Optimization-based control strategies for real-time power dispatch and bidding

Alberto Bemporad

http://cse.lab.imtlucca.it/~bemporad

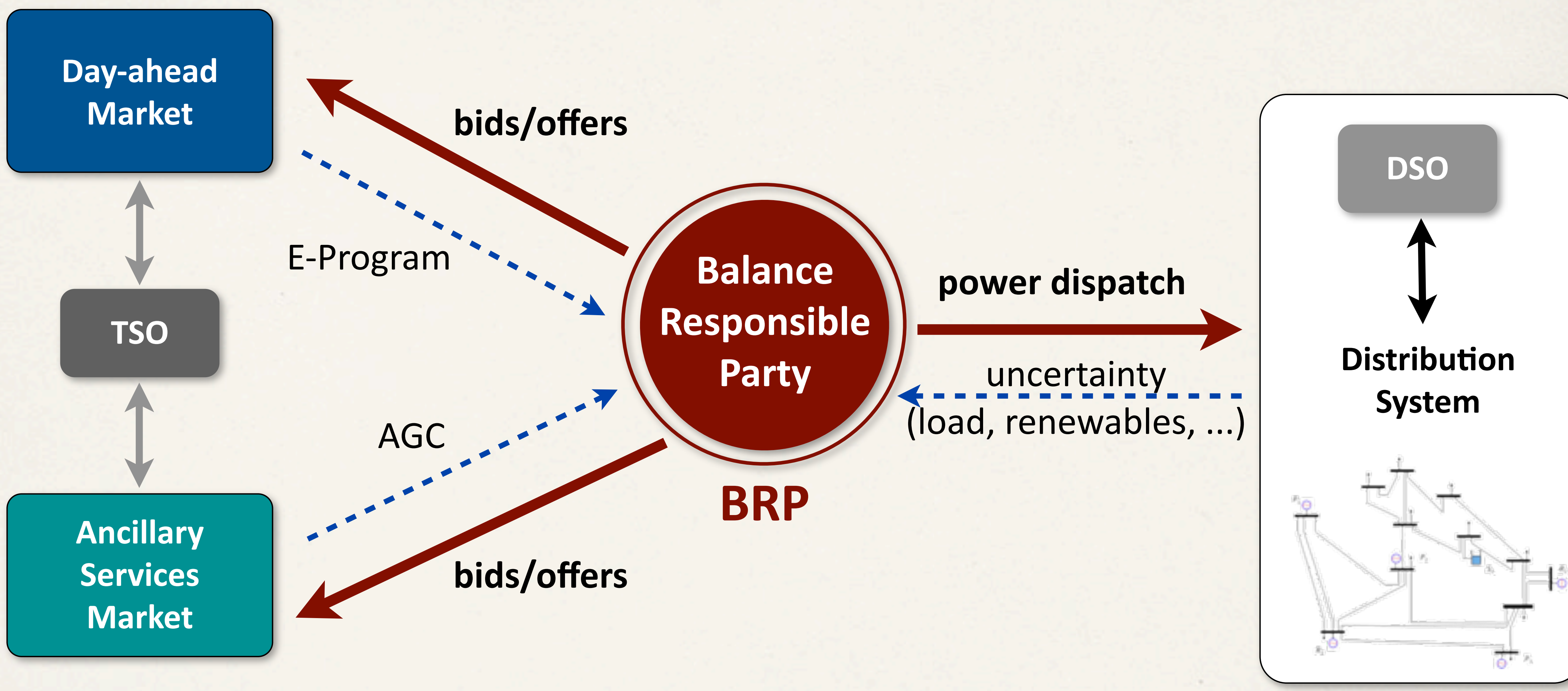
Institutions Markets Technologies
IMT
INSTITUTE FOR ADVANCED STUDIES LUCCA

