Mapping of the Cyprus energy storage potential. Implications in the penetration of renewables and the operational mode of the conventional units

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1. Introduction

From previous study – presentation:

- Pumped-Hydro (PH) the most suitable storage technology to achieve high RES penetration in the power system of Cyprus, avoiding unnecessary RES energy curtailment
- Mature and technologically advanced energy storage technology
- Existing water reservoirs in Cyprus provide an important potential for energy storage application at relatively reduced cost providing many side benefits

The main objective of the specific study:

- **Sizing and siting of storage** and/or hybrid plants in Cyprus. **A map based data base** was prepared including all the main technical parameters of the proposed plant
- Estimate **possible implications** of the operation of storage/hybrid plants together with smart operation algorithms for the whole Cyprus transmission grid
- **To simulate** the grid's behavior in order to quantify the impact of various storage/RES scenarios

2. Assessing the underlying potential of storage in Cyprus (1/4)

For appropriate sizing and siting selection, the following constraints were taken into account:

Technologies	Sub-technologies	Energy Capacity	Power installed capacity	Storage duration at full power	Round-trip efficiency (%)	Response Time	Level of maturity (TRL, 3: very mature, 1: not mature)
Mechanical	Pumped Hydro Storage (PHS)	1 100 GWh	100 MW 1 GW	several hours	80	Seconds - Minutes	3
	Compressed Air Energy Storage (CAES)	10 MWh 10 GWh	10 300 MW	several hours	45 60	Minutes	2
	Flywheel	5 10 kWh	1 20 MW	5 30 minutes	85	Minutes	1.5
Electro Chemical	Lithium ion batteries	< 10 MWh	< 50 MW	10 min to 4 hours	86	Milliseconds	2
	Redow flow batteries Zn Fe	< 100 MWh	< 10 MW	some hours		Milliseconds	2
	Redox flow batteries Vanadium	< 100 MWh	< 10 MW	some hours	70	Milliseconds	2
	Redox flow batteries Zn Br	< 100 MWh	< 10 MW	some hours	70	Milliseconds	2
Electrical	Superconducting Magnetic Energy Storage (SMES)	1 10 kWh	100kW 5MW	1 100 seconds	>90	Milliseconds	1.5
Chemical	Power to Gas (H2)	up to 100 GWh	1kW 1 GW	several hours several months	20 40	Minutes	1

Technologies	Sub-technologies	Services provided	Major technological issues experienced
Mechanical	Pumped Hydro Storage (PHS)	Renewables integration shifting, Load levelling, Frequency regulation, Voltage support	Geographical constraint
	Compressed Air Energy Storage (CAES)	Renewables integration shifting, Load levelling, Frequency regulation, Voltage support	Low efficiency, Geographical constraint
	Flywheel	levelling	power for energising magnetic bearings
ElectroChemical	Lithium ion batteries	Renewables integration shifting, Load levelling, Frequency regulation, Voltage support, Blackstart	Lithium ressource
	Redow flow batteries Zn Fe	Renewables integration shifting, Load levelling, Frequency regulation, Voltage support, Blackstart	Unoptimised electrolyte flow rates can increase pumping energy requirements and reduce energy efficiency
	Redox flow batteries Vanadium	Frequency regulation, Voltage support, Blackstart	membrane,designs, Unoptimised electrolyte flow rates
	Redox flow batteries Zn Br	Frequency regulation, Voltage support, Blackstart	pumping energy requirements and reduce energy
Electrical	Superconducting Magnetic Energy Storage (SMES)	Renewables integration shifting, Load levelling, Frequency regulation	Maturity of the technology, expensive, low energy density
Chemical	Power to Gas (H2)	Renewable integration shifting, fuel utilisation, energy arbitrage, chemical and petrochemical uses	Low efficiency, expensive, low energy density

- TRL ranking and typical main characteristics
- Storage technologies services to the grids together with their main constraints
- These data are available and according to the “European Association for Storage of Energy (EASE)”

2. Assessing the underlying potential of storage in Cyprus (2/4)

Additional common constraints should be taken into account:

- Finding suitable landscape and available land for the potential required project's capacity
- No significant environmental or grid connection issues

Potential sites considered, have to have:

- At least one storage reservoir that is not currently used for potable water
- height difference for the sitting of the second water storage reservoir

- Preliminary investigation of the potential size and sitting of PHS projects in Cyprus **resulted in the specific map based data base**
- The sitting of the upper and lower reservoirs for each potential PHS with some information on the required reservoir volume to be created

2. Assessing the underlying potential of storage in Cyprus (3/4)

- Data on long term **water availability** of the reservoirs and their filling percentage also in draught periods
- The PHS systems were sized, based on worst case scenario of water availability and other **design parameters – assumptions – calculations**:
  - Required volume of the upper reservoir → the available height difference between reservoirs and the length of the penstock
  - Nominal power in MW → nominal water flow → suitable penstock diameter
  - The nominal autonomy of the system was calculated for 70% use of the upper reservoir water content
  - Estimation of the cost of the proposed system based on sizing – dimensioning was also performed
  - Recalculation of the crucial parameters (upper reservoir volume and potential nominal power) → the nominal autonomy will be at least 10 hours

The resulting PHS systems were ranked by employing the following selection and ranking criteria:

CRITERIA	CASE 1	RANK 1	CASE 2	RANK 2
LOWER RESERVOIR WATER CONTENT	≥ 40%	1.75	< 40%	0
PROJECT CAPACITY	≥ 10 MW	1.00	< 10 MW	0
AUTONOMY	≥ 10 h	1.00	< 10 h	0
ENVIRONMENTAL ISSUES	NO	1.50	YES	0
GRID CONNECTION ISSUES	NO	1.00	YES	0
SOUTHERN MAIN WATER PIPELINE	NO	1.25	YES	0
PRIVATE LAND FOR THE UPPER RESERVOIR	NO	1.50	YES	0

2. Assessing the underlying potential of storage in Cyprus (4/4)

Based on the selection and ranking criteria, the potential PHS projects were ranked further as first priority and second priority

existing reservoirs	Water availability													
	lower reservoir [m3]	Upper reservoir [m3]	mean volume of lower reservoir % nominal	minimum water volume in the lower reservoir [m3]	water volume ratio - lower/upp	height difference [m]	penstock (m)	Nominal Power [MW]	specific water energy content [kJ/kg]	water flow nominal [m3/sec]	penstock diameter [m]	autonomy nominal [hours]	upper reservoir cost estimation[keuro]	upper reservoir specific cost (€/kW)
FIRST RANK PROJECTS														
Arminou	4,300,000	800,000	62.0	2,666,000	3.3	580	4,000	60	4,836	12.4	2.0	12.5	16,000	267
Asprokremos	52,375,000	1,500,000	72.7	38,076,625	25.4	320	5,500	60	2,668	22.5	2.7	13.0	30,000	500
Kanaviou	17,168,000	700,000	63.2	10,850,176	15.5	466	5,600	40	3,886	10.3	1.8	13.2	14,000	350
Evretou	24,000,000	1,200,000	62.6	15,024,000	12.5	400	4,000	60	3,335	18.0	2.4	13.0	24,000	400
Kalopanagiotis	363,000	180,000	90.4	328,152	1.8	550	2,100	15	4,586	3.3	1.0	10.7	3,600	240
Mavrokolympos	2,180,000	700,000	54.3	1,183,740	1.7	435	4,000	40	3,627	11.0	1.9	12.3	14,000	350
Partial Summary	**98,206,000**	**4,380,000**						**275**						
OTHER PROJECTS														
Dipotamos	15,500,000	500,000	15.0	2,325,000	4.7	220	3,500	15	1,834	8.2	1.6	11.9	10,000	667
Lefkara	13,850,000	500,000	16.2	2,243,700	4.5	400	3,500	30	3,335	9.0	1.7	10.8	10,000	333
Kouris	115,000,000	1,800,000	33.1	38,065,000	21.1	250	1,000	60	2,085	28.8	3.0	12.2	36,000	600
Germasogia	13,500,000	450,000	34.3	4,630,500	10.3	250	1,000	20	2,085	9.6	1.7	9.1	9,000	450
Kalavassos	17,100,000	750,000	10.9	1,863,900	2.5	350	3,800	35	2,918	12.0	2.0	12.2	15,000	429
Argaka	990,000	300,000	26.2	259,380	0.9	400	3,000	15	3,335	4.5	1.2	13.0	6,000	400
Pomos	860,000	200,000	17.6	151,360	0.8	420	1,500	13	3,502	3.7	1.1	10.5	4,000	308
Ksiliatos	1,430,000	250,000	33.1	473,330	1.9	300	1,500	10	2,502	4.0	1.1	12.2	5,000	500
Lefka	368,000	200,000	no data			400	1,500	8	3,335	2.4	0.9	16.2	4,000	500
Klirou	2,000,000	300,000	no data			280	5,500	15	2,335	6.4	1.4	9.1	6,000	400
Paleochori	620,000	200,000	no data			300	1,500	8	2,502	3.2	1.0	12.2	4,000	500
Partial Summary	**181,218,000**	**5,450,000**						**229**						
TOTAL								**504**						

