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Market strategies of large-scale energy storage: vertical integration versus stand-alone models

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Agenda

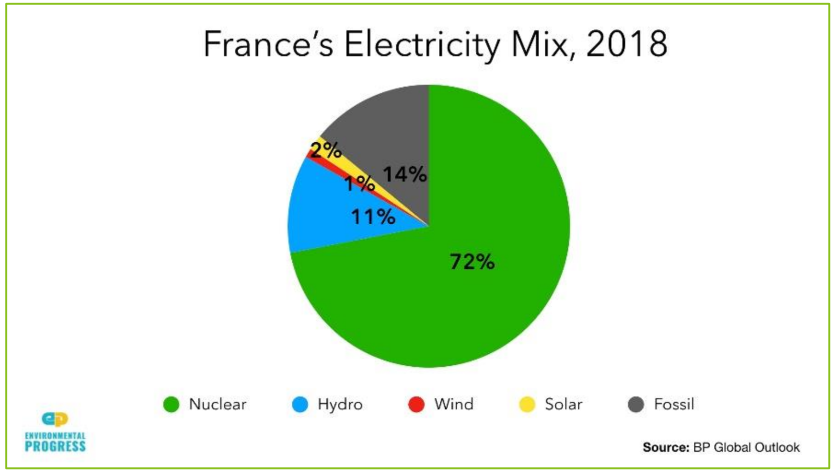
- **1. Context**: low financial interest to invest in storage
- **2. Case study**: French PHS Grand'maison plant
- **3. Methodology**: dynamic optimisation model (*Python*)
- **4. Results**: weekly / daily horizons
- **5. Concluding remarks**

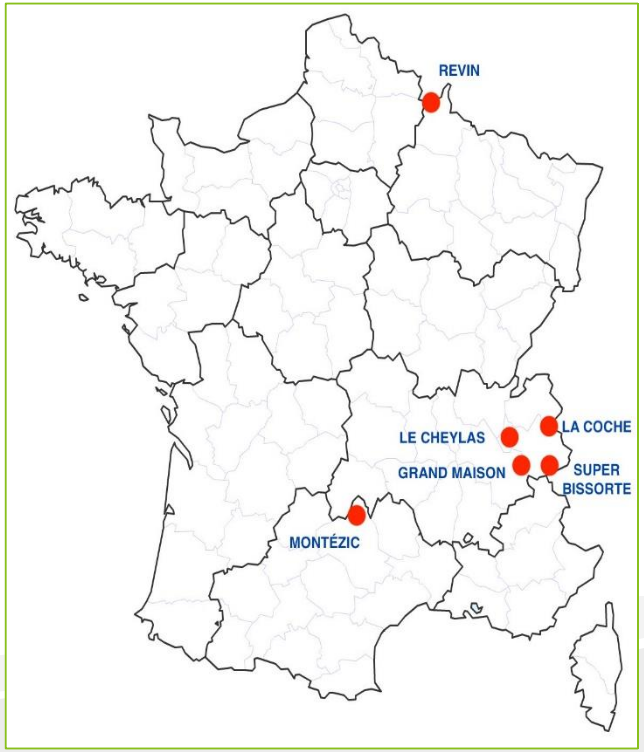
Bassin of Grand Maison

1. The Context

1. Nuclear-dominated French power mix: **need of storage**
   - 6 PHS sites, 4.2 GW cumulated pumping (2017)
2. Energy Transition Act (2015) **target: 2 GW** PHS by 2030
   - Significant remaining geological potential (30-90 sites / 400 GWh, JRC 2015).
   - Yet, no PHS project in construction.
3. Increased system flexibility needs in the long-run
   - Grid congestion issues, security of supply, balancing.
4. Yet **low economic incentives** to trigger PHS projects, if based on only on-peak – off-peak price differential.

Goal: investigating why / how building unprofitable PHS projects?





PHS sites in France (Google Map)

2. Case study: French PHS fleet (1/3)

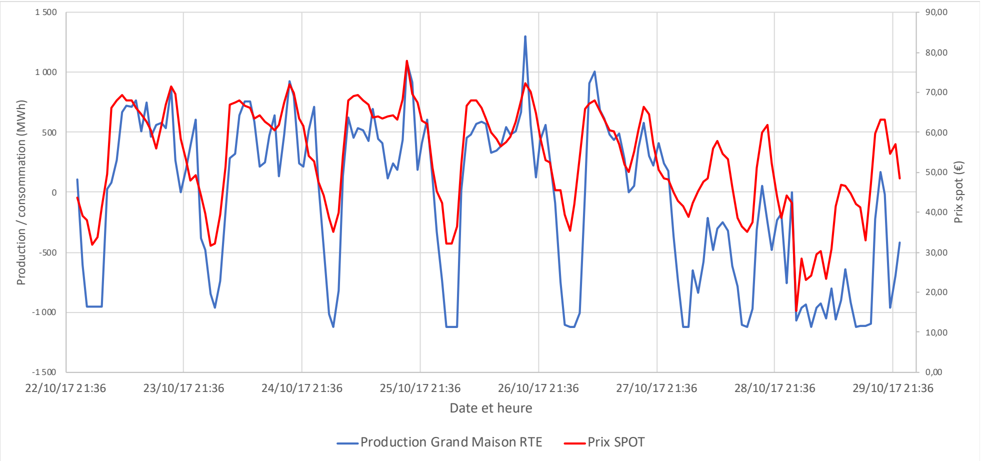
- The EdF PHS fleet is meant to provide (EdF, 2011) :
  - Price-arbitrage: pumping during low demand and discharging during demand peaks, driven by delivery obligations rather than by prices (yet correlated with prices).
  - Support to the EdF energy mix.
  - Balancing services, negative/positive reserves.

