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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Abstract

It has been proven that energy storage can largely assist increased penetration of renewables into the grids. This is more important in autonomous grids as the one in Cyprus. One of the most technologically advanced and mature energy storage technologies is Pumped- Hydro (PH). PH is also considered as the most suitable storage technology to achieve high Renewable Energy Sources (RES) penetration levels in autonomous power systems, such as Cyprus', avoiding unnecessary RES energy curtailment. The existing water reservoirs in Cyprus provide an important potential for energy storage application at relatively reduced cost providing many side benefits. Sizing and siting of potential PH Storage (PHS) systems are evaluated within the present study. It is shown that existing reservoirs can cope with the energy storage demands for high renewables' penetration exceeding the current Cyprus state goals. DISPA-SET model is used in order to quantify impact and implications of the potential energy storage projects and in order to identify the optimal transmission grid behavior (in terms of re-scheduling operation of conventional units). Conventional units will be assisted to achieve more efficient operational modes with less idle loads, significantly enhancing the operational safety of the grid. Simulations for the selected scenarios were performed both for the Cypriot isolated-autonomous grid and for an interconnected grid between Cyprus, Greece and Israel.

Keywords: RES penetration, Energy Storage, Pumped hydro storage, Cyprus

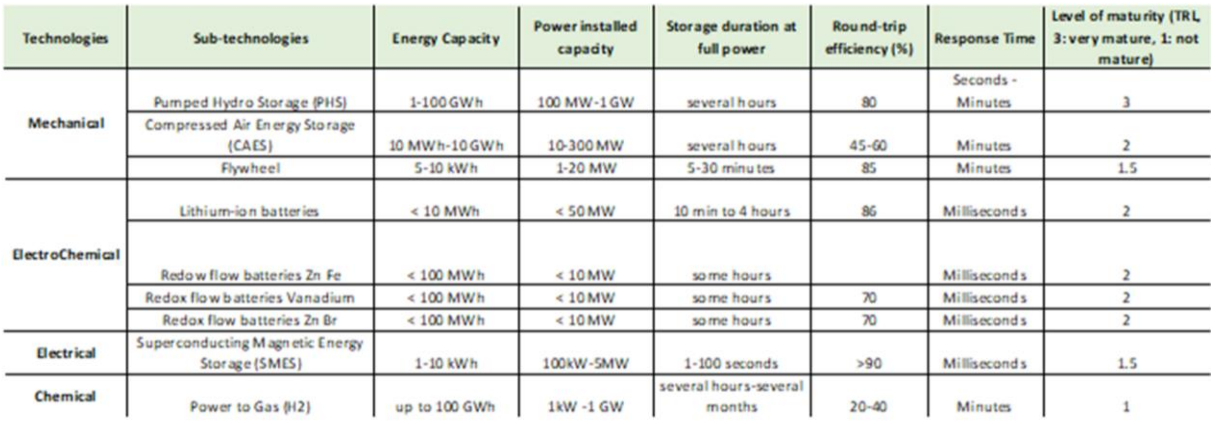
1. Introduction

Energy storage systems employed worldwide cope with the intermittent nature of distributed power generation from Renewable Energy Sources (RES) (Ziyu Z. et al., 2021, McIlwaine N. et al., 2021, Kang M. T. et al., 2021), mitigating its impact on operational practices of transmission system operators (TSOs). Determining the size (power rating and energy storage capacity) of the storage systems, as well as their location and connection to the grid is a fundamental problem. Multiple grid services may be provided by storage systems of different technologies coupled together, thus increasing the potential exploitation of their capacity and their feasibility (Kang M. T. et al., 2021, Bahloul M. and Shafiuzzaman K. K., 2021, Günter N. and Marinopoulos A., 2016).

One of the most technologically advanced and mature energy storage technologies is Pumped- Hydro (PH) (Shafiqur R. et al., 2015, Barbour E. et al., 2016, Mahmouda M. et al., 2020). PH is also considered as the most suitable storage technology to achieve high RES penetration levels in autonomous power systems, such as Cyprus', avoiding unnecessary RES energy curtailment. The existing water reservoirs in Cyprus provide an important potential for energy storage application at relatively reduced cost providing many side benefits.

According to European Association for Storage of Energy (EASE) the typical characteristics (sizes) for energy storage projects having a rated maturity level (TRL at least 1) are shown in the following table (European Association for Storage of Energy):

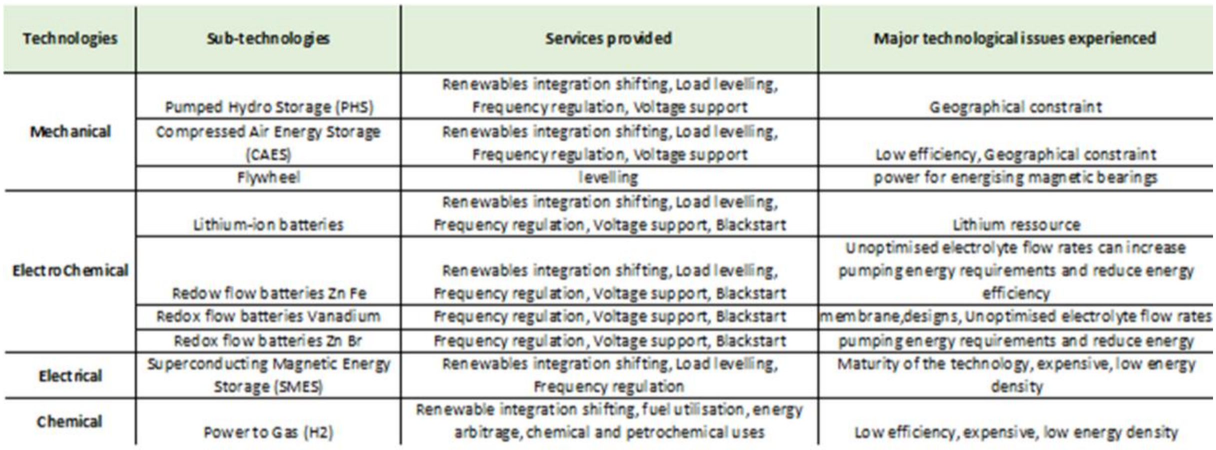
Table 1: Technology readiness level ranking of various storage technologies and typical main characteristics



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
ElectroChemical	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

The potential services provided by each storage technology, along with their inherent development issues are presented in the following table:

Table 2: Storage technologies services to the grids and their main constraints



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

In order to select the appropriate size and the sitting of electrical energy storage systems, the previous constraints have to be taken into account and the potential problem storage is addressing.

Based on the above information, the present study focuses on the following:

- The sizing and the siting of storage and/or hybrid plants in Cyprus. A map based data base is prepared including all the main technical parameters of the proposed plant.