DYSCO
Research Unit

Dynamical Systems, Control, and Optimization

Joint work with **D. Bernardini, P. Patrinos, L. Puglia**

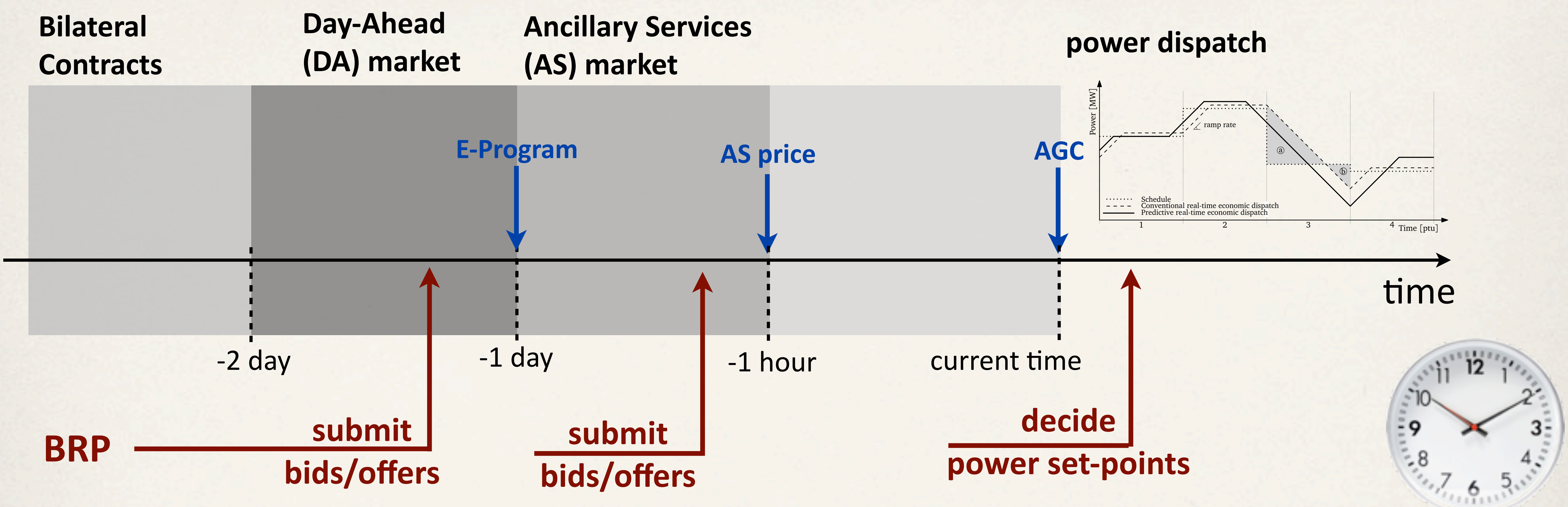
Operations of energy market players



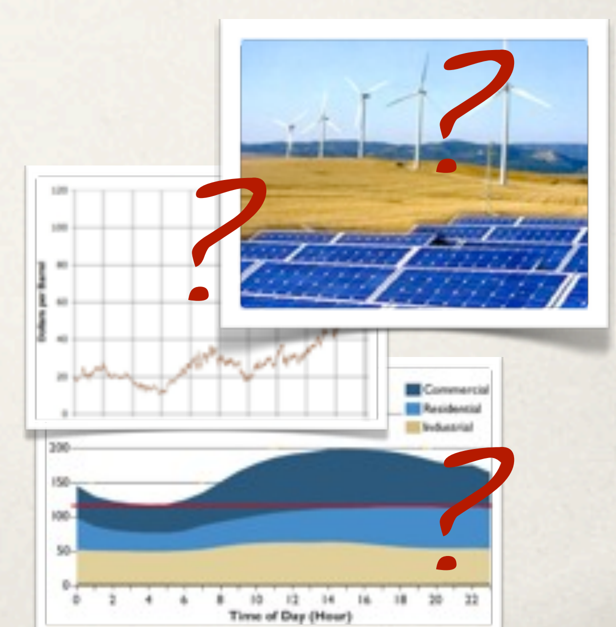
Objective: maximize BRP's profit !

(while satisfying local power demand and all grid constraints)

Operations of energy market players

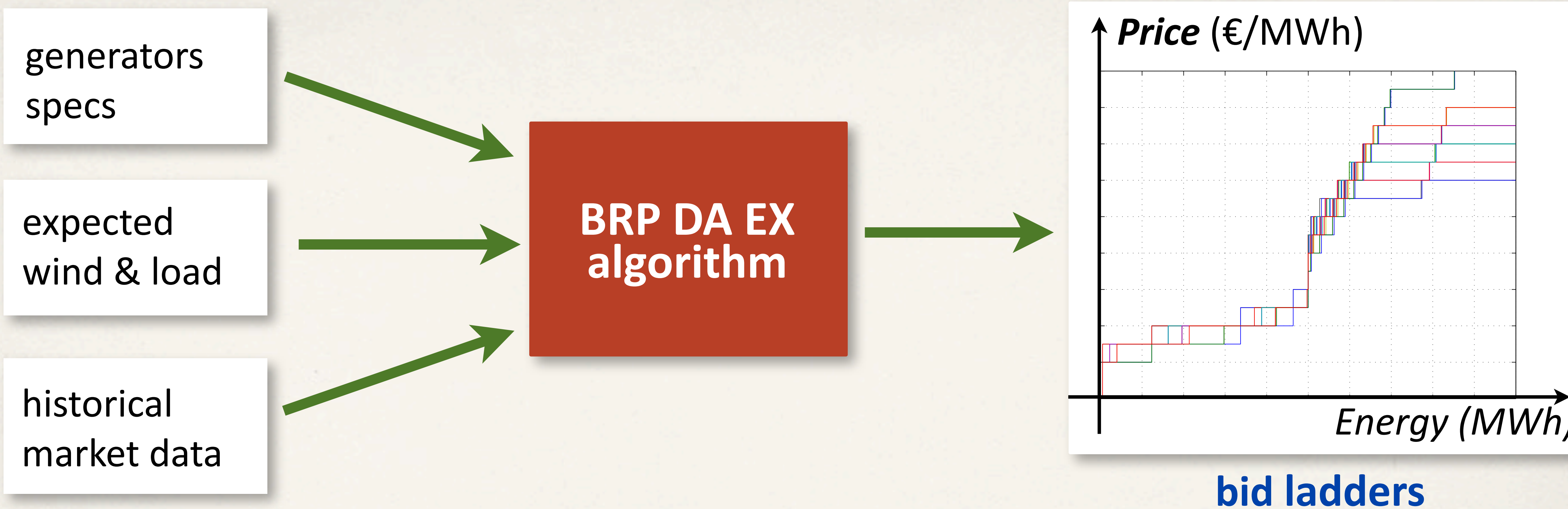


- In E-PRICE, we proposed new control strategies for solving:
  - The two bidding problems
  - The power dispatch problem



- The decision process is heavily affected by **uncertainty** (prices, load, renewables, ...)

Bidding on the Day-Ahead (EXchange) market



bid ladders

For each hour, given:

1. generator data (current power profile, min and max power, efficiency, etc.)
2. expected load and wind profiles for each hour of the following day
3. scenarios for AS prices, which are not disclosed yet (**stochastic disturbance**)

compute optimal allocation of energy on the EX market

that **maximizes profits** and **minimize imbalance risks**

Output:

- 24 bid curves (one for each hour of the following day)

Bidding on the day-ahead (DA) market

- **Price-taking point of view**: the offer has no influence on the cleared price

