Department of Water Resources & Environmental Engineering, School of Civil Engineering, National Technical University of Athens

Supplementary material

Social prosperity and natural resource management: Stochastic evaluation of two operational paradigms of pumped-storage hydropower in North Euboea under renewable energy integration and energy market dynamics

Saperopoulou, D.; Kouzelis, V.; Sargentis, G.-F.; Efstratiadis, A.; Tepetidis, N.

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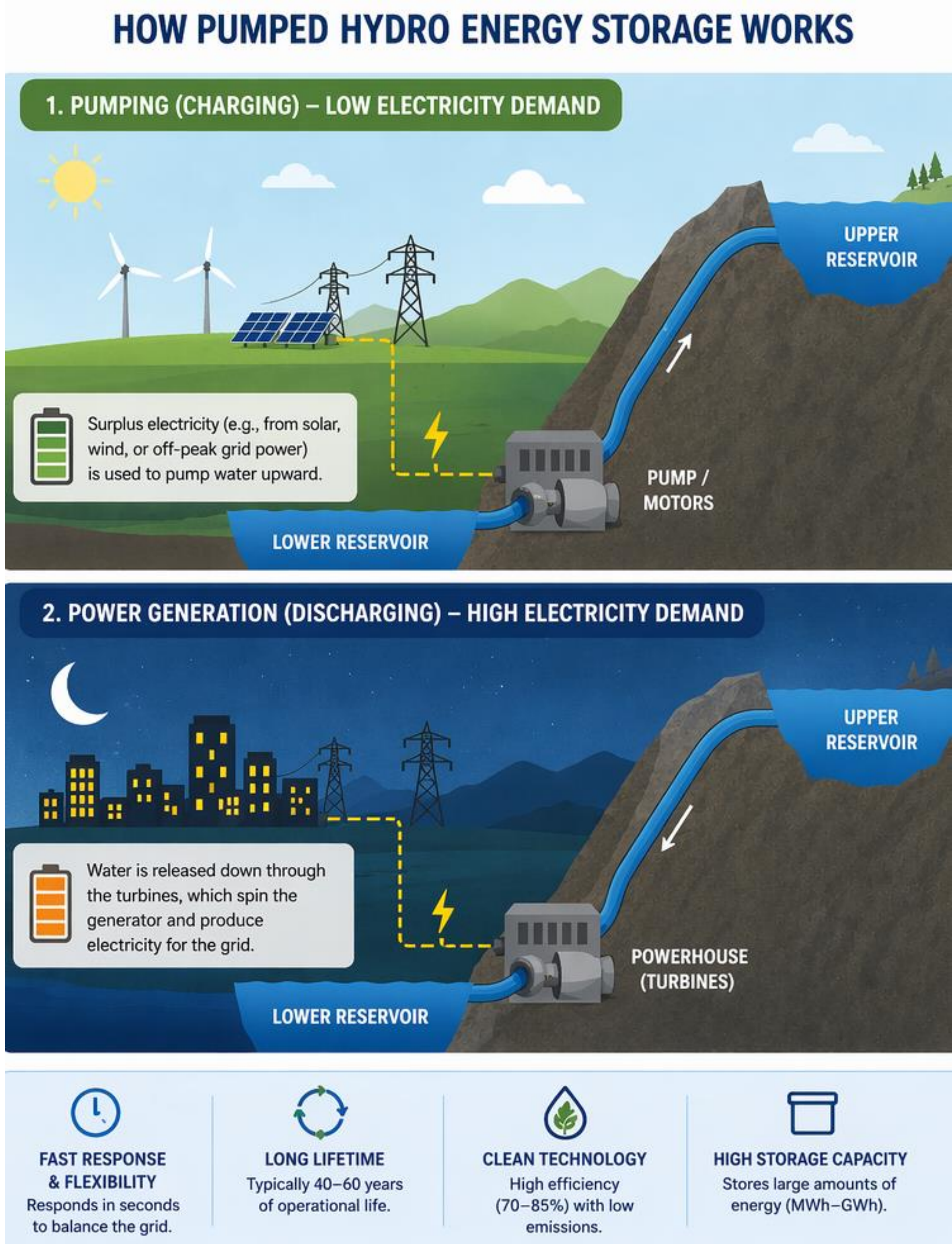
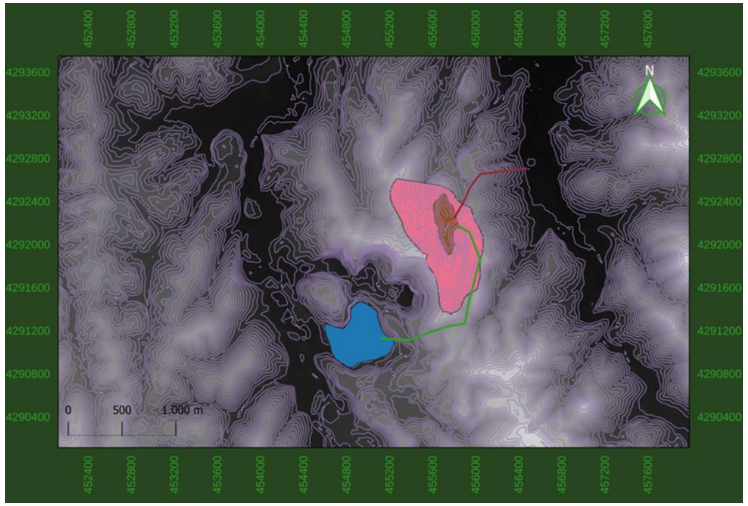
Research question

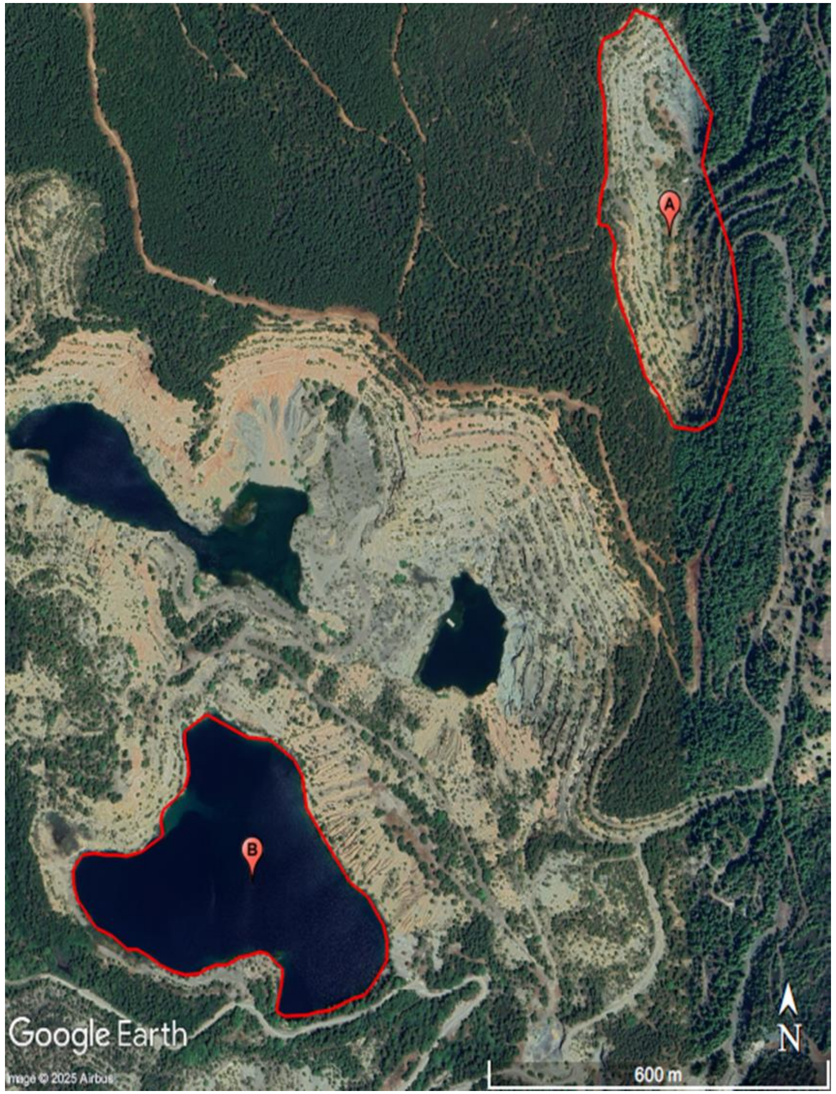
The stochastic nature of renewable energy sources (RES) and the lack of regulation at the large scale, unavoidably leads to periods of excess energy that cannot be effectively utilized, and periods of deficits. In energy markets, this oversupply is typically reflected in terms of very low electricity prices. In this study, we follow two different approaches to manage the inherent variability of RES:

1. In the first case, we seek the energy self-sufficiency of a municipality and estimate the associated unit cost, by assuming a highly conservative payback period of 20 years for the corresponding RES investment.
2. In the second case, we implement an energy balancing solution— via pumped hydropower storage (PHS) —and exploit energy price fluctuations in the electricity market. The overall management strategy is to store excess energy when prices are low and generate when prices are high. For this approach, we calculate both the project’s payback period and its expected annual return.



