CONTROL AND OPTIMIZATION IN SMART-GRIDS

Fredy Ruiz Ph.D.
Pontificia Universidad Javeriana, Colombia
Visiting Profesor - Politecnico di Torino
ruizf@javeriana.edu.co

May, 2018

Course topics

- Session 1: Introduction to Power systems
  - Context and motivation
  - Power flow analysis
  - Economic dispatch
- Session 2: Renewable sources
  - Stochastic models of variable sources
  - Dispatching random sources
- **Session 3: Energy dispatch**
  - **Risk-limiting dispatch**
  - **Matlab session**

Course topics

- Session 4: Incentive-based demand response
  - Modeling demand
  - Peak time rebates
  - Contract design for demand response
- Session 5: Flexible loads
  - Modeling flexibility
  - Load dispatch
  - Case study: Electric vehicles
- Session 6: Micro-grids
  - Lean energy concept
  - Joint generation and load dispatch

Day-ahead Market

- Given a demand forecast D_k
- And a set of generators $G_1, G_2, G_3, \ldots, G_N$
- What is the lowest cost generation program that supplies the demand?

This is the economic dispatch problem!

Economic Dispatch

$$\min J = \sum_{k=1}^{K} \sum_{j=1}^{N} C(p_{jk})$$ *Sum of generation costs*

Subject to

$$\sum_{j=1}^{N} p_{jk} = D_k \qquad \forall k$$ Energy Balance

$$p_j{}^{min} \leq p_{jk} \leq p_j^{max}$$ Operational constraints

Wind Energy in the Market

- Once a proper stochastic model of generation is available,
- How can a renewable generator participate in the market?
- It depends on the Dispatch model.
- Must-run units
  - 100% renewable capacity usage
  - Reliability problems
  - Increase of reserves requirements
- Open market
  - The risk of uncertainty is assumed by the generator

Wind energy in an open market

Simplified market model:

- The wind farm has a rated capacity, normalized to 1.
- For given period $[t_o, t_f]$ the owner of the wind farm knows the Cdf (pdf) of generation.
- $w \in [0, 1]$ is the R.V. modeling wind power.

Wind energy in the market

Market operation:

- Generator is price taker
- Gen. participates in the day ahead market
- Deviations are penalized
- Imbalance prices are unknown, modeled as R.V.

Problem: *How much energy shall the generator offer to the system operator, given his private information on wind power (pdf) and imbalance prices?*

Wind energy in the market

Economic balance of the Generator:

- Sold energy:

$$I = CT$$

- Negative imbalance:

$$\sum_{-}(C, \boldsymbol{w}) = \int_{to}^{tf} [C - w(t)]^{+} dt$$

- Positive imbalance:

$$\sum_{+}(C, \boldsymbol{w}) = \int_{to}^{tf} [w(t) - C]^{+} dt$$

Wind energy in the market

Economic balance of the generator:

$$\prod(C,w,q,\lambda) = pI - q\sum\nolimits_{-}(C,\mathbf{w}) - \lambda\sum\nolimits_{+}(C,\mathbf{w})$$

- The only decision variable for the generator is *C.*

What is a good (optimal) strategy in this context?

Wind energy in the market

What is a good (optimal) strategy in this context?

- Maximize Π, using expected values for w, q and λ
- *Generate samples of R.V. from their pdf and maximize for each case. Then ….*
- *Maximize the expected value of* Π
- Minimize variance of Π
- A joint criteria of previous performance measures