Table. The French PHS fleet

French PHS plant characteristics	Montézic	Revin	G. Maison	S.Bissorte	La Coche	Le Cheylas
Year of operation	1982	1976	1985	1987	1977	1979
Turbine, MW	910	720	1790	730	330	460
Pumping, MW	870	720	1160	630	310	480
Number of pumps	4	4	8	4	2	2
Discharge, hours	40	5	30	5	3	6

2. **Case study:** French PHS **cost** (2/3)

Effective discharge is correlated with the Spot market price in 2017



Grand Maison actual Discharge versus spot Price

Price-arbitrage: low price differential to ensure profitability.

Implicitly: by only acting on the spot market as a stand-alone actor, the PHS plan cannot be profitable.

Other service compensation necessarily adds.

Table. Statistics based on RTE real data (2017). LCOE value.

Buying average price on the spot market	€/MWh	35
Selling price on the spot market	€/MWh	52
LCOE	**€/MWh**	**105**

2. **Case study:** French PHS **management** (3/3)

- PHS **fleet**: correlation between the spot price and the operation of the PHS fleet.
- PHS **plant level**: frequent uncorrelated operations:
  - some plants are pumping while, at the same time, others are discharging.
- Decentralized management of PHS plants. Stand-alone market players?

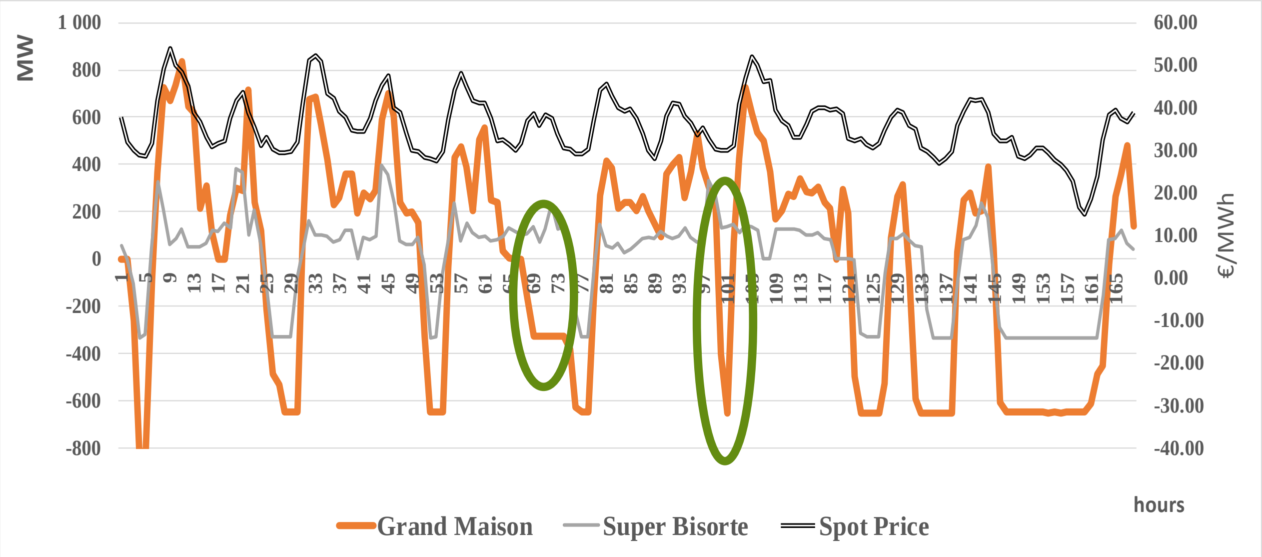


Fig. *The operation of two PHS plants over one week in 2017*

Nomber of events of uncorrelation among PHSs				
	Grand maison	Montezic	Revin	Super Bissorte
Grand maison		1084	923	1234
Montezic	1084		889	1282
Revin	923	889		1007
Super Bissorte	1234	1282	1007	

3. Methodology

Modeling **objective function** options:

- For short-term storage (day)
- For long-term seasonal storage (week)
- Longer this horizon, price information is less accurate.
- No need to store bulk energy in well interconnected areas.

