Hydro valley valuation at EDF

Currently used methods, future needs and perspectives

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Plan

- Large scale energy management: how to match supply to demand?
- River-chain valuation
  - The problem
  - How to solve?
  - Two methods: outer approximation (SDPP) and multi-modeling (sequential relaxation)
- Experiments
  - The models: Vicdessos and Dordogne
  - Basic model
  - Including one type of non-convexities: head effect
- Conclusions and perspectives

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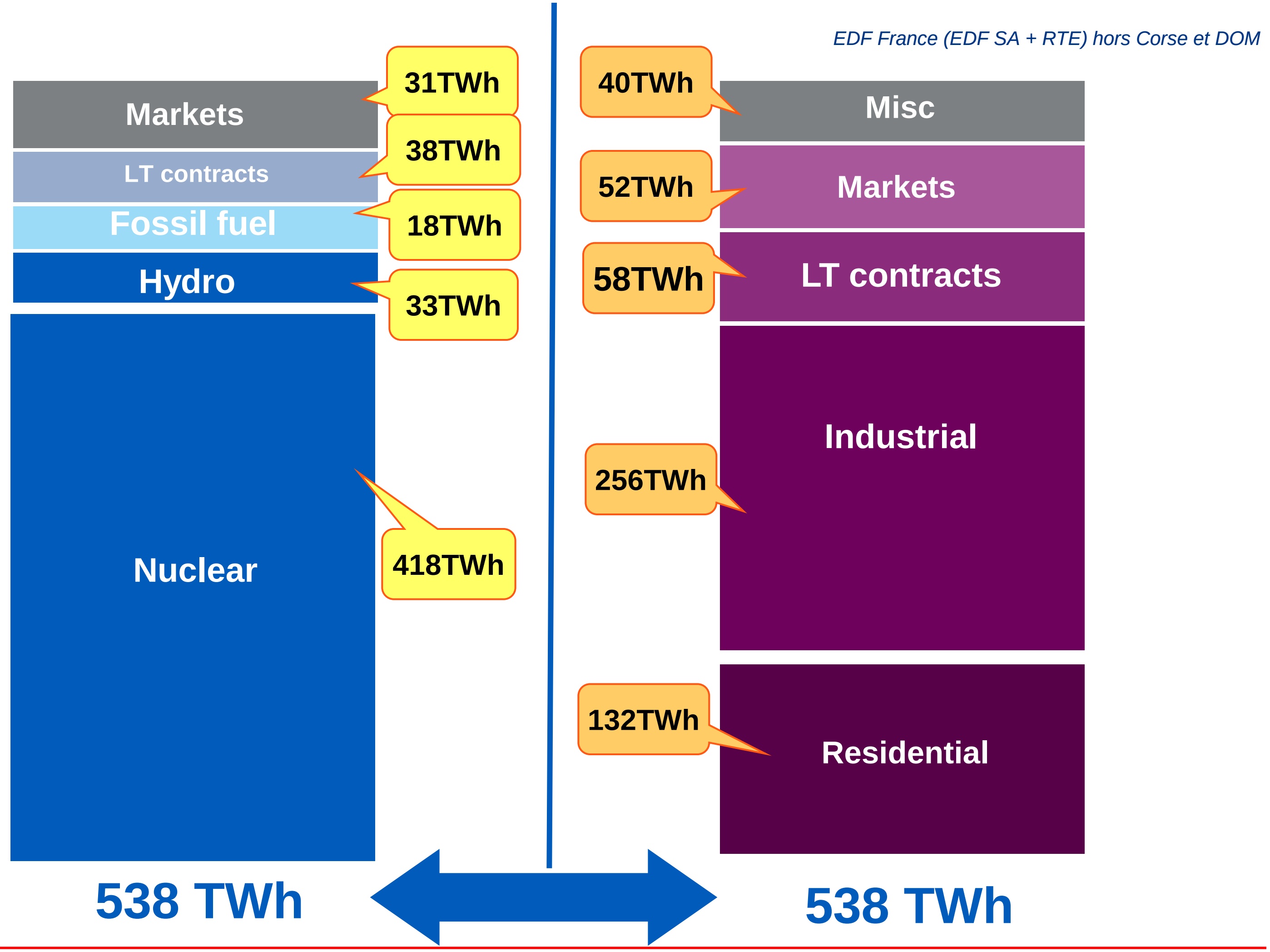
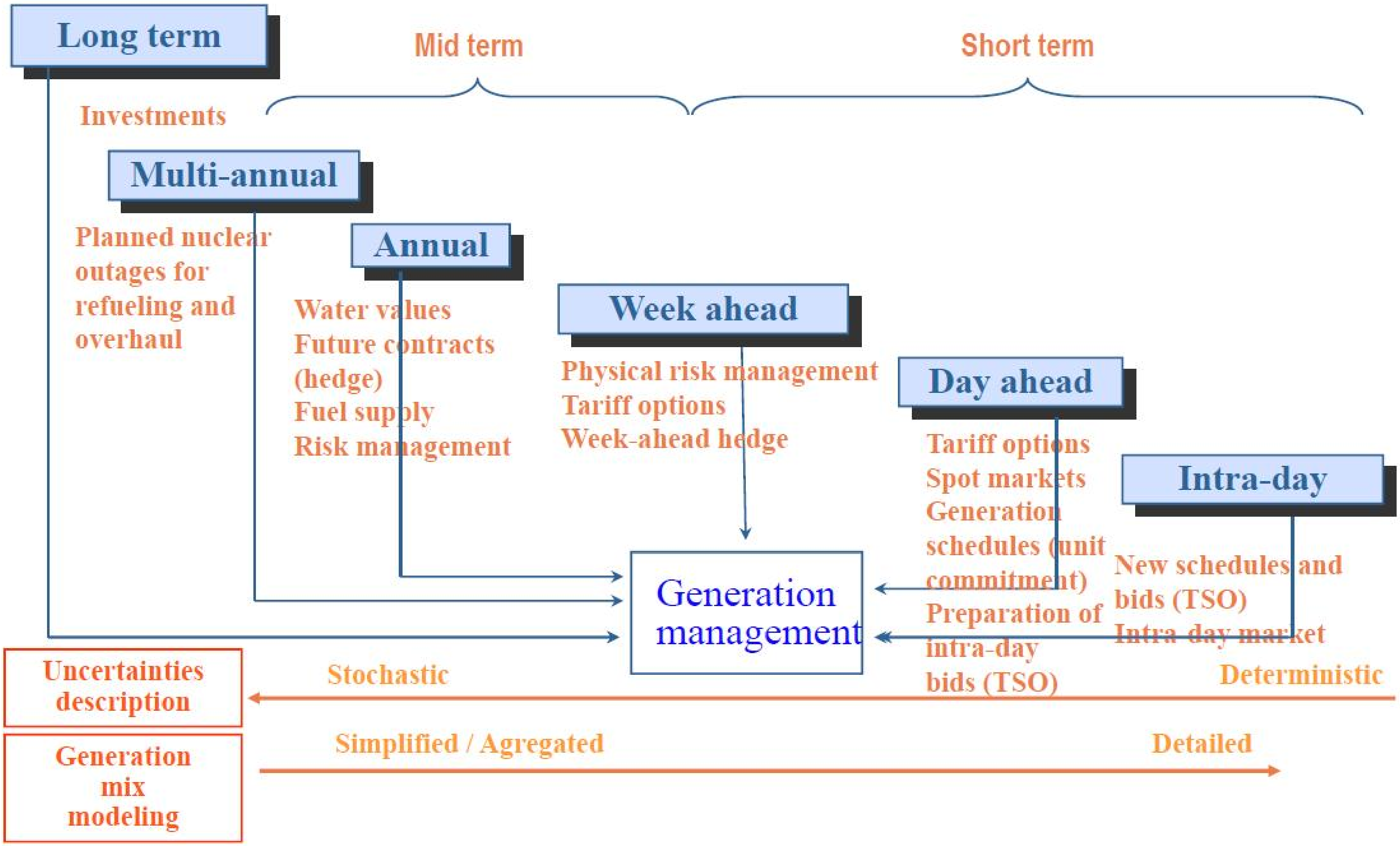
EDF generation mix