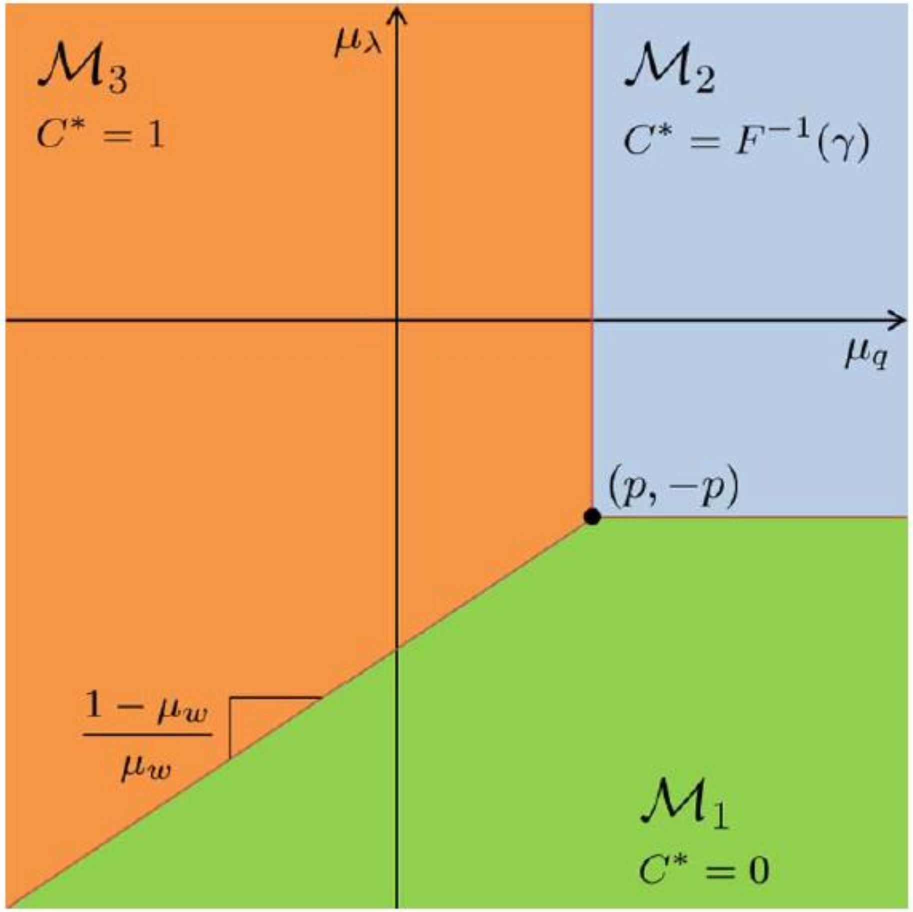
Wind energy in the market

- The basic stochastic solution is to maximize the expected value of the generator profit:

$$C^* = \mathbf{E}\left[\prod(C, w, q, \lambda)\right]$$

With respect to *w, q* and *λ.*

Wind energy in the market



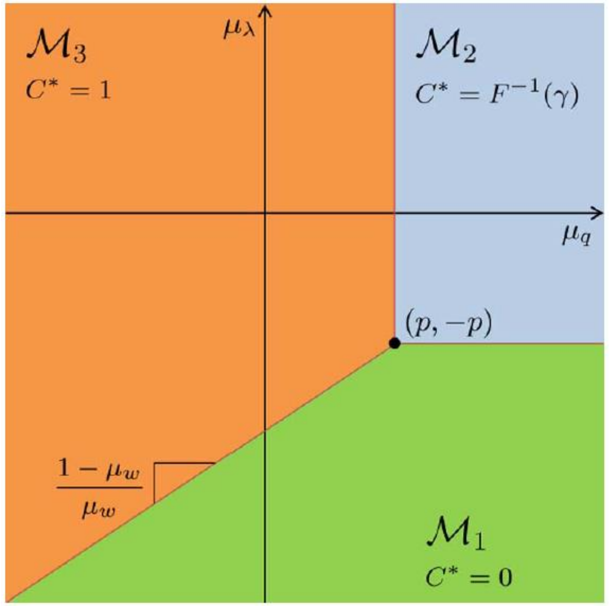
Optimal Contract:

$$C^* = \begin{cases} 0, & \pi \in \mathcal{M}_1 \\ F^{-1}(\gamma), & \pi \in \mathcal{M}_2 \\ 1, & \pi \in \mathcal{M}_3 \end{cases}$$

$$\text{where } \gamma = \frac{p + \mu_\lambda}{\mu_q + \mu_\lambda}.$$

Wind energy in the market

Optimal Expected Profit:



$$\frac{J(C^*)}{T} = \frac{J^*}{T}$$

$$= \begin{cases} -\mu_\lambda \mu_w, & \pi \in \mathcal{M}_1 \\ \mu_q \int_0^\gamma F^{-1}(x)dx - \mu_\lambda \int_\gamma^1 F^{-1}(x)dx, & \pi \in \mathcal{M}_2 \\ p - \mu_q(1-\mu_w), & \pi \in \mathcal{M}_3 \end{cases}$$

Wind energy in the market

Expected shortfall:

$$S_-(C^*) = S_-^* = T\int_0^{F(C^*)} \left[C^* - F^{-1}(x)\right] dx$$

Expected surplus:

$$S_+(C^*) = S_+^* = T\int_{F(C^*)}^{1} \left[F^{-1}(x) - C^*\right] dx.$$

Wind energy in the market

- The generator behaves as inelastic supply in regions M1 and M3
- In region M2 the offered energy *C** varies with *p.*
- What does the expected shortfall tells to the system operator?

$$S_{-}\left(C^{*}\right)=S_{-}^{*}=T\int_{0}^{F\left(C^{*}\right)}\left[C^{*}-F^{-1}(x)\right]dx$$

- ***Reserves:*** *Generation units contracted to provide energy ONLY in case of unpredicted power deficits. Corrective actions!!*

Wind energy in the market

Self-supplied balancing service:

- The generator may have a contract with a conventional generator (e.g. fast gas plant) that provides energy at a price $q_L>0$.
- The fast generator has a capacity L.
- Assume $q_L < q$, otherwise it is better to pay deviations to the SO.
- For simplicity assume no penalty for positive imbalances, $\lambda=0$.

Wind energy in the market

Self-supplied balancing service:

- New cost function:

$$J_L(C) = \mathbb{E} \int_{t_0}^{t_f} pC - \phi\,(C - w(t),\ L)\,dt$$

- Where:

$$\phi(x, L) = \begin{cases} qx - (q - q_L)L & x \in (L, \infty) \\ q_L x & x \in [0, L] \\ 0 & x \in (-\infty, 0) \end{cases}$$