Case study area



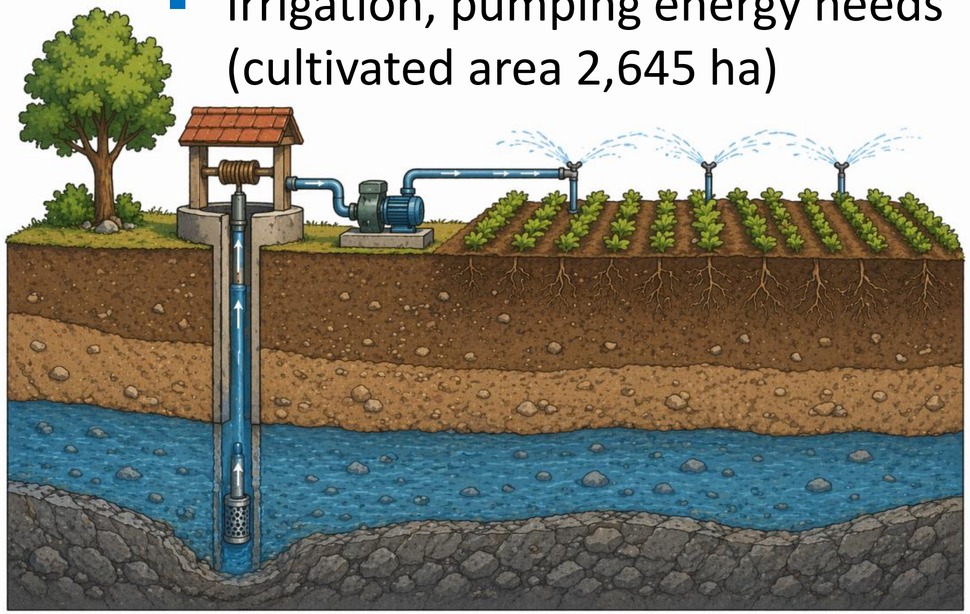


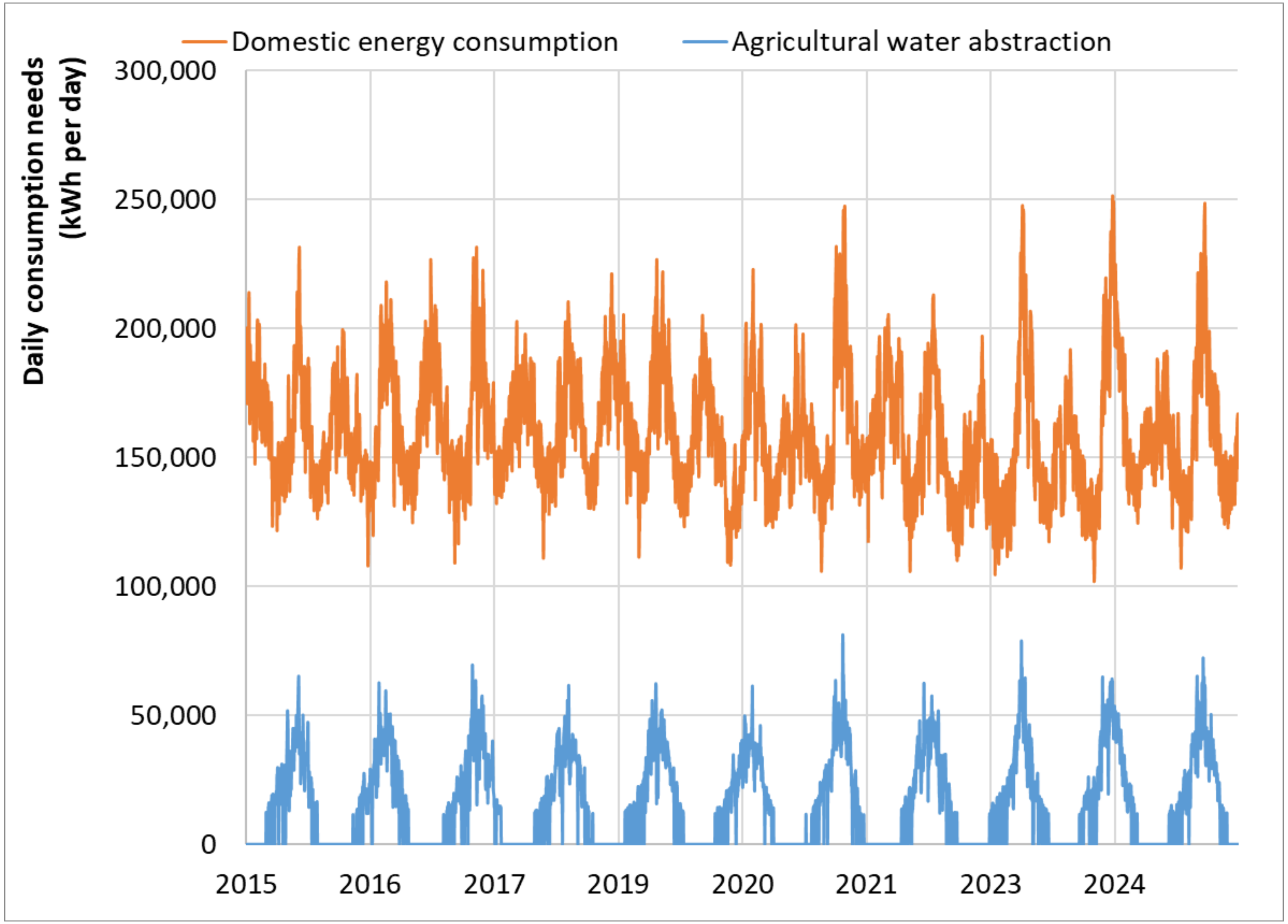
1st scenario

The energy needs

- Domestic needs
  (population 12,235 capita)

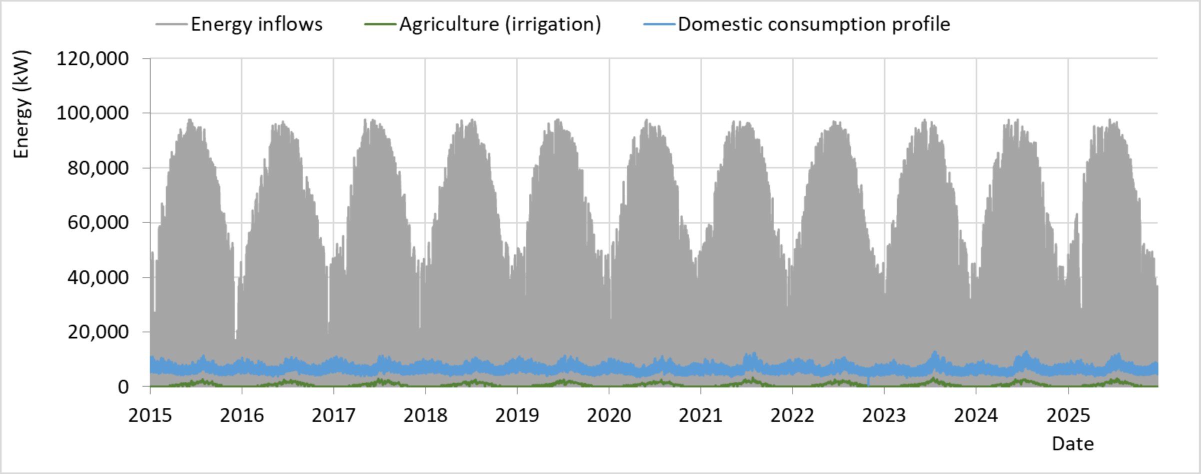
- Irrigation, pumping energy needs
  (cultivated area 2,645 ha)