- Electricité de France is one of the European leaders in the energy field and the major electricity producer in France
- 58 nuclear units and 47 thermal units (fuel, coal and gas turbine),
- 50 hydro-valleys. Each hydro-valley is a set of interconnected reservoirs (150) and power plants (448). Water stock : 7000hm3
- 25 withdrawal options
- Other : wind, solar, biomass in significant growth

EDF portfolio



How to match supply to demand



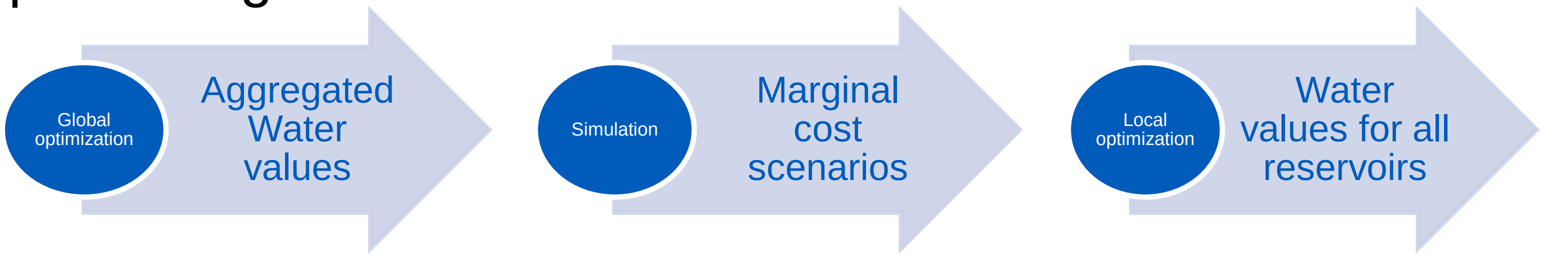
Optimization process: time decomposition

- The main goal is to make, at all times, the exact balance between electricity consumption and electricity production while minimizing the overall cost.
- Due to storage units, investments, LT contracts etc., the time horizon over which we need to minimize management cost is too large → time decomposition.