- The 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 and quantify the impact of various storage/RES scenarios.

2. Assessing the underlying potential of storage in Cyprus

Since the most technologically advanced and mature storage technology is Pumped- Hydro (PH), the assessment of the underlying potential in Cyprus started with this storage technology. This is considered as the most suitable storage technology to achieve high RES penetration levels in autonomous power systems, such as Cyprus', avoiding unnecessary RES energy curtailment.

For the sitting of the PH Storage (PHS) systems the major constraint is finding suitable landscape. Furthermore, there has to be available land for the potential required project's capacity and there should be 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, as well as height difference for the sitting of the second water storage reservoir.

To this end, a preliminary investigation of the potential size and sitting of PHS projects in Cyprus resulted in the following map bellow (Figure 1). In Figure 1 the sitting of the upper and lower reservoirs for each potential PHS is shown, with some information on the required reservoir volume to be created.

Further investigation provided data on long term water availability of the reservoirs and their filling percentage, also in draught periods (Ministry of Agriculture Rural Development and the Environment, Water Development Department). Then, the PHS systems were sized based on worst case scenario of water availability and other design characteristics. The dimensioning method followed is described in steps below:

1. For each existing reservoir (taking as an assumption that it will be the lower water reservoir), the required volume of the upper reservoir was calculated based on water availability (% nominal) of the lower one.
2. For the calculated upper reservoir volume, the available height difference between reservoirs and the length of the penstock required were also calculated.
3. A preliminary nominal power in MW was selected for the system and the specific water energy content was further calculated (taking as assumption 15% system losses).
4. The nominal water flow and a suitable penstock diameter were then calculated.
5. Calculation of the nominal autonomy of the system (in hours) for 70% use of the upper reservoir water content followed.
6. Estimation of the cost of the proposed system based on sizes (reservoir, penstock length) was the next step.
7. Recalculation of the crucial parameters (upper reservoir volume and potential nominal power), so that the nominal autonomy will be at least 10 hours was the final step.

Further to the above design procedure, the resulting PHS systems were ranked by employing the following selection and ranking criteria (Table 3):

Table 3: Selection and ranking criteria for PHS systems

CRITERIA	CASE 1	RANK 1	CASE 2	RANK 2
LOWER SESERVOIR 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

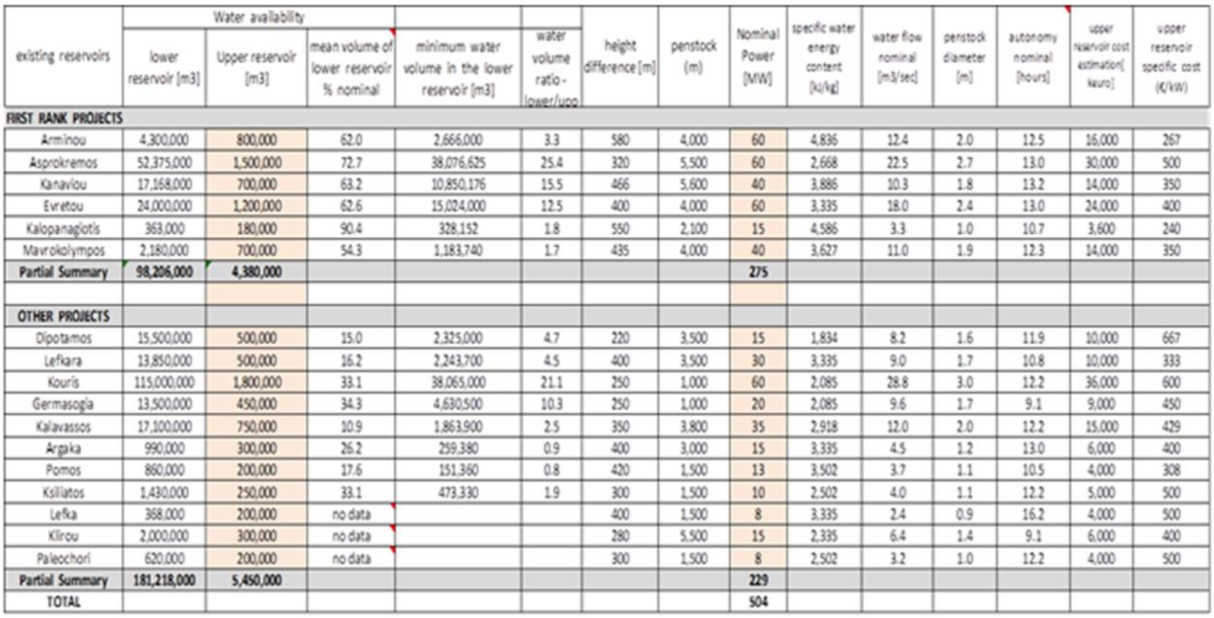
Based on the selection and ranking criteria, the potential PHS projects were ranked as first priority and second priority. Design characteristics emerged for the investigated PHS projects are shown in Table 4, whereas their ranking is presented in Table 5 bellow.

First rank projects (having a rank over 6.00 AND water content of lower reservoir >40%) of a total of 275 MW nominal power have been identified. Other projects of ranks equal to or less than 6.00 account for another 229 MW nominal power.

It has to be stated here that the nominal power of the PHS systems may be increased by increasing each project's size (upper reservoir, penstock). Thus, in the next section, simulations were set up and run to investigate the impact of the various scenarios on the grid and in the case of high RES penetration conditions.

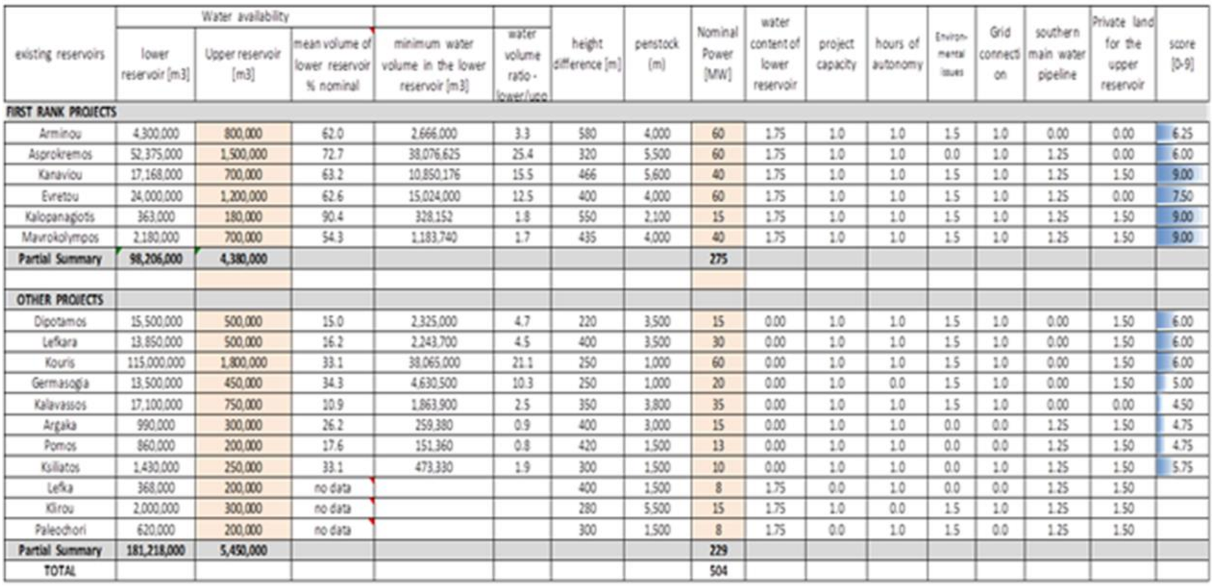
Figure 1: Map based representation of potential HPS projects in Cyprus. Sitting and sizing of reservoir