Assumptions:

- Perfect foresights over one day (week), myopic in rest.
- Future price evolution in weeks, months cannot affect current storage in the French mix, due to high market liquidity.
- PHS Grand'maison operator supplies the spot market.
- *Python*, 8,760 time-slices, 365 recursive dynamic blocks (~52)

Eq1. Operational profit maximization (the objective function):

$$\boldsymbol{\pi_s} = \sum_{1}^{B_s} Max_{d,h} \sum_{\substack{h=1\\d=1}}^{\substack{d=t_s\\h=24}} p_{d,h} \cdot (\boldsymbol{PD_{d,h}} - \boldsymbol{PC_{d,h}})$$

Eq2. Dynamics of the storage reservoir:

$$\boldsymbol{R_{d,h}} = \boldsymbol{R_{d,h-1}} + \boldsymbol{PC_{d,h}} \cdot eff - \boldsymbol{PD_{d,h}}$$

Eq3. Min load (storage reservoir does not get empty). Max level of charging:

$$MinLoad \cdot K_R \leq \boldsymbol{R_{d,h}} \leq K_R$$

Eq4. Power discharged is lower than the power charged over the year:

$$\sum_{1}^{B_s} \sum_{\substack{h=1\\d=1}}^{\substack{d=t_s\\h=24}} \boldsymbol{PD_{d,h}} \leq \sum_{1}^{B_s} \sum_{\substack{h=1\\d=1}}^{\substack{d=t_s\\h=24}} \boldsymbol{PC_{d,h}} \cdot eff$$

Eq5. Power discharged does not exceed the capacity of turbines:

$$\boldsymbol{PD_{d,h}} \leq K_T$$

Eq6. Power charged does not exceed the capacity of pumps:

$$\boldsymbol{PC_{d,h}} \leq K_P$$

Eq7. PHS Net present value:

$$\boldsymbol{NPV_s} = \sum_{y=1}^{60} [(\boldsymbol{\pi_s} - c\_OM_y)/(1+r)^y] - INV_0$$

Eq8. PHS Levelised Costs of Energy:

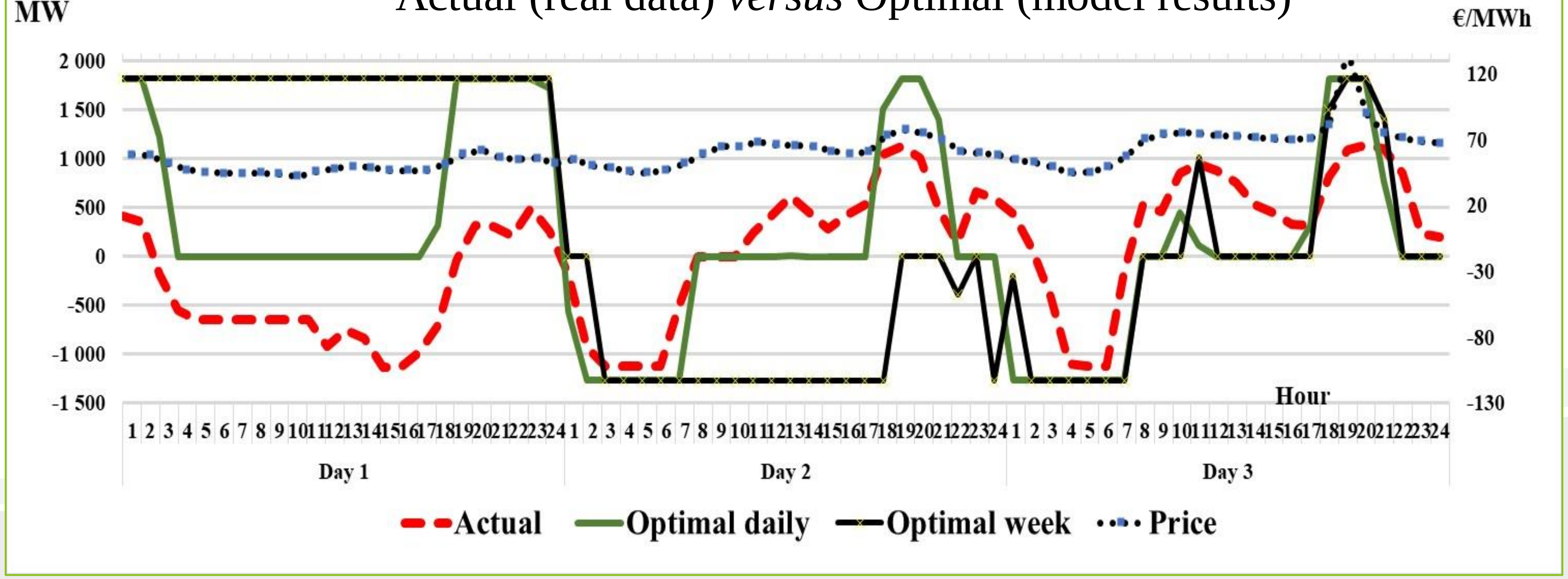
$$\boldsymbol{LCOE_s} = \frac{INV_0 + \sum_{y=1}^{60} \frac{c\_OM_y}{(1+r)^y}}{\sum_{y=1}^{60} \frac{\sum_{h=1,d=1}^{h=24,d=t_s} \boldsymbol{PD_{d,h}}}{(1+r)^y}}$$

4. Results of the Grand'maison PHS optimisation

- Over the year, the strategy weekly / daily storage is not constant, they alternate on an irregular basis.
- This partly confirms that the economic model of the PHS plant is not driven by the spot market only, but it simply correlates with (75% over the year).
- Other strategies build the PHS economic model: contractual arrangements with other power plants.

