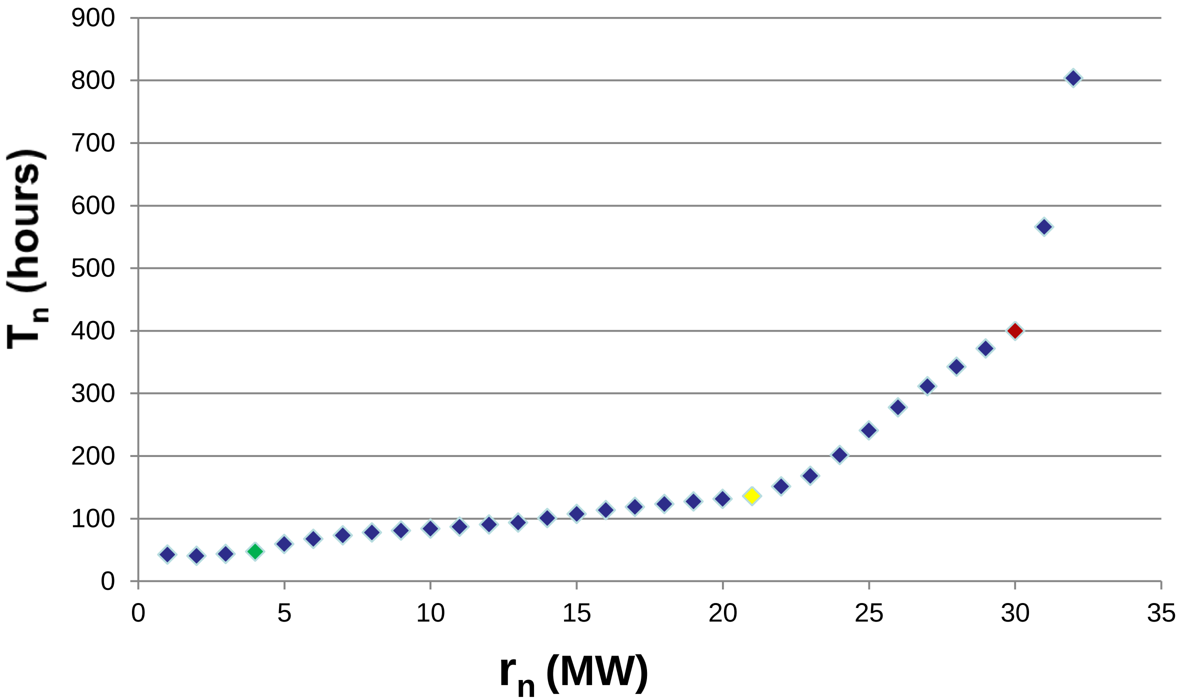


Service Curve



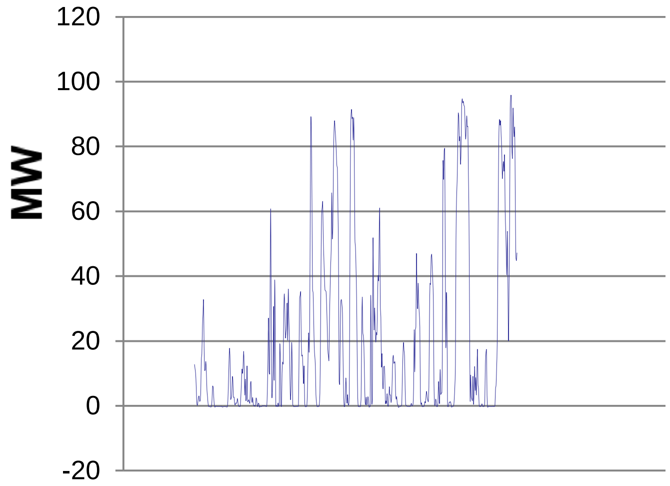
Service Curve = $\max_n r_n(t-T_n)^+$

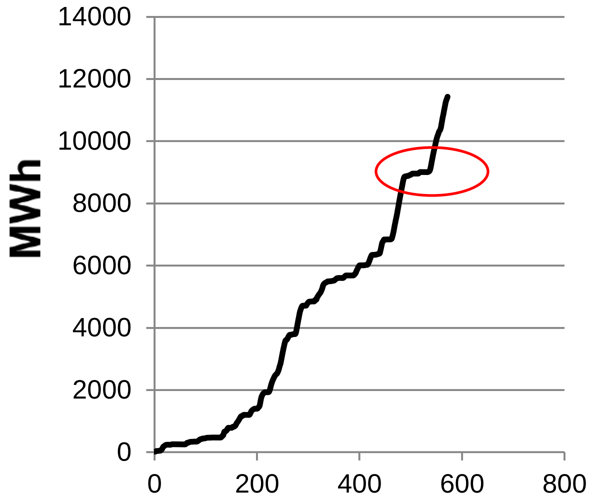
QoS-Parameters



- r_4 = 4MW, T_4 = 47.5 Hours **[I have to wait for 2days?!]**
- r_{21}=21MW, T_{21}=136.1 Hours
- r_{30}=30MW, T_{30}=400.0 Hours