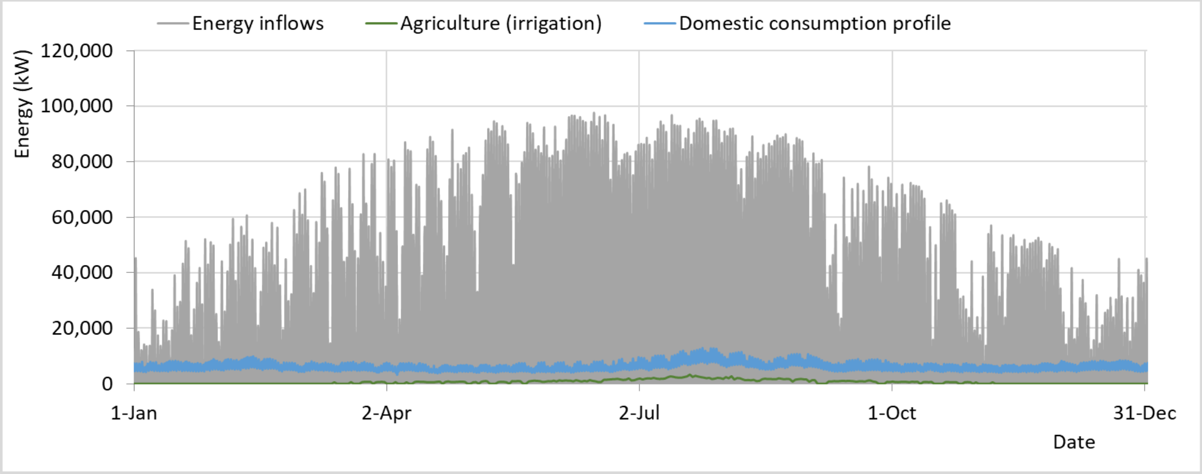


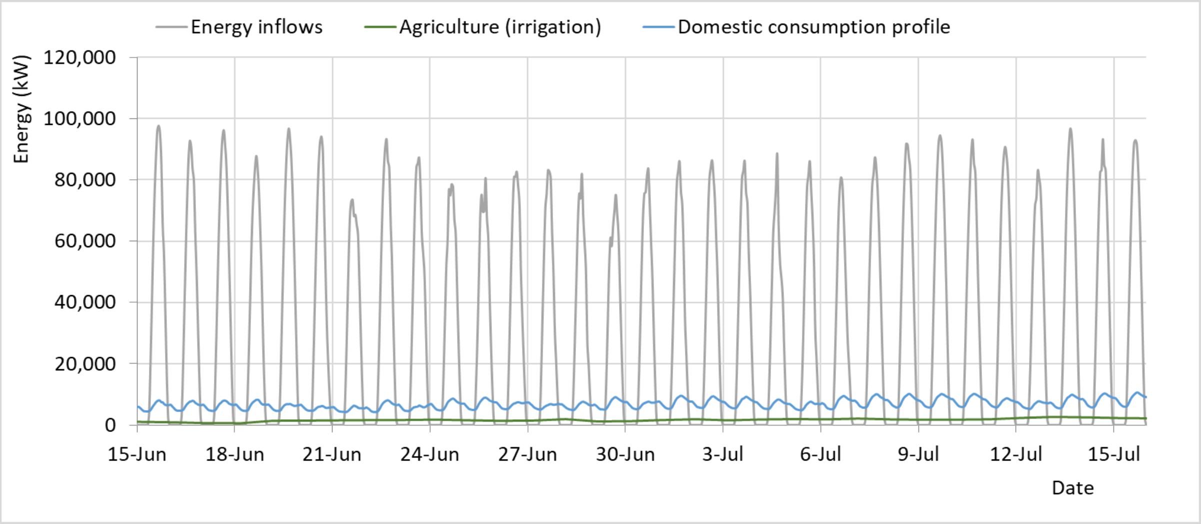


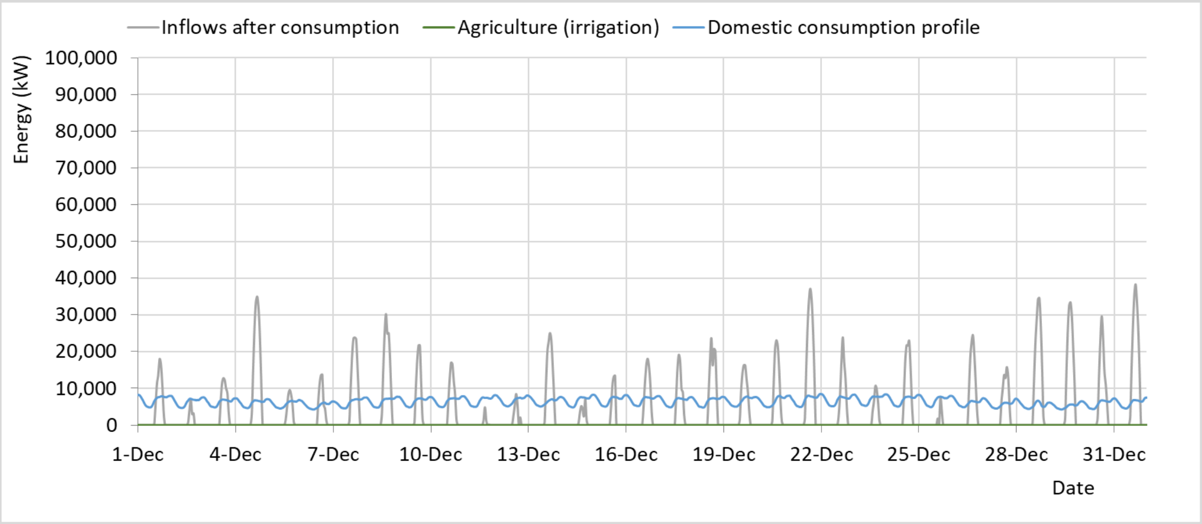
Energy production contrasted to demand

- PV panels: 45 ha
- Reliability: 41%



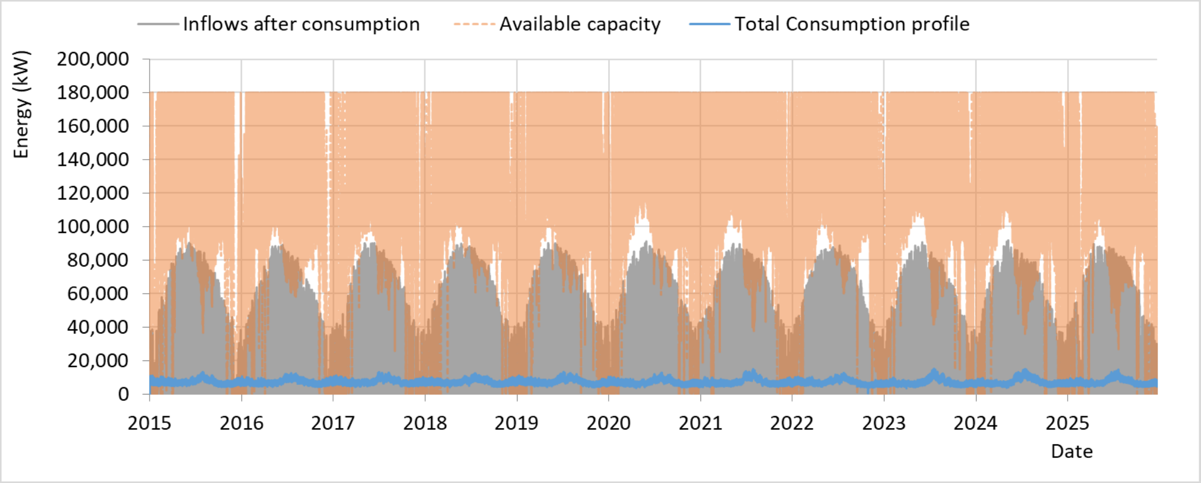


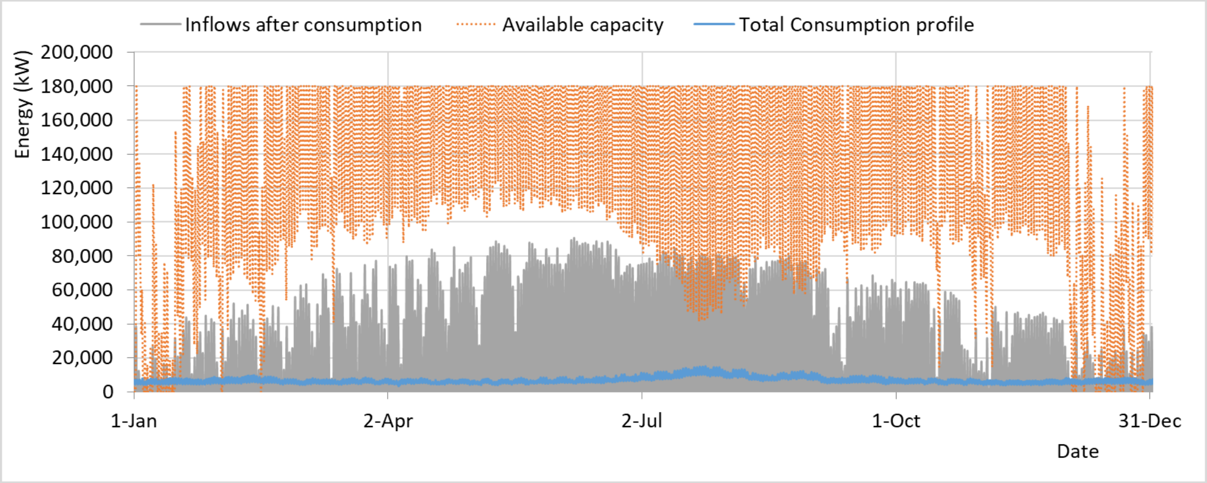


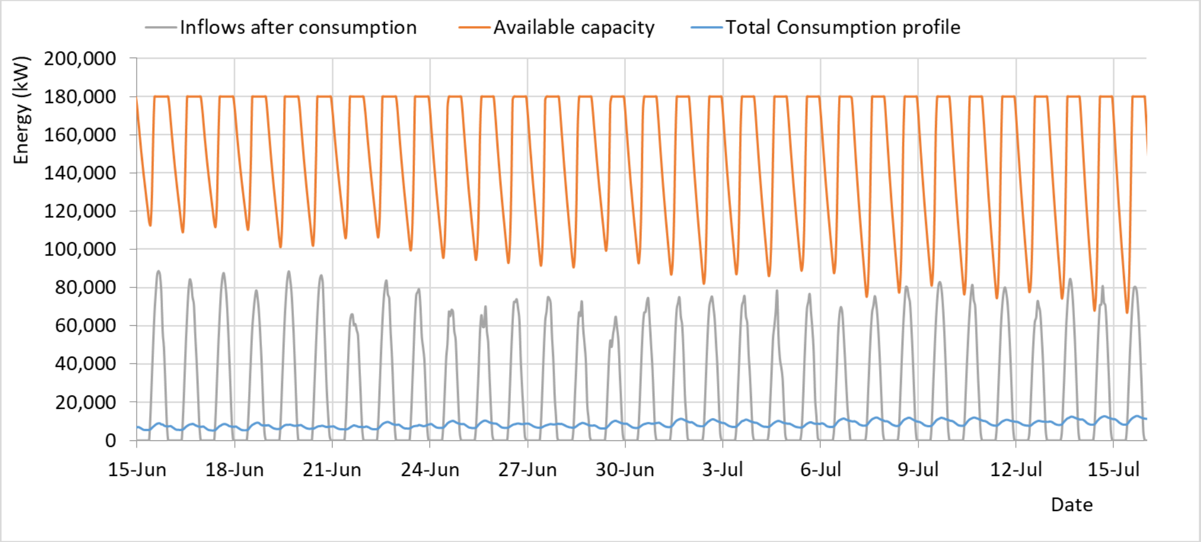


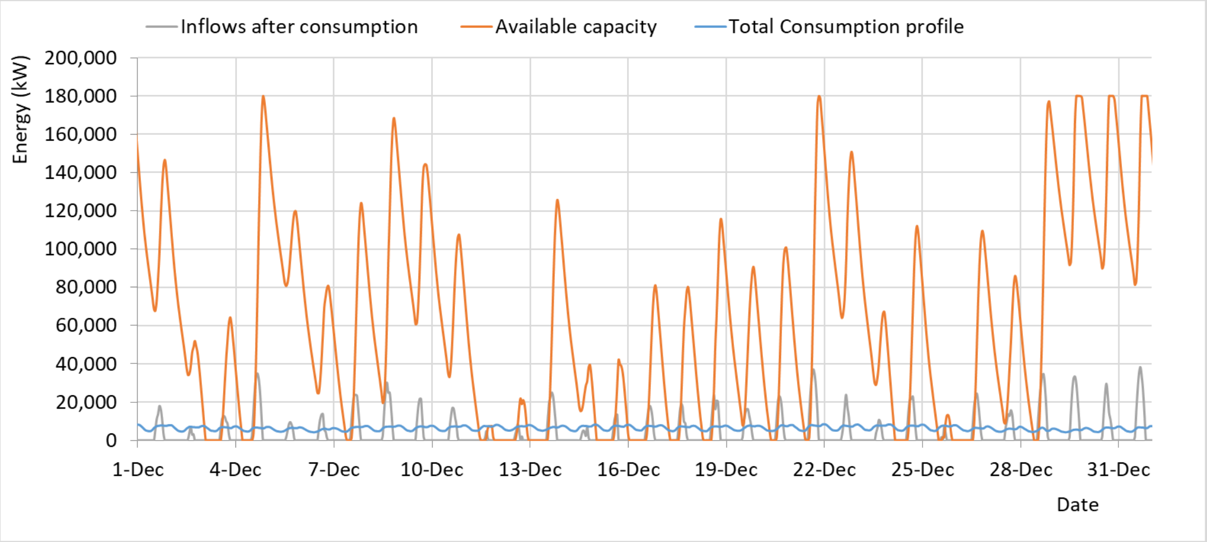
Energy regulation via PHS

- Storage capacity: 180 MWh