Wind energy in the market

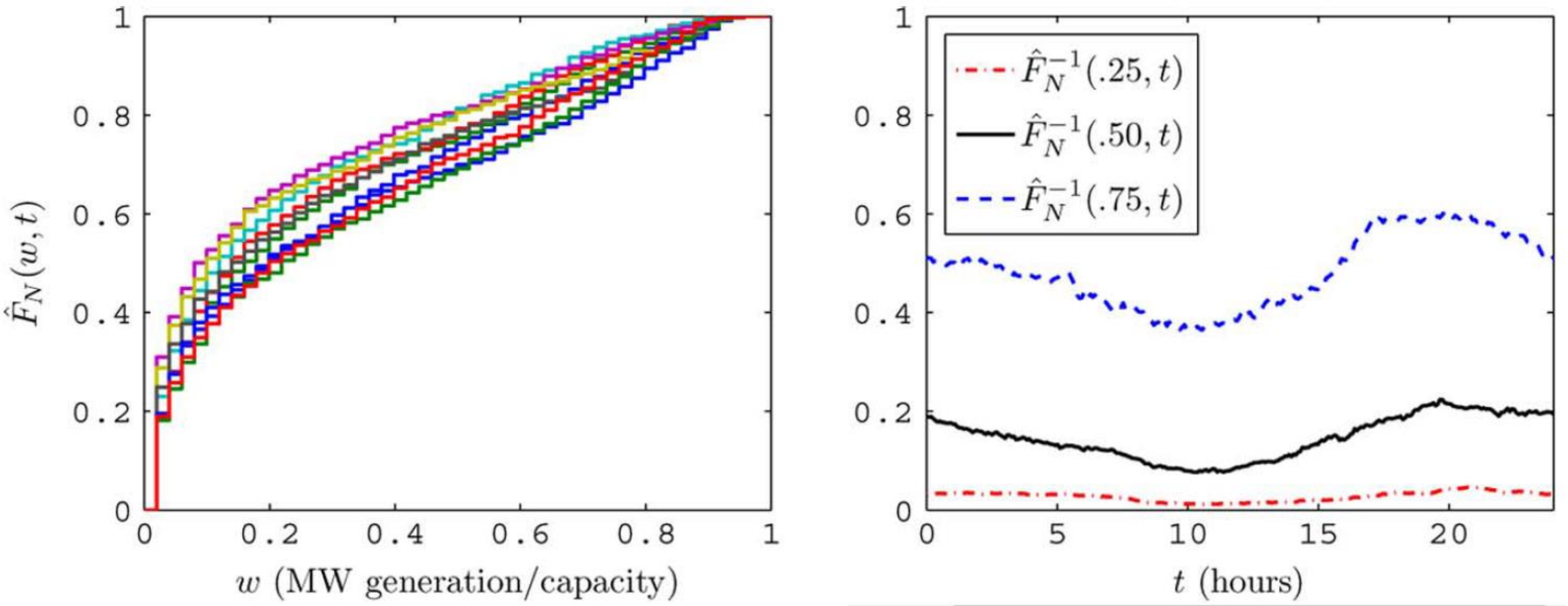
Self-supplied balancing service:

- The optimal contract C* in this case is given by the solution to:

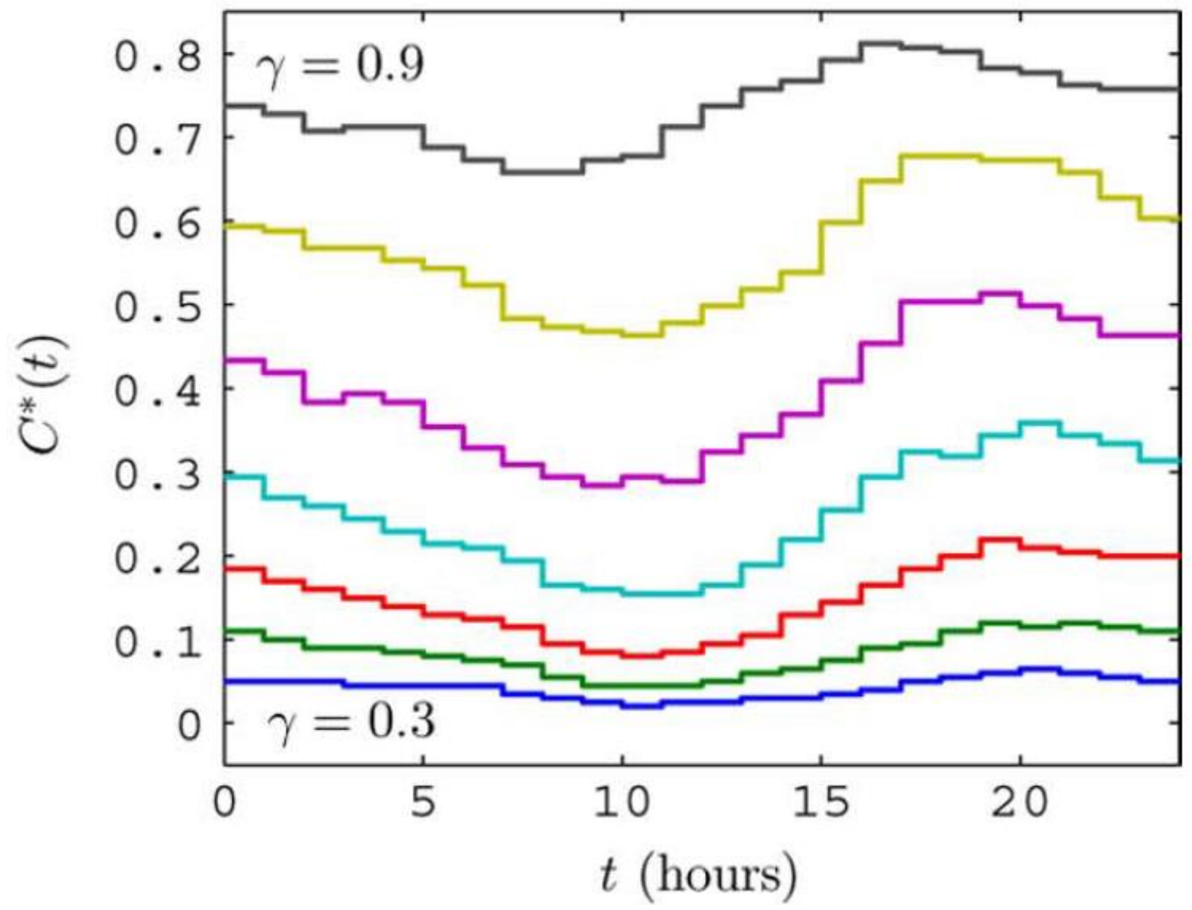
$$p = q_L F(C) + \left(\mu_q^+ - q_L\right) F(C - L)$$

