Integrated day-ahead and intraday self-schedule bidding for energy storages using approximate dynamic programming

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GOR Workshop, Bochum

October 2020

UNIVERSITÄT DUISBURG ESSEN
Open-Minded

Agenda

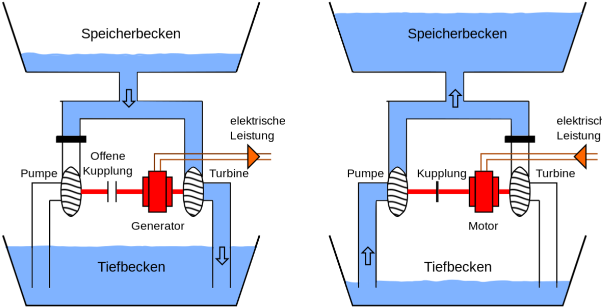
i) Storage and market setting
ii) Dynamic program
iii) Numerical study
iv) Summary

Energy storage

Consider storage with following properties:

- Capacity $R_{\max}$
- Minimum and maximum power x^{pump}_{min}, x^{pump}_{max}, $x^{turbine}_{min}$, $x^{turbine}_{max}$
- Efficiencies η^{pump}, $\eta^{turbine}$
- Start-up cost c^{pump}_{su}, $c^{turbine}_{su}$
- Ramping time Δt^{ramp}

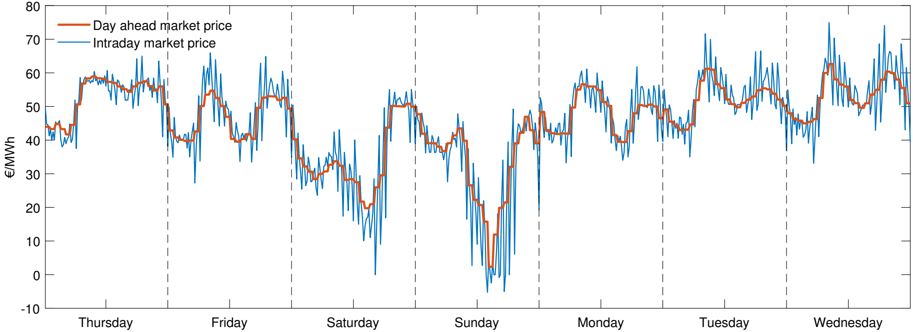
e.g. hydro pump storage:



Considered German electricity markets

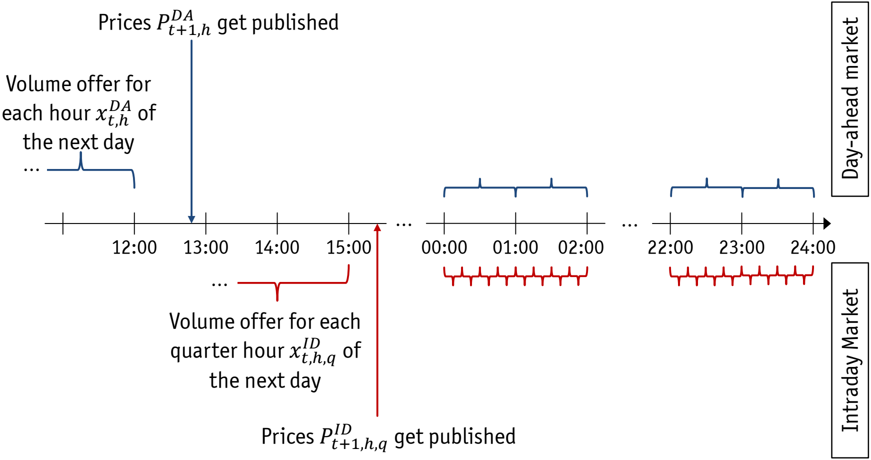
DA: PCR Day-Ahead Auction (daily at 12:00, hourly products)

ID: EPEX Intraday Auction (daily at 15:00, quarterhourly products)



- Ignore all other markets (OTC, Intraday continuous, EXAA, derivative markets, etc.), and complex/smart/block bids

Information Flow



- time index (day, hour, quarterhourly) $\equiv (t, h, q)$

Dynamic Programming

Ingridients

- Exogenous information (price processes)
- State Variable
- Action Variable
- Contribution Function
- Transition function