- Reliability: 95%



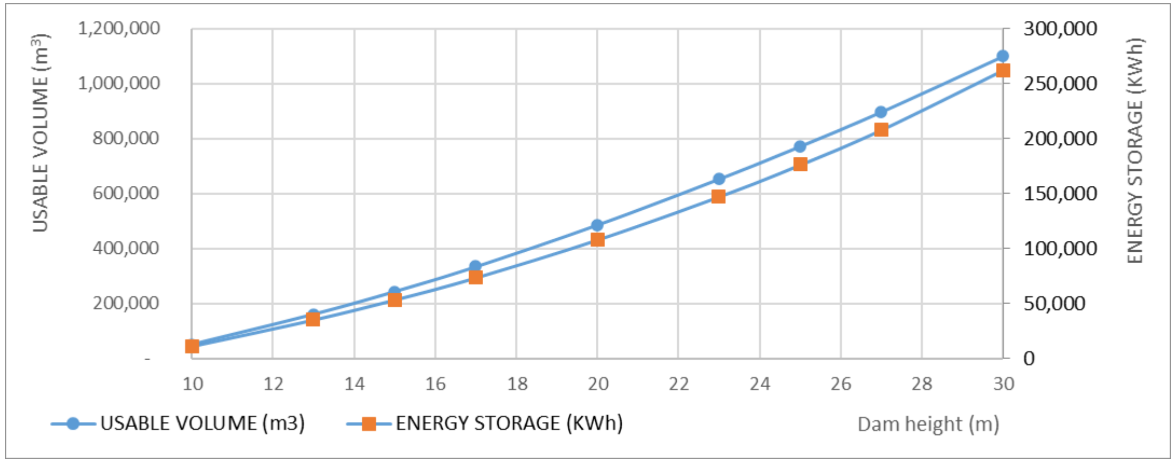






Dam height associated with power storage

DAM HEIGHT (m)	RESERVOIR CAPACITY (m^3)	USABLE VOLUME (m^3)	ENERGY STORAGE (KWh)
10	244,043	50,809	11,094
13	354,263	161,029	35,224
15	436,527	243,293	53,356
17	527,003	333,769	73,491
20	678,874	485,640	107,994
23	846,265	653,031	147,230
25	965,291	772,057	176,248
27	1,090,794	897,560	208,027
30	1,292,881	1,099,647	262,234