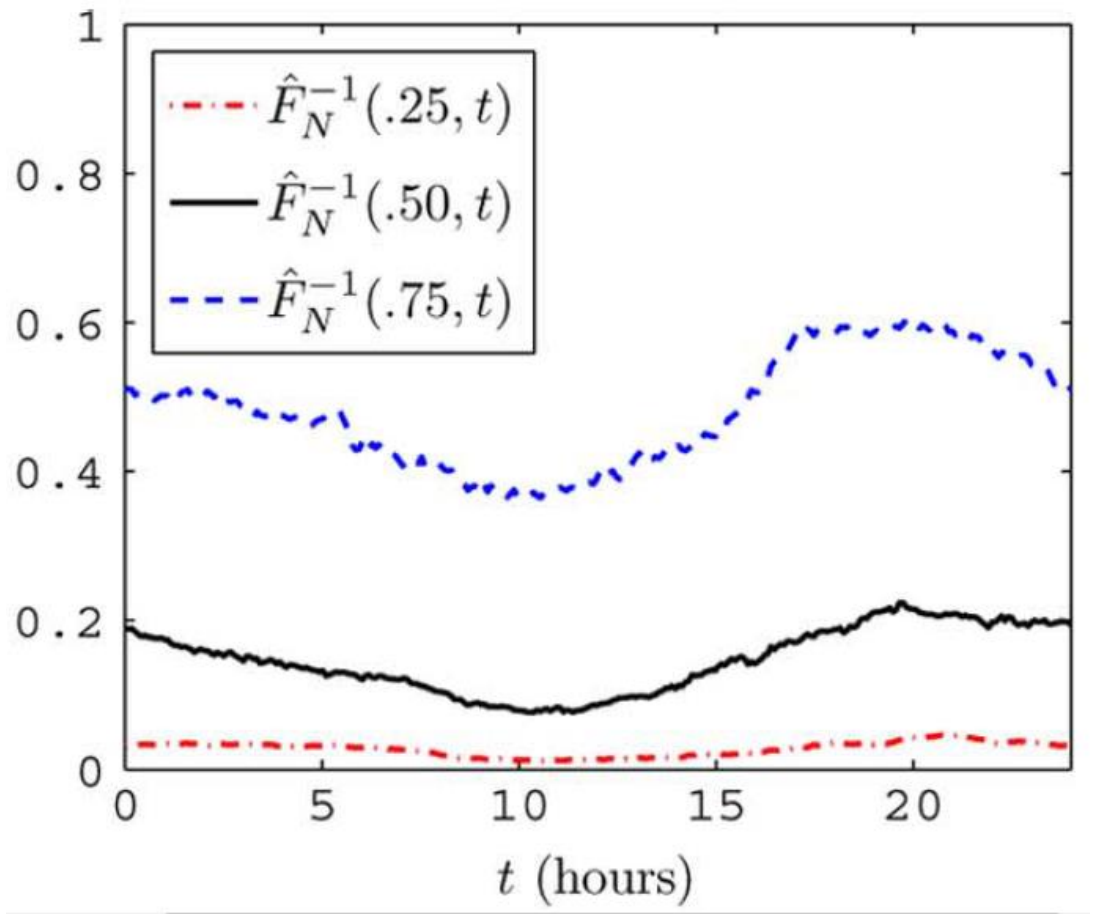
- If it exists.

Wind energy in the market



Wind energy in the market





Risk-limited dispatch

Limitations of traditional dispatch:

- It is a worst-case approach.
- For wind generation, typically SO schedules reserves for 90% of installed capacity.
- Inefficient solution!!!!