- Each optimization problem still too large and we need to separate a global aggregated optimization from a local one

Optimization process: space decomposition

- The mid-term management process focus on minimizing expected cost over 3 to 5 years.
- It is a large scale stochastic optimization problem:
  - 80 thermal units, 50 hydro-valleys. Each hydro-valley is a set of interconnected reservoirs (150) and power plants (448), 25 withdrawal options, Markets, 60x121x4 scenarios, etc.
- The hydro-valleys are aggregated into 3 big reservoirs and one withdrawal option → solve the problem using ADP
- Simulating the optimal policies of the aggregated reservoirs, we compute marginal cost scenarios → decentralize decision



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River-chain valuation: the problem

- We focus on the local optimization process.
  - Input: marginal cost scenarios.
  - Output: water values.
- The problem is to maximize the expected revenue for a hydro river-chain when releases must be made in each hour, over a couple of years.
- The specific features that we shall study are:
  - Modeling the head effects from river heights in the head ponds and tailraces that affect the efficiency of generation;
  - Provision of energy by committing a number of turbines to be running;
  - Provision of spinning reserve by committing turbines to be in synchronized condensing mode;
  - Provision of frequency-keeping services from a selection of turbines;
  - Avoidance of rough running ranges in turbine curves;
  - Uncertainty in both future price, inflows and bounds on flow rate;

River-chain valuation: how to solve ?

- Solving this problem require optimization methods that can handle non-convexities appearing in the objective (head effects) and constraints (running ranges).
- Stochastic dynamic programming looks at first glance as an appropriate method (solving transition problems as MIPs).

$$
\begin{aligned}
V_t(x, w(t)) = \quad & \max_{x(t+1),h(t)} \; p(t)^T q_t(x, f(t)) + E[V_{t+1}(x(t+1), w(t+1)], \\
& s.t. \quad x(t+1) = x - ADf(t) + w(t), \\
& \qquad 0 \leq f(t) \leq b_t(x), \qquad 0 \leq x(t+1) \leq r(t+1).
\end{aligned}
$$

- Considering large river-chains (up to 20 reservoirs), we are faced with the curse of dimensionality.
- Then, we use ADP heuristic based on multi-modeling methods (aggregation techniques) → separable policies.
- Questions:
  - Can we use outer approximation techniques?
  - What is the trade-off between non-convexities and multivariate policies?

River-chain valuation: two methods

Multi-modelling

- The multi-modeling heuristics are close to sequential relaxation techniques.
- They assume separability of the Bellman function → univariate water values.
- They can handale non-convexities → transition are "small" MIPs
- Considering a river chain with *n* reservoirs, in order to compute release policy for reservoir *I, we fix the reservoir level of the others*

Outer approximation

- The outer approximation method also called SDDP is an iterative algorithm based on dynamic programming, backward passes and simulations
- It is mainly based on the convexity of the Bellman function → the basic method can not handle non-convexities
- It gives multivariate Bellman functions → the policy of one reservoir depend on the others

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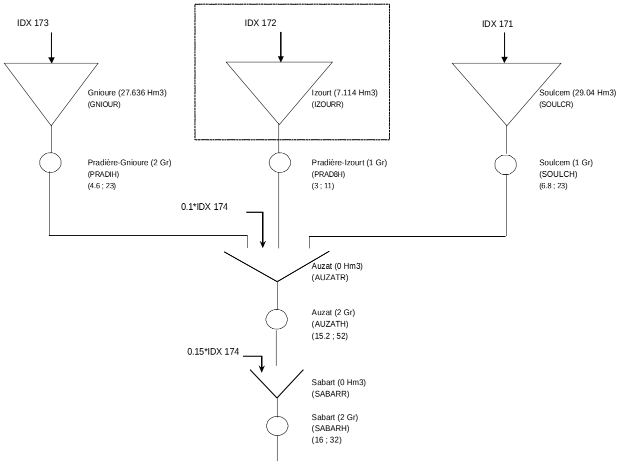
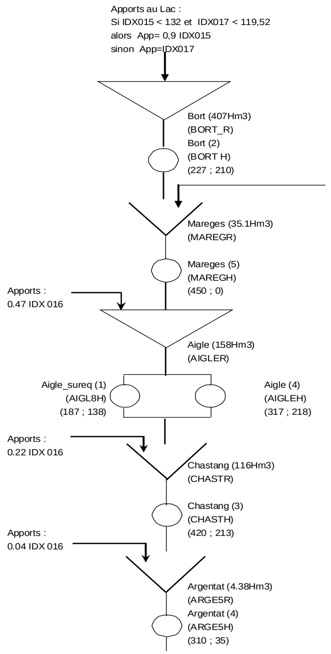
Experiments: the models

- A first river-chains where the separability of policies (Bellman functions) seems to be a relatively good assumption: $V_t(x,w(t))=\Sigma V^i_t(x^i,w^i\,(t))$
- *Vicdessos : 141 MW (0.7% of hydro power)*