- the **daily storage strategy best fits** the PHS actual behaviour.
- the operator **fails to capture** 4.2% of the optimal profit of a virtual rational independent PHS (= -1.4 M€$_{2017}$; - 25% less flows.
- Other **constraints** may add: internal (related to the technology itself) + external due to centralized dispatching of power generators + exports + imports which punctually complement or substitute the PHS.

Fig. Operation of Grand'maison PHS plant over three days: Actual (real data) *versus* Optimal (model results)



4. Results of the Grand'maison PHS optimisation

- Higher profits through optimisation than the actual behaviour.
- Seasonal storage results in larger volume supplied to the wholesale market than the daily storage, but at a lower price in average (47.8 €/MWh against 49.6 €/MWh).
- Market promotes daily pumped-storage installations rather than seasonal (Gaudard & Madani, 2019).
- The weekly storage, less profitable than the daily storage, has missing market opportunity, thus cannot be the choice of a rational independent player, but rather a contractual agreement between the PHS plant and other operator (generator, TSO).

	Actual data (RTE, 2017)	Daily Optimisation Results	Weekly Optimisation Results (from Monday to Monday)
Operational Profits (€)	33 201 059	53 854 040	20 075 708

4. Results: new LCOS calculus by cost component

- Conventional indicators of cost calculation based on LCOE seem inappropriate to storage.
- Braking down the LCOS allows accounting for the duration of the storage.
- Need of valuation as a function of seasonality.
- Short-term duration would have a greater value (Strbac et al 2012).

$$LCOS_{plant} = LCOS_{turbines} + LCOS_{pumpes} + LCOS_{reservoir}$$

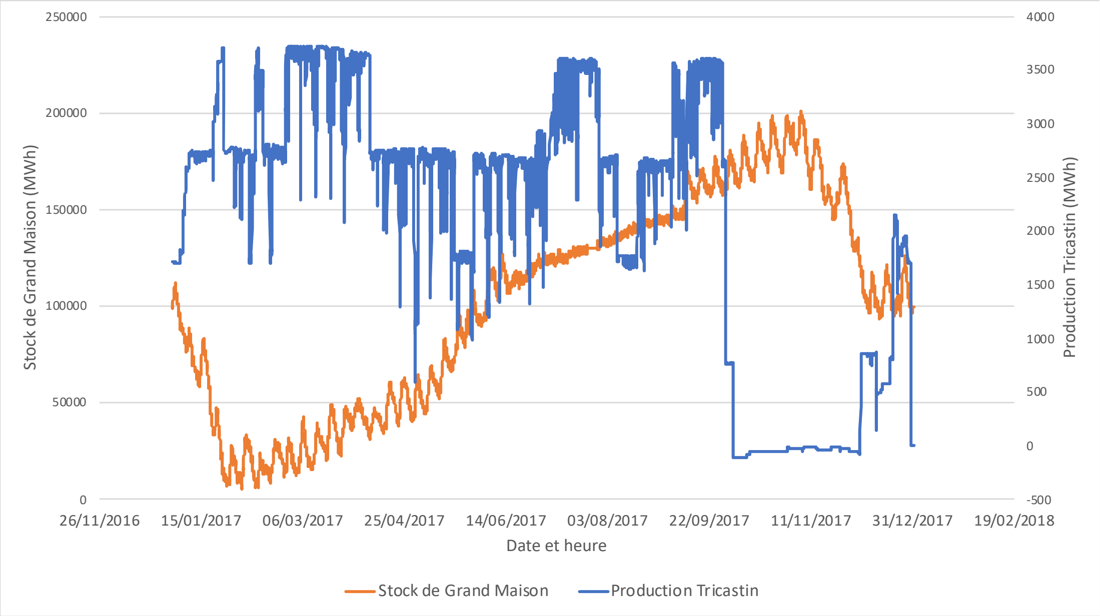
$$LCOS_{turbines} = \frac{I_{turbines}}{\sum_{t=1}^{n} \frac{E_{discharged}}{(1+r)^t}}$$

	LCOS storage €/MWh	LCOS turbinage €/MWh	LCOS pumping €/MWh	**LCOS plant €/MWh**
Actual operation	0.12	36.83	68.30	**105.25**
Weekly strategy	0.67	22.65	58.85	**82.18**
Daily strategy	2.82	25.83	63.12	**91.78**

Correlation PHS Grand'm plant - Tricastin nuclear power plant

Most likely a strong complementarity between EdF power plants, but difficult to find any formal evidence.