- **Profit**: for each hour, for each fixed price λ_{DA}, the profit is

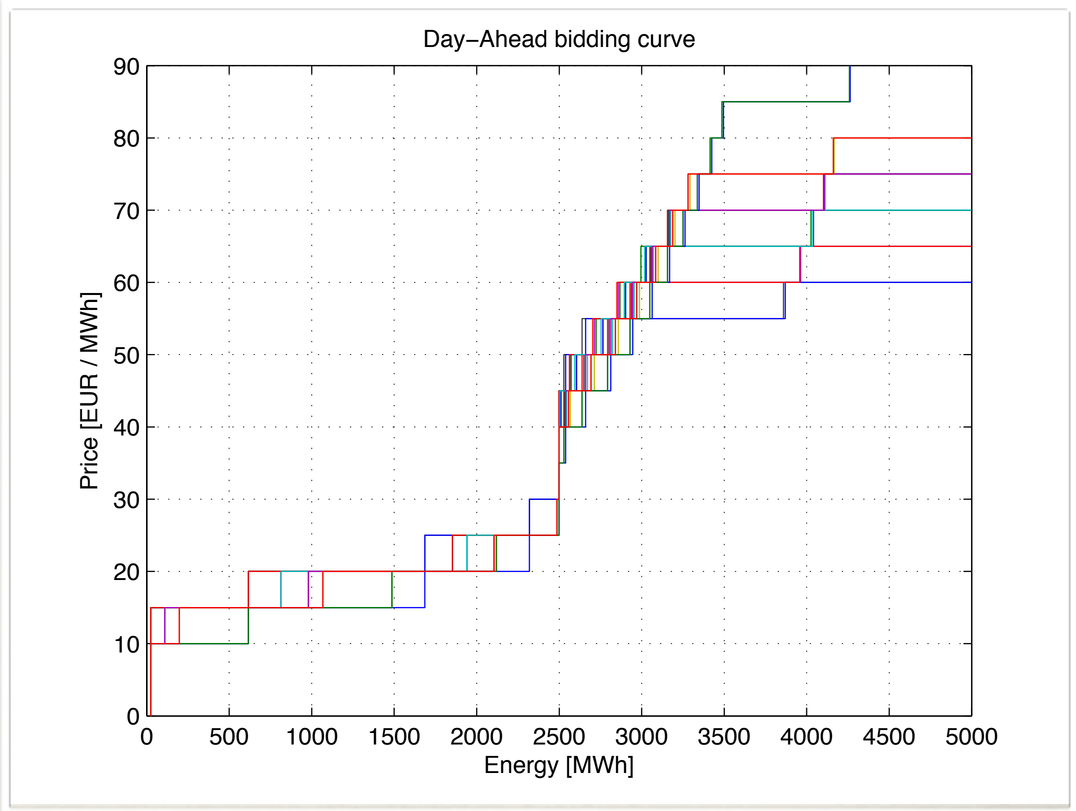
stochastic variable — decision variables

$$P = \lambda_{\mathrm{DA}} x_{\mathrm{DA}} + \lambda_{\mathrm{AS}} x_{\mathrm{AS}} - (c_2 p^2 + c_1 p + c_0)$$

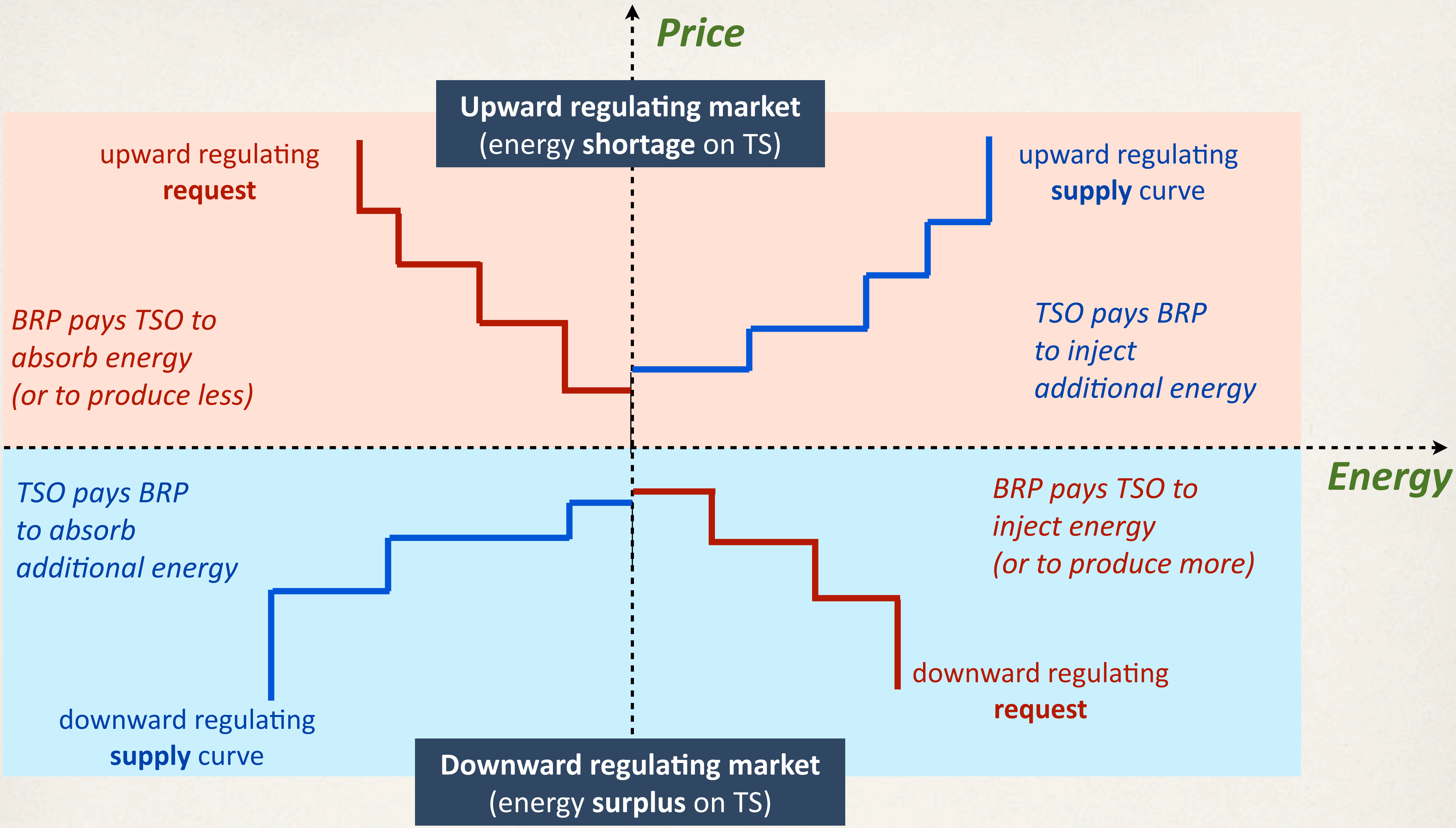
revenues from DA market — revenues from AS market — marginal costs for power generation

- **Objective**: minimize {CVaR of Profit}

- **Constraints:**
  - production limits
  - internal balancing
  - non-decreasing conditions