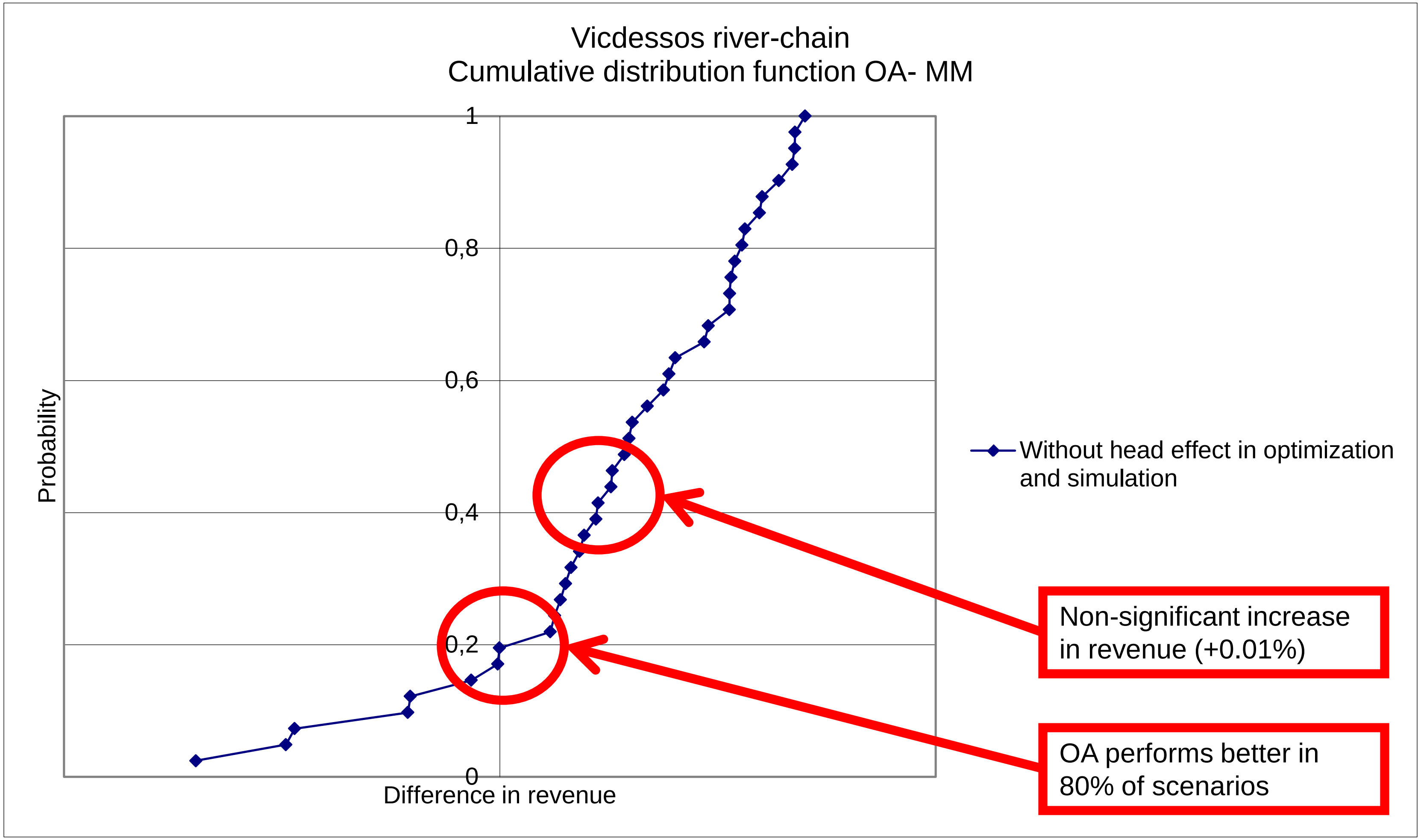
- A second one where the policy of one reservoir depends strongly on the policies of the upstream and downstream reservoirs.
- Dordogne 871 MW (4.4% of hydro power)



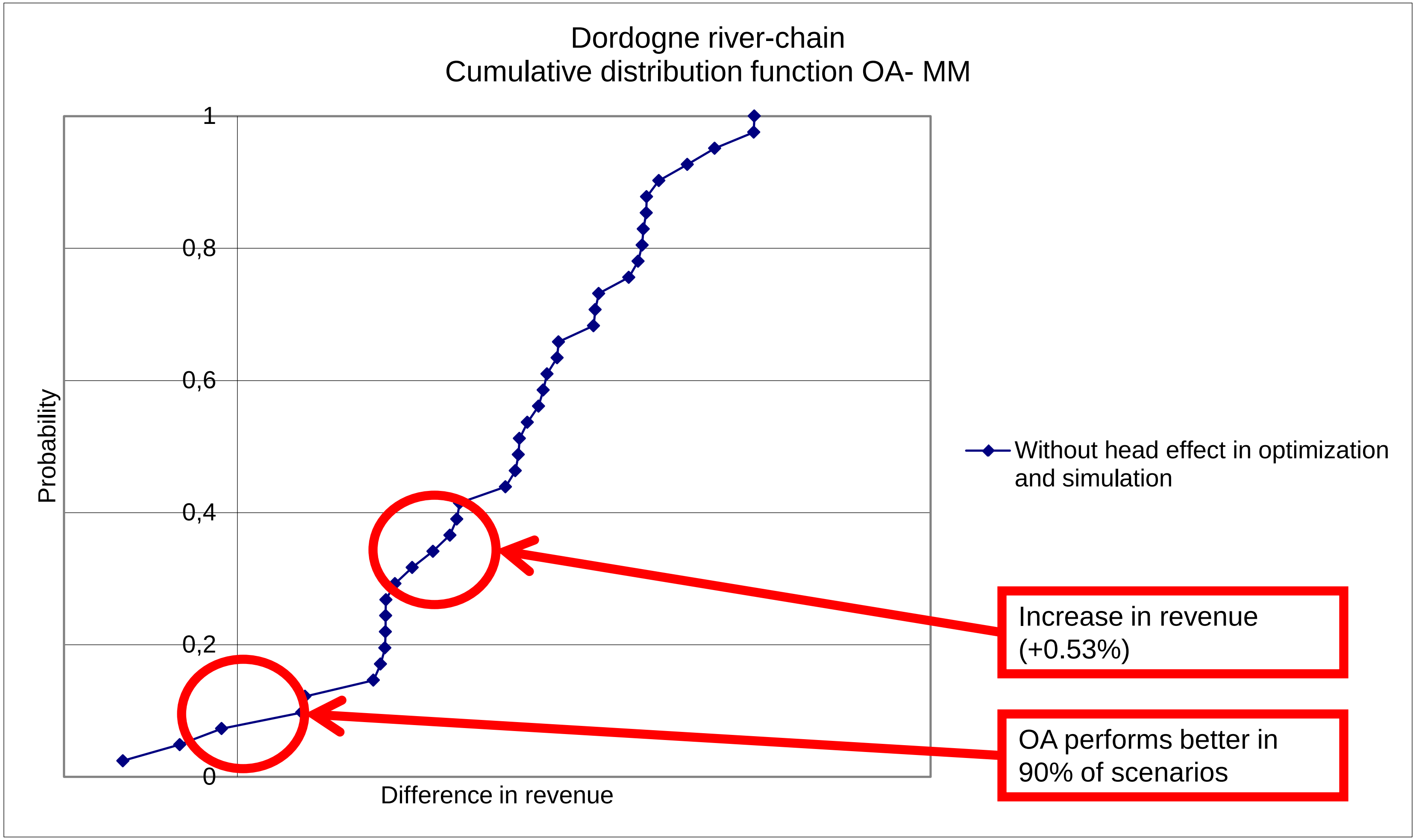
Experiments: the basic model assumptions