The gap actual-optimal reveals the provision of a service close to ramping energy blocks, specific to systems exposed to high ramping (Cigre, 2019).



Stock Grand Maison vs nuclear generation at Tricastin (RTE, 2017)

Four large nuclear power plants are located in the proximity of Grand'm plant.

Despite reactors flexibility, they are subject to technological constraints of efficiency, safety. During fast response, long lasting reserves provision, operations could be limited by the reactor design in terms of ramping and minimum load safety requirements.

PHS sites (Google Map)

Nuclear reactors (IRSN, 2017)

Concluding remarks

- **Unclear role** of energy storage: daily/weekly, stand-alone market player/ service provider.
- Decision to invest into new PHS facilities = integrated into broad **central energy planning** strategy. But the PHS plants' **management seems to be decentralized** with some plants pumping and other discharging at the same time.
- Future: longer and faster system services. The regulator needs rethinking the role of both energy storage and generators in providing ancillary services, on the **complementary or substituting role**.
- **Multiple contract-based** economic model = difficult, conflicting since the capacity reserved for one service is unavailable for the provision of another market segment. Transactions costs could add to computational issues to determine in real-time the optimal share to supply wholesale market and the share reserved for balancing:
  - Two simple contractual options: a fixed share for ancillary services, residual share for spot market.
  - **Vertical integration**, e.g. with the TSO (Transmission System Operator), RES, or NPP.

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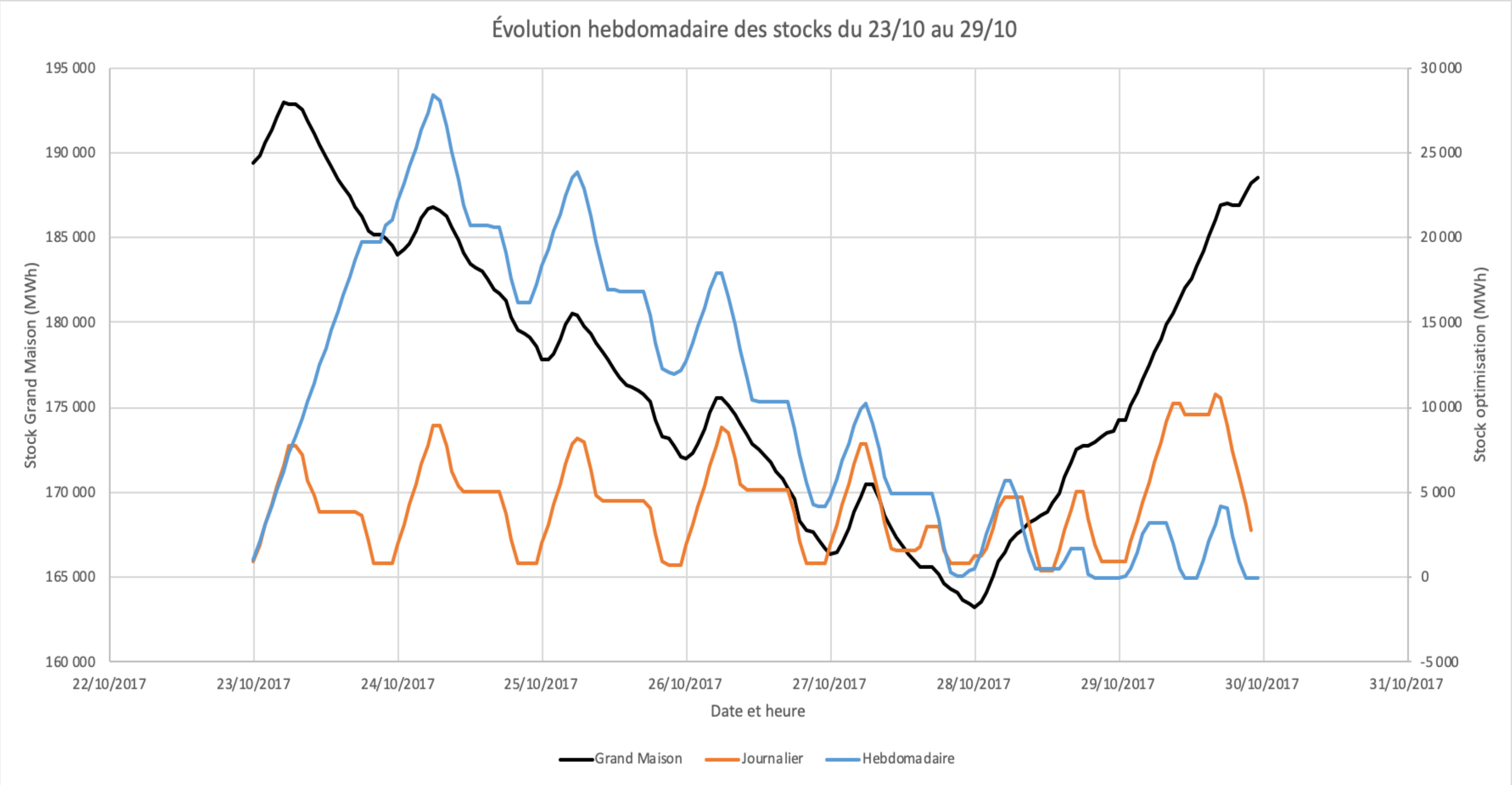
ANNEXES

4. Results of the Grand'maison PHS optimisation

- The PHS plant starts filling up on Friday night until Sunday night and gets empty during the week.



