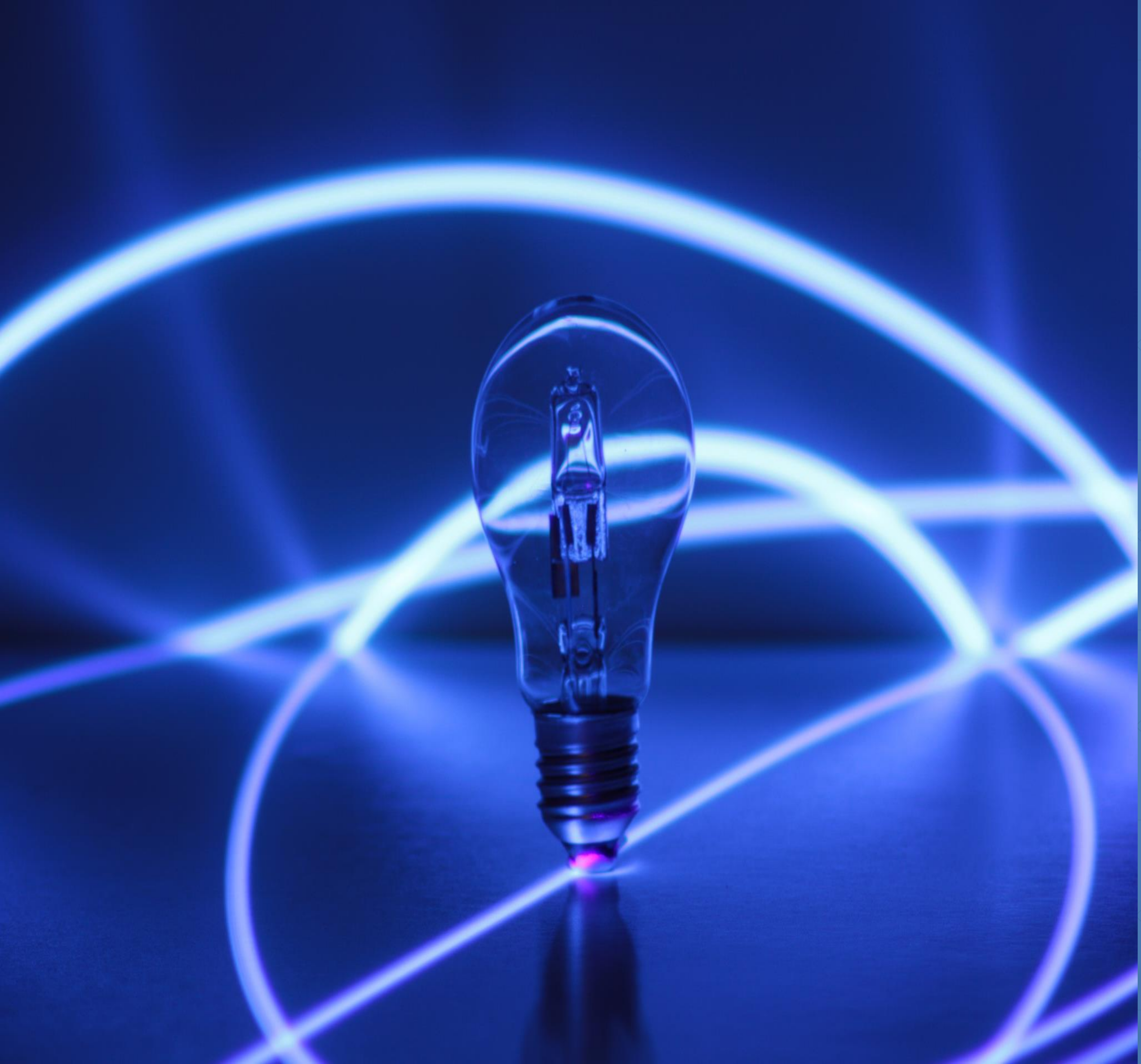

Economic assessment of storage investment in Greece

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E3Modelling Energy Economy Environment

Economic assessment of hydro-pumping investment in Greece

Questions:

In the context of a high-RES and low-CO2 power sector

- Optimum storage capacity in the medium and long-term
- Comparison of batteries to hydro-pumping storage

The approach:

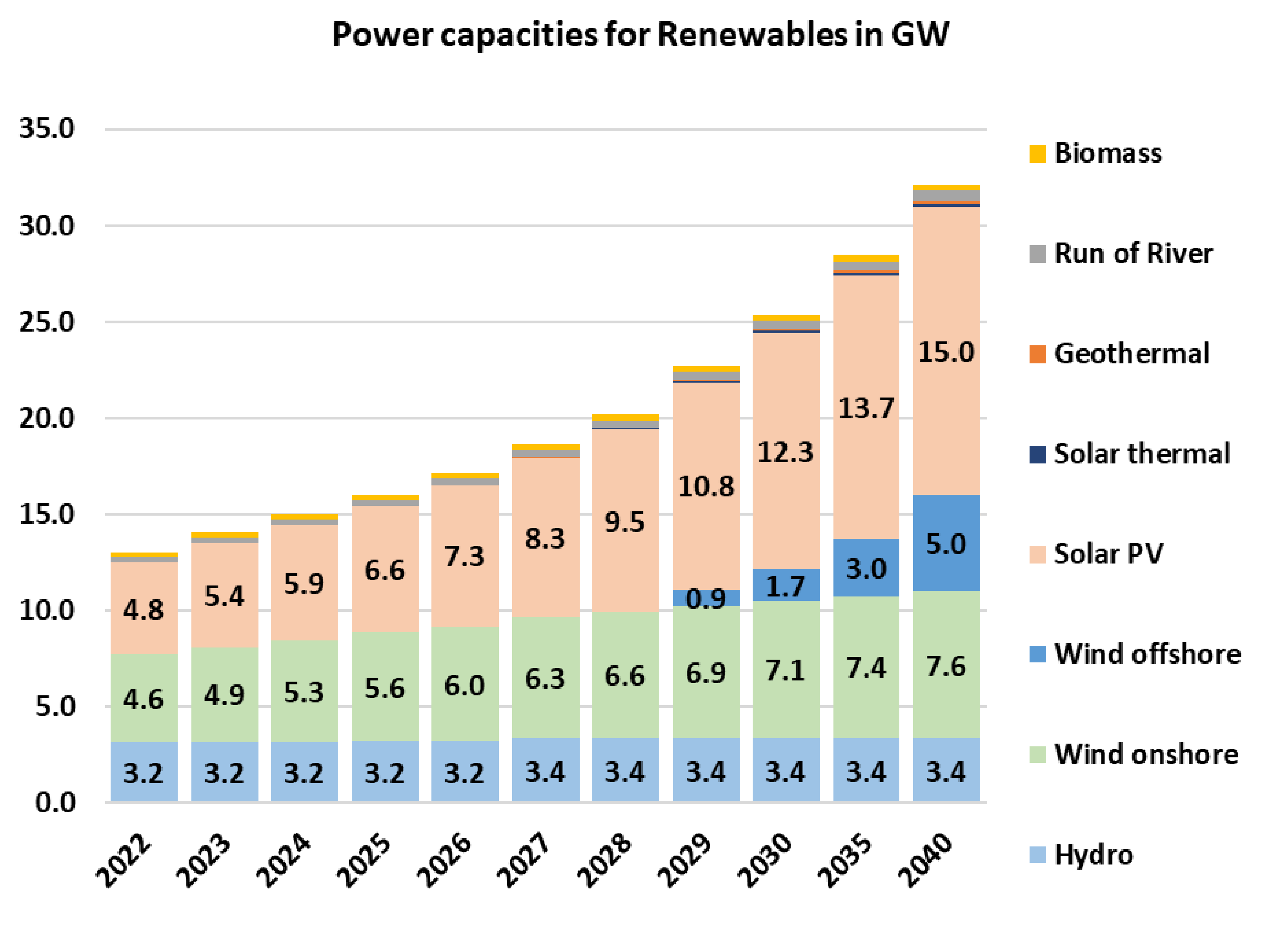
- Hourly simulation model (PRIMES) of wholesale market and unit commitment to calculate projections for the years from 2025 until 2040
- Large number of sensitivity analysis model runs to determine optimal storage capacity
- The simulator co-optimizes energy and ancillary services and derives market equilibrium prices
- The model includes various storage technologies (batteries, hydro pumping and hydrogen) at different timeframes (2, 4, 8 hours)

Assessment perspectives:

- System: Benefits from avoidance of RES curtailment and load management versus system operation costs (ignoring financial performance of storage)
- Private: Operating margin and capital cost recovery
- Positive externality analysis – is there a discrepancy between social and private optimum?