existing reservoirs	Water availability																	
	lower reservoir [m3]	Upper reservoir [m3]	mean volume of lower reservoir % nominal	minimum water volume in the lower reservoir [m3]	water volume ratio - lower/upp	height difference [m]	penstock (m)	Nominal Power [MW]	water content of lower reservoir	project capacity	hours of autonomy	Environ-mental issues	Grid connection	southern main water pipeline	Private land for the upper reservoir	score [0-9]
FIRST RANK PROJECTS																
Arminou	4,300,000	800,000	62.0	2,666,000	3.3	580	4,000	60	1.75	1.0	1.0	1.5	1.0	0.00	0.00	6.25
Asprokremos	52,375,000	1,500,000	72.7	38,076,625	25.4	320	5,500	60	1.75	1.0	1.0	0.0	1.0	1.25	0.00	6.00
Kanaviou	17,168,000	700,000	63.2	10,850,176	15.5	466	5,600	40	1.75	1.0	1.0	1.5	1.0	1.25	1.50	9.00
Evretou	24,000,000	1,200,000	62.6	15,024,000	12.5	400	4,000	60	1.75	1.0	1.0	1.5	1.0	1.25	0.00	7.50
Kalopanagiotis	363,000	180,000	90.4	328,152	1.8	550	2,100	15	1.75	1.0	1.0	1.5	1.0	1.25	1.50	9.00
Mavrokolympos	2,180,000	700,000	54.3	1,183,740	1.7	435	4,000	40	1.75	1.0	1.0	1.5	1.0	1.25	1.50	9.00
Partial Summary	**98,206,000**	**4,380,000**						**275**								
OTHER PROJECTS																
Dipotamos	15,500,000	500,000	15.0	2,325,000	4.7	220	3,500	15	0.00	1.0	1.0	1.5	1.0	0.00	1.50	6.00
Lefkara	13,850,000	500,000	16.2	2,243,700	4.5	400	3,500	30	0.00	1.0	1.0	1.5	1.0	0.00	1.50	6.00
Kouris	115,000,000	1,800,000	33.1	38,065,000	21.1	250	1,000	60	0.00	1.0	1.0	1.5	1.0	0.00	1.50	6.00
Germasogia	13,500,000	450,000	34.3	4,630,500	10.3	250	1,000	20	0.00	1.0	0.0	1.5	1.0	0.00	1.50	5.00
Kalavassos	17,100,000	750,000	10.9	1,863,900	2.5	350	3,800	35	0.00	1.0	1.0	1.5	1.0	0.00	0.00	4.50
Argaka	990,000	300,000	26.2	259,380	0.9	400	3,000	15	0.00	1.0	1.0	0.0	0.0	1.25	1.50	4.75
Pomos	860,000	200,000	17.6	151,360	0.8	420	1,500	13	0.00	1.0	1.0	0.0	0.0	1.25	1.50	4.75
Ksiliatos	1,430,000	250,000	33.1	473,330	1.9	300	1,500	10	0.00	1.0	1.0	0.0	1.0	1.25	1.50	5.75
Lefka	368,000	200,000	no data			400	1,500	8	1.75	0.0	1.0	0.0	0.0	1.25	1.50	
Klirou	2,000,000	300,000	no data			280	5,500	15	1.75	1.0	0.0	1.5	1.0	1.25	1.50	
Paleochori	620,000	200,000	no data			300	1,500	8	1.75	0.0	1.0	1.5	0.0	1.25	1.50	
Partial Summary	**181,218,000**	**5,450,000**						**229**								
TOTAL								**504**								