Table 4: Design characteristics of investigated PHS projects throughout Cyprus



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**						

Table 5: Ranking of the potential PHS projects from Table 4



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	Environmental 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**								

3. Impact and implications of potential storage projects – Isolated grid

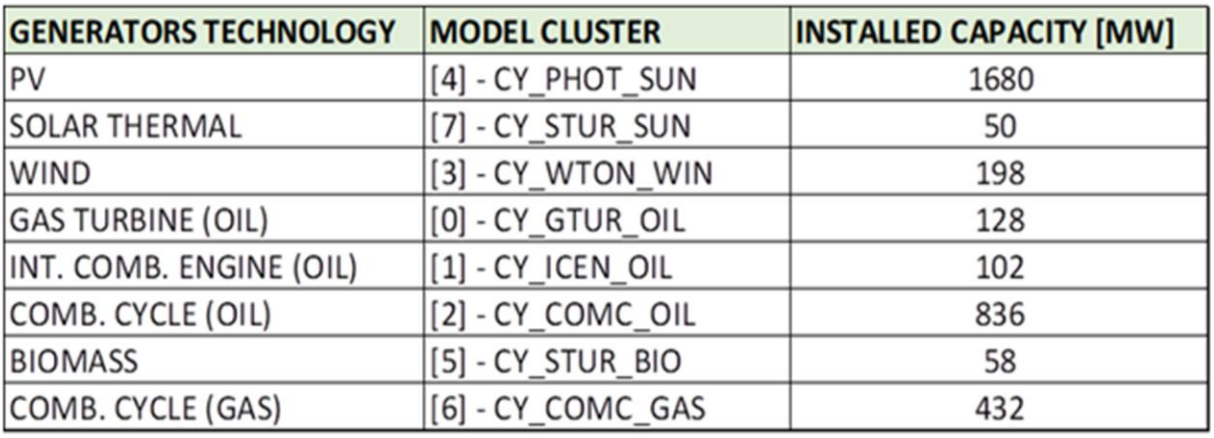
The DISPA-SET model has been used In order to identify the optimal transmission grid behavior (in terms of scheduling conventional generators) in the presence of high RES penetration and varying storage projects nominal capacity. For the investigation it has been assumed that by 2030:

a) RES penetration will be maximized - 1680 MW PV will be installed
b) Cyprus grid will remain isolated

c) 0 MW to 725MW of PHS systems may be installed, having nominal capacity for 8h
d) A total annual demand of 6120 GWh for 2030

The following capacity distribution for the clustered generators is envisaged:

Table 6: Capacity distribution for the clustered generators

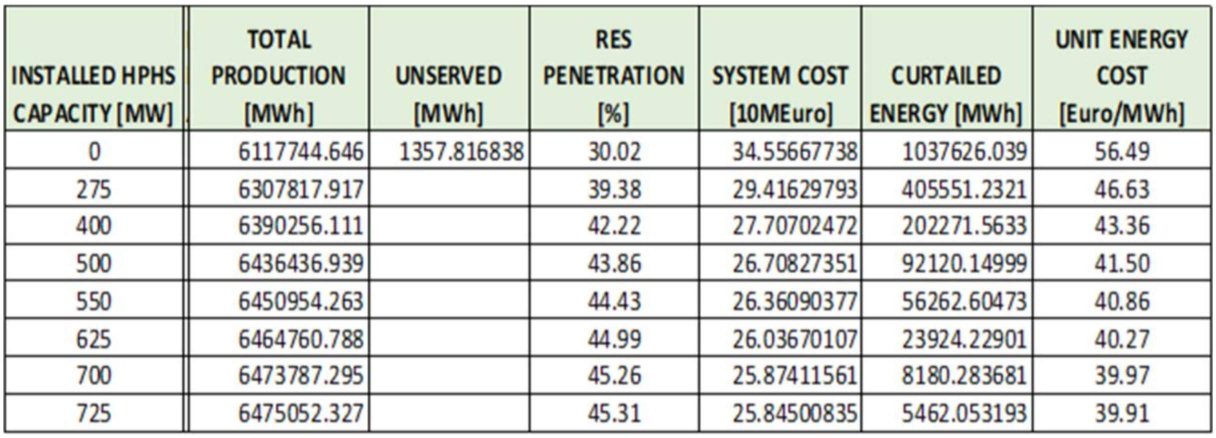


GENERATORS TECHNOLOGY	MODEL CLUSTER	INSTALLED CAPACITY [MW]
PV	[4] - CY_PHOT_SUN	1680
SOLAR THERMAL	[7] - CY_STUR_SUN	50
WIND	[3] - CY_WTON_WIN	198
GAS TURBINE (OIL)	[0] - CY_GTUR_OIL	128
INT. COMB. ENGINE (OIL)	[1] - CY_ICEN_OIL	102
COMB. CYCLE (OIL)	[2] - CY_COMC_OIL	836
BIOMASS	[5] - CY_STUR_BIO	58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

The goal was to estimate the RES penetration potential, the curtailed energy and the energy cost, when accounting only for operation costs (and no installation costs), for the isolated grid and for an Additional Measures Scenario (AMS, without interconnection). According to National Centers for Environmental Prediction (NCEP) for the AMS (i.e. with all energy efficiency measures in place, as compared to the Current Measures Scenario (CMS) of the plan), the RES penetration in the electricity sector has been estimated in 30.3% of the total energy consumption by 2030 (National Centers for Environmental Prediction).

The configuration above has been run in DISPA-SET and the following results have been obtained, summarized in Table 7 and Figure 2 bellow.

Table 7: Cyprus' system characteristics estimated for 2030 – Isolated grid



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

Indicative results for four weeks during the year are presented in graphical form in ANNEX.