⇒ Policy

Exogenous Information: Price Processes

DA day-ahead auction price process:

$$P^{DA}_{t+1,h} = \beta^{DA}_{0,h} + \sum_{j=1}^{7} \beta^{DA}_{j,h} DoW^{j}_{t+1} + \sum_{j=1}^{7}\sum_{k=0}^{23} \beta^{DA}_{j,k,h} P^{DA}_{t+1-j,k} + \epsilon^{DA}_{t+1,h} \forall h \in \{0, \cdots, 23\}$$

$$\epsilon^{DA}_{t+1} = \left(\epsilon^{DA}_{t+1,0}, \cdots, \epsilon^{DA}_{t+1,23}\right) \sim N\left(0, \Sigma^{DA}\right),$$

ID intraday opening auction price process:

$$P^{ID}_{t+1,h,q} = \beta^{ID}_{0,h,q} + \sum_{j=1}^{7} \beta^{ID}_{j,h,q} DoW^{j}_{t+1} + \sum_{j=0}^{7}\sum_{k=0}^{23} \beta^{ID}_{j,k,h,q} P^{DA}_{t+1-j,k}$$

$$+ \sum_{j=1}^{7}\sum_{k=0}^{23}\sum_{m=0}^{3} \beta^{ID}_{j,k,m,h,q} P^{ID}_{t-j,k,m} + \epsilon^{ID}_{t+1,h,q} \forall h \in \{0, \cdots, 23\}, q \in \{0, \cdots, 3\}$$

$$\epsilon^{ID}_{t} = \left(\epsilon^{ID}_{t,0,0}, \cdots, \epsilon^{ID}_{t,23,3}\right) \sim N\left(0, \Sigma^{ID}\right)$$

- High-dimensional regression model, trained by CV-lasso
- Depends on past prices (also cross-products) and weekday

State Variable

- State S_t^{DA} just before day-ahead market decision x_t^{DA}:

$$S_t^{DA} = \left(R_t^{start}, x_t^{start}, P_{t-6}^{DA}, \cdots P_t^{DA}, P_{t-6}^{ID}, \cdots, P_t^{ID}\right) = \left(R_t^{start}, x_t^{start}, P_t^{history}\right) \tag{1}$$

- State S_t^{ID} just before intraday market decision x_t^{ID} and day-ahead market prices P_{t+1}^{DA}:

$$S_t^{ID} = \left(S_t^{DA}, x_t^{DA}, P_{t+1}^{DA}\right) \tag{2}$$

Action variable for DA and ID

- DA action:

$x_t^{DA} = \left(x_{t,0}^{DA}, \cdots, x_{t,23}^{DA}\right)$ s.t. for all $h \in \{0, 1, \cdots, 23\}$:

i) (no physical short-selling / speculation) $x_{t,h}^{DA} \in \left[-x_{max}^{turbine}, x_{max}^{pump}\right]$

Action variable for DA and ID

- DA action:

$x_t^{DA} = (x_{t,0}^{DA}, \cdots, x_{t,23}^{DA})$ s.t. for all $h \in \{0, 1, \cdots, 23\}$:

i) (no physical short-selling / speculation) $x_{t,h}^{DA} \in \left[-x_{max}^{turbine}, x_{max}^{pump}\right]$

- ID action:

$x_t^{ID} = (x_{t,0,0}^{ID}, \cdots, x_{t,23,3}^{ID})$ s.t. for all $q \in \{0, 1, 2, 3\}$ and $h \in \{0, \cdots, 23\}$:

ii) (traded vol. = stored - generated energy) $x_{t,h}^{DA} + x_{t,h,q}^{ID} = x_{t,h,q}^{pump} - x_{t,h,q}^{turbine}$

iii) (binary decisions) $y_{t,h,q}^{pump} = 1\{x_{t,h,q} > 0\}, y_{t,h,q}^{turbine} = 1\{x_{t,h,q} < 0\} \in \{0, 1\}$

iv) (feasible region for pumping power) $x_{min}^{pump} y_{t,h,q}^{pump} \leq x_{t,h,q}^{pump} \leq x_{max}^{pump} y_{t,h,q}^{pump}$

v) (feasible region for power generation)