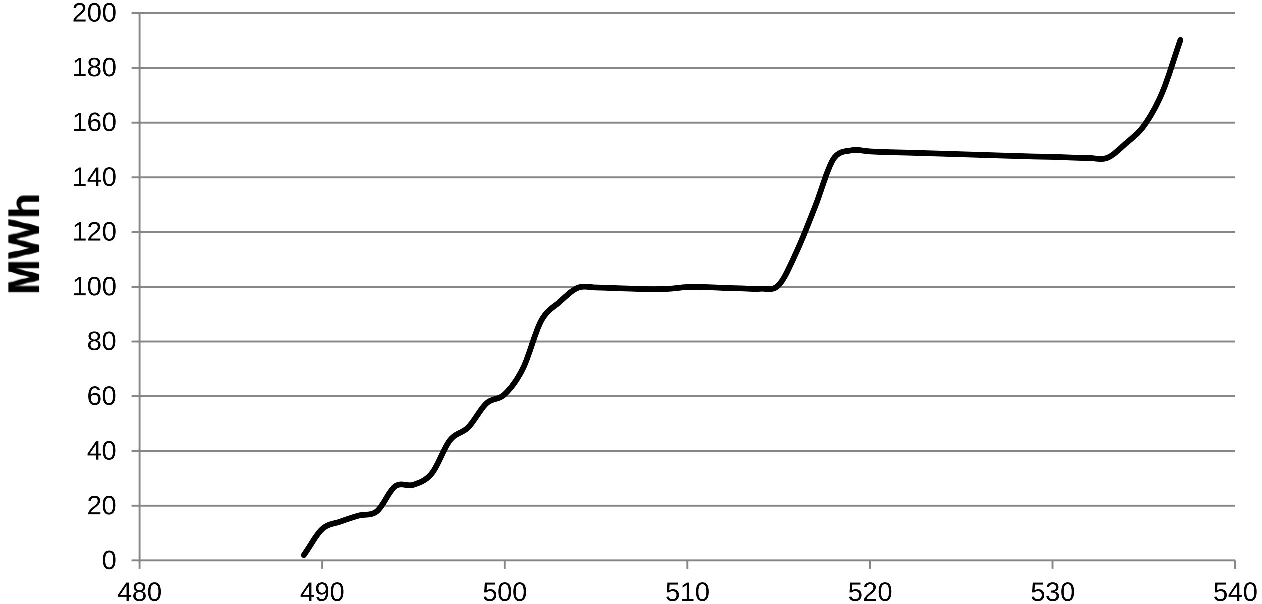
Observations





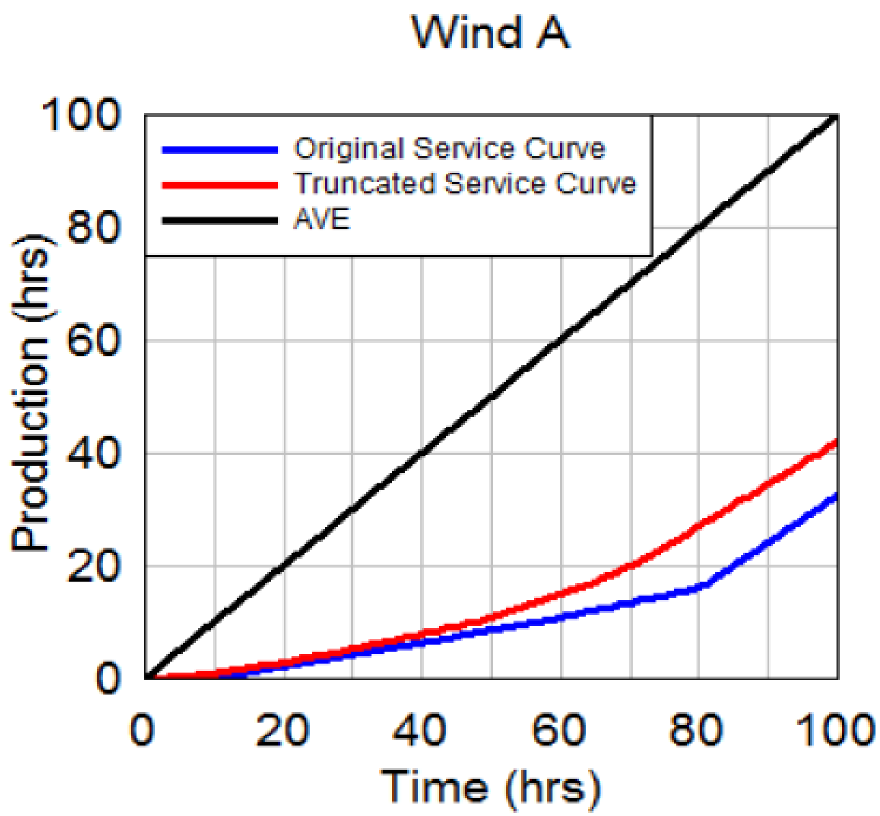
Hourly Data from 6am 9/4/08 to 1am 10/18/08