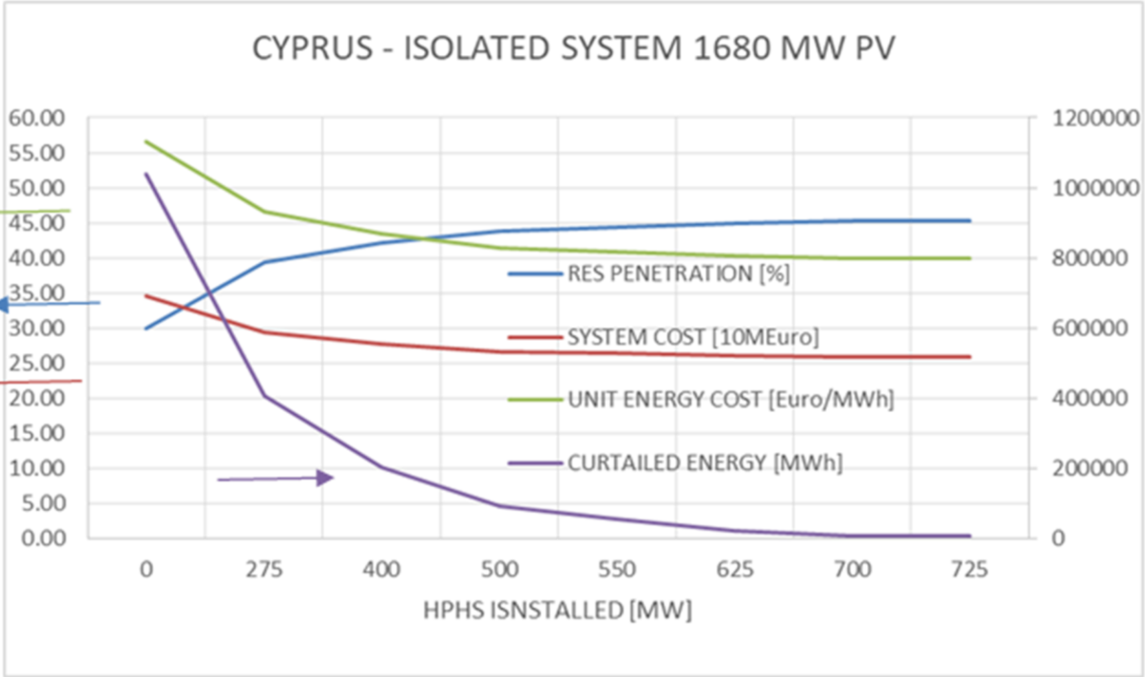


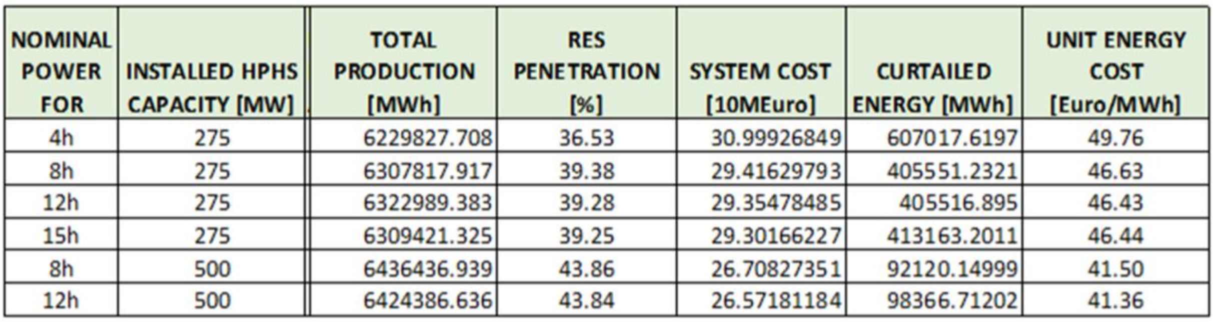
Figure 2: Effect of HPS installed capacity by 2030 to the Cypriot electricity system

The conclusions that might be drawn from the above are that in case of maximizing RES penetration by 2030:

- In case of no PHS systems installed there exists an issue of unserved energy, even in the optimal scheduling configuration.
- RES penetration 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 and unit energy cost is only marginally decreasing for PHS systems of over 500 MW installed capacity.
- Curtailed power decreases by 60% only by the first 275MW of PHS capacity, when the RES penetration potential increases by 10%.

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. The results have been summarized in the following table:

Table 8: Effect of changing the duration of nominal power of HPS



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

Again, from Table 8 the following conclusions might be drawn:

- 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 to 12h from 8h is marginally decreased, while unit energy cost is decreased by 0.2 Euro/MWh.
- In the 275MW PHS case moving to 12h from 8h has no effect on curtailed energy, while for the 500MW system the case is worse.

Another implication investigated is the average daily usage/commitment span of the conventional generators for the various periods of nominal storage capacity. The results for the 275 MW PHS system are summarized in the following figure. The 0h case is for the case where no PHS system is installed.

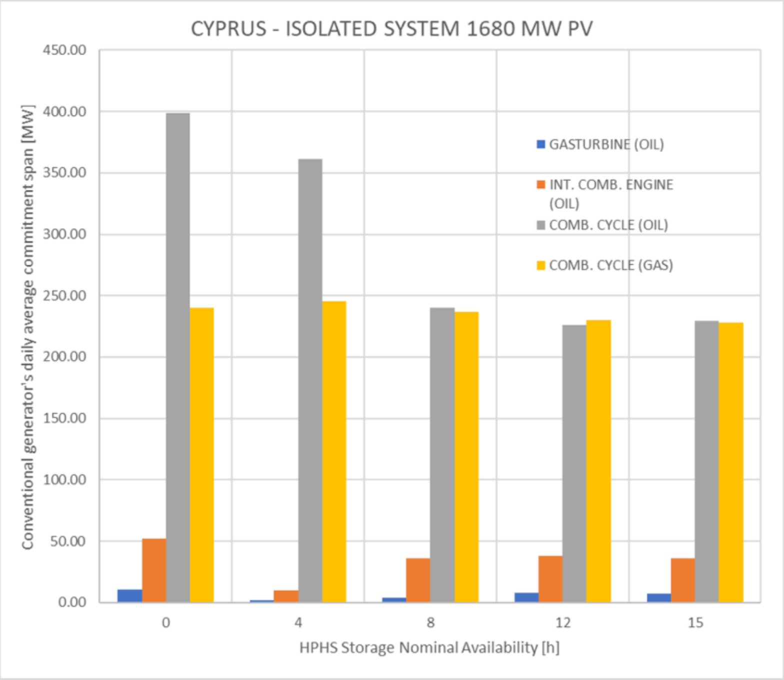


Figure 3: Overview of the effect of availability of nominal capacity to the usage of conventional generators