$x_{min}^{turbine} y_{t,h,q}^{turbine} \leq x_{t,h,q}^{turbine} \leq x_{max}^{turbine} y_{t,h,q}^{turbine}$

vi) (either pump or generate) $y_{t,h,q}^{pump} + y_{t,h,q}^{turbine} \leq 1$

vii) (storage level constraint) $R_{t,h,q} \in [0, R_{max}]$

viii) (new storage level) $R_{t,h,q} =$

$$R_{t,h,q-1} + \eta^{pump} \left(\Delta t^{ID} x_{t,h,q}^{pump} - \frac{\Delta t^{ramp}}{2} \Delta x_{t,h,q}^{pump,up} + \frac{\Delta t^{ramp}}{2} \Delta x_{t,h,q}^{pump,down}\right) - \frac{1}{\eta^{turbine}} \left(\Delta t^{ID} x_{t,h,q}^{turbine} - \frac{\Delta t^{ramp}}{2} \Delta x_{t,h,q}^{turbine,up} + \frac{\Delta t^{ramp}}{2} \Delta x_{t,h,q}^{turbine,down}\right)$$

Action variable for DA and ID (continued)

ix) (ramping pump to get $x^{pump}_{t,h,q}$)

$\Delta x^{pump,up}_{t,h,q} - \Delta x^{pump,down}_{t,h,q} = x^{pump}_{t,h,q} - x^{pump}_{t,h,q-1}$

x) (ramping turb. to get $x^{turbine}_{t,h,q}$)

$\Delta x^{turbine,up}_{t,h,q} - \Delta x^{turbine,down}_{t,h,q} = x^{turbine}_{t,h,q} - x^{turbine}_{t,h,q-1}$

xi) (binary start-up decisions)

$z^{pump}_{t,h,q} = 1\{y^{pump}_{t,h,q} - y^{pump}_{t,h,q-1} > 0\}, z^{turbine}_{t,h,q} = 1\{y^{turbine}_{t,h,q} - y^{turbine}_{t,h,q-1} > 0\} \in \{0,1\}$

xii) (pump start-up constraint) $y^{pump}_{t,h,q} - y^{pump}_{t,h,q-1} \leq z^{pump}_{t,h,q}$

xiii) (generation start-up constraint) $y^{turbine}_{t,h,q} - y^{turbine}_{t,h,q-1} \leq z^{turbine}_{t,h,q}$

xiv) (positivity I) $x^{pump}_{t,h,q}, x^{turbine}_{t,h,q}, z^{pump}_{t,h,q}, z^{turbine}_{t,h,q} \geq 0$

xv) (positivity II) $\Delta x^{pump,up}_{t,h,q}, \Delta x^{pump,down}_{t,h,q}, \Delta x^{turbine,up}_{t,h,q}, \Delta x^{turbine,down}_{t,h,q} \geq 0$

with $(\cdot)_{t,h,4} = (\cdot)_{t,h+1,0}$, $R_{t,0,-1} = R^{start}_t$, $x^{pump}_{t,0,-1} = (x^{start}_t)^+$ and $x^{turbine}_{t,0,-1} = (x^{start}_t)^-$, $y^{pump}_{t,0,-1} = 1\{x^{start}_t > 0\}$ and $y^{turbine}_{t,0,-1} = 1\{x^{start}_t < 0\}$.

Contribution function

Day-ahead market revenue

- $$C_t^{DA}\left(S_t^{DA}, x_t^{DA}, W_{t+1}^{DA}\right) = -\sum_{h=0}^{23} \underbrace{\Delta t^{DA} P_{t+1,h} x_{t,h}^{DA}}_{\text{DA buy/sell}}$$

Intraday market revenue

- $$C_t^{ID}\left(S_t^{ID}, x_t^{ID}, W_{t+1}^{ID}\right) = \sum_{h=0}^{23}\sum_{q=0}^{3} -\underbrace{\Delta t^{ID} P_{t+1,h,q}^{ID} x_{t,h,q}^{ID}}_{\text{ID buy/sell}} - \underbrace{\Delta t^{ID} c^{gf} x_{t,h,q}^{pump}}_{\text{grid fees}}$$

$$+\underbrace{Q_{t+1,h,q}^{over}(\Delta x_{t,h,q}^{pump,up} + \Delta x_{t,h,q}^{turbine,up}) - Q_{t+1,h,q}^{under}(\Delta x_{t,h,q}^{pump,down} + \Delta x_{t,h,q}^{turbine,down})}_{\text{balancing costs due to over/under-supply during ramping}}$$

$$-\underbrace{c^{pump} z_{t,h,q}^{pump} - c^{turbine} z_{t,h,q}^{turbine}}_{\text{start-up costs}}$$