Observations (Cont'd)



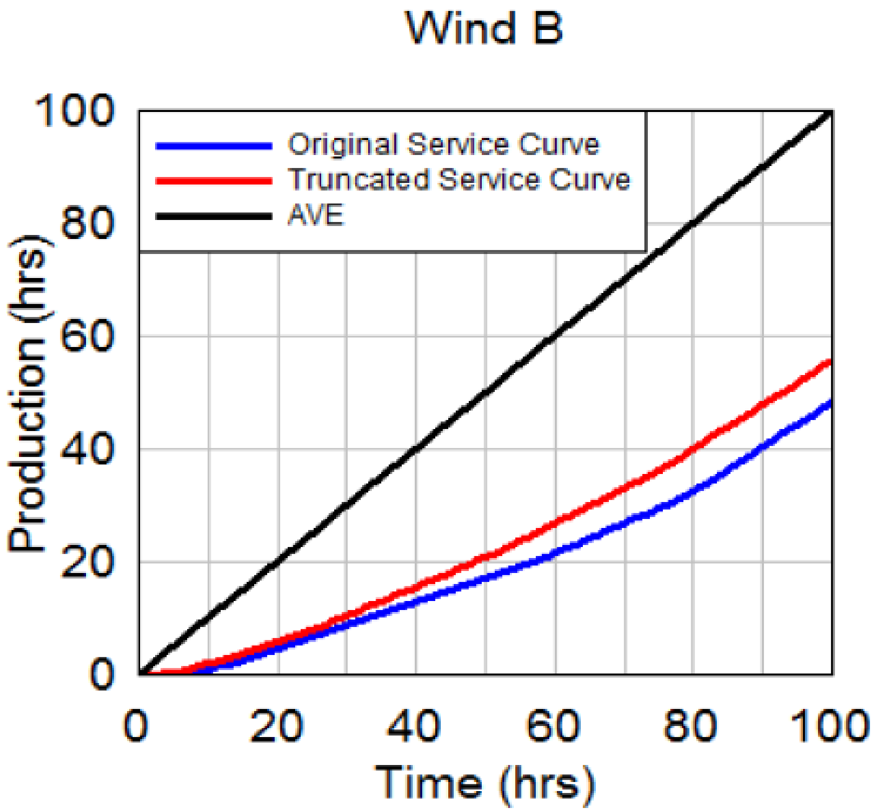
Hourly Data from 2pm 10/4/08 to 2pm 10/6/08 (the calmest two-days)