- **Design characteristics** emerged for the investigated PHS projects → **Ranking results**
- First rank PHS projects have been identified with a total of 275 MW nominal power (having a rank over 6.00 AND water content of lower reservoir >40%)
- Other projects of ranks equal to or less than 6.00 account for another 229 MW nominal power
- **The nominal power of the PHS systems** may be increased by increasing each project's size (upper reservoir, penstock) → increased **CAPEX and OPEX**

3. Impact and implications of potential storage projects (1/4)

- **The DISPA-SET model** was used for the estimation of impact and implications on the grid by the suggested PH energy storage systems
- For the specific investigation, **it has been assumed that by 2030**:
  - RES penetration will be maximized - 1680 MW PV will be installed
  - Cyprus grid will remain isolated
  - Up to 725MW of PHS systems may be installed, having nominal capacity for 8h
  - A total annual demand of 6120 GWh for 2030

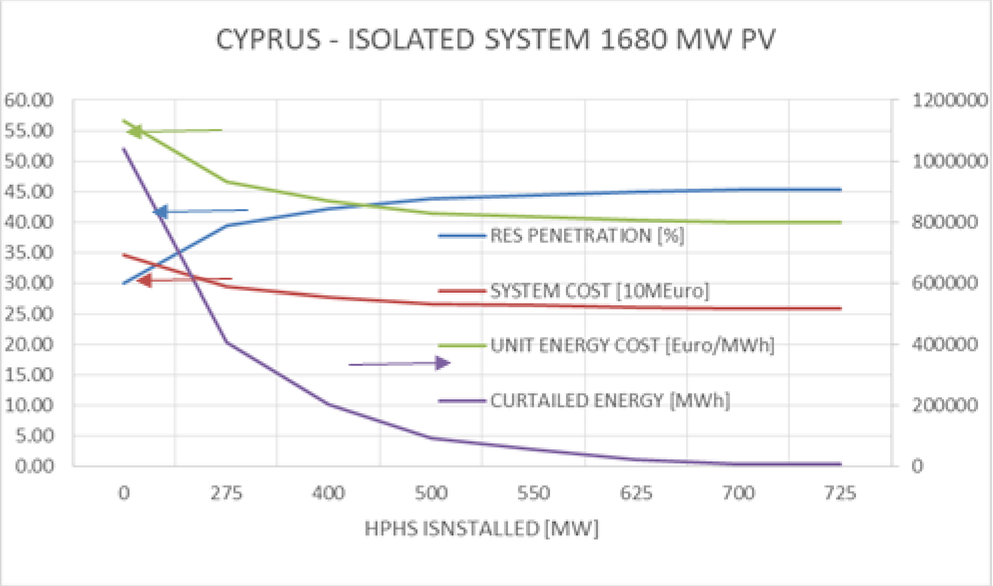
The following **capacity distribution** for the clustered generators was envisaged and integrated to our models as main input parameter

GENERATORS TECHNOLOGY	MODEL CLUSTER	INSTALLED CAPACITY [MW]
PV	[4] - CY_PHOT_SUN	1680
SOLAR THERMAL	[7] - CY_STUR_SUN	50
WIND	[3] - CY_WTON_WIN	198
GAS TURBINE (OIL)	[0] - CY_GTUR_OIL	128
INT. COMB. ENGINE (OIL)	[1] - CY_ICEN_OIL	102
COMB. CYCLE (OIL)	[2] - CY_COMC_OIL	836
BIOMASS	[5] - CY_STUR_BIO	58
COMB. CYCLE (GAS)	[6] - CY_COMC_GAS	432