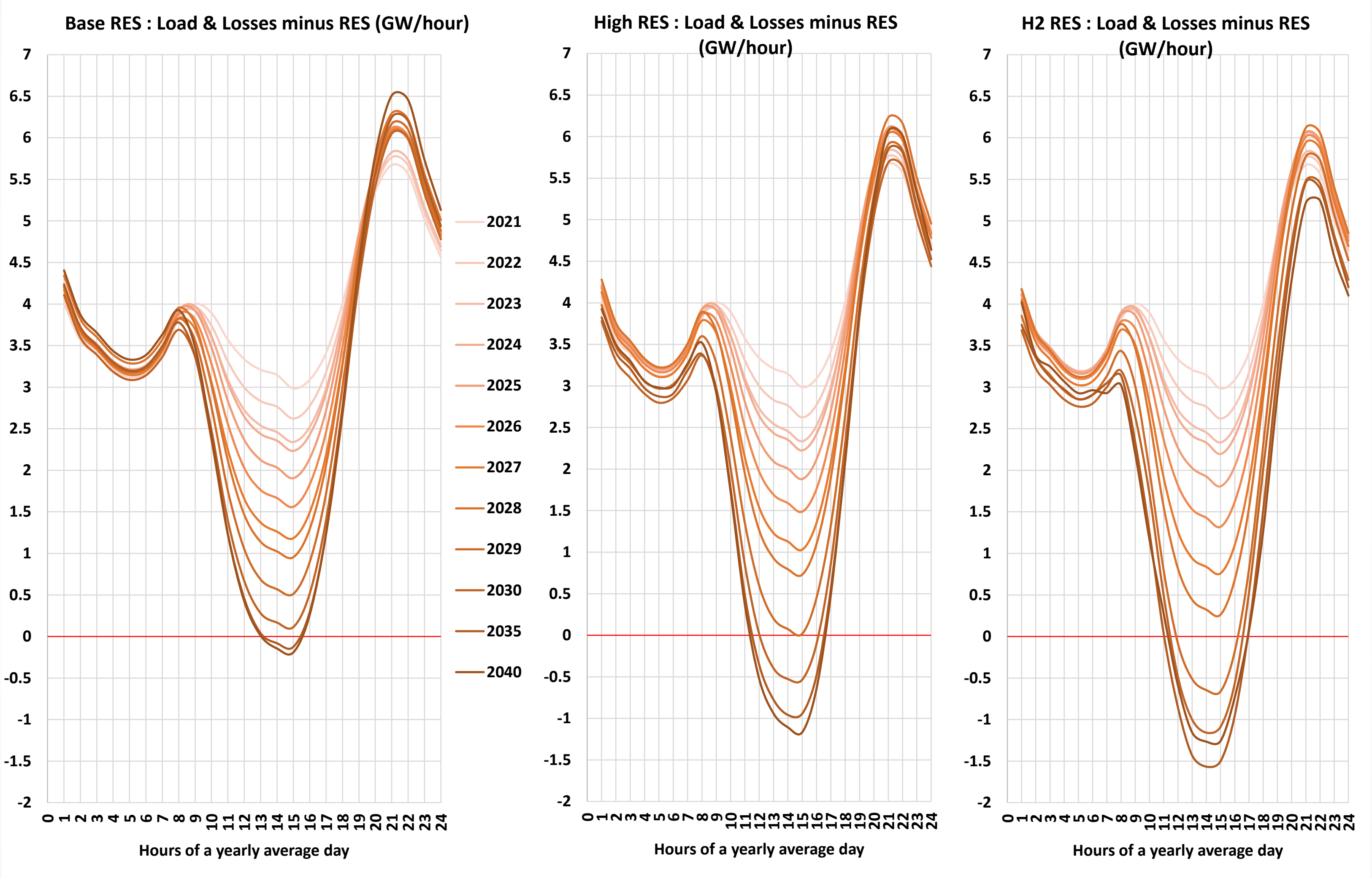
Strategy to finance storage investment :

- Subsidies and wholesale market margin, versus
- Levelized price of firm customer supply portfolio based on RES and storage



Renewable capacity projections

- Significant increase in renewable capacities to meet the energy & climate targets
- Solar PV increase more rapidly compared to wind onshore
- Emergence of wind offshore from 2029 onwards
- Few investments in other RES technologies (biomass, geothermal, solar thermal)
- RES in total net power generation reaches 75% in 2030



Net Load becoming negative as RES increases

- Net Load is Load minus variable RES, i.e., the volume met by dispatchable units
- Solar PV magnifies the gap between valleys and peak load
- Significant negative net load to address, as also dispatchable units face constraints due to technical minimum levels.
- Solutions:
  - Curtail RES, or
  - Use storage, which is essential to fill-in the valleys