More Real Data and Curves



Based on 1-Minute Data during June 1-30, 2007, CAISO

More Real Data and Curves



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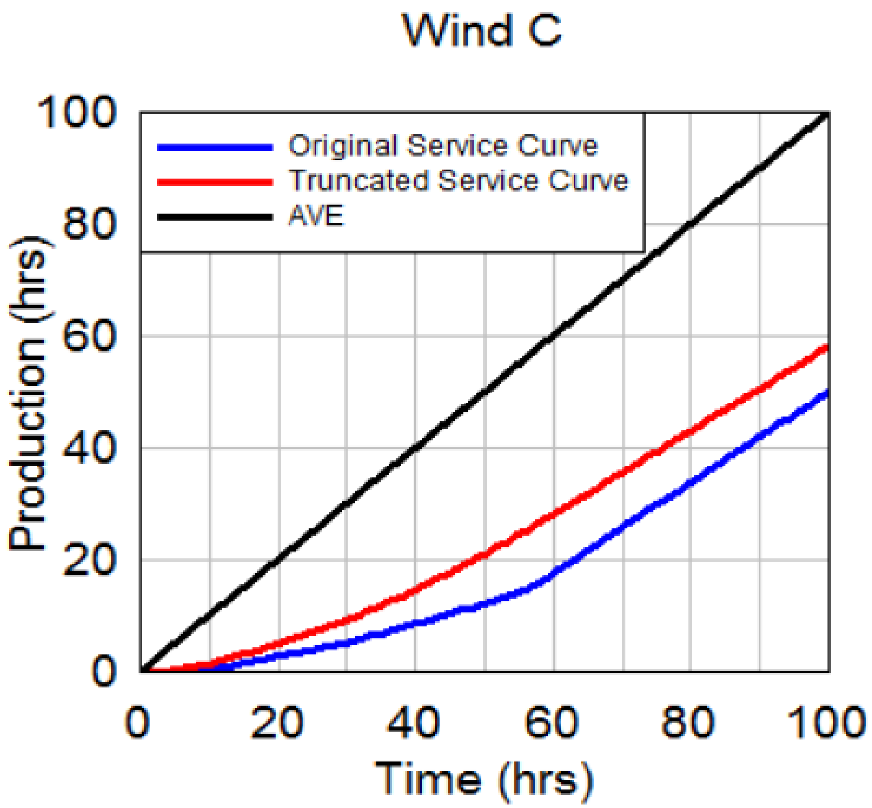

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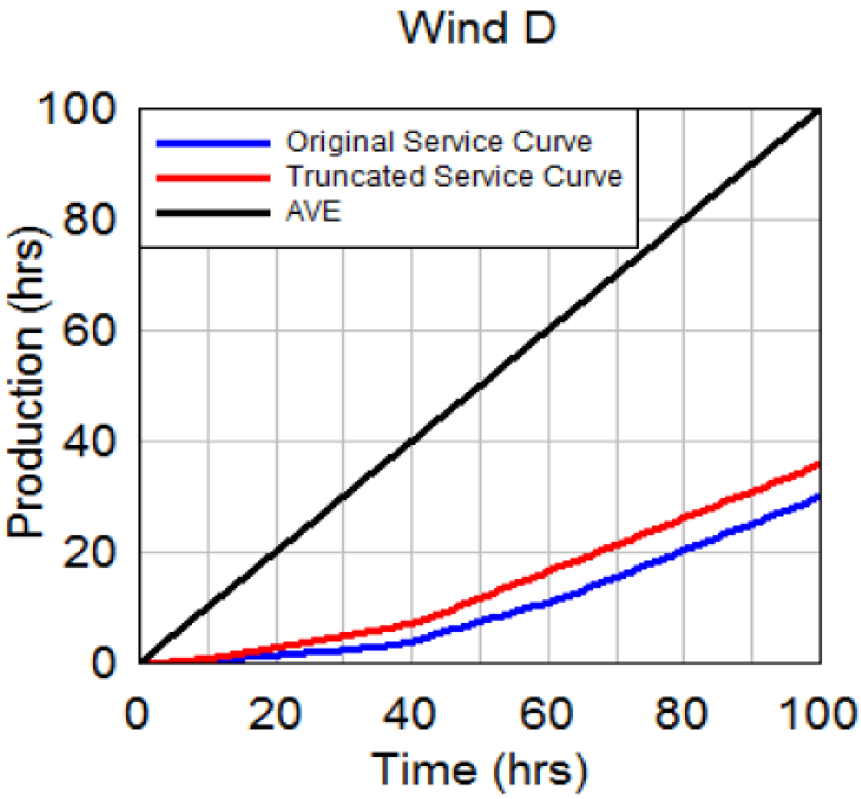