Risk-limited dispatch

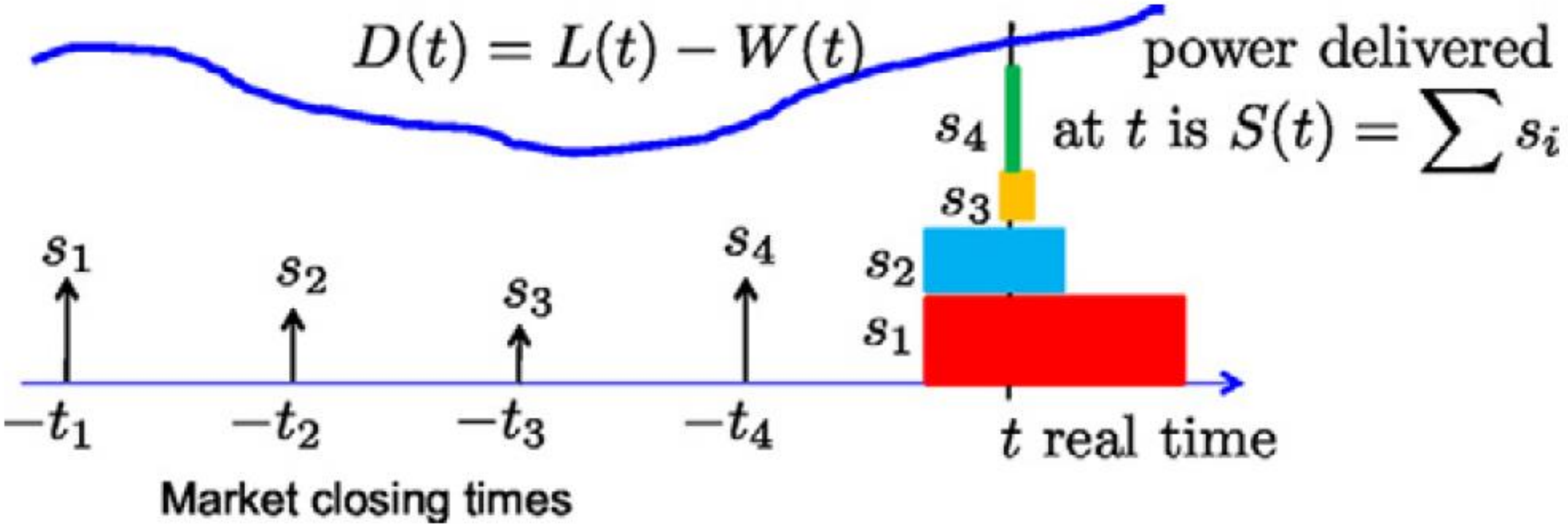
Traditional dispatch:

- Cost function: minimize operational cost
- Constraints:
  - Balance
  - Capacity
- Risk: (N-1) criterion
- **Result:** a lot of reserves scheduled!!!!

Risk-limited dispatch:

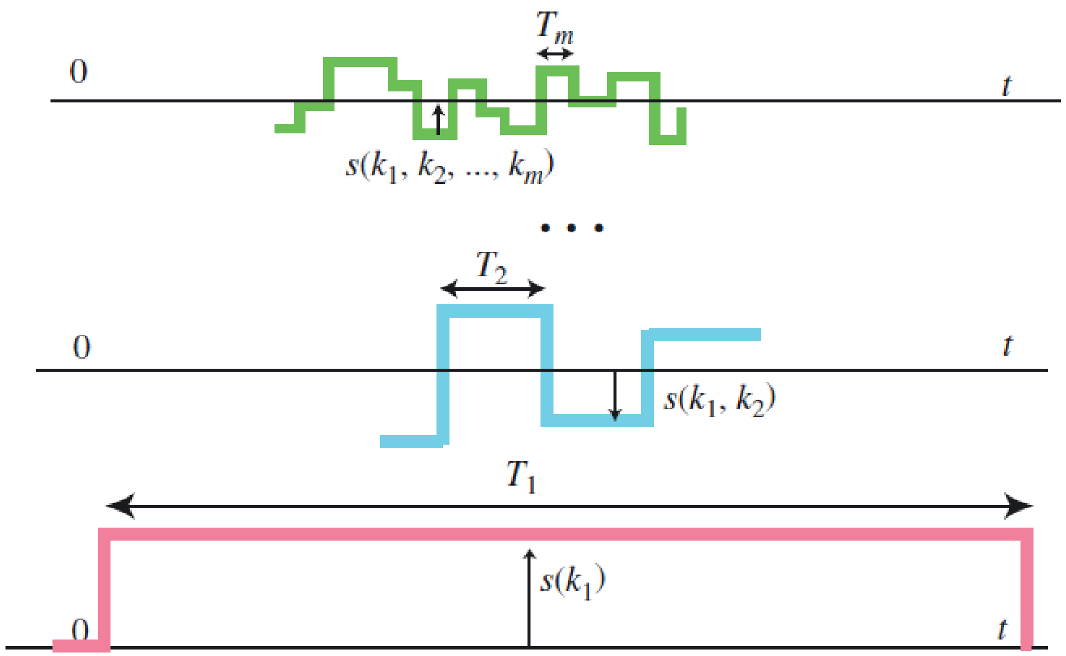
- Cost function: Expected cost of suppling demand
- Constraints:
  - Guaranteeing a probability level of not having a failure, imbalance, excess Tx capacity,…
- Limited-risk: $p_f < (1-\alpha)$
- ***Result:** Reduced reserves, reduced prices!!!!*