Bidding on AS market (double-sided market)



- **AS bidding algorithm:** for each (supply, request) price pair, **compute the best energy allocation** (considering stochastic scenarios of available wind power minus load)

Simulation results

- Economic performance metrics calculated to test the effectiveness of the E-Price market structure and algorithms

- **Dutch TN**: 7 BRPs consisting of gas/coal plants and wind farms

- Wind power forecast in E-program = actual wind power:

	Production Costs (€)	Imbalance Costs (€)	AS Profit (€)
Single-sided market	1,821,846	36,602	285,294
Double-sided market	1,824,743	16,899	366,895

- Simulation = 1 day
- Sum of all BRPs

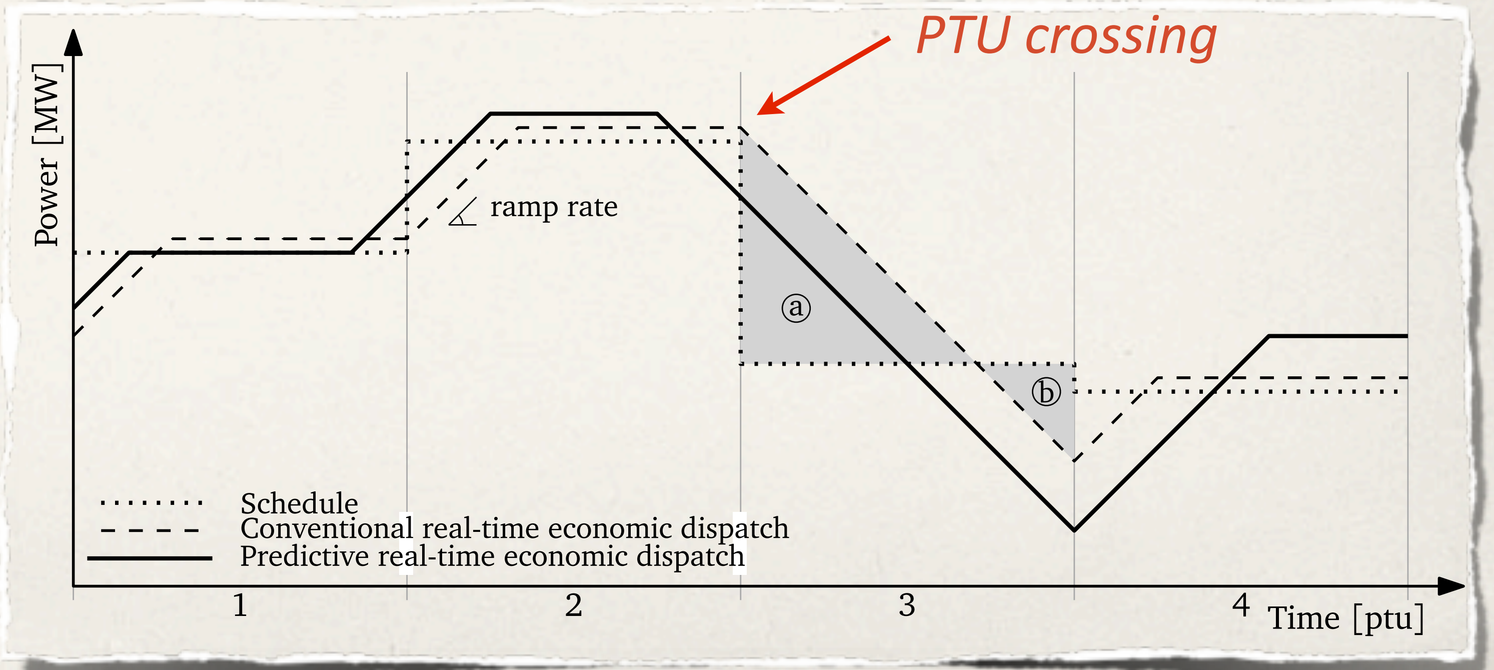
- Imprecise wind forecast (actual wind power > expected during DA bidding):

	Production Costs (€)	Imbalance Costs (€)	AS Profit (€)
Single-sided market	1,749,858	105,577	347,151
Double-sided market	1,750,263	98,024	452,491

- As creating imbalance is more expensive in the double-sided market, BRPs have higher incentives to efficiently allocate resources

Real-time power dispatch problem

- **Current practice:**
  - **On the day-ahead**: **schedule generators** and compute **power set-points** (often based on rough estimates of **uncertainty**)
  - **In real-time**: **track power set-points**
- **Cons:**
  - difficulty in handling **ramp-rate constraints**
  - difficulty in handling **PTU coupling**
  - sharp **economic optimization** needed



Real-time power dispatch control

- Control problem: **determine power set-points** for the controllable generators

- Goal #1: **Minimize generation costs**
(=use intermittent resources as much as possible)

- Goal #2: "**Economically" track the E-Program** (sometimes it may be convenient to deviate from E-Program, depending on imbalance prices)

- We consider **energy and power time scales** to decompose the problem from a temporal point of view in two layers:

  - **Energy time-scale (30-60 sec):** economic optimization to determine power and energy set-points

  - **Power time-scale (4 sec):** refine power profiles to minimize tracking error, considering detailed dynamics and constraints of the generators

Two-timescale hierarchical control solution

Upper-level control (economic optimization)

problem data
- E-Program and generators' schedule
- generation costs
- imbalance costs
- generator constraints
- estimated disturbances (wind, load, imbalance prices, AS bids...)

energy time-scale (60 sec)

TSO

E-Program, activated AS bids

energy and power set-points

wind, load, generated power

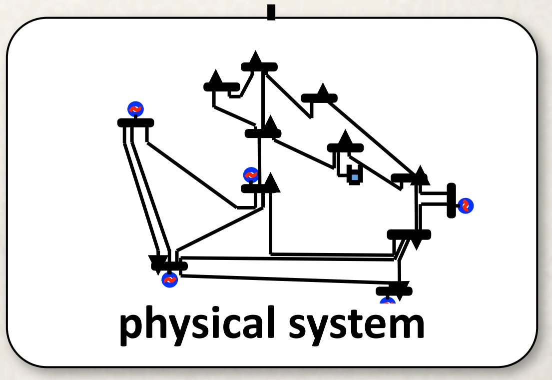
Lower-level control (tracking)

problem data
- tracking error
- detailed generator **dynamics**
- operating **constraints** on generators