- Assumption balancing penalty linear in $P_{t+1,h,q}^{ID}$:

$$Q_{t+1,h,q}^{over} = \frac{\Delta t^{ramp}}{2}\left(Q_{intercept}^{over} + Q_{slope}^{over} P_{t+1,h,q}^{ID}\right)$$

$$Q_{t+1,h,q}^{under} = \frac{\Delta t^{ramp}}{2}\left(Q_{intercept}^{under} + Q_{slope}^{under} P_{t+1,h,q}^{ID}\right)$$

Transition function

- From Day-ahead auction to Intraday auction $(\text{DA}_t \rightarrow \text{ID}_t)$:

$$S_t^{ID} = S^{M,DA}\left(S_t^{DA}, x_t^{DA}, W_{t+1}^{DA}\right) = \left(S_t^{DA}, x_t^{DA}, P_{t+1}^{DA}\right) \tag{3}$$

- From Intraday auction to Day-ahead auction $(\text{ID}_t \rightarrow \text{DA}_{t+1})$:

$$\begin{aligned} S_{t+1}^{DA} &= S^{M,ID}\left(S_t^{ID}, x_t^{ID}, W_{t+1}^{ID}\right) = \left(R_{t+1}^{start}, x_{t+1}^{start}, P_{t+1}^{history}\right) \\ &= \left(R_{t,23,3}, x_{t,23}^{DA} + x_{t,23,3}^{ID}, P_{t-5}^{DA}, \cdots, P_{t+1}^{DA}, P_{t-5}^{ID}, \cdots, P_{t+1}^{ID}\right) \end{aligned} \tag{4}$$

where $R_{t,23,3}$ follows the storage level equation viii).

Problem statement and value function

- Policy π maps states S_t^{DA} and S_t^{ID} to decision $X_t^{DA,\pi}(S_t^{DA})$ and $X_t^{ID,\pi}(S_t^{ID})$

$$\max_{\pi} \mathbb{E}\left[\sum_{t=0}^{T-1} \underbrace{C_t^{DA}\left(S_t^{DA}, X_t^{DA,\pi}(S_t^{DA}), W_{t+1}^{DA}\right)}_{\text{DA contribution}} + \underbrace{C_t^{ID}\left(S_t^{ID}, X_t^{ID,\pi}(S_t^{ID}), W_{t+1}^{ID}\right)}_{\text{ID contribution}} \middle| S_0^{DA}\right]$$

- Alternative formulation using the recursive Bellman equations:

$$V_t^{DA}\left(S_t^{DA}\right) = \max_{x_t^{DA}} \mathbb{E}\left[C_t^{DA}\left(S_t^{DA}, x_t^{DA}, W_{t+1}^{DA}\right) + V_t^{ID}\left(S_t^{ID}\right) | S_t^{DA}\right] \quad (5)$$

$$V_t^{ID}\left(S_t^{ID}\right) = \max_{x_t^{ID}} \mathbb{E}\left[C_t^{ID}\left(S_t^{ID}, x_t^{ID}, W_{t+1}^{ID}\right) + V_{t+1}^{DA}\left(S_t^{DA}\right) | S_t^{ID}\right] \quad (6)$$

with the boundary condition $V_T^{DA}\left(S_T^{DA}\right) = 0$

Policy model

- Replace alternating decision stages by expectation model.
- Policy model:

$$S_t^{policy} = S_t^{DA} = \left(R_t^{start}, x_t^{start}, P_t^{history}\right) \quad \text{(state variable)}$$

$$x_t^{policy} = \left(x_t^{DA}, x_t^{ID}\right) \quad \text{(action variable)}$$

$$W_{t+1}^{policy} = \left(W_{t+1}^{DA}, W_{t+1}^{ID} | W_{t+1}^{DA}\right) \quad \text{(exogenous information)}$$

$$S_{t+1}^{policy} = S^{M,policy}\left(S_t^{policy}, x_t^{policy}, W_{t+1}^{policy}\right)$$

$$= S^{M,ID}\left(S^{M,DA}\left(S_t^{DA}, x_t^{DA}, W_{t+1}^{DA}\right), x_t^{ID}, W_{t+1}^{ID}\right) \quad \text{(new state variable)}$$