Risk-limited dispatch



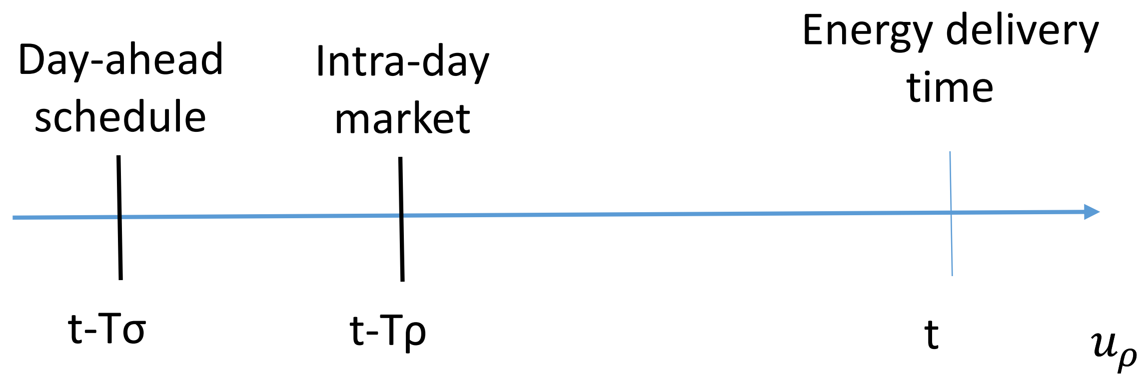
Intra-day markets: *Energy is traded in multiple periods, each time closer to the delivery time.*

Risk-limited dispatch



- Several markets
- Closer to the dispatch time:
  - Energy becomes more expensive
  - Uncertainty reduces
  - SO can buy *or sell* blocks of energy.

Risk-limited dispatch



$$\min J(u_\sigma)$$
s.t.
$$pr\left[f(u_\sigma) = D(t); g(u_\sigma) \leq 0 | y_{t-T_\sigma}\right] \geq \alpha$$

- First market, at time t-Tσ :
- Decision: generation u_σ
- Constraint: Probability of satisfying demand and operational constraints is higher than α

NO worst-case, there is a limited risk of failure!!!

Risk-limited dispatch

$$\min J(u_\rho)$$

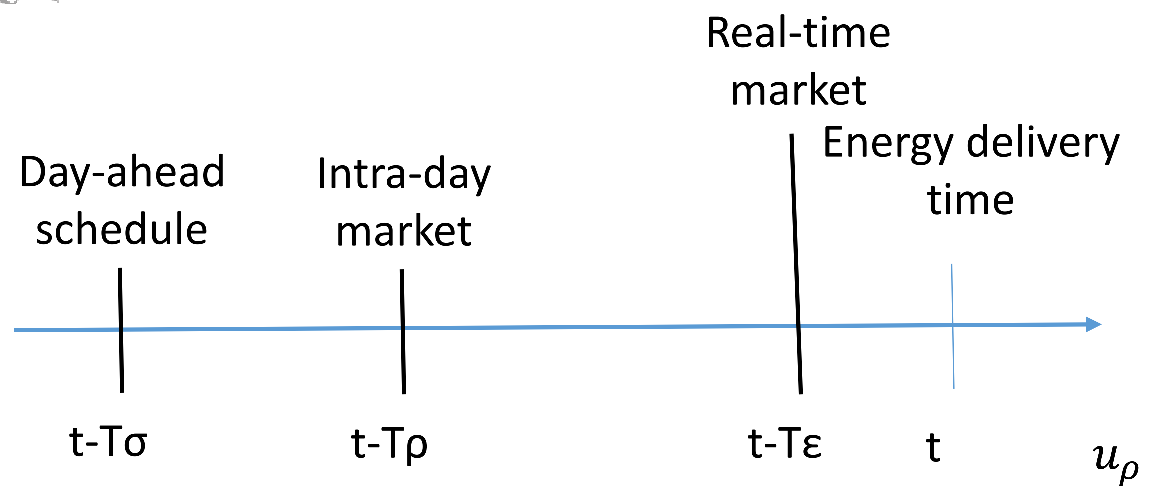
s.t.

$$pr\left[\begin{matrix} f(u_\sigma+u_\rho)=D(t); \\ g(u_\sigma+u_\rho)\le 0; \end{matrix} \middle| y_{t-T_\rho}\right] \ge \alpha'$$

- Second market, at time t-Tρ:
- Decision: generation u_ρ
- Constraint: Probability of satisfying demand and operational constraints is higher than α'

NO worst-case, there is a limited risk of failure!!!

Risk-limited dispatch



$$\min J(u_\varepsilon)$$

s.t.

$$pr\left[\begin{matrix} f\left(u_\sigma + u_\rho + u_{\varepsilon_\varepsilon}\right) = D(t); \\ g(u_\sigma + u_\rho + u_\varepsilon) \leq 0; \end{matrix} \middle| y_{t-T_\varepsilon}\right] = 1$$

- Real-time market, at time t-Tε :
- Decision: generation u_ε
- Constraint: Must satisfy balance and operational constraints.

Risk-limited dispatch

- It ca

$$J(\pi) = \mathbb{E}\Bigg\{T_1 \sum_{k_1=0}^{N_1-1} [c^+(k_1)s_+(k_1) + c^-(k_1)s_-(k_1)]$$

$$+T_2 \sum_{k_1=0}^{N_1-1}\sum_{k_2=0}^{N_2-1} [c^+(k_1,k_2)s_+(k_1,k_2) + c^-(k_1,k_2)s_-(k_1,k_2)] + \cdots$$

$$+T_m \sum_{k_1=0}^{N_1-1}\sum_{k_2=0}^{N_2-1} \cdots \sum_{k_m=0}^{N_m-1} [c^+(k_1,\ldots,k_m)s_+(k_1,\ldots,k_m)$$

$$+c^-(k_1,\ldots,k_m)s_-(k_1,\ldots,k_m)]$$

$$+T_m \sum_{k_1=0}^{N_1-1}\sum_{k_2=0}^{N_2-1} \cdots \sum_{k_m=0}^{N_m-1} [g(d(k_1,\ldots,k_m),x(k_1,\ldots,k_m))]\Bigg\}$$