Weekly stock dynamics from Monday 23/10 to Sunday 29/10

Table. Levelized Cost of Storage

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

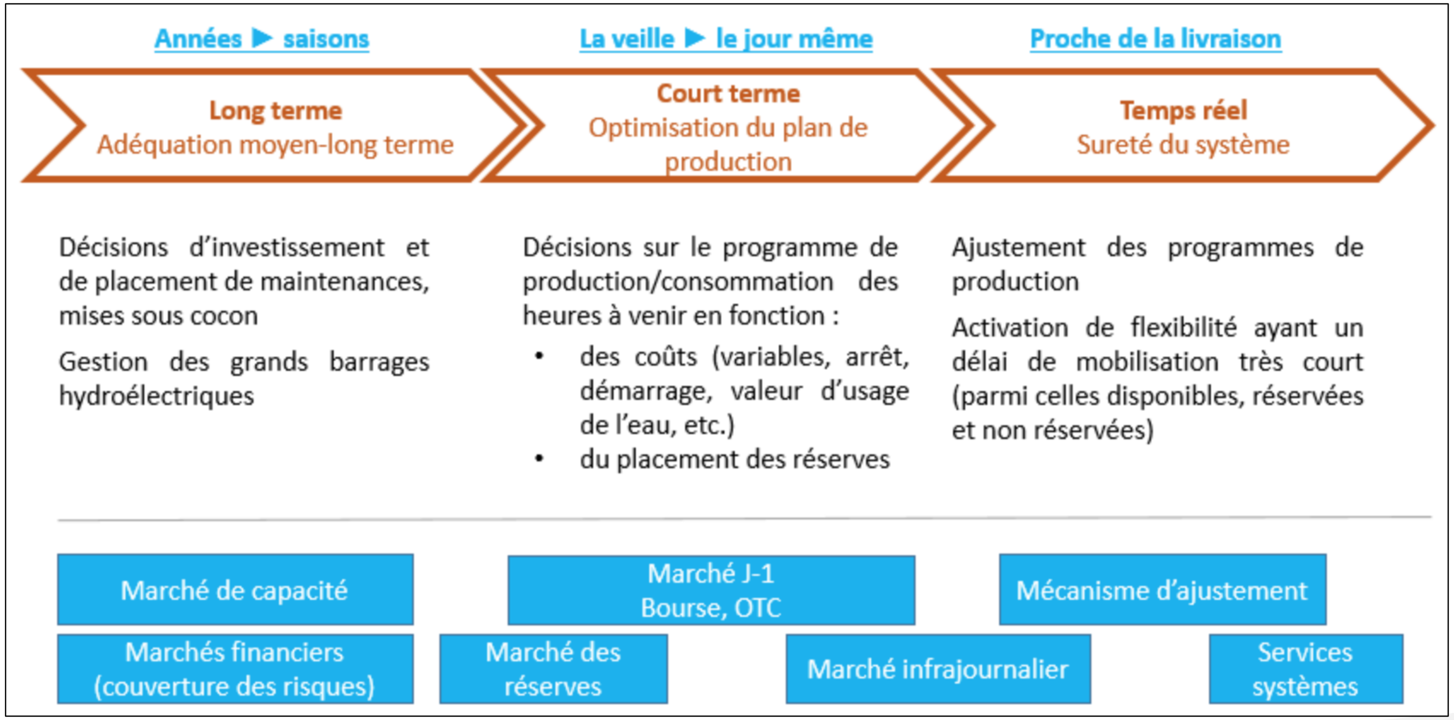
Indicateurs Technologiques / Économiques	Unité	Valeur
Capacité nominale turbinage	MW	1820
Capacité nominale pompage	MW	1270
Investissement (overnight cost)	€/kW	1600
Autres coûts	€/kW	
Durée de vie technique	années	50
Durée de construction	années	7
Retard chantier	années	0
Pénalité retard de livraison	€/kW	50
Coût du délai de construction	€/kW/an	0
Taux d'intérêt	%	0,05
Démantèlement	%	0,05
Taux d'actualisation	%	0,08
Coût total d'investissement	€/kW	1816
Coûts fixes O&M (FOM)	€/kW/an	11
Coût fixe total actualisé	€	135
Facteur de capacité (Load Factor) turbinage	%	0,13
Facteur de capacité (Load Factor) pompage		0,23
Production sur 20 ans actualisée d'1 kW	MWh	14
Coût variable	€/MWh	1
Coût variable total actualisé	€	13
LCOS, Coût total par unité stockée	€/MWh	141
Prix d'achat moyen marché spot	€/MWh	35
Prix de vente moyen marché spot	€/MWh	52
Prix de vente réglementé	€/MWh	173

Taux d'utilisation	Réservoir	Pompes	Turbines
Taux Annuel	50%	23%	15%
Taux Hebdomadaire	6%	34%	23%
Taux Journalier	2%	29%	22%

Tableau 6 : Taux d'utilisation des différentes composantes d'une STEP en fonction du mode d'optimisation

Fonctionnement des marchés de l'électricité

La **difficulté de prévoir avec précision** l'offre et la demande futures induit une chronologie des décisions qui permet un **ajustement constant**.