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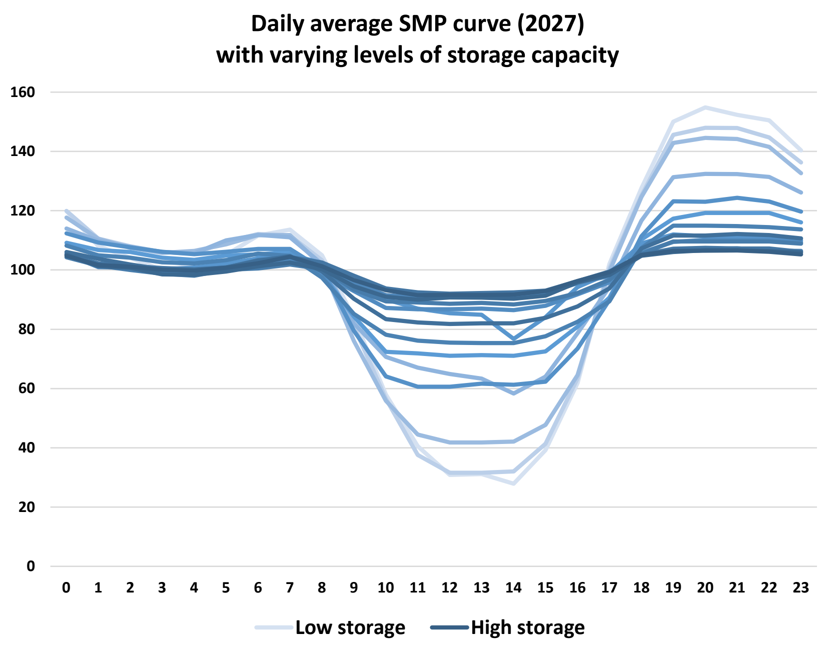
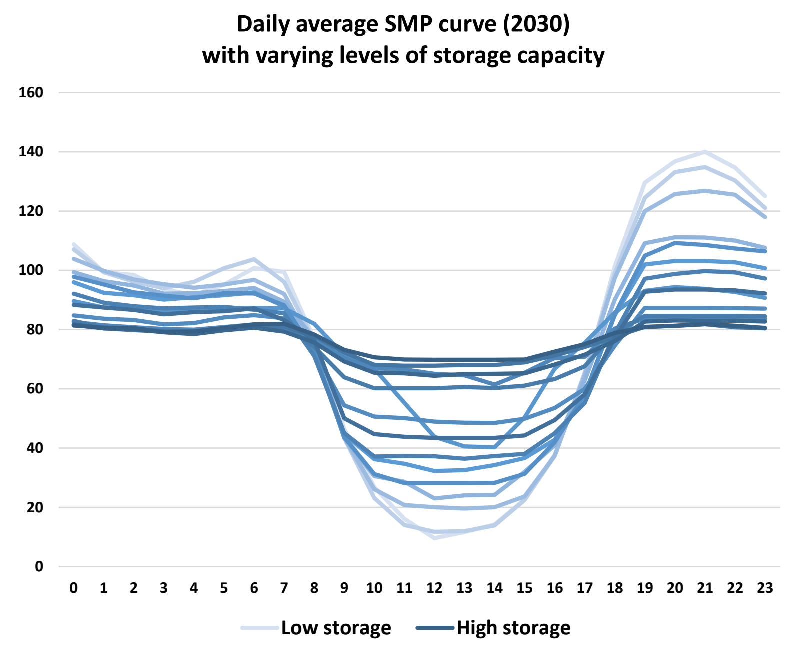
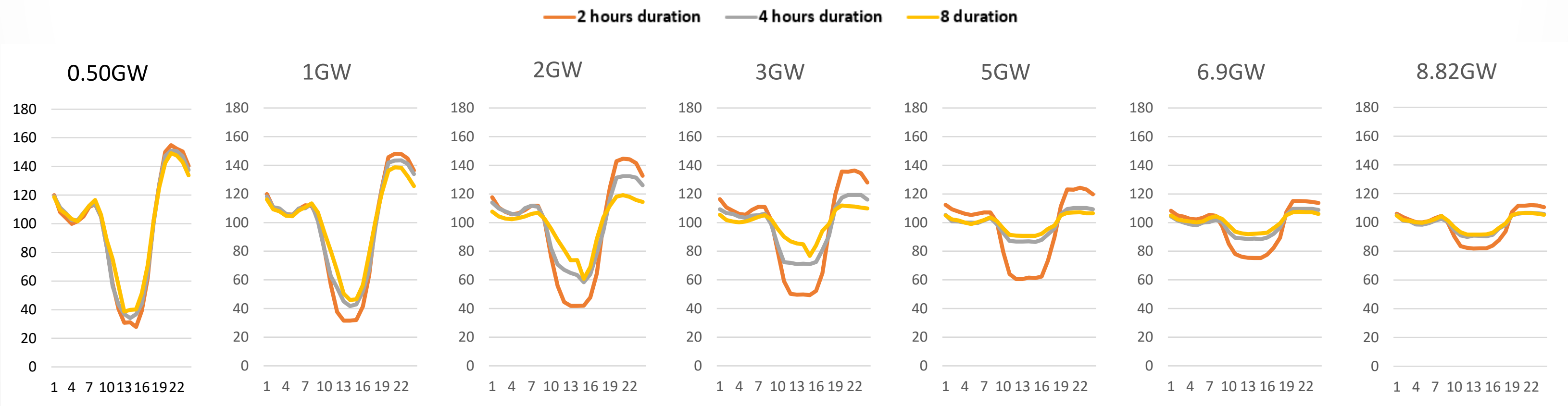






Positive externalities

- The economics of storage investment are peculiar

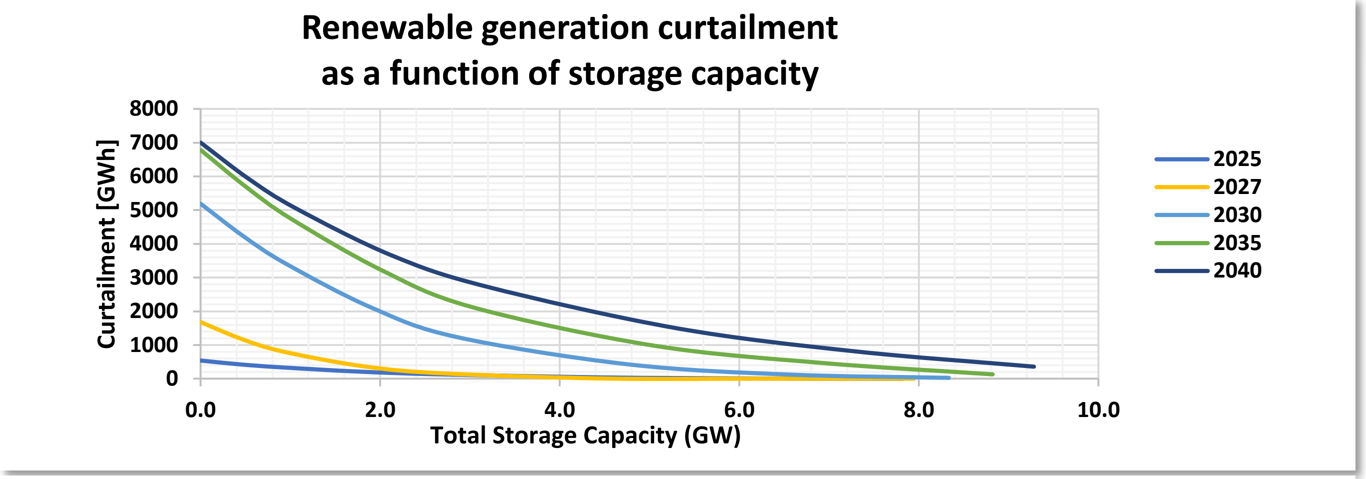
  Higher the storage investment, lower will be the differential of wholesale market prices from which storage expects financing capital costs

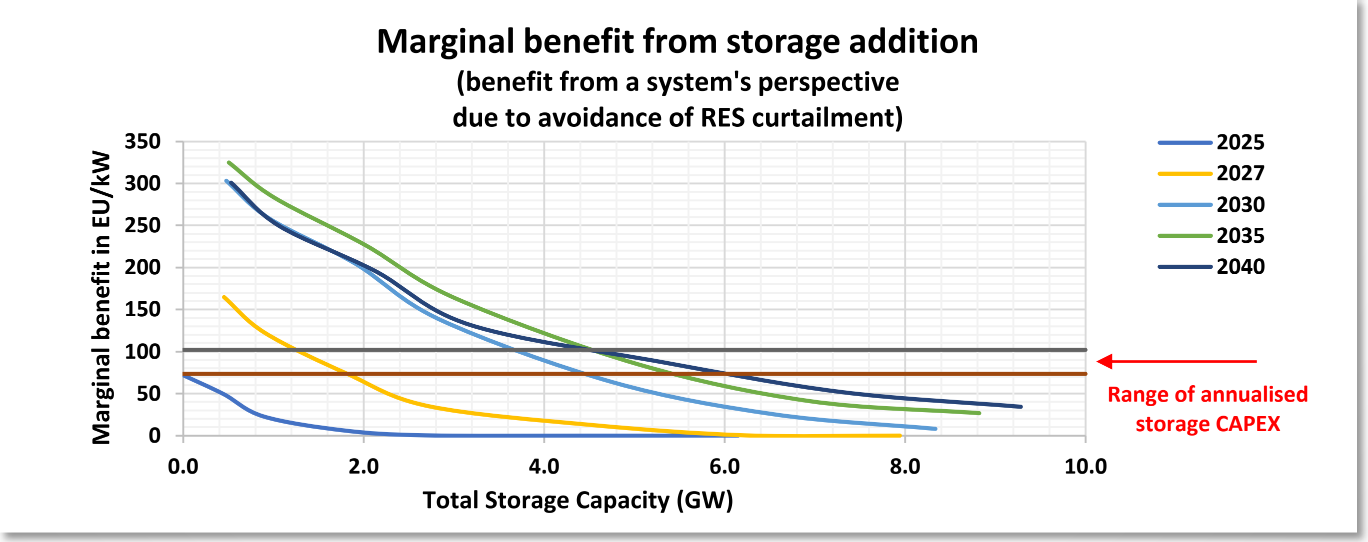
  Daily SMP curve becomes flatter, as storage capacity increases, thus price arbitraging reduces

- Technologies with high storage volumes are more likely to flatten the net load curve, thus lowering the SMP variability, than technologies with low storage volume
- The system, thus the consumer, benefits from high and voluminous storage, which acts against investor’s profitability

Optimum storage determined from cost-benefit analysis, i.e.,

- marginal benefits foe the system to avoid RES curtailment and reduce system costs compared to
- annualized CAPEX of storage (worth remunerating from a system's perspective



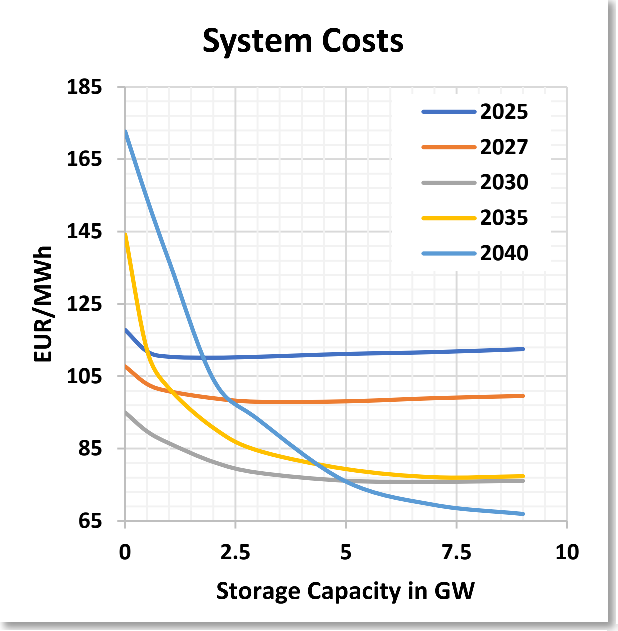


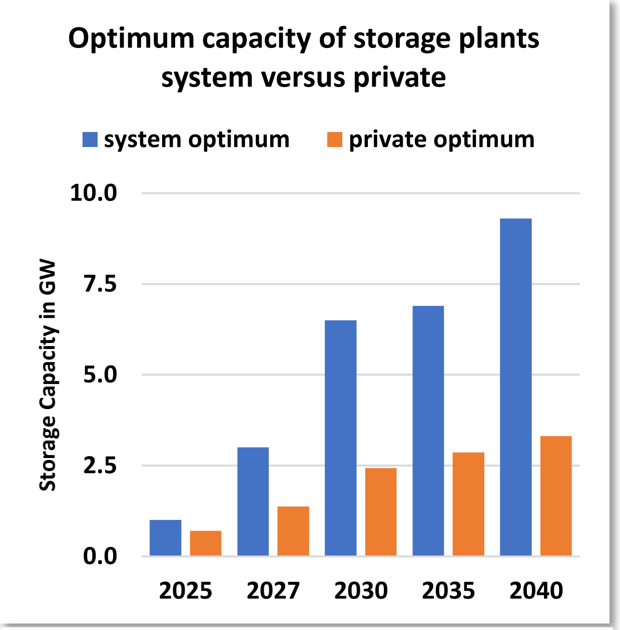
Benefits from storage measured as the avoidance of renewable curtailment

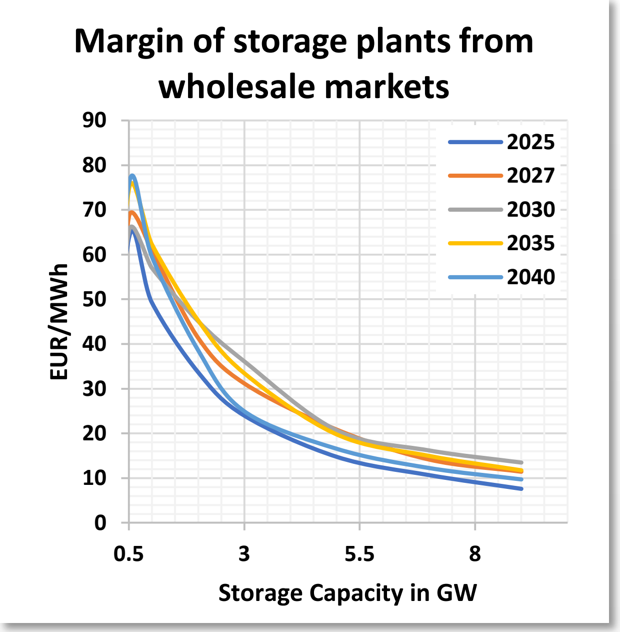
- Curtailment of RES increases when RES investment and in particular solar PV increases
- In the absence of storage plants, 5% to 14% of the renewable generation would not be absorbed by the system and should be curtailed
- Storage plants absorb electricity during net-load valleys
- The system benefits from RES curtailment avoidance: costs and reliability
- Marginal Benefit is the additional benefit by unit of increase of storage capacity, monetized assuming 150EUR/MWh curtailed

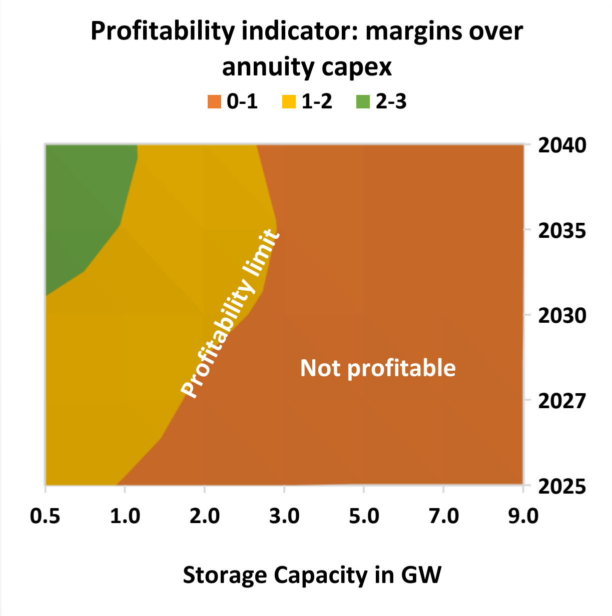
Discrepancy between system's optimum & investor's optimum

- System cost is equal to the wholesale market turnover, adding cost of reserves and curtailment costs
- System costs decrease with storage capacity up to a significant volume of storage. The system costs do not include storage CAPEX.
- But from the perspective of storage plant economics, the margin from wholesale markets decreases with storage capacity
- As the margin tends to be insufficient to finance CAPEX, optimum storage capacity for a private investor would be low
- First movers will have higher margins, but as more enter the market, the storage margins diminish



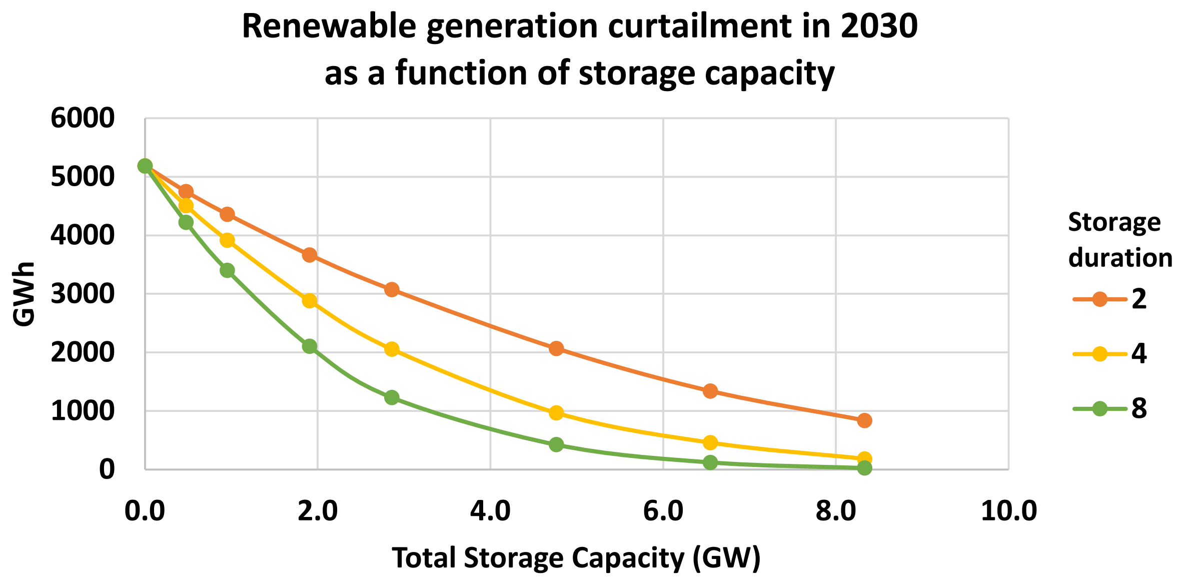


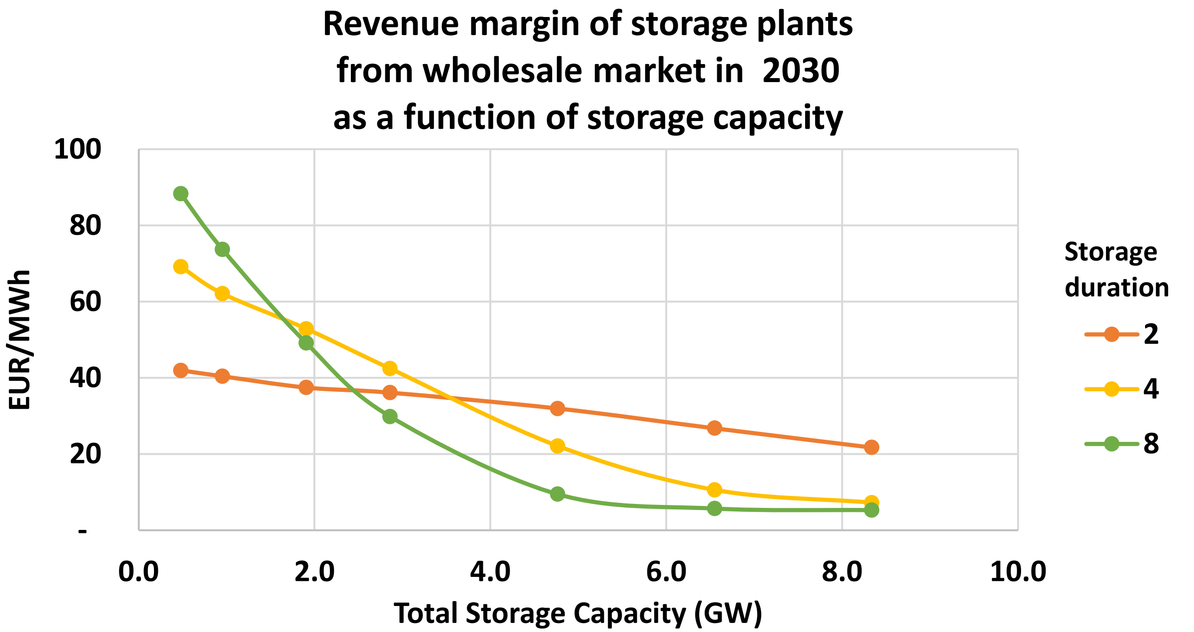




Impact of different storage technologies

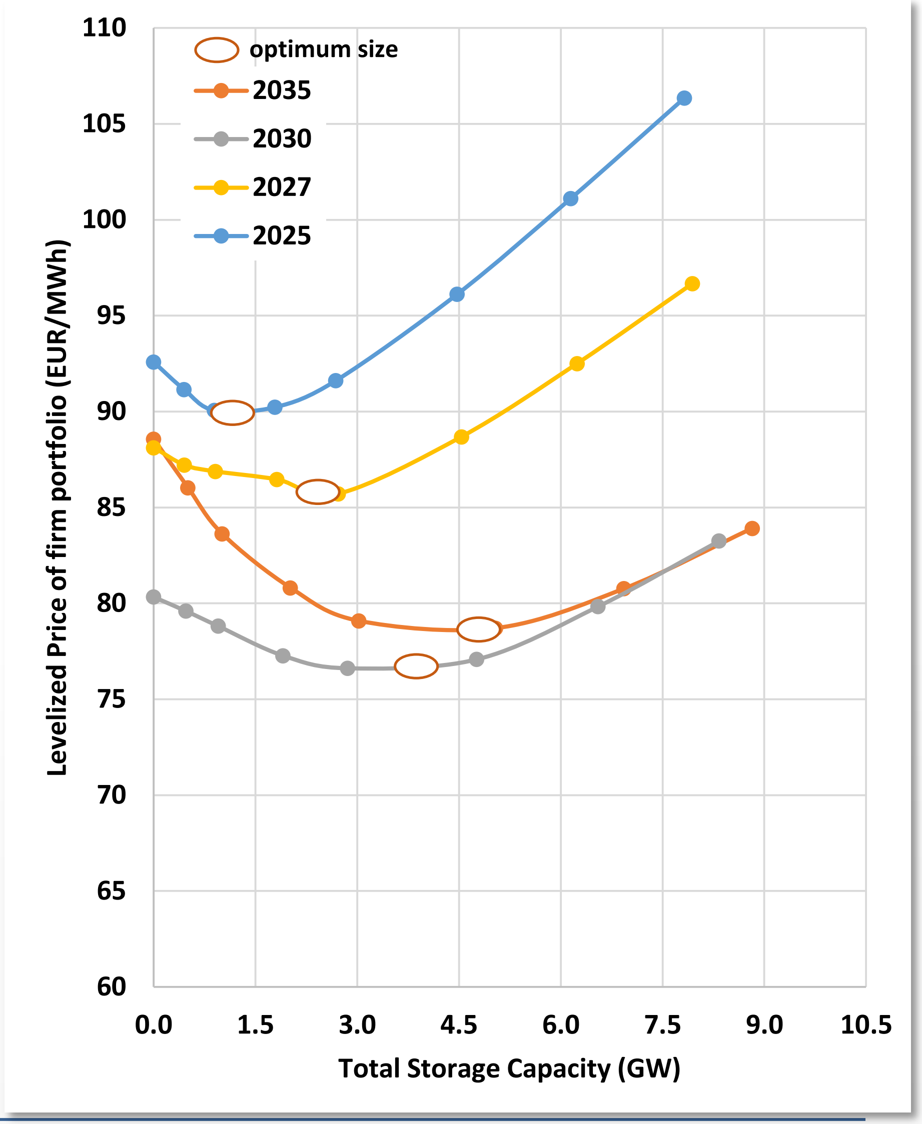
- Analysis based on many sensitivity model runs which vary the storage volume and the duration of the storage cycle
- Storage technologies with a short storage cycle duration fail to flatten the net-load curve
- Storage technologies with long storage cycle duration (e.g., 8 hours) address the RES curtailment issue more effectively
- However, as the 8-hours storage technologies reduce the price differentials, they entail lower operating margins compared to 2-hours storage





Optimum storage based on portfolio offered in the retail market

- Assumption:
  - An aggregator contracts RES and storage (as they hourly operate in the mix) and complements the bundle by purchasing system-based electricity (at SMP) to match the load profile of the average consumer (or any other client's profile)
  - The market handles the portfolio as a firm supply and the client remunerates according to a contract for economic differences
  - The price of the contract is as needed to recover portfolio's total costs, including CAPEX and OPEX of RES and storage, and the SMP-based electricity purchasing
- By performing many model runs per year with varying storage capacity levels, the analysis calculates the "levelized price of the portfolio"
- This price matches storage financing from a private perspective
- If the levelized price is competitive in the retail market, then the private storage optimum is at reach



General conclusions

A power system dominated by RES needs considerable storage capacity volumes to meet low carbon emission targets and natural gas independence at the same time

The storage volume should significantly increase with RES when the planning is from a system's, thus social, perspective

However, storage will get diminishing operating margins from the wholesale markets when storage capacity increases, as storage tends to diminish price differentials between valleys and peak load (thus reducing arbitraging)