3. Impact and implications of potential storage projects (2/4)

The following results have been obtained from the DISPA-SET model simulation tool:

INSTALLED HPHS CAPACITY [MW]	TOTAL PRODUCTION [MWh]	UNSERVED [MWh]	RES PENETRATION [%]	SYSTEM COST [10MEuro]	CURTAILED ENERGY [MWh]	UNIT ENERGY COST [Euro/MWh]
0	6117744.646	1357.816838	30.02	34.55667738	1037626.039	56.49
275	6307817.917		39.38	29.41629793	405551.2321	46.63
400	6390256.111		42.22	27.70702472	202271.5633	43.36
500	6436436.939		43.86	26.70827351	92120.14999	41.50
550	6450954.263		44.43	26.36090377	56262.60473	40.86
625	6464760.788		44.99	26.03670107	23924.22901	40.27
700	6473787.295		45.26	25.87411561	8180.283681	39.97
725	6475052.327		45.31	25.84500835	5462.053193	39.91



In case of maximizing RES penetration by 2030:

- No PHS systems installed → unserved energy, even in the optimal scheduling configuration
- **RES penetration** (**blue**) increases from 30% in the case of no storage facilities to 45%. For PHS capacity of over 500 MW the RES penetration increases only for 0.5% for over 200MW additional PHS
- **System cost** (**red**) and **unit energy cost** (**green**) are only marginally decreasing for PHS systems of over 500 MW installed capacity
- **Curtailed power** (**purple**) decreases by 60% only by the first 275MW of PHS capacity, when the RES penetration potential increases by 10%

3. Impact and implications of potential storage projects (3/4)

To investigate further the impact of the storage systems to the grid, for the 275MW and 500 MW installed nominal capacity, **further scenarios of energy storage capacity from 4h to 15h** of providing nominal power have been investigated

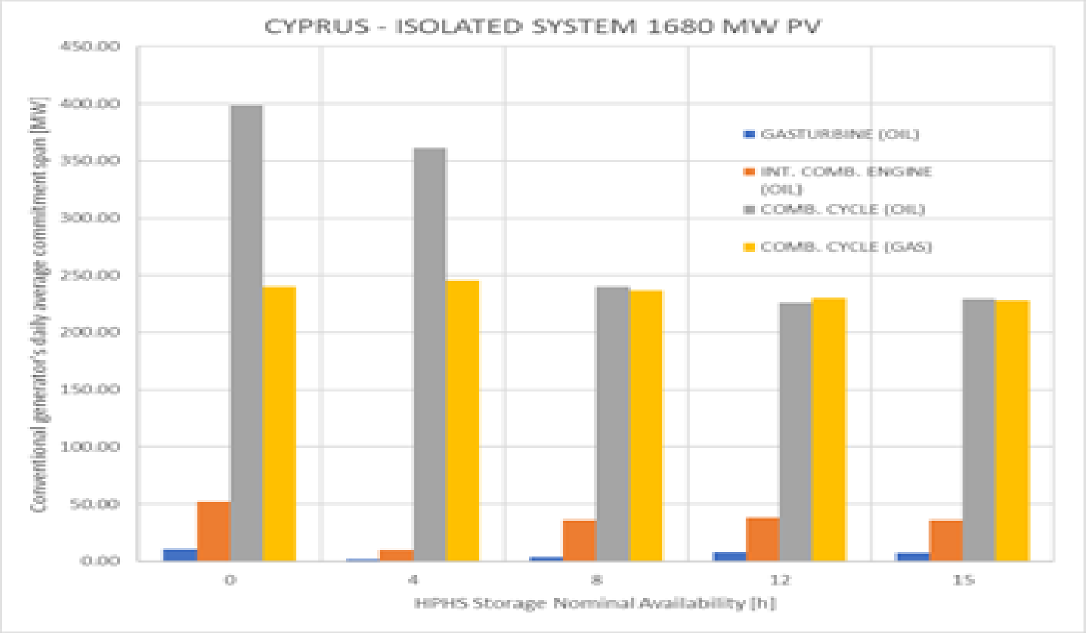
NOMINAL POWER FOR	INSTALLED HPHS CAPACITY [MW]	TOTAL PRODUCTION [MWh]	RES PENETRATION [%]	SYSTEM COST [10MEuro]	CURTAILED ENERGY [MWh]	UNIT ENERGY COST [Euro/MWh]
4h	275	6229827.708	36.53	30.99926849	607017.6197	49.76
8h	275	6307817.917	39.38	29.41629793	405551.2321	46.63
12h	275	6322989.383	39.28	29.35478485	405516.895	46.43
15h	275	6309421.325	39.25	29.30166227	413163.2011	46.44
8h	500	6436436.939	43.86	26.70827351	92120.14999	41.50
12h	500	6424386.636	43.84	26.57181184	98366.71202	41.36