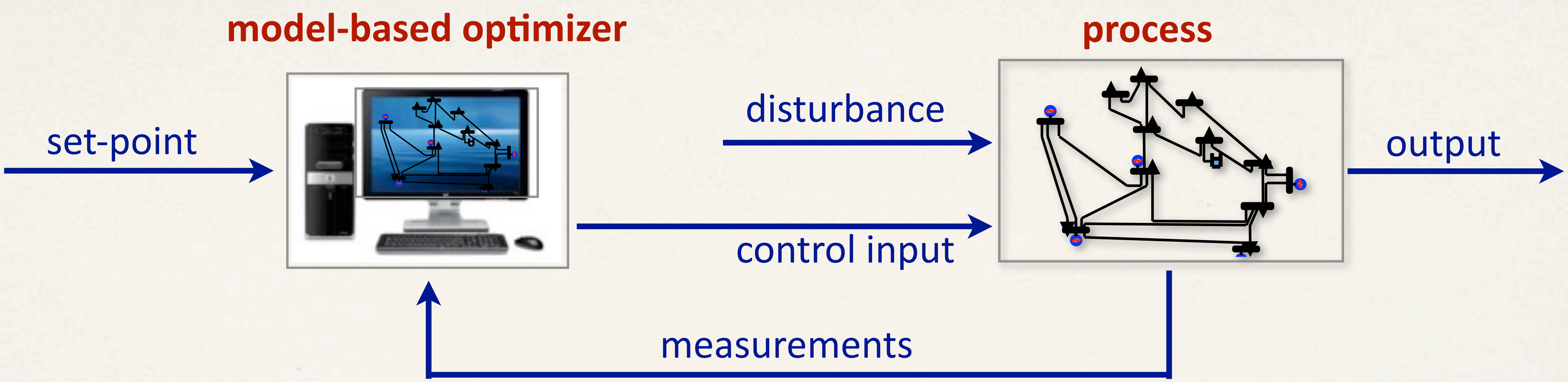
power time-scale (4 sec)

frequency deviations

real-time power set-points

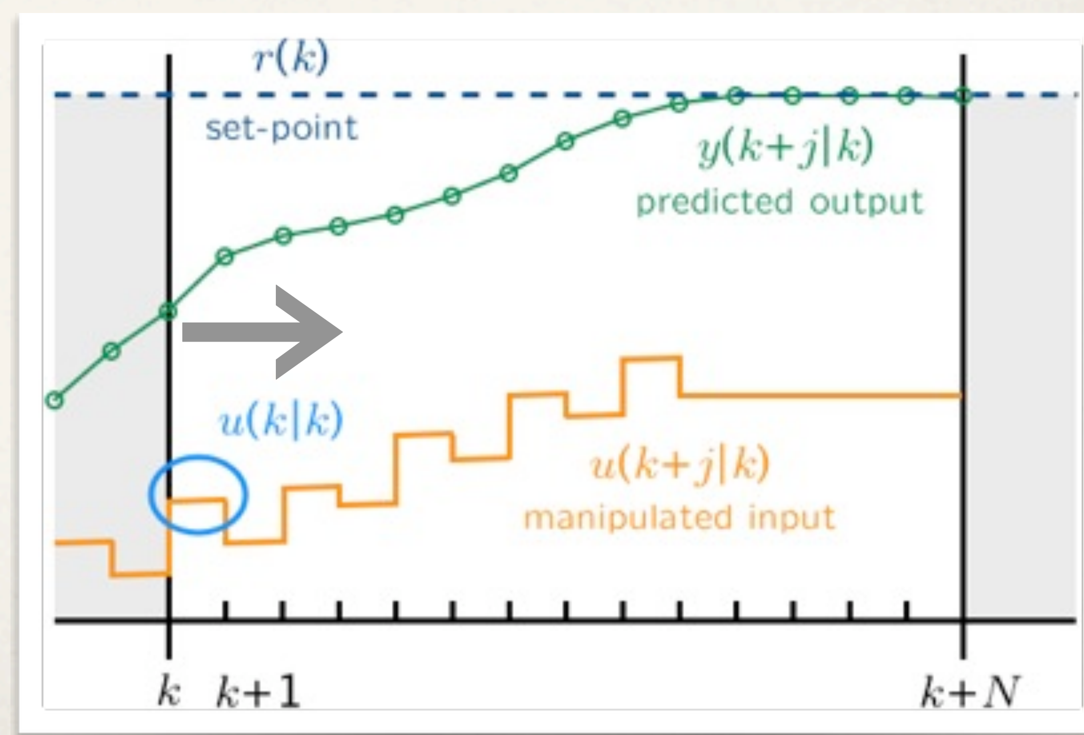


Model Predictive Control (MPC) approach



Use a dynamical model of the process to predict its future evolution and choose the “best” control signal

- **MPC strategy:**
  - At every time step k, solve an optimal control problem over a time window horizon of N steps
  - Apply the **first control move** $u(k|k)$
  - At time $k+1$, get **new measurements** and repeat the optimization



BRP model on the energy time-scale

- **Generation costs** for each of the n_p generators are modeled as convex quadratic functions of the power p

$$\ell_i^p(p^i) = a_i(p^i)^2 + b_i\bar{p}^i + c_i, \quad a_i \geqslant 0, \quad i \in \{1, \ldots, n_p\}$$

- **Energy imbalance** is defined as the difference between the energy produced by the BRP and the energy requested by the TSO at PTU n

$$\Delta e(n) = e(n) - e^{\text{final}}(n)$$

- If $\Delta(e(n)) > 0$ (*surplus*), TSO buys this energy from BRP at price λ^+_{IM}
- If $\Delta(e(n)) < 0$ (*shortage*), BRP buys this energy from TSO at price λ^-_{IM}
- The imbalance prices can be negative, but usually $\lambda^-_{\mathrm{IM}} \geq \lambda^+_{IM}$
- Hence, BRP **imbalance costs** are computed as

$$\ell_{\mathrm{IM}}(\Delta e) = \tfrac{1}{2}(\lambda^-_{IM} - \lambda^+_{IM})|\Delta e| - \tfrac{1}{2}(\lambda^-_{IM} + \lambda^+_{IM})\Delta e$$