Optimization following the social needs

A/A	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5	TEST 6
PV area [217 W/ m2] (ha)	19	25	25	35	45	35
Total intsalled capacity (MW)	41,23	54,25	54,25	75,95	97,65	75,95
PV cost (M€)	16,49	21,7	21,7	30,38	39,06	30,38
Reservoir volume (m^3)	364,528	364,528	496,128	800,745	800,745	929,385
Reservoir cost 2024 (€/m^3)	12.87	12.87	11.59	9.84	9.84	9.35
Reservoir cost (M€)	4.7	4.7	5.7	7.9	7.9	8.7
Installed capacity (KW)	11,245	11,245	15,000	22,500	22,500	25,000
Installed capacity (M€)	11.2	11.2	15.0	22.5	22.5	25.0
Total cost (M€)	32	38	42	61	69	64

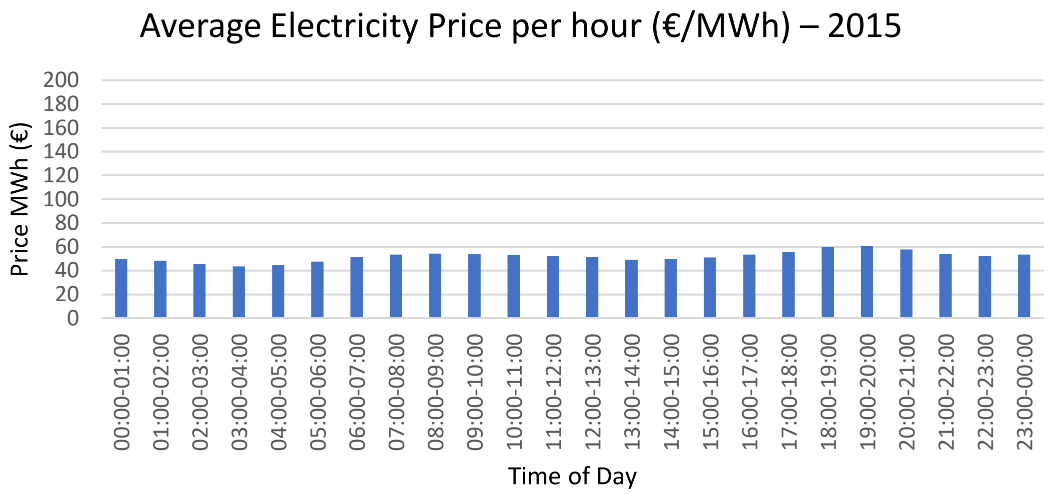
Test 5
Cost: 69 × 1,25 = 86,8 M€

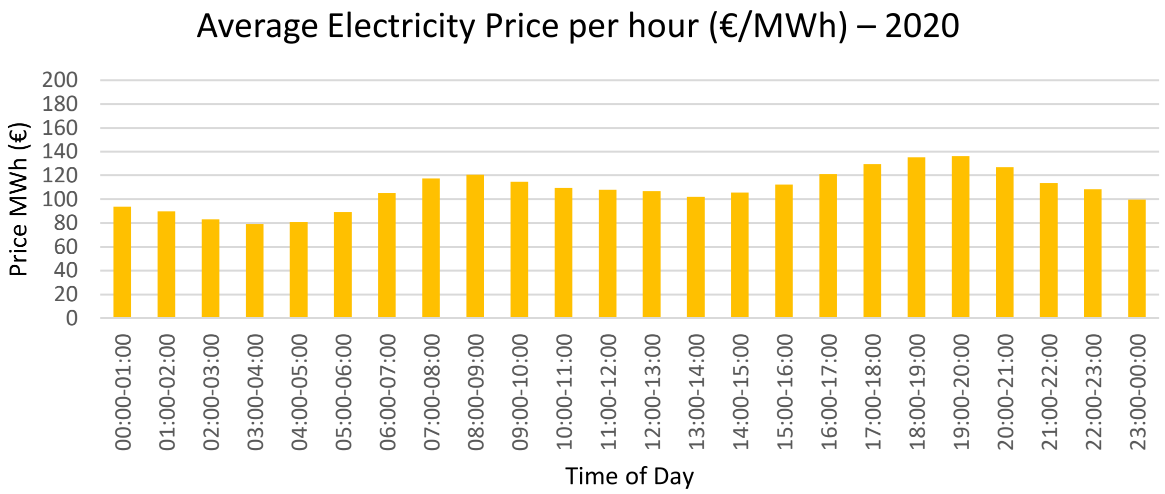
Estimated utility time: 20y

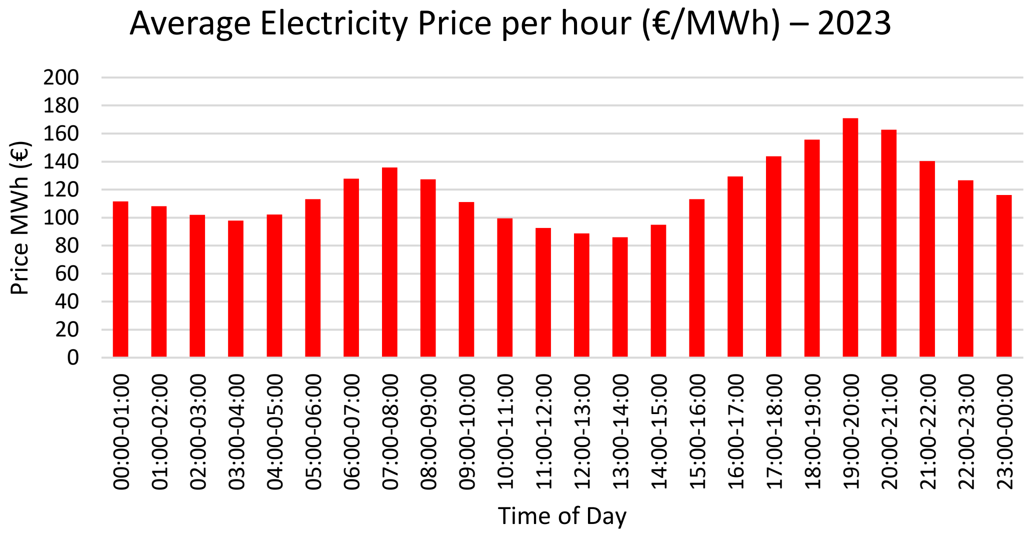
Cost €/KWh ≈ 0,07€
+ benefits from selling the surplus in the market