- Weekly stages
- No head effects
- Linear turbine curves
- Reservoir bounds are 0 and capacity
- Full plant availability
- Known price sequence, 21 per stage
- stagewise independent inflows
- 41 inflow outcomes per stage

Experiments: the basic model results (1/2)



Experiments: the basic model results (2/2)



Experiments: Including head effect (1/3)

- Power output *q* depends on net head level *h* which is the difference in headwater and tailwater heights.
- Here *v* is an effciency factor that varies with *h* and flow rate *f*.
- Assuming a fixed tailwater height, we have that *h* is a concave function of reservoir volume x, so

$$q(f,x) = \nu(f,x)\rho g h(x) f$$

- Approximate this by a piecewise linear function:

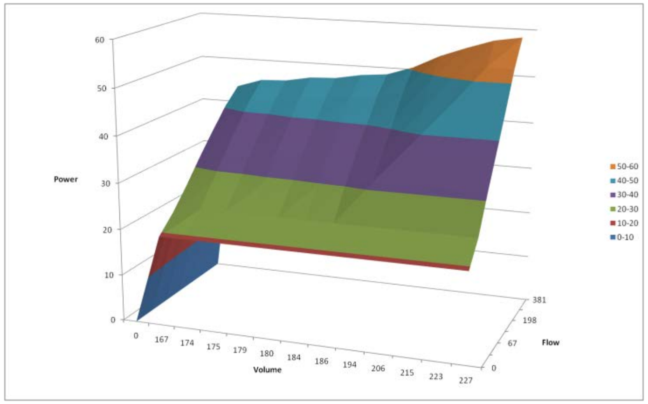
$$\begin{aligned} q(f,x) = \quad & \max_{f_1,f_2} \quad \eta_e(x) f_1 + \eta_m(x) f_2, \\ & s.t. \quad f_1 + f_2 = f, \\ & \qquad\quad f_1 \le f_e(x), \qquad f_2 \le f_m(x) - f_e(x). \end{aligned}$$

- *Where:*

$$\begin{aligned} & f_e(x) = \arg\max_f \nu(f,x), \\ & f_m(x) = \text{maximum flow rate when reservoir level is } x, \\ & \eta_e(x) = \nu(f_e(x),x)\rho g h(x), \\ & \eta_m(x) = \nu(f_m(x),x)\rho g h(x), \end{aligned}$$

Experiments: Including head effect (2/3)

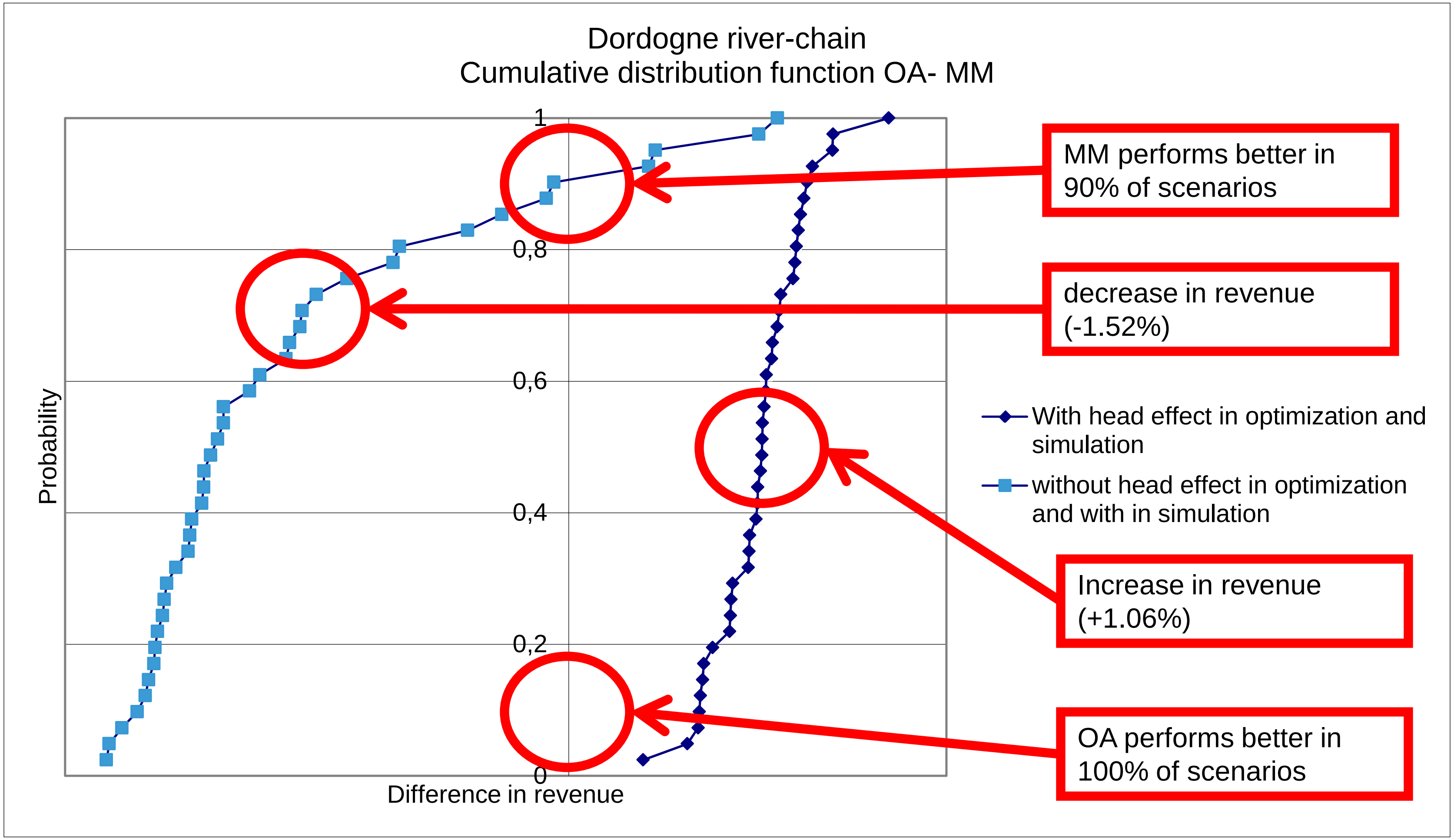
- Power output for a given flow rate assumed to increase linearly with volume stored:



- The problem to solve is concave for all given *x*. But the Bellman function is not concave → discretize *the storage level* → *approximation+increase in computation time*:

$$
\begin{aligned}
V_t(x, w(t)) = \quad & \max_{x(t+1), q, f_1, f_1, f} \quad p(t)^T q(x,t) + E[V_{t+1}(x(t+1), w(t+1))], \\
s.t. \quad & x(t+1) = x - ADf(t) + w(t), \\
& 0 \le f(t) \le b, \quad 0 \le x(t+1) \le r, \\
& q(x,t) = \eta_e(x) f_1 + \eta_m(x) f_2, \\
& f_1 + f_2 = f(t), \\
& f_1 \le f_e(x), \\
& f_2 \le f_m(x) - f_e(x),
\end{aligned}
$$

Experiments: Including head effect (3/3)



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Future works

- Outer approximation methods needs further approximation steps to handle non-convexities.
- The trade-off between the increase in computational time and the increase in revenue has to be studied.
- How to include further constraints such:
  - Provision of energy by committing a number of turbines to be running;
  - Provision of spinning reserve by committing turbines to be in synchronized condensing mode;
  - Provision of frequency-keeping services from a selection of turbines;
- How to include other non convexities such:
  - Avoidance of rough running ranges in turbine curves;
  - Uncertainty in both future price, inflows and bounds on flow rate;
- …. To be continued