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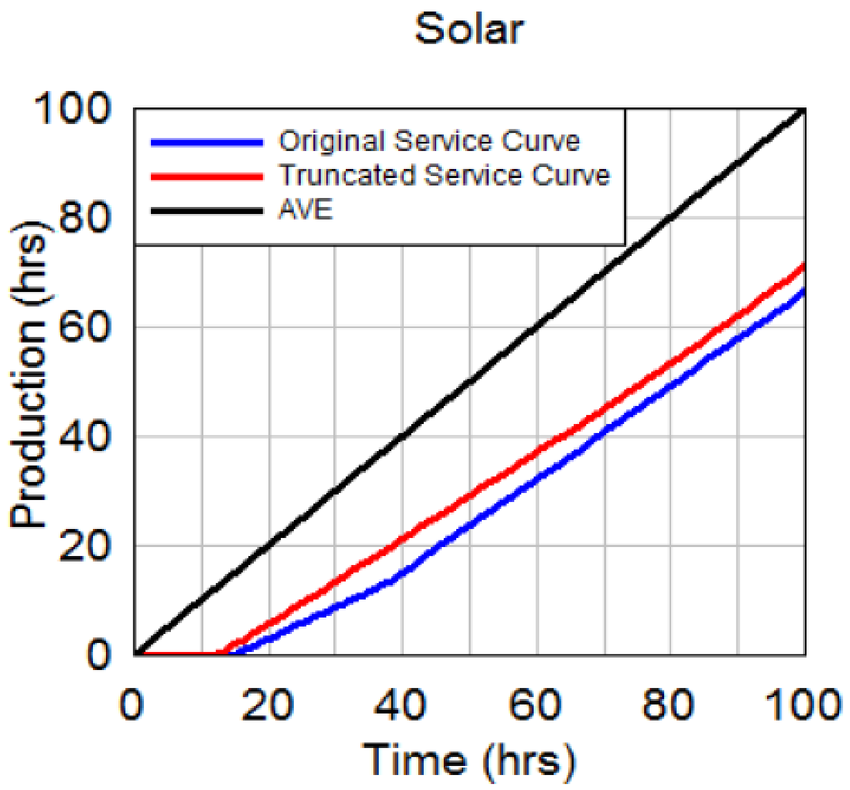