- The value function is:

$$V_t^{policy}\left(S_t^{policy}\right) = \max_{x_t^{policy}} \left\{C_t^{policy}\left(S_t^{policy}, x_t^{policy}\right) + \mathbb{E}\left[V_{t+1}^{policy}\left(S_{t+1}^{policy}\right) \middle| S_t^{policy}\right]\right\}$$

s.t. $V_T^{policy}\left(S_T^{policy}\right) = 0$ and i) - xv),

Approximation of value function

- The value function V_t^{policy} is approximated by $\bar{V}_t^{policy}$:

Considered different techniques for approximating $\bar{V}_t^{policy}$:

- Backwards approximate dynamic programming (BADP)
- Weighted backwards approximate dynamic programming (w-BADP)
- Lasso based Least Squares Monte Carlo (LSMC-lasso)
- Approximate dual dynamic programming algorithm (ADDP)

And other benchmarks:

- 7 days-horizon expectation model (EM-7)
- Perfect foresight

Backwards approximate dynamic programming (BADP)

Algorithm 1 BADP

sample scenario lattice $P^{history}_{t,n}, t \in \{1, \cdots, T\}, n \in \{1, \cdots, N\}$
initialize lookup table $\bar{V}^{pol}_T = 0$
for $t = T - 1$ to 0 **do**
  for $n = 1$ to N **do**
    compute expected price history $\bar{P}^{history}_{t,t+1,n} := \mathbb{E}\left[P^{history}_{t+1} | P^{history}_{t,n}\right]$
    $(\bar{\rho}_1, \cdots, \bar{\rho}_N) := \underset{\rho_1, \cdots, \rho_N}{\arg\min} \left\| \bar{P}^{history}_{t,t+1,n} - \sum_{k=1}^{N} \rho_k P^{history}_{t+1,k} \right\|_2$
    for $R^{start}_t = 0$ to R_{max} **do**
      for $x^{start}_t = -x^{turbine}_{max}$ to x^{pump}_{max} **do**
        $\bar{V}^{pol}_t\left(S^{pol}_{t,n}\right) := \max_{x^{pol}_t} \left\{ C^{pol}_t\left(S^{pol}_t, x^{pol}_t\right) + \sum_{k=1}^{N} \bar{\rho}_k \bar{V}^{pol}_{t+1}\left(S^{pol}_{t+1} | P^{hist}_{t+1,k}\right)\right\}$
      end for
    end for
  end for
end for