The following conclusions came out:

- **Storage capacity of 8h is considered to be optimal** when compared to 4h or 12h and 15h in terms of RES penetration increase
- **System cost change** from 8h to 12h is marginally decreased, while **unit energy cost** is decreased by 0.2 Euro/MWh
- In the 275MW PHS case, moving from 8h to 12h has no effect on curtailed energy, while for the 500MW system the case is worse

3. Impact and implications of potential storage projects (4/4)

The average daily **usage/commitment span of the conventional generators** for the various periods of nominal storage capacity



Results for the 275 MW PHS system were summarized → The 0h value is for the case where no PHS system is installed

The following conclusions came out:

- PHS has a significant effect in **decreasing the span of the daily conventional generators usage**
- PHS availability of over 8h does not provide any significant advantages

4. Impact and implications of potential storage projects – Interconnected grid

The case of Cyprus **interconnection with Greece and Israel** additional → **The generator capacities for each country** were used as main input parameters in DISPA-SET:

VARIATION	INSTALLED HPHS CAPACITY [MW]	CY RES PENETRATION [%]	SYSTEM COST [10MEuro]	CY CURTAILED ENERGY [MWh]	UNIT ENERGY COST [Euro/MWh]	NET TRANSFER FROM CY [MWh]
TRANSMISSION COST 5 Euro/MWh	0	1.31	839.4558048	14855.15	49.04	653865.5
	275	39.14	835.4127998	1738.22	48.62	366348.5
	400	38.49	831.1620751	264.37	48.32	239038.5
	700	37.11	828.7360296	0.00	48.08	31292.2
TRANSMISSION COST 30 Euro/MWh	0	1.27	854.3155082	16735.32	49.82	1403662.6
	275	35.10	847.4484627	3750.86	49.22	1067688.4
	400	34.28	846.1323013	305.39	49.08	1034403.8
	700	32.92	843.9192049	16.02	48.85	989428.4

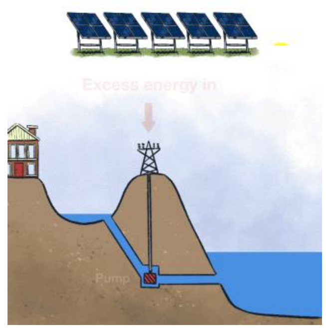
Other crucial input parameters: annual demand of 95GWh for Israel and 62GWh for Greece – Interconnector capacity of 2000MW to and from each country

The following conclusions came out:

- **Limited RES penetration in case of no PHS installation** to accommodate the extra energy → not achieving the goals posed
- **Cyprus will be energy exporter** with larger RES share in the case of 275MW PHS installed capacity
- **Curtailed energy is practically zero** by employing 700MW PHS, achieving marginally better unit energy cost but also less RES penetration and energy exports

5. Conclusions

- **PHS power systems can be coupled with batteries** integrating an important potential to provide required energy services to the Cypriot grid
- **Significant room for such hybrid power systems** to assist in achieving maximum penetration of available RES through PVs in particular
- A hybrid power system of **1.7GW of PVs together with 275MW of PHS**, may assist in achieving current and future goals for the electricity system, both in the case of isolated and interconnected Cypriot grid



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THANK YOU FOR YOUR ATTENTION!

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