Risk-limited dispatch

$$J(\pi) = \mathbb{E}\Big\{ T_1 \sum_{k_1=0}^{N_1-1} [c^+(k_1)s_+(k_1) + c^-(k_1)s_-(k_1)]$$

$$+T_2 \sum_{k_1=0}^{N_1-1} \sum_{k_2=0}^{N_2-1} [c^+(k_1,k_2)s_+(k_1,k_2) + c^-(k_1,k_2)s_-(k_1,k_2)] + \cdots$$

$$+T_m \sum_{k_1=0}^{N_1-1} \sum_{k_2=0}^{N_2-1} \cdots \sum_{k_m=0}^{N_m-1} [c^+(k_1,\ldots,k_m)s_+(k_1,\ldots,k_m)$$

$$+c^-(k_1,\ldots,k_m)s_-(k_1,\ldots,k_m)]$$

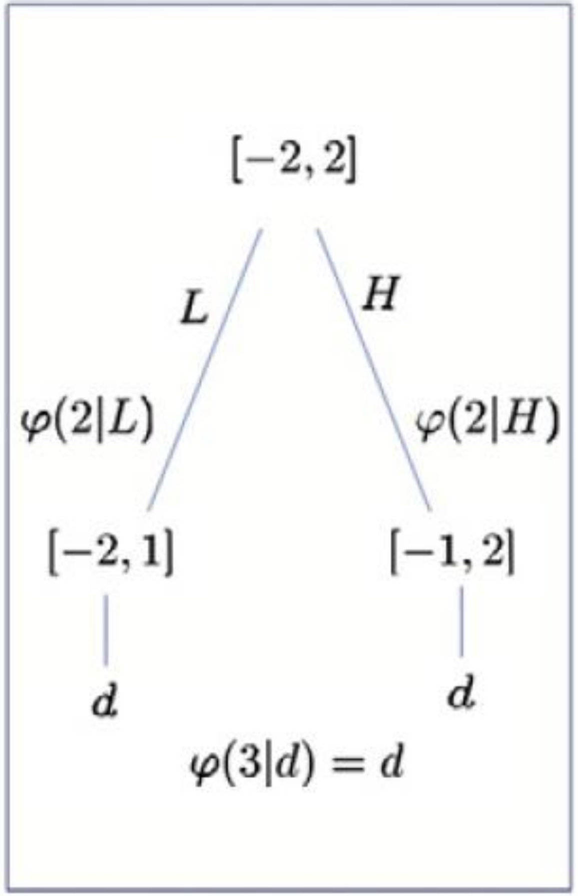
$$+T_m \sum_{k_1=0}^{N_1-1} \sum_{k_2=0}^{N_2-1} \cdots \sum_{k_m=0}^{N_m-1} [g(d(k_1,\ldots,k_m),x(k_1,\ldots,k_m))] \Big\}$$

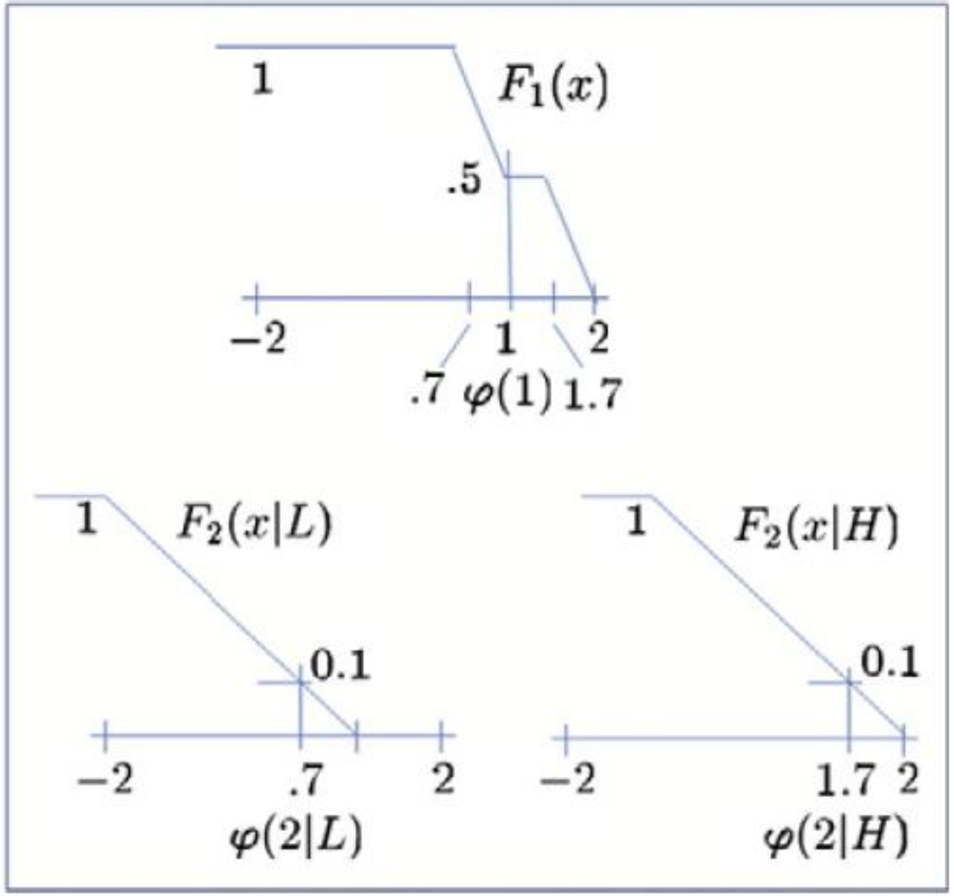
Risk function!!