BRP model on the power time scale

- Detailed model of **generator dynamics** is considered in the lower level
- This model consists of two parts:
  - a **fast model** for primary reserve action,

    $$p^i_{\text{fast}}(s) = \frac{\tau^i_{\text{H}} s}{\tau^i_{\text{H}} s+1} \frac{K^i}{\tau^i_{\text{L}} s+1} p^i_{\text{prim}}(s)$$

  - a **slow model** for the secondary reserve activation,

    $$p^i_{\text{slow}}(s) = \frac{e^{-T^i_{\text{delay}} s}}{\tau^i s+1}(u^i(s) + p^i_{\text{prim}}(s))$$

  - the generator power output is given by their sum, $p^i(s) = p^i_{\text{fast}}(s) + p^i_{\text{slow}}(s)$
- This can be expressed as a discrete-time linear system with 4 states and 1 input for each generator i, $i \in \{1, \ldots, n_p\}$

$$\begin{aligned} x^i(t+1) &= A^i x^i(t) + B^i u^i(t) + E^i \delta f(t) \\ y^i(t) &= C^i x^i(t) \end{aligned}$$

- The **overall BRP model** is given by aggregating all n_p generators models

Simulation results

- Consider a BRP with **10 controllable plants** and **1 wind farm**

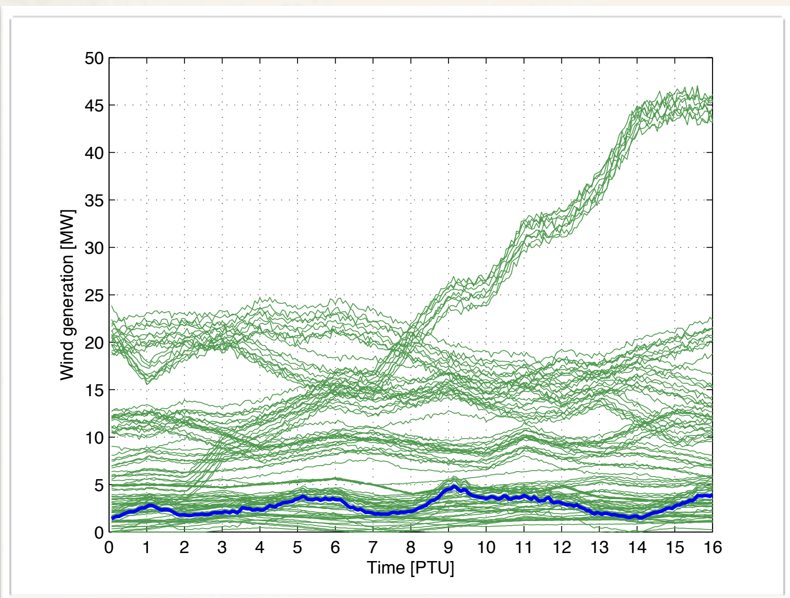
Plant ID	Fuel type	Max efficiency	Min power	Max power	Max ramp rate
#1	Gas	38%	25 MW	53 MW	3%/min
#2	Gas	42%	25 MW	64 MW	3%/min
#3	Gas	47%	133 MW	332 MW	3%/min
#4	Gas	47%	133 MW	332 MW	3%/min
#5	Gas	48%	140 MW	350 MW	3%/min
#6	Coal	39%	240 MW	602 MW	1.5%/min
#7	Gas	54%	670 MW	1675 MW	3%/min
#8	Gas	59%	280 MW	440 MW	5%/min
#9	Gas	59%	280 MW	440 MW	5%/min
#10	Coal/biomass	39%	400 MW	800 MW	1.5%/min

- Comparison against heuristic **Set-Point Tracking (SPT)**:
  - static computation of power set-points for each plant of the BRP, done on the day-ahead to track the E-Program
- **Simulation interval:** 16 PTUs (4 hours)

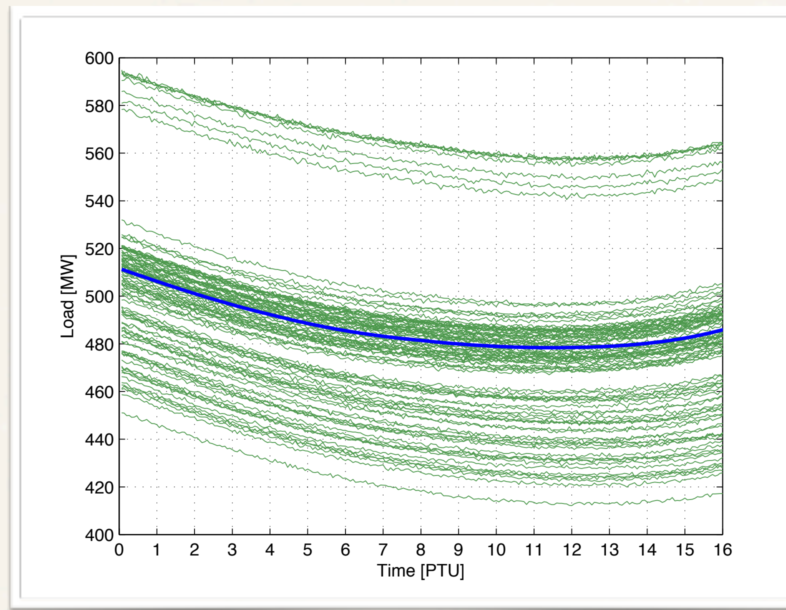
Simulation results

- **Historical data** used to carry out simulations (from TenneT and KEMA)