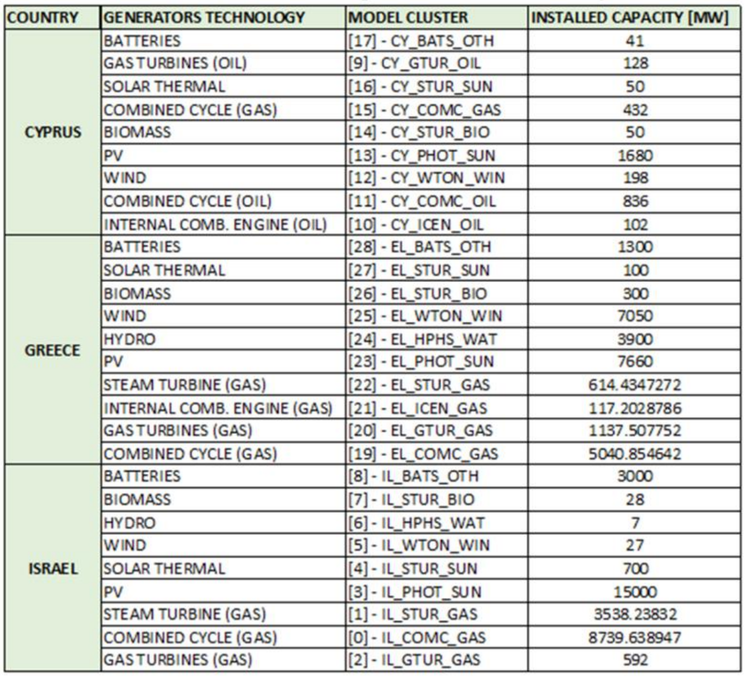
From the figure above it may be stated that:

- 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

In the case Cyprus will be interconnected with Greece and Israel by 2030 additional scenarios have been investigated. The generator capacities for each country are the followings (Table 9):

Table 9: Generator capacities for each country

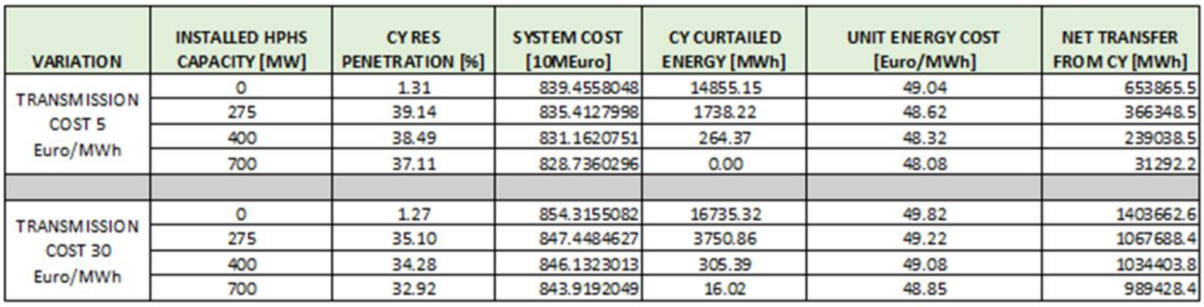


COUNTRY	GENERATORS TECHNOLOGY	MODEL CLUSTER	INSTALLED CAPACITY [MW]
CYPRUS	BATTERIES	[17] - CY_BATS_OTH	41
	GAS TURBINES (OIL)	[9] - CY_GTUR_OIL	128
	SOLAR THERMAL	[16] - CY_STUR_SUN	50
	COMBINED CYCLE (GAS)	[15] - CY_COMC_GAS	432
	BIOMASS	[14] - CY_STUR_BIO	50
	PV	[13] - CY_PHOT_SUN	1680
	WIND	[12] - CY_WTON_WIN	198
	COMBINED CYCLE (OIL)	[11] - CY_COMC_OIL	836
	INTERNAL COMB. ENGINE (OIL)	[10] - CY_ICEN_OIL	102
GREECE	BATTERIES	[28] - EL_BATS_OTH	1300
	SOLAR THERMAL	[27] - EL_STUR_SUN	100
	BIOMASS	[26] - EL_STUR_BIO	300
	WIND	[25] - EL_WTON_WIN	7050
	HYDRO	[24] - EL_HPHS_WAT	3900
	PV	[23] - EL_PHOT_SUN	7660
	STEAM TURBINE (GAS)	[22] - EL_STUR_GAS	614.4347272
	INTERNAL COMB. ENGINE (GAS)	[21] - EL_ICEN_GAS	117.2028786
	GAS TURBINES (GAS)	[20] - EL_GTUR_GAS	1137.507752
	COMBINED CYCLE (GAS)	[19] - EL_COMC_GAS	5040.854642
ISRAEL	BATTERIES	[8] - IL_BATS_OTH	3000
	BIOMASS	[7] - IL_STUR_BIO	28
	HYDRO	[6] - IL_HPHS_WAT	7
	WIND	[5] - IL_WTON_WIN	27
	SOLAR THERMAL	[4] - IL_STUR_SUN	700
	PV	[3] - IL_PHOT_SUN	15000
	STEAM TURBINE (GAS)	[1] - IL_STUR_GAS	3538.23832
	COMBINED CYCLE (GAS)	[0] - IL_COMC_GAS	8739.638947
	GAS TURBINES (GAS)	[2] - IL_GTUR_GAS	592

The annual demand by 2030 has been for Israel around 95 GWh and for Greece around 62 GWh. The interconnector capacity has been taken as 2000MW to and from each country.

The results are summarized for two cases of transmission cost in the table 10 bellow:

Table 10: Cyprus' system characteristics estimated for 2030 – Interconnected grid



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

The following conclusions might again be drawn:

- There is extremely 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

The potential of electricity storage in Cyprus has been investigated. PHS can be coupled with batteries to provide for required energy services to the grid. There is significant room for PHS to assist in achieving maximum penetration of available RES, PVs in particular. Moreover, targeting

275MW PHS for 1680MW PV installed both in the case of isolated and interconnected Cypriot grid may assist in achieving current and future goals for the electricity system.