Chronologie de l'équilibre production et consommation (RTE, 2018)

Les rôles des STEP selon EdF

1. « Les opportunités de **générer un revenu en effectuant des cycles de pompage-turbinage** dépendent :
   - de l'importance de l'écart de prix entre heures creuses et heures pleines
   - du rendement du cycle (rapport entre l'énergie produite et l'énergie consommée, de 75 à 80%) »
2. « **Les STEP d'EDF participent aux services système :**
   - **Réglage de tension** assuré en pompage et en turbinage sur toutes les STEP, équipées de régulateurs de tension
   - **Réglage de fréquence** en turbinage sur les STEP équipées de distributeurs réglables (cas des chutes moyennes, soit 50% du parc STEP EDF France) »
3. « La gestion journalière est faite en déterministe, selon un corps d'hypothèses: on se réadapte continuellement en journalier pour **rééquilibrer la production** et **faire face aux aléas** : en optimisation infra-journalière **pour le compte d'EDF** »

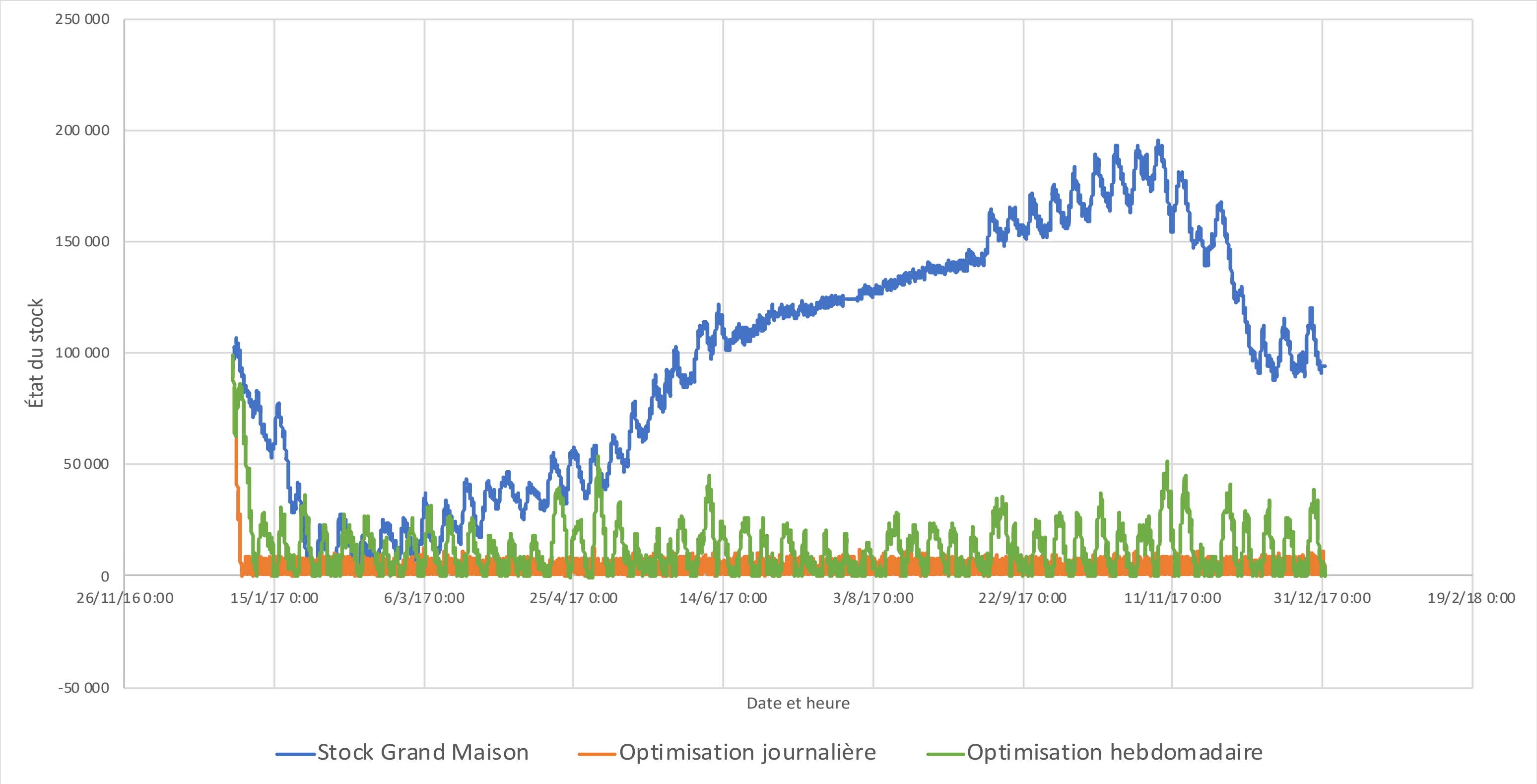
EDF, 2011

Support au réseau : services système

« Le principe de rémunération de ces services est identique à celui des autres ensembles de production français (**disponibilité pour primaire** fréquence et tension, **disponibilité + énergie pour secondaire** fréquence). » (EdF, 2011)