Risk-limited dispatch

- It is a stochastic programming problem with m stages
- Agent (system operator) makes decisions in sequence with the available information on R.V.
- Optimal policies are solved backwards in time.
  - First: solve the last decision, given previous actions and remaining uncertainty
  - Second: solve the previous decision, given previous actions ***AND Optimal Policy for the last decision***
  - *…*
  - Last: solve the first decision, given *Optimal Policies for the decision to come*

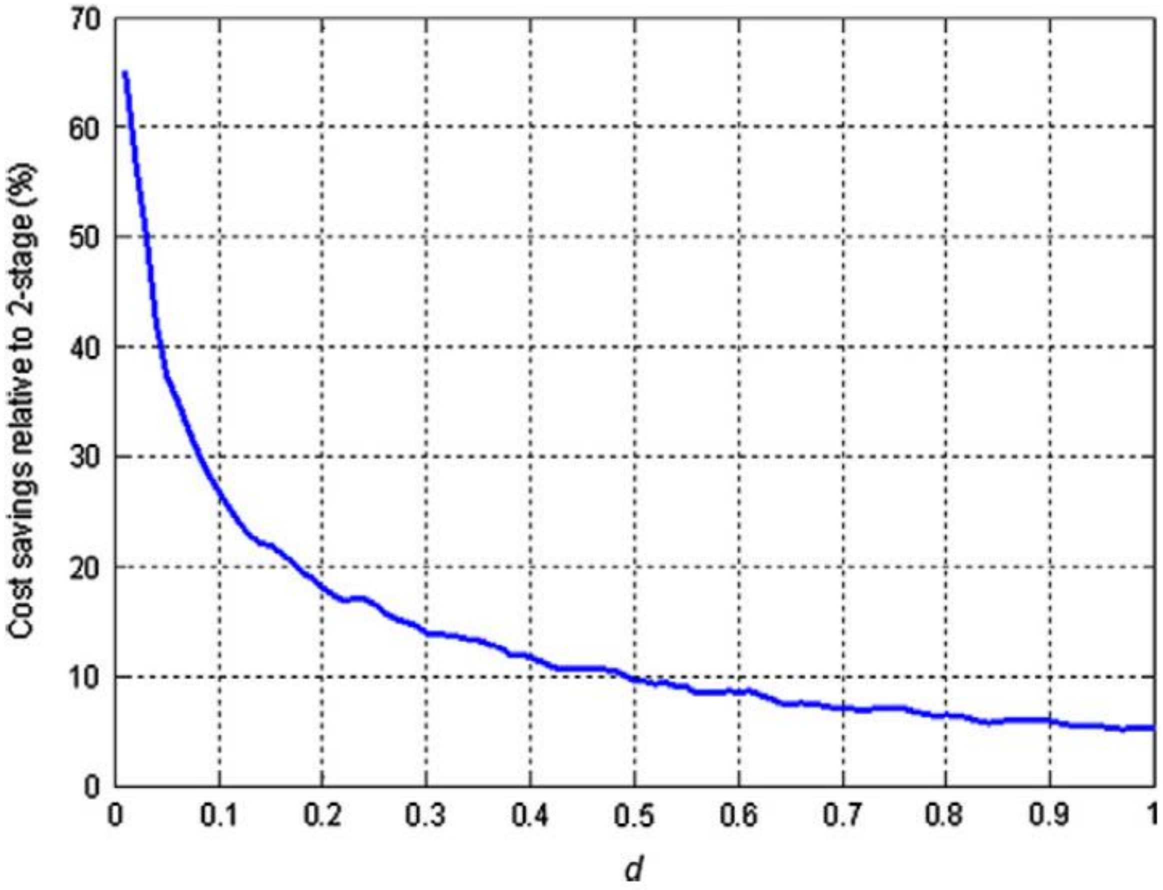
Risk-limited dispatch





- Decision tree for m=3.
- R.V. are modeled by scenarios (H,L)
- Solution is given by thesholds
- Buy or sell form

Risk-limited dispatch



- Performance comparison
- m=2 vs m=10
- d: demand level.

Bibliography

[1] Morales González, JM, Conejo, AJ, Madsen, H, Pinson, P & Zugno, M 2014, *Integrating Renewables in Electricity Markets: Operational Problems*. Springer. International Series in Operations Research and Management Science, vol. 205, DOI: 10.1007/978-1-4614-9411-9.

[2] E. Y. Bitar, R. Rajagopal, P. P. Khargonekar, K. Poolla and P. Varaiya, "Bringing Wind Energy to Market," in IEEE Transactions on Power Systems, vol. 27, no. 3, pp. 1225-1235, Aug. 2012. doi: 10.1109/TPWRS.2012.2183395.

[3] Rajagopal, R. Bitar, E., Varaiya, P., Wu, F., (2011). Risk-Limiting Dispatch for Integrating Renewable Power. International Journal of Electrical Power & Energy Systems. 44. 10.1016/j.ijepes.2012.07.048.