Acknowledgement

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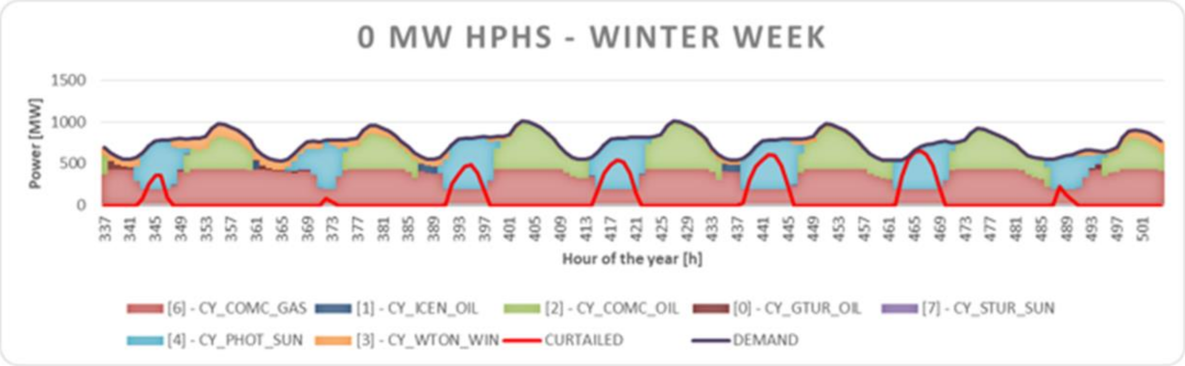
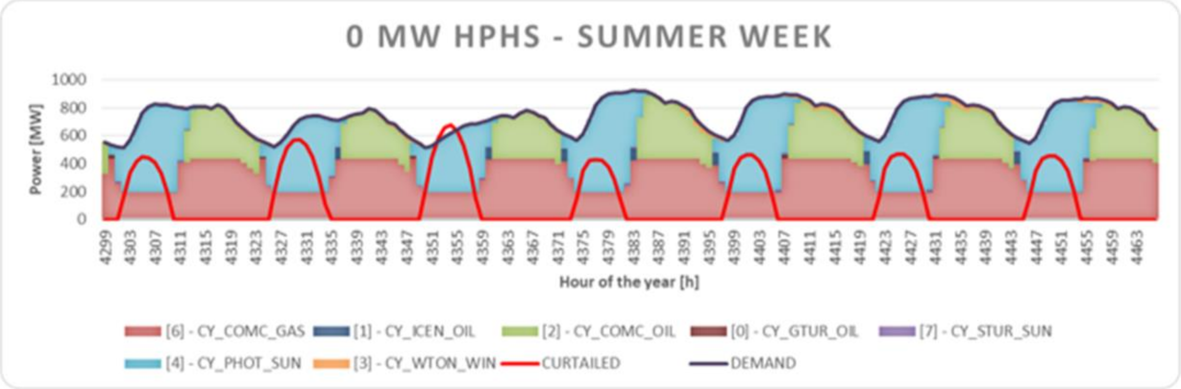
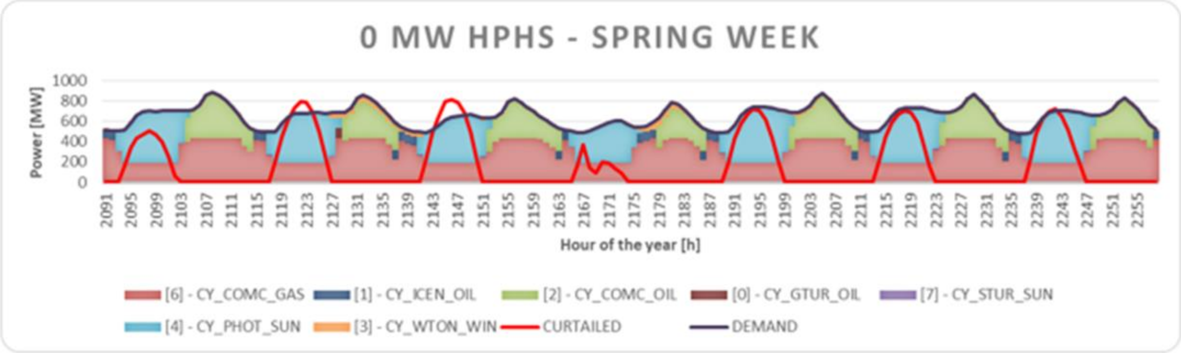
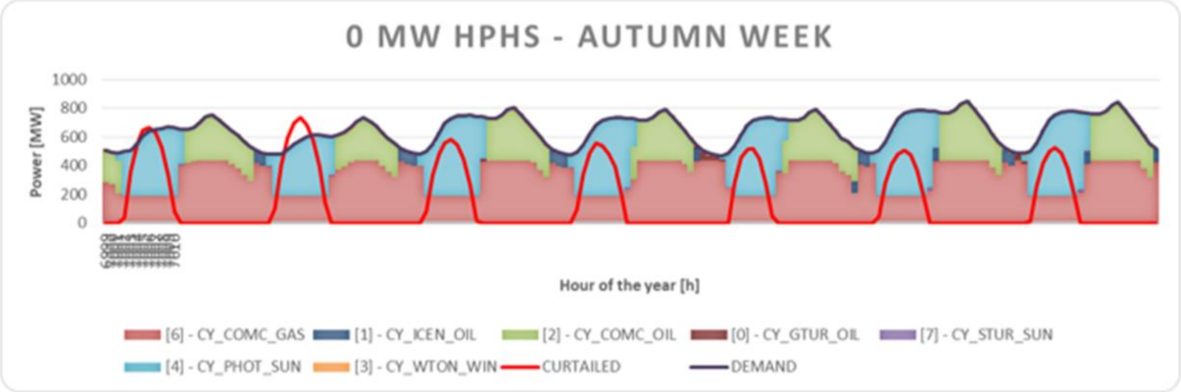
ANNEX

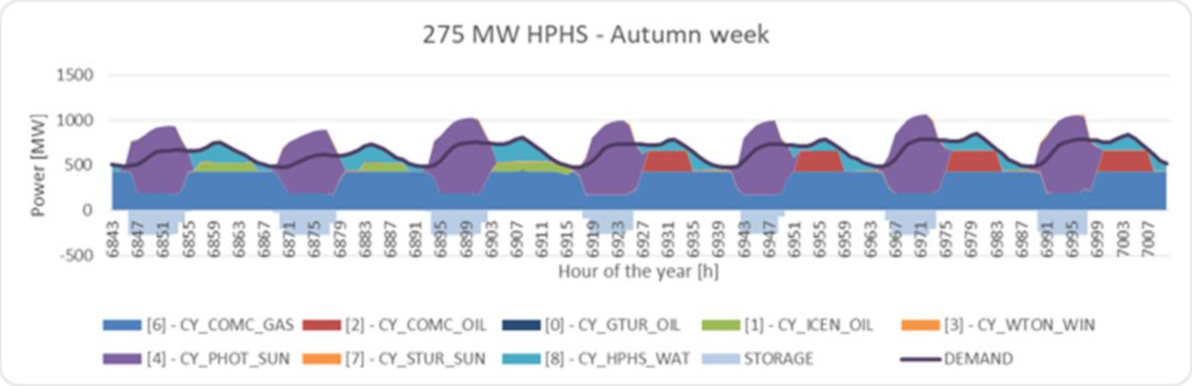
Indicative simulation results for 0MW, 275MW and 500MW PHS systems installed in the isolated grid of Cyprus