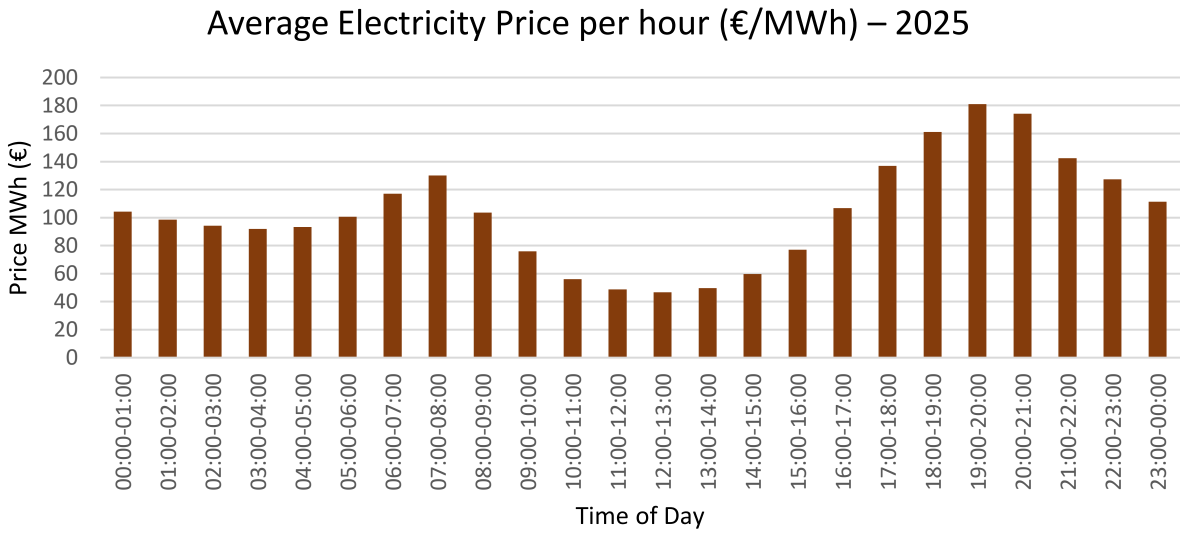
2nd scenario

The energy prices in Greece

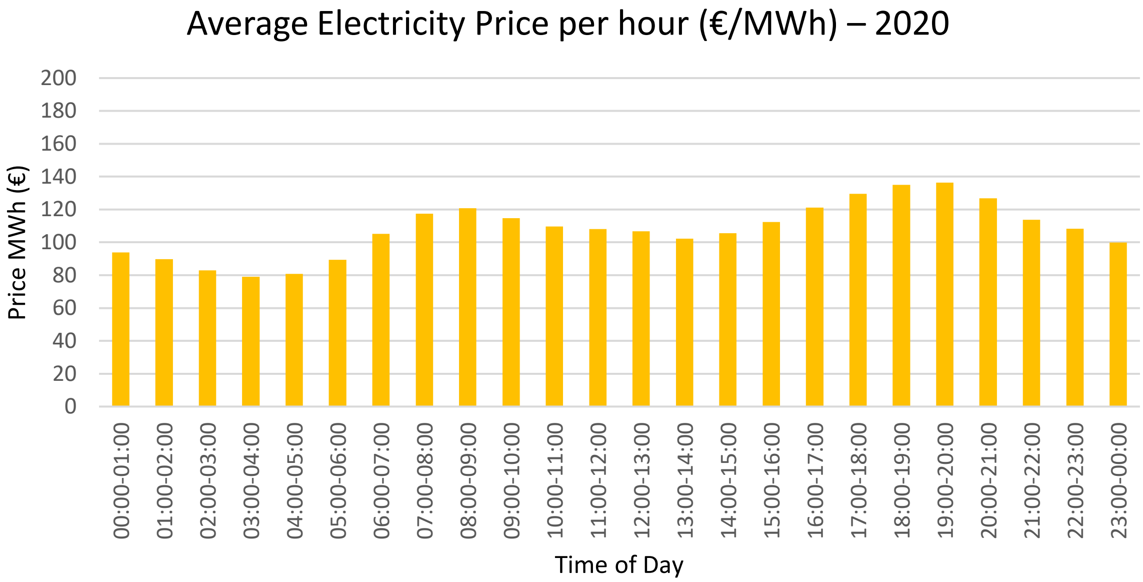


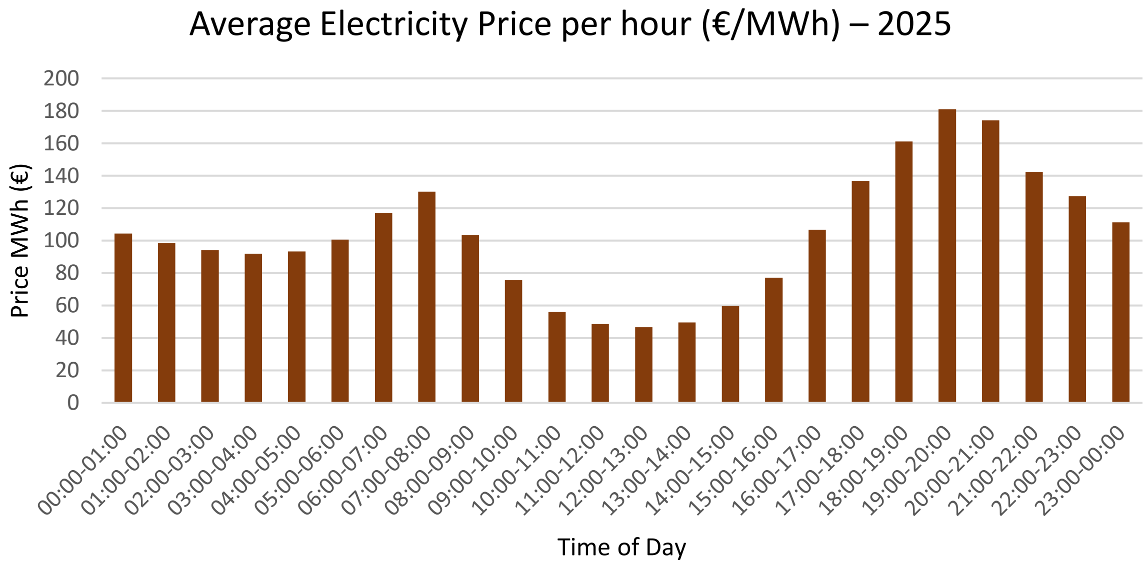


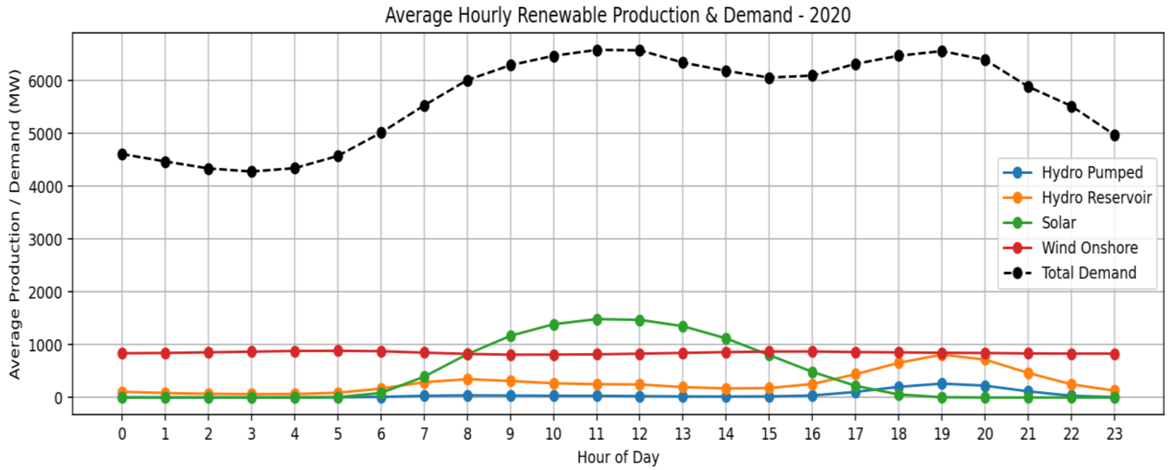


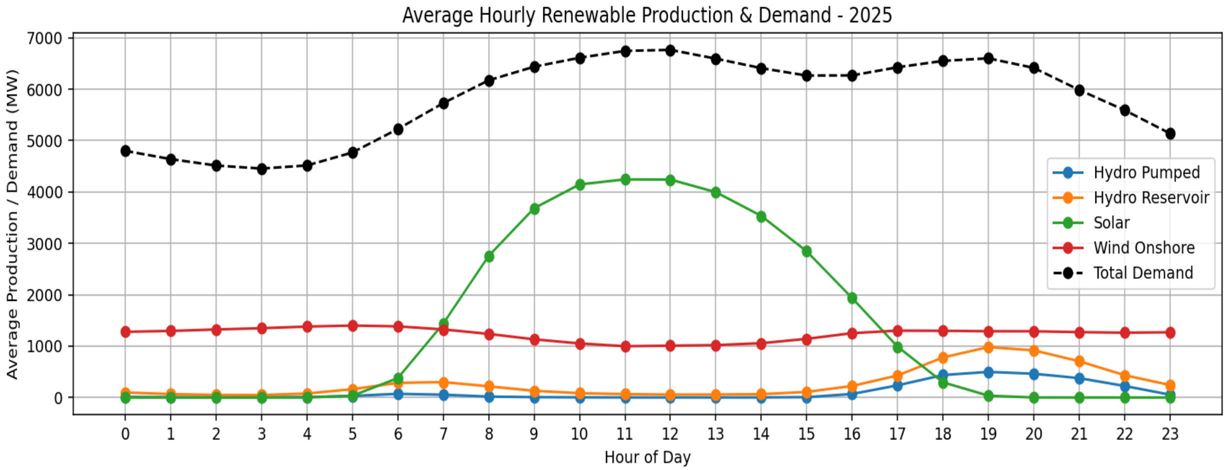


Energy production associated with energy prices

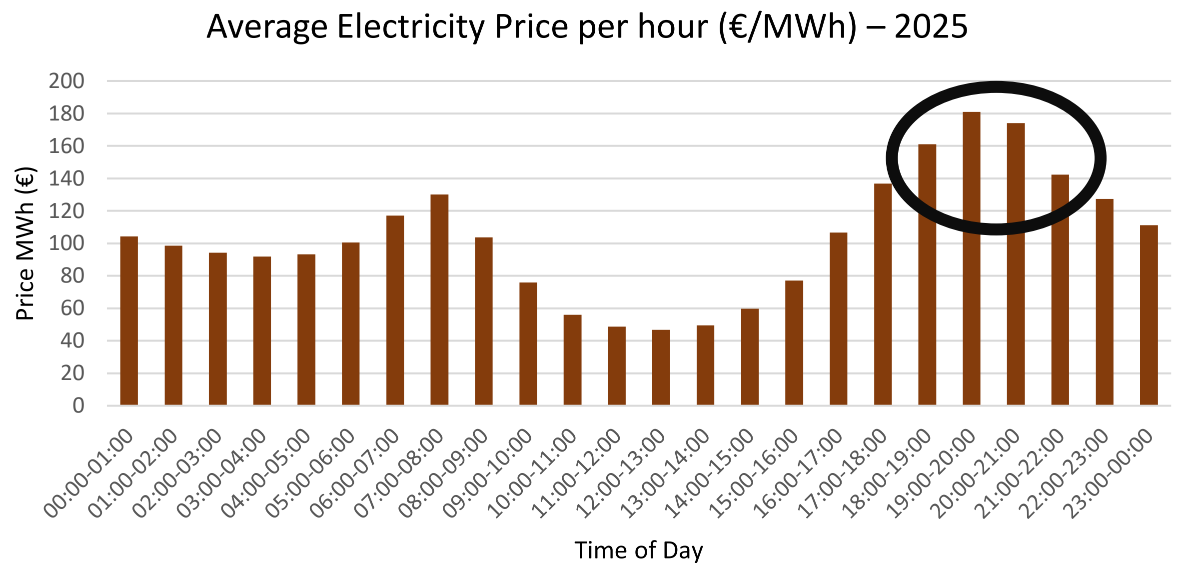


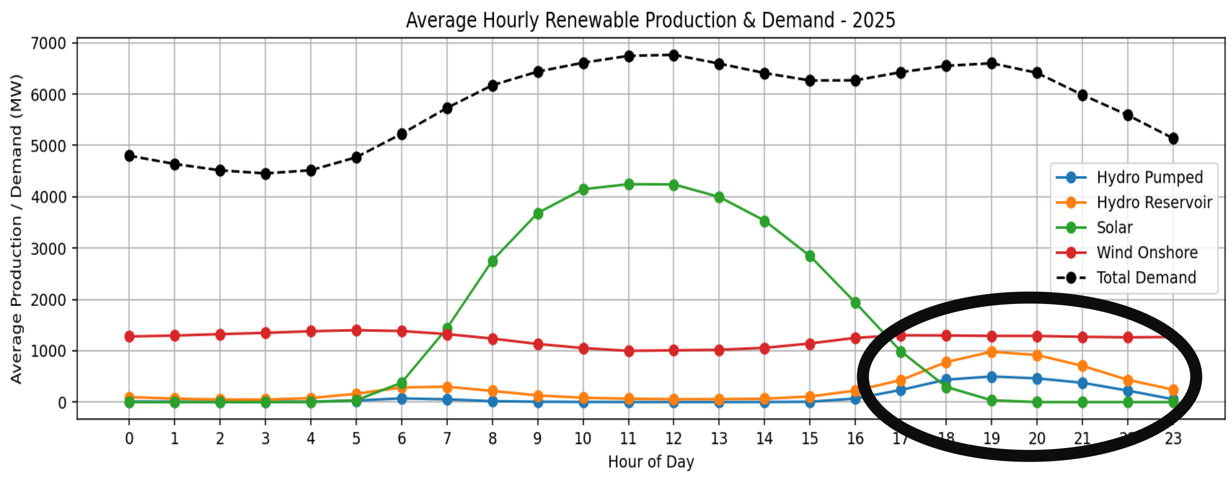






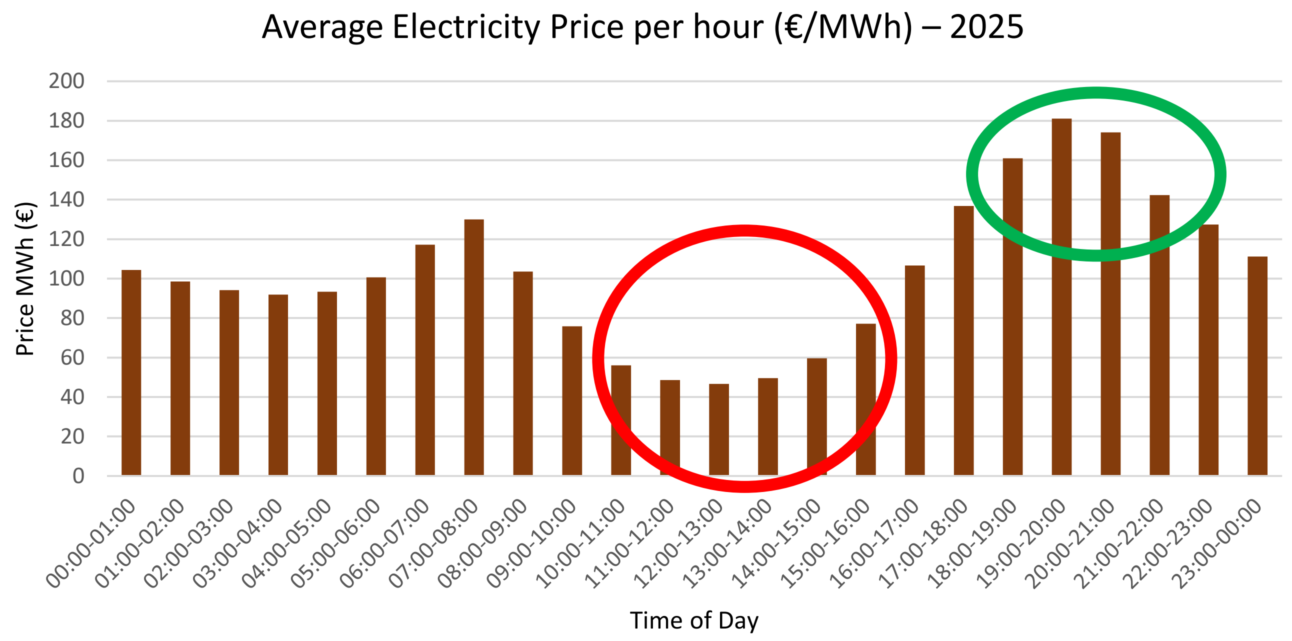
Energy regulation





- Hydroelectricity is the sole form of renewable energy that can store energy and generate electricity on demand
- Hydropower plants are essential for grid balance purposes, especially during hours when other renewables cannot meet electricity demand
- Both producers and consumers benefit from hydropower: producers can sell electricity at higher prices, while hydro generation allows to reduce the overall electricity prices in the market

Optimization according to market's dynamics



Daily operation plan of the PHS system

Hour	Average electricity price per hour 2025	Pump	Production	Expenses - Profits	Reservoir Volume
00:00-01:00	104.35			0.00	0.00