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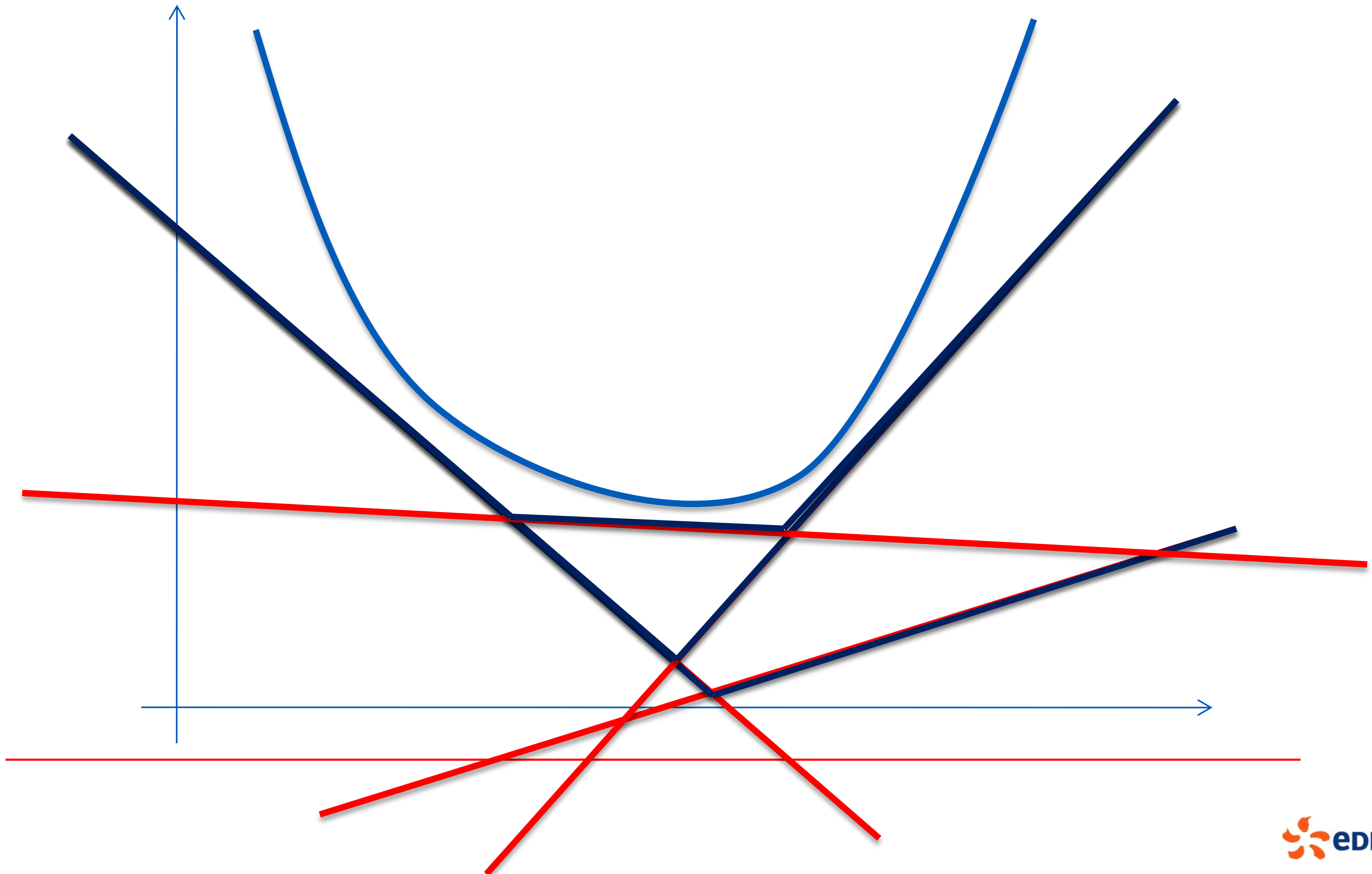
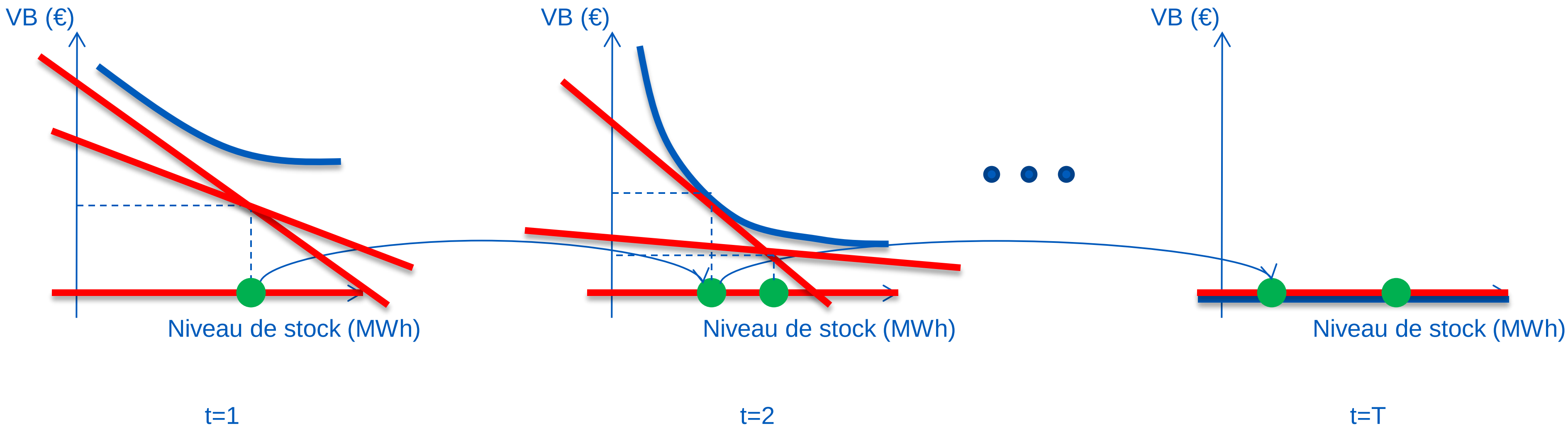
APPENDIX

River-chain valuation: outer approximation (2/4)

- A convex function can be approximated by the superior envelop of affine functions



River-chain valuation: outer approximation (3/4)



We need to approximate the real Bellman function / water value

We start with given water values (nill ?)