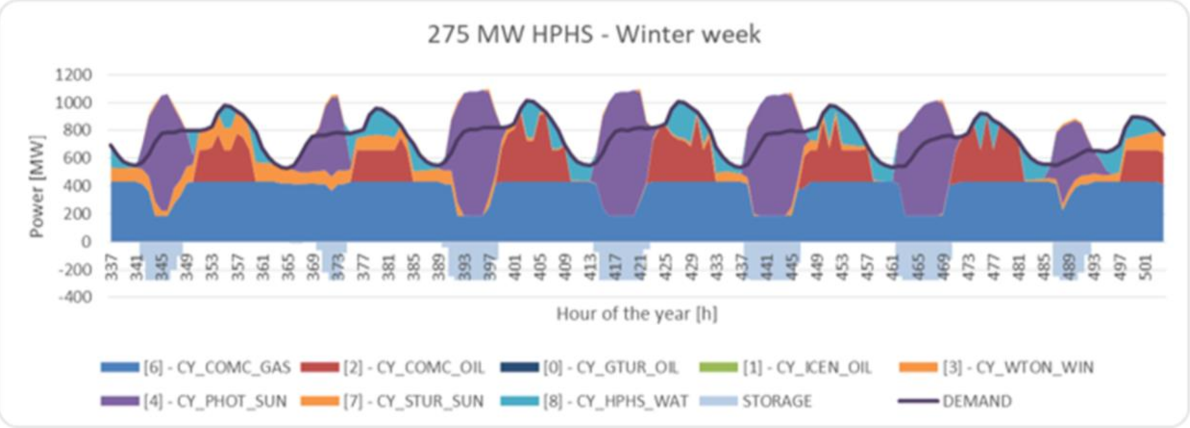

0 MW HPHS - WINTER WEEK
Power [MW]
1500
1000
500
0
337 341 345 349 353 357 361 365 369 373 377 381 385 389 393 397 401 405 409 413 417 421 425 429 433 437 441 445 449 453 457 461 465 469 473 477 481 485 489 493 497 501
Hour of the year [h]
[6] - CY_COMC_GAS
[1] - CY_ICEN_OIL
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[7] - CY_STUR_SUN
[4] - CY_PHOT_SUN
[3] - CY_WTON_WIN
CURTAILED
DEMAND

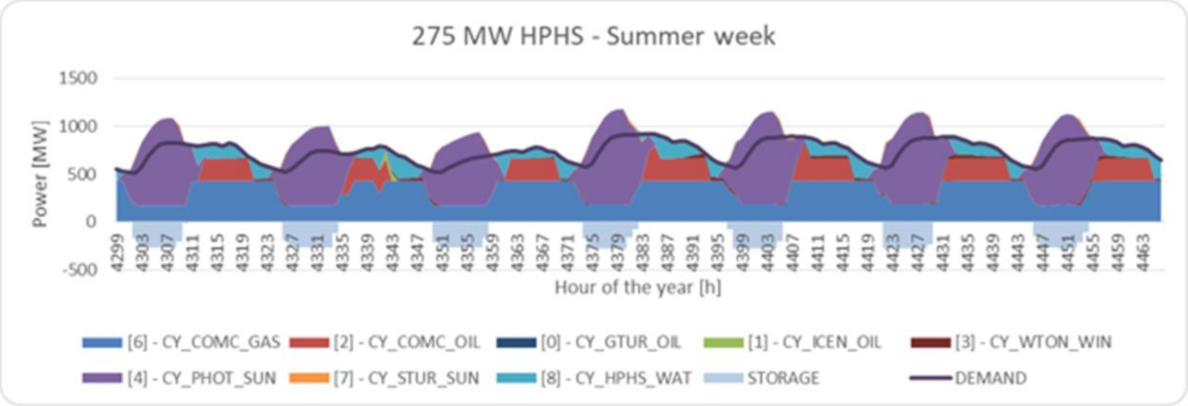

0 MW HPHS - SUMMER WEEK
Power [MW]
1000
800
600
400
200
0
4299 4303 4307 4311 4315 4319 4323 4327 4331 4335 4339 4343 4347 4351 4355 4359 4363 4367 4371 4375 4379 4383 4387 4391 4395 4399 4403 4407 4411 4415 4419 4423 4427 4431 4435 4439 4443 4447 4451 4455 4459 4463
Hour of the year [h]
[6] - CY_COMC_GAS
[1] - CY_ICEN_OIL
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[7] - CY_STUR_SUN
[4] - CY_PHOT_SUN
[3] - CY_WTON_WIN
CURTAILED
DEMAND

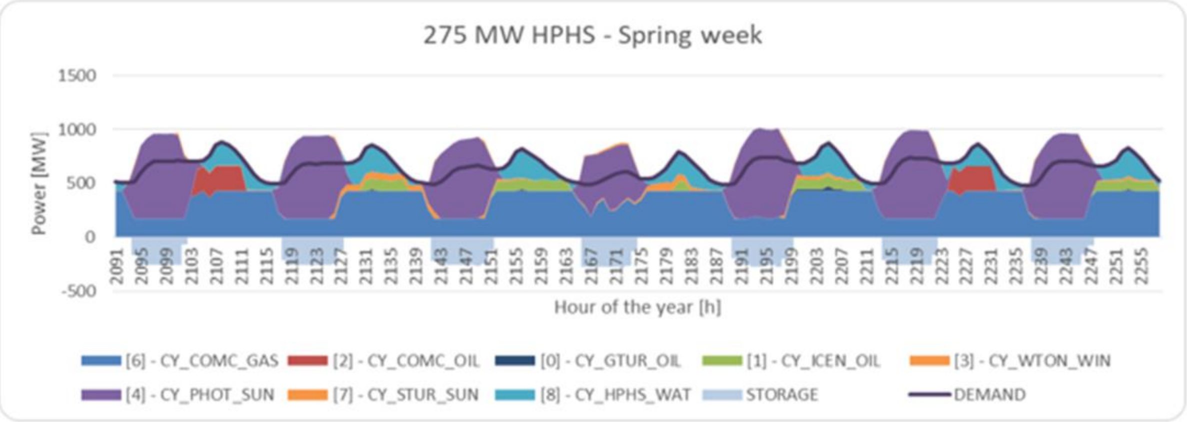

0 MW HPHS - SPRING WEEK
Power [MW]
1000
800
600
400
200
0
2091 2095 2099 2103 2107 2111 2115 2119 2123 2127 2131 2135 2139 2143 2147 2151 2155 2159 2163 2167 2171 2175 2179 2183 2187 2191 2195 2199 2203 2207 2211 2215 2219 2223 2227 2231 2235 2239 2243 2247 2251 2255
Hour of the year [h]
[6] - CY_COMC_GAS
[1] - CY_ICEN_OIL
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[7] - CY_STUR_SUN
[4] - CY_PHOT_SUN
[3] - CY_WTON_WIN
CURTAILED
DEMAND