01:00-02:00	98.60			0.00	0.00
02:00-03:00	94.20			0.00	0.00
03:00-04:00	91.91			0.00	0.00
04:00-05:00	93.28			0.00	0.00
05:00-06:00	100.61			0.00	0.00
06:00-07:00	117.12			0.00	0.00
07:00-08:00	130.08			0.00	0.00
08:00-09:00	103.63			0.00	0.00
09:00-10:00	75.87			0.00	0.00
10:00-11:00	56.09	PUMP		-1224.65	0.06
11:00-12:00	48.66	PUMP		-1062.46	0.13
12:00-13:00	46.70	PUMP		-1019.57	0.19
13:00-14:00	49.54	PUMP		-1081.68	0.26
14:00-15:00	59.70	PUMP		-1303.55	0.32
15:00-16:00	77.15	PUMP		-1684.48	0.39
16:00-17:00	106.67			0.00	0.39
17:00-18:00	136.83			0.00	0.39
18:00-19:00	161.04		PRODUCTION	3623.34	0.29
19:00-20:00	181.02		PRODUCTION	4072.90	0.19
20:00-21:00	174.08		PRODUCTION	3916.76	0.10
21:00-22:00	142.38		PRODUCTION	3203.66	0.00
22:00-23:00	127.39			0.00	0.00
23:00-00:00	111.25			0.00	0.00
Sum				7440.25	

- Pumping for 6 hours at the lowest electricity prices
- Generation for 4 hours at the highest electricity prices

Optimization according to market dynamics

If the project were designed purely to maximize profits, we would need to modify the installed power capacity and reduce the reservoir size.