Application	Puissance	τ décharge	Energie	τ réponse	Centralisé / Décentralisé	STEP	CAES	H2	Batterie NaS	Batterie Redox	Batterie Li-ion	Volant d'inertie	Super capacité	SMES
Qualité du signal, stabilisation des réseaux	< 1 MW	Sec	< 0,2 MWh	< 8 ms	décentralisé						●	●		●
Réserve de puissance primaire	1 à 100 MW	< 30 min	0,5 à 50 MWh	< 30 s	décentralisé			●	●	●	●			
Stockage résidentiel	4 kW	6 h	24 kWh	< 1min	décentralisé						●			
Lissage de la pointe industrielle	Qq MW	1 h	Qq MWh	< 1min	décentralisé					●	●			
Intégration des Enr	Qq 10 MW	2 h	QQ 10 MWh	< 1min	décentralisé			●	●	●	●			
Réserve de puissance secondaire	10 à 1000 MW	< 30 mn	5 à 500 MWh	< 15 min	centralisé	●	●	●	●	●	●			
Réserve tertiaire	> 10MW	Qq h	>10MWh	< 13 min	mix	●	●	●	●					
Arbitrage prix	10 MW à 500 MW	6-10 h	0,06 à 5 GWh	< 30min	mix	●	●	●	●	●	●			
Secours	1 MW	24 h	24	min	centralisé	●	●	●	●	●	●			

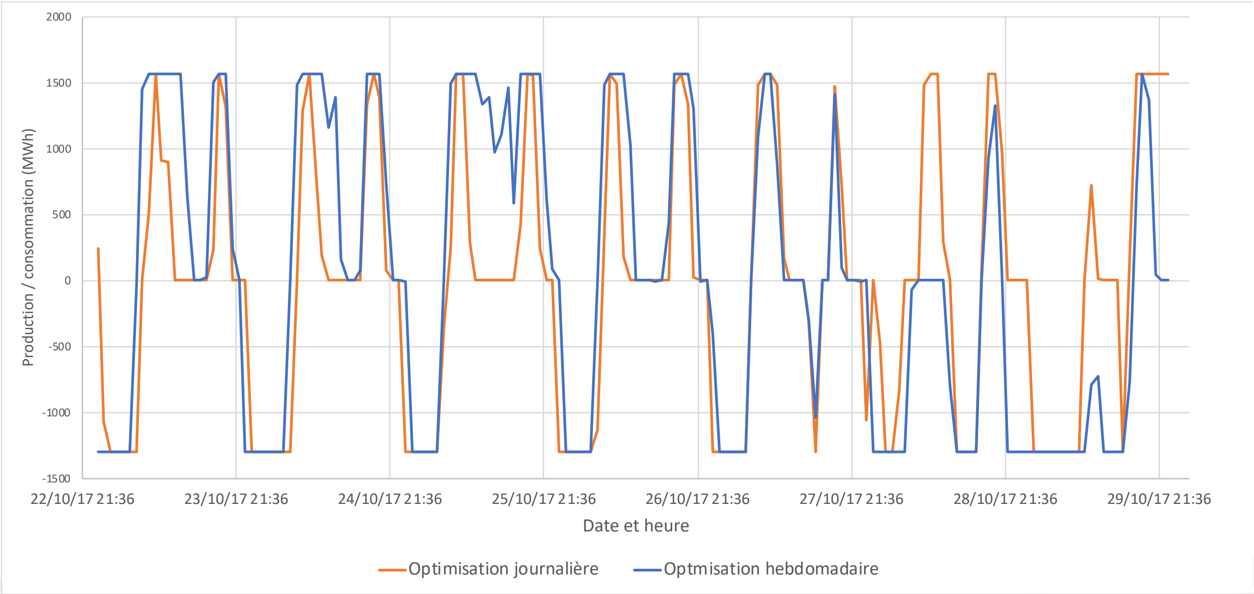
Technologies de stockage adaptées au différents besoins (Supélec, 2013)



Évolution annuelle des stocks

4. Results of the Grand'maison PHS optimisation

- Similar trends for Daily, Weekly optimisation strategies (Fig left), and of the Actual discharge with the Spot price (Fig Right)



Daily versus Weekly Optimisation – Discharging curves