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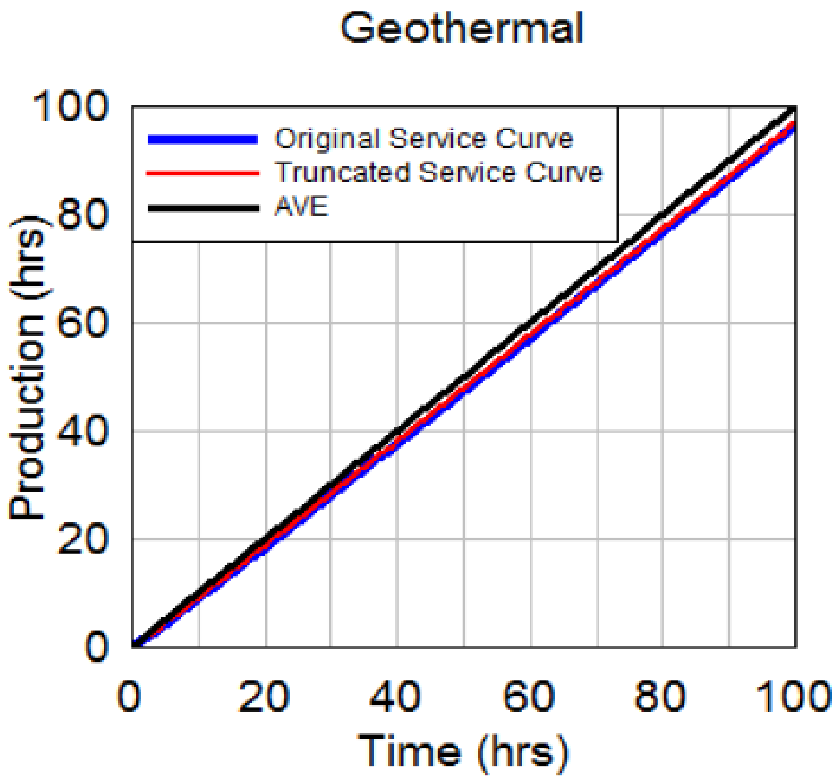

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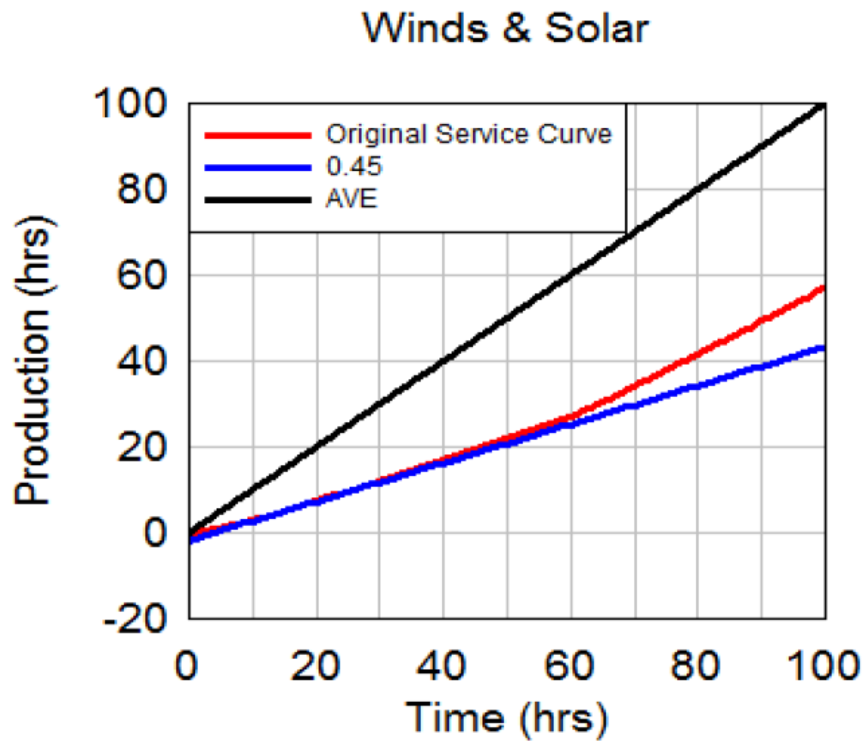
Capacity Contributions



Aggregated Wind & Solar gets 45% capacity credit from its UCAP. By further broken down between Wind and Solar, Solar gets 62% and Wind gets 37%.

Summary

- This approach quantifies the dependence of intermittent resources on the system as backup
- It calls for QoS-based capacity evaluation for intermittent
- It calls for capacity evaluation and potential QoS incentive mechanisms for both the supply and the demand sides

How about a Capacity Market?

- It demonstrates the usefulness of storage, and provides a tool to model and optimize the integration of intermittent source and storage.

Q: What if we need only to serve the load several hours a day, say during the peak hours?

Storage enables us to better match supply with demand, and to turn intermittent sources from base-load generators into peakers.

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5. Le Boudec, Jean-Yves and Patrick Thiran (2001). *Network Calculus-- A Theory of Deterministic Queuing Systems for the Internet.*

Thanks!

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