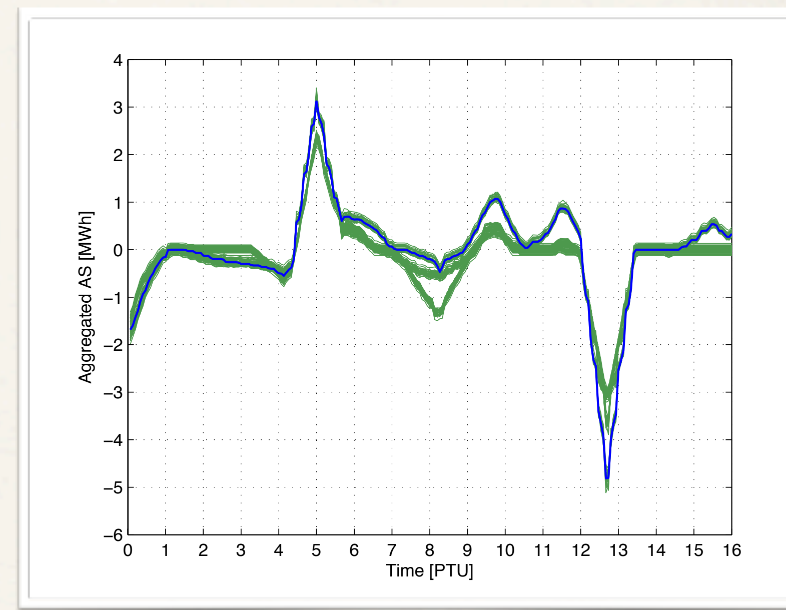
wind generation



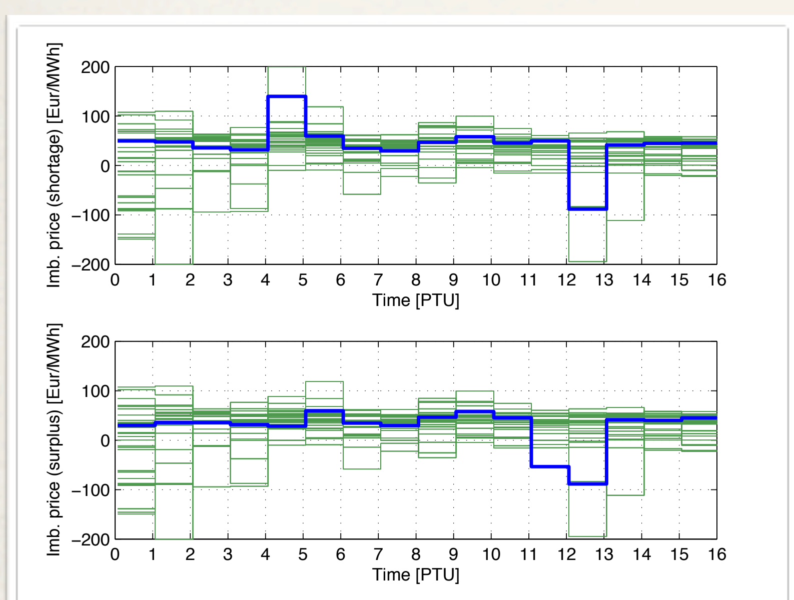
internal loads



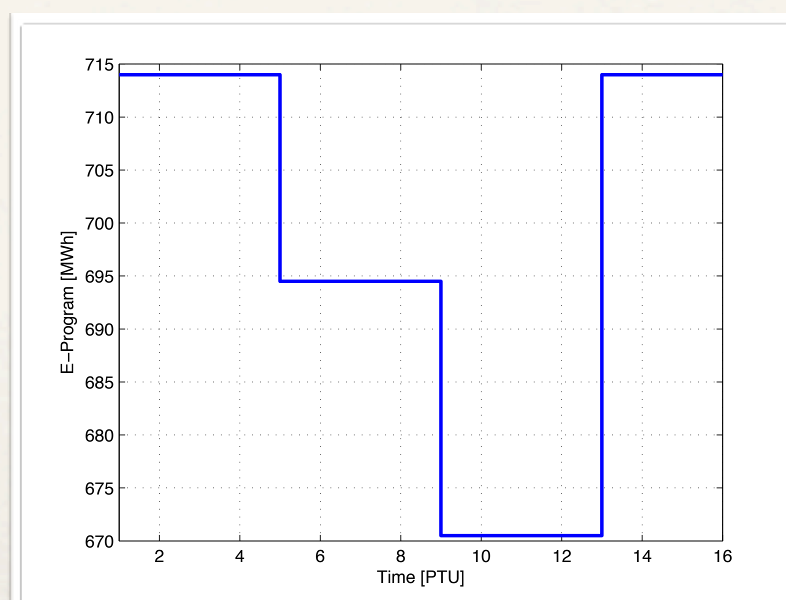
activated AS bids



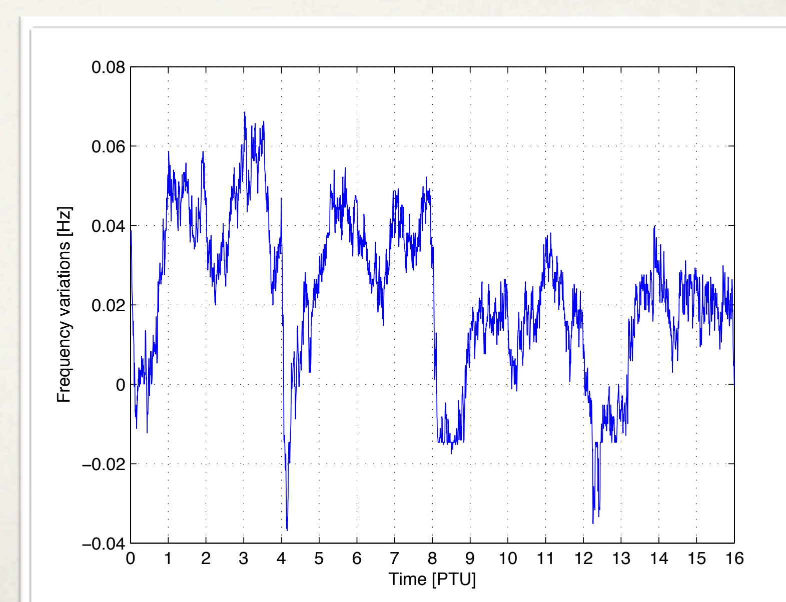
imbalance prices



E-program



frequency variations



Simulation results

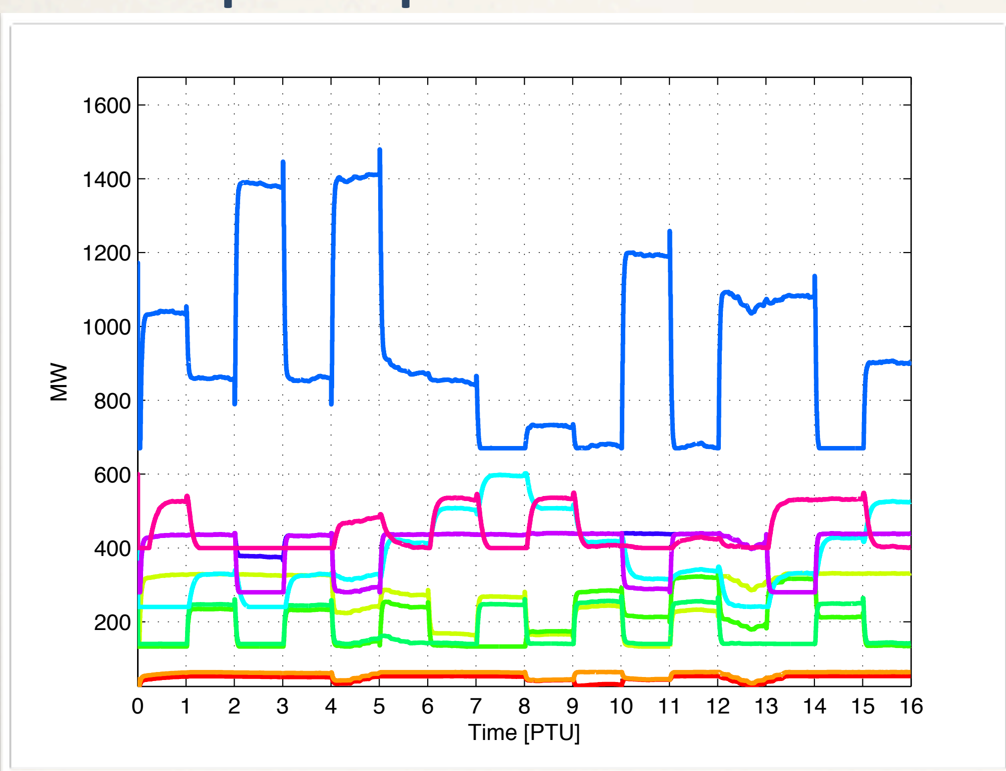
- **MPC outperforms SPT** in terms of both **constraints fulfillment** and **total cost**

CPU time on a MacBook
Upper level ≈ 250 ms
Lower level ≈ 600 ms

Controller	Generation	Imbalance	Total cost
MPC	578,674 €	-49,057 €	529,617 €
SPT	549,257 €	-3,285 €	545,973 €

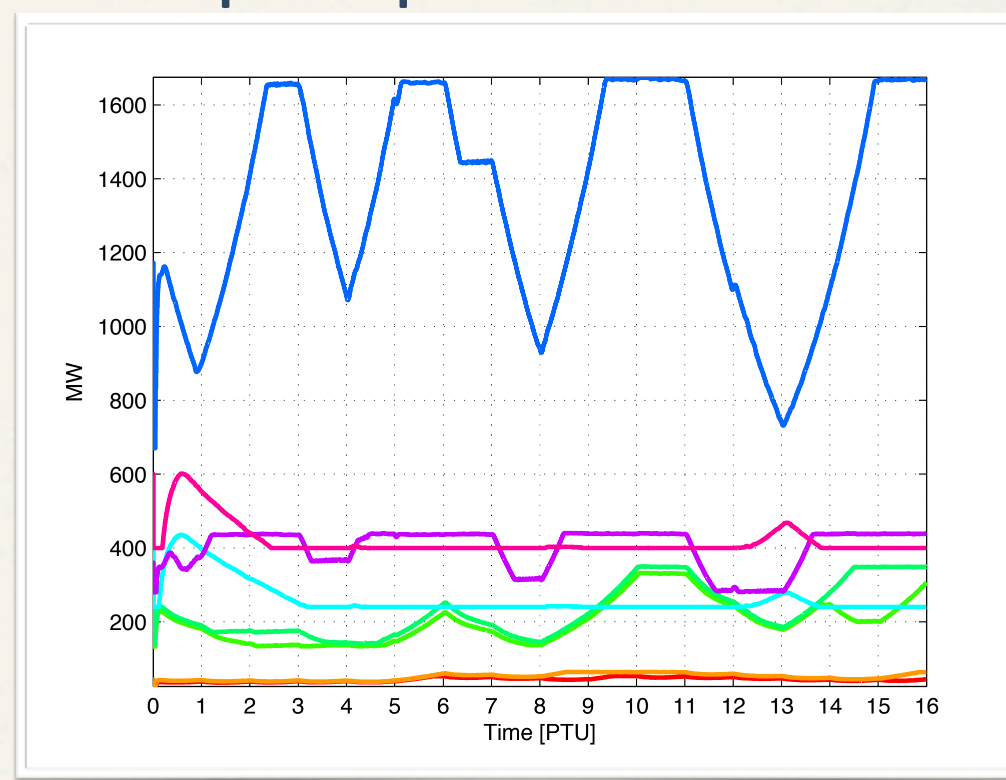
16 k€ saved
≈ 96 k€/day

power profiles with SPT



- x ramp-rate violations at PTU crossings
- x do not take advantage of imbalance prices
- x higher total cost

power profiles with MPC



- ✓ safe handling of ramp-rate constraints
- ✓ exploits imbalance prices to make profits
- ✓ fast response to disturbances

Conclusions

- New optimization-based algorithms for real-time power dispatch and optimal bidding for BRPs

- Pros and cons:

  - ✖ Need dynamical **models**, historical **data** (renewable energy, prices, demand, ...)
  - ✖ Need to **gather data in real-time** from distributed energy resources to take decisions

  - ✓ Reliable and robust solution for **integrating renewables**
  - ✓ Reduced **generation costs** and **imbalance costs**
  - ✓ **Respond promptly** to signals sent by TSO
  - ✓ Handle **ramp-rate limits,** safely eliminating discrepancies at PTU crossings
  - ✓ Handle **risk associated to bidding** in an optimal way
  - ✓ Useful decision support system for market operators

www.imtlucca.it

www.odys.it

www.e-price-project.eu