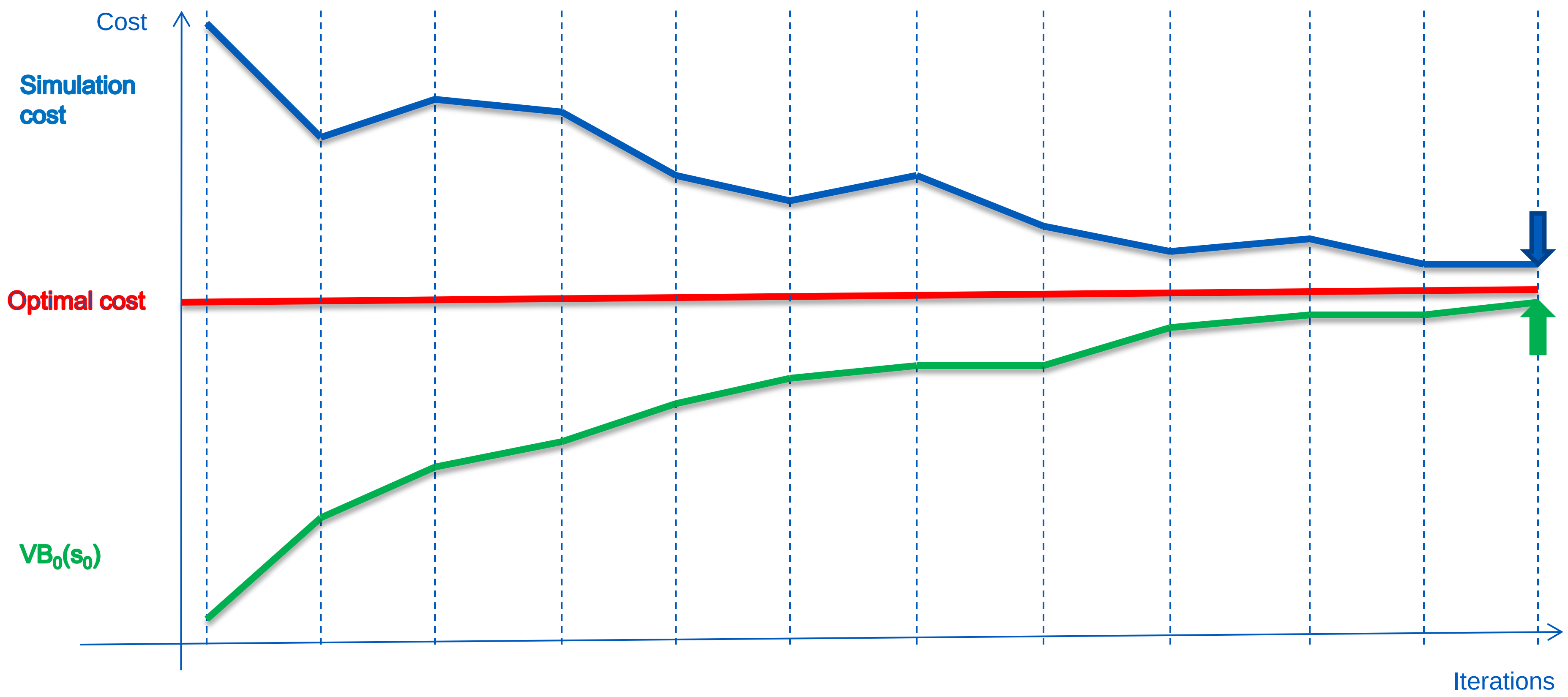
We simulate 1 (or several) scenarios → reservoirs levels trajectories

We compute the water values and Bellman functions on the obtained trajectories

We re-simulate to obtain new trajectories

We iterate this process

River-chain valuation: outer approximation (4/4)



River-chain valuation: the model

- We consider a river-chain represented by a network of *n* nodes (reservoirs and junctions) and *m* arcs (canals or river reaches). The topology of the network can be represented by the *n x m* incidence matrix *A*, where:

$$a_{ij} = \begin{cases} 1, \text{if node } i \text{ is the tail of arc } j, \\ -1, \text{if node } i \text{ is the head of arc } j, \\ 0, \text{otherwise.} \end{cases}$$

- Let *x(t)* denotes a vector of reservoir storages in each node at the beginning of each week.
- Let *w(t)* denotes a vector of reservoir inflows in each node at the beginning of each week.
- Let *h(t)* denotes a vector of flow rates in the arcs at each week.
- Let *p(t)* denotes a vector of prices in each arc at the beginning of each week. These prices are adjusted to account of converting factors η_j.
- Each week is split into $K=21$ blocks each of duration d_k.

$$D = \begin{bmatrix} d_1 & \cdots & d_K & 0 & \cdots & 0 & \cdots & \cdots & 0 & \cdots & 0 \\ 0 & \cdots & 0 & d_1 & \cdots & d_K & \cdots & \cdots & \vdots & & \vdots \\ \vdots & & & & & & \ddots & \ddots & 0 & \cdots & 0 \\ 0 & \cdots & 0 & \cdots & & & \cdots & 0 & d_1 & \cdots & d_K \end{bmatrix}$$

- The total quantity of flow through arc *j* in week *t* is *Dh(t)*, and the revenue earned is $p(t)^T h(t)$, where component $K(j-1)+k$ of *p(t)* now equals the electricity price $\pi_k(t)$ (€/MWh) in block *k* in week *t* multiplied by both d_k and η_j: $p_{K(j-1)+k}(t) = \pi_k(t)\, d_k\, \eta_j$

River-chain valuation: the model

- The hydro-electric river-chain problem we wish to solve seeks to construct a policy for generating electricity from the river-chain so as to maximize the expected revenue.

$$\begin{aligned} V_t(x, w(t)) = \quad & \max \quad p(t)^T h(t) + E[V_{t+1}(x(t+1), w(t+1)], \\ & s.t. \quad x(t+1) = x - ADh(t) + w(t), \\ & \qquad 0 \le h(t) \le b, \quad 0 \le x(t+1) \le r. \end{aligned}$$

- The relationship between conversion factor and head is expressed using a finite set of hydro production functions that depend on reservoir level *x*. Each production function is modeled using two linear pieces defined by the most efficient flow rate h_e and the maximum flow rate h_m, both of which depend on *x*.
- When the reservoir volume is *x*, the power generated by flow rate *h* is:

$$\begin{aligned} E(h, x) = \quad & \max_{h_1, h_2} \quad \eta_e(x) h_1 + \eta_m(x) h_2, \\ & s.t. \quad h_1 + h_2 = h, \\ & \qquad h_1 \le h_e(x), \quad h_2 \le h_m(x) - h_e(x). \end{aligned}$$