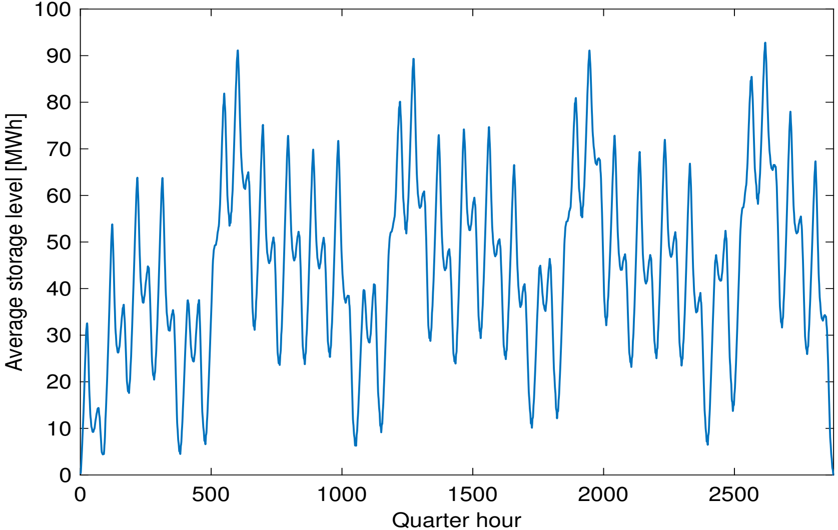
Numerical study

- Parameter setting (realistic pumped hydro storage):
  - Capacity: $R_{max} = 100$ MWh
  - pump and turbine power range: $[x^{pump}_{min}, x^{pump}_{max}] = [x^{turbine}_{min}, x^{turbine}_{max}] = [5, 10]$ MW
  - efficiencies: $\eta^{pump} = \eta^{turbine} = 0.9$
  - start-up costs: $c^{pump} = c^{turbine} = 15$ EUR
  - ramping times: $\Delta t^{ramp} = 2$ min
  - balancing cost parameters: $Q^{over}_{intercept} = -3$ EUR/MWh, $Q^{over}_{slope} = 1/1.2$, $Q^{under}_{intercept} = 3$ EUR/MWh, $Q^{under}_{slope} = 1.2$ (deviation from commitments is financially unattractive)
  - optimization horizon: $T = 30$
- Backtesting setting (validate on 4×30 days):

Season	Training data	Test data
Winter	16.01.2019 to 15.01.2020	16.01.2020 to 14.02.2020
Spring	02.05.2019 to 30.04.2020	01.05.2020 to 30.05.2020
Summer	01.08.2018 to 31.07.2019	01.08.2019 to 30.08.2019
Autumn	17.10.2019 to 15.10.2020	16.10.2020 to 14.11.2020

Numerical study - Results

- Example: Evolution of storage level R_t over time

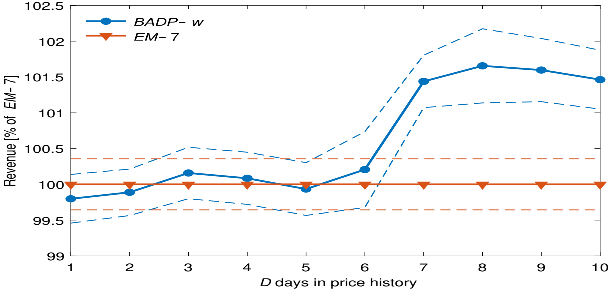


Numerical study - Results

Algorithm	Rel. revenue	95% confidence	Machine time [s]
EM-7	100.00 $\%$	$[99.64, 100.36]$	0
BADP	99.70 $\%$	$[99.09, 100.30]$	$1,401$
BADP-w	101.44 $\%$	$[101.04, 101.84]$	$1,412$
BADP-w (re-opt.)	101.47 $\%$	$[101.00, 101.93]$	$2,139$
LSMC-lasso	94.31 $\%$	$[93.62, 95.00]$	$4,316$
ADDP	82.80 $\%$	$[82.17, 83.44]$	$5,172$
Perfect foresight	185.70 $\%$	–	0

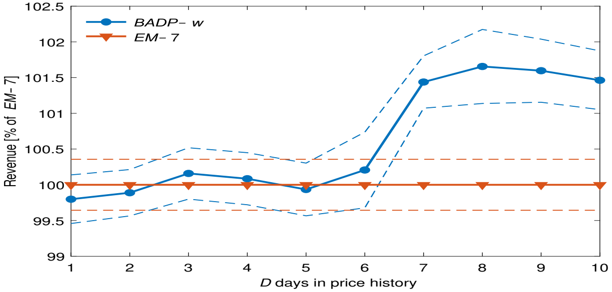
- BADP-w about 1.5% revenue increase compared to *EM-7*
  profit increase in practice usually substantially larger
- *EM-7* is quite competitive

Impact of memory in price process:



- History in price process matters

Impact of memory in price process:



- History in price process matters

Impact of integrated bidding:

Trading and optimization	Relative revenue	95% confidence band
Only day-ahead (DA)	39.75%	[39.03, 40.47]
Only intraday (ID)	97.51%	[97.20, 97.83]
DA+ID, sequential	91.98%	[91.74, 92.22]
DA+ID, integrated	100.00%	[99.61, 100.39]

- Integrated bidding yields +9% revenue

Summary results

- Integrated bidding for storages on day-ahead and intraday auction feasible
- Weighted backwards approximate dynamic programming (BADP) gives 1.5% improvement over expectation model
- Memory in price process important
- Integrated bidding substantially better than sequential bidding (+9% revenue!)

Summary results

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- Memory in price process important
- Integrated bidding substantially better than sequential bidding (+9% revenue!)

Thank you for your attention!