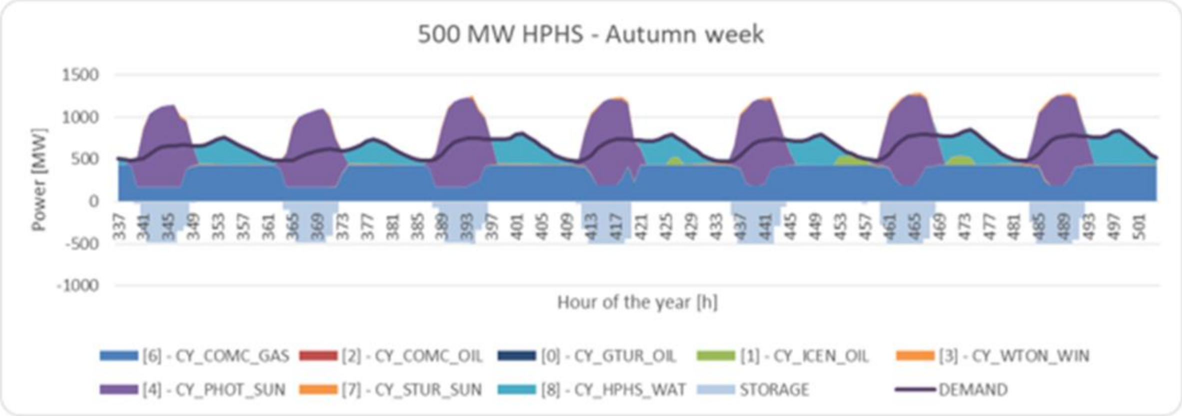

0 MW HPHS - AUTUMN WEEK
Power [MW]
1000
800
600
400
200
0
Hour of the year [h]
[6] - CY_COMC_GAS
[1] - CY_ICEN_OIL
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[7] - CY_STUR_SUN
[4] - CY_PHOT_SUN
[3] - CY_WTON_WIN
CURTAILED
DEMAND

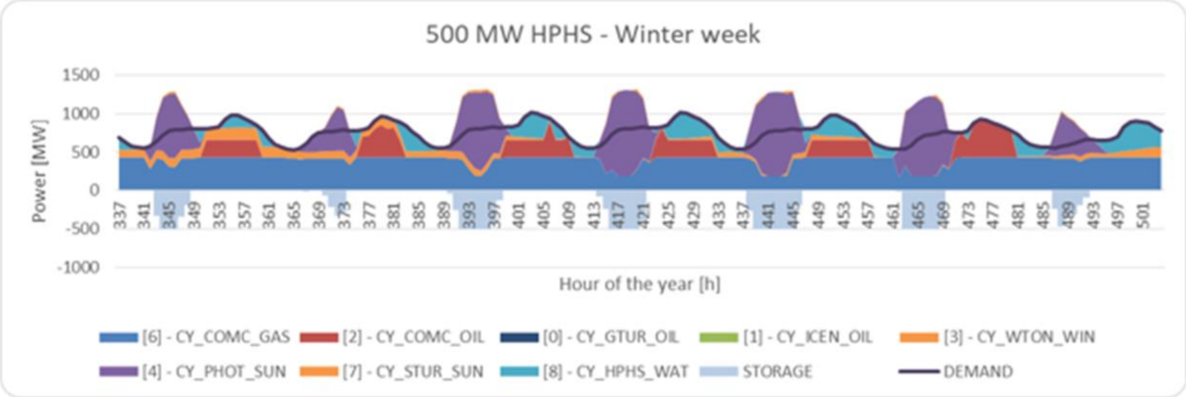

275 MW HPHS - Autumn week
Power [MW]
1500
1000
500
0
-500
Hour of the year [h]
6843 6847 6851 6855 6859 6863 6867 6871 6875 6879 6883 6887 6891 6895 6899 6903 6907 6911 6915 6919 6923 6927 6931 6935 6939 6943 6947 6951 6955 6959 6963 6967 6971 6975 6979 6983 6987 6991 6995 6999 7003 7007
[6] - CY_COMC_GAS
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[1] - CY_ICEN_OIL
[3] - CY_WTON_WIN
[4] - CY_PHOT_SUN
[7] - CY_STUR_SUN
[8] - CY_HPHS_WAT
STORAGE
DEMAND

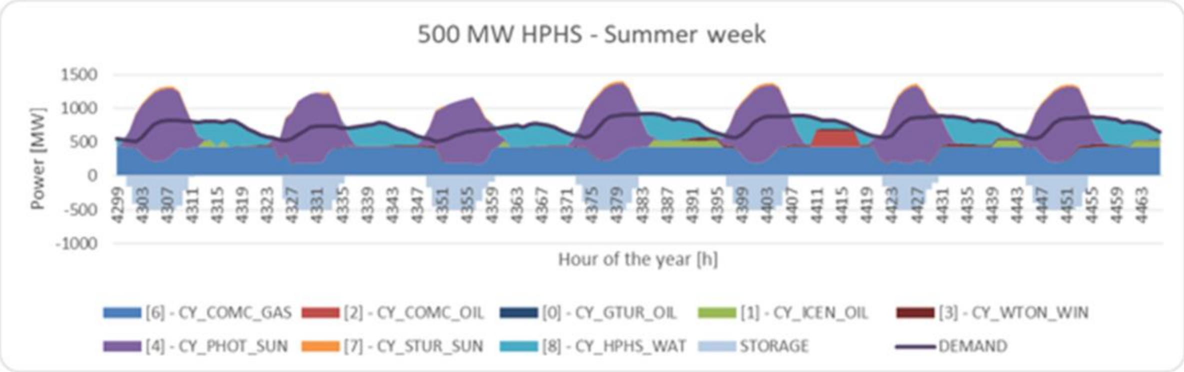

275 MW HPHS - Winter week
Power [MW]
1200
1000
800
600
400
200
0
-200
-400
Hour of the year [h]
337 341 345 349 353 357 361 365 369 373 377 381 385 389 393 397 401 405 409 413 417 421 425 429 433 437 441 445 449 453 457 461 465 469 473 477 481 485 489 493 497 501
[6] - CY_COMC_GAS
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[1] - CY_ICEN_OIL
[3] - CY_WTON_WIN
[4] - CY_PHOT_SUN
[7] - CY_STUR_SUN
[8] - CY_HPHS_WAT
STORAGE
DEMAND