Therefore, there is a discrepancy between social and private optimum, hence a typical positive externalities case needs regulation via public intervention

From a system's perspective, long-duration storage is more beneficial than short-duration storage, but the former reduces price differentials more than the latter and thus worsens private profitability

Under high storage volumes and high RES, the yearly variance of system marginal prices is huge, while the hourly variation of prices in an average day is very low: this is the opportunity for seasonal storage provided that an adequate storage technology is available. The future system with very high RES will need massive seasonal storage.

Highlights for Greece

The revised NECP for Greece will have to limit gas use and increase RES to comply with the REPowerEU policy plan, therefore the Greek system requires significantly higher storage volumes and a variety of technologies, mostly with a long storage duration, to accommodate the RES

System optimum for Greece indicates a need for at least 5GW storage in 2030 under the REPowerEU scenario, a scaling up by a factor of two, compared to older plans

All storage plants, with exceptions only in the short-term, will encounter operating losses in the wholesale market in the medium and long term, especially when the fleet of storage facilities is as high as needed to accommodate RES

Within private PPAs bundling RES + storage adequately, it is possible to recover all costs, including storage, as part of offering competitive prices in the retail market and firm supplies

Regarding the public support of storage investment: it is necessary in the short run to kick-start the storage industry.

However, excessive public support, especially in the longer-run, acts to the detriment of private PPAs (bundles RES + storage).

Challenging market design issues arise to make firm supply RES + storage portfolios cost-effective. Example: regulations setting the rules for the TSO to handle firm supply based on RES + storage as a usual power plant supply or a nominated bilateral contract