This approach would significantly increase profitability, lower the initial capital investment, and ultimately shorten the payback period.

	TEST 1	TEST 2	TEST 3	TEST 4
Reservoir storage capacity (m^3)	364,528	496,128	800,745	929,385
Reservoir cost 2024 (€/m^3)	12.87	11.59	9.84	9.35
Reservoir cost (M€)	4.7	5.7	7.9	8.7
Installed capacity(KW)	24,070	32,760	52,880	61,380
Installed capacity (M€)	24.07	32.76	52.88	61.38
Profits per day (€)	8,883.67	12,090.81	19,514.43	22,649.43
Total cost (M€)	28.76	38.50	60.76	70.07
Payback period (years)	8.87	8.73	8.53	8.48

Conclusions

- The stochastic nature of renewables requires large-scale storage solutions, so that a larger share of the generated energy can be effectively utilized.
- Through the first scenario we examined, we demonstrated that such storage projects can provide energy autonomy to local communities at a very low cost per kWh.
- Market dynamics also highlight this limitation of renewable energy sources, as low electricity prices are often associated with oversupply from photovoltaic generation.
- Energy storage projects operating under the second scenario can be both useful for the society and economically attractive, since they offer short payback periods.
- Nevertheless, this market-based approach depends on the existence of a specific electricity pricing structure in the long run, which is not guaranteed to remain in place throughout the entire lifetime of the project.

Contact:

- Danai Saperopoulou dansap4967@gmail.com
- Viktoras Kouzelis vick.kzl09@gmail.com
- Andreas Efstratiadis andreas@hydro.ntua.gr
- G.-Fivos Sargentis fivos@itia.ntua.gr
- Nikolaos Tepetidis nikolaostepetidis@mail.ntua.gr

References (1)

1. Angelidis, M. A., Arvanitidis, I., Ioannidis, R., and Sargentis, G.-F.: Spatial Analysis of Desalination Energy Demand in Greece: Feasibility Zones from the Coastline for Water-Energy Planning, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-8222, https://doi.org/10.5194/egusphere-egu26-8222, 2026.
2. Arvanitidis, I. and Sargentis, G.-F.: Spatial Indicators of Dynamic Self-Sufficiency and Resilience in the Water–Energy–Food Nexus. Case study: Small Rural Village in North Euboea, Greece, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-14761, https://doi.org/10.5194/egusphere-egu26-14761, 2026.
3. Koutsoyiannis, D. Scale of water resources development and sustainability: Small is beautiful, large is great, Hydrological Sciences Journal, 56 (4), 553–575, 2011. https://doi.org/10.1080/02626667.2011.579076
4. Maravelakis, M., Iliopoulou, T., and Sargentis, G.-F.: The Water-Energy-Food Nexus in Naxos Island: Enhancing Self-Sufficiency Through Traditional Techniques, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-12878, https://doi.org/10.5194/egusphere-egu26-12878, 2026.
5. Markantonis, D.; Sargentis, G.-F.; Dimitriadis, P.; Iliopoulou, T.; Siganou, A.; Moraiti, K.; Nikolinakou, M.; Meletopoulos, I.T.; Mamassis, N.; Koutsoyiannis, D. Stochastic Evaluation of the Investment Risk by the Scale of Water Infrastructures—Case Study: The Municipality of West Mani (Greece). World 2023, 4, 1-20. https://doi.org/10.3390/world4010001
6. Sargentis G.-F.; Markantonis D. Water-energy-food nexus and its stochastic dynamics: case study Greece. Discover Sustainability, Springer-Nature, 2024, 5, 511. https://doi.org/10.1007/s43621-024-00751-z
7. Sargentis, G.-F.; Ioannidis, R.; Karakatsanis, G.; Sigourou, S.; Lagaros, N.D.; Koutsoyiannis, D. The Development of the Athens Water Supply System and Inferences for Optimizing the Scale of Water Infrastructures. Sustainability 2019, 11, 2657. https://doi.org/10.3390/su11092657.
8. Sargentis G.-F.; Ioannidis R.; Dimitriadis,P.; Malamos N.; Lyra O.; Kitsou O.; Kougkia M.; Mamassis N.; Koutsoyiannis D. Energy Self-Sufficiency in Rural Areas, Case Study: North Euboea, Greece. Advances in Environmental and Engineering Research, 2024, 2766-6190. https://doi.org/10.21926/aeer.2404025
9. Sargentis, G.-F. Issues of Prosperity: Stochastic Evaluation of Data Related to Environment, Infrastructures, Economy and Society. Ph.D. Thesis, National Technical University of Athens, School of Civil Engineering, Athens, Greece, 2022. https://doi.org/10.5281/zenodo.6785733

References (2)

10. Sargentis G.-F.; Markantonis D. Water-energy-food nexus and its stochastic dynamics: case study Greece. Discover Sustainability, Springer-Nature, 2024, 5, 511. https://doi.org/10.1007/s43621-024-00751-z
11. Sargentis G.-F.; Kougkia M. Vulnerabilities of water-energy and food nexus in cities of digital era. Insight - Civil Engineering. 2024, 7(1): 608. https://doi.org/10.18282/ice.v7i1.608
12. Sargentis, G.-F. Fragility in Human Progress. A Perspective on Governance, Technology and Societal Resilience Front. Complex Systems 2025. https://doi.10.3389/fcpxs.2025.1609467
13. Sargentis G.-F.; Ioannidis R.; Mamassis N.; Zoukos V.; Koutsoyiannis D. A Review of the Energy Policy in Greece in the Last 50 Years and Its Implications for Prosperity. Clean Energy and Sustainability 2024, 2, 10021. https://doi.org/10.70322/ces.2024.10021
14. Sargentis, G.-F.; Koutsoyiannis, D. The Function of Money in Water–Energy–Food and Land Nexus. Land 2023, 12, 669. https://doi.org/10.3390/land12030669
15. Sargentis G.-F., Baroudi S, Angelidis M.-A., Arvanitidis I, Mamassis N, Ioannidis R. Restoring the Resilience of Water-Energy-Food Nexus Based on Desalination through Biomass Management: Case Study West Mani, Greece. Adv Environ Eng Res 2026; 7(1): 005; http://dx.doi.org/10.21926/aeer.2601005.
16. Sargentis G.-F.; Arvanitidis I.; Angelidis M.-A. Geospatial Analysis of Energy Requirements for Supplying Desalinated Seawater to the Greek Territory. Clean Energy and Sustainability 2026, 4, 10001. https://doi.org/10.70322/ces.2026.10001
17. Sargentis G.-F.; Papadodimas N.; Benekos I.; Katsoulakos N.M.; Dimitriadis P.; Tepetidis N.; Ioannidis R.; Arvanitidis I.; Angelidis M.-A.; Saperopoulou D.; Laoutaris G.-D.; Maravelakis M.; Amiralis O.-I.; Markantonis D.; Alexandridou A.; Mamassis N.; Koutsoyiannis D. Stochastic Assessment of Renewable Energy Reliability: A Case Study of North Euboea, Greece. Journal of Energy and Power Technology 2026; 8(2): 008; http://dx.doi.org/10.21926/jept.2602008.
18. Zisos, A; Sakki G.-K.; Efstratiadis A., Mixing renewable energy with pumped hydropower storage: Design optimization under uncertainty and other challenges, Sustainability 2023, 15 (18), 13313, doi:10.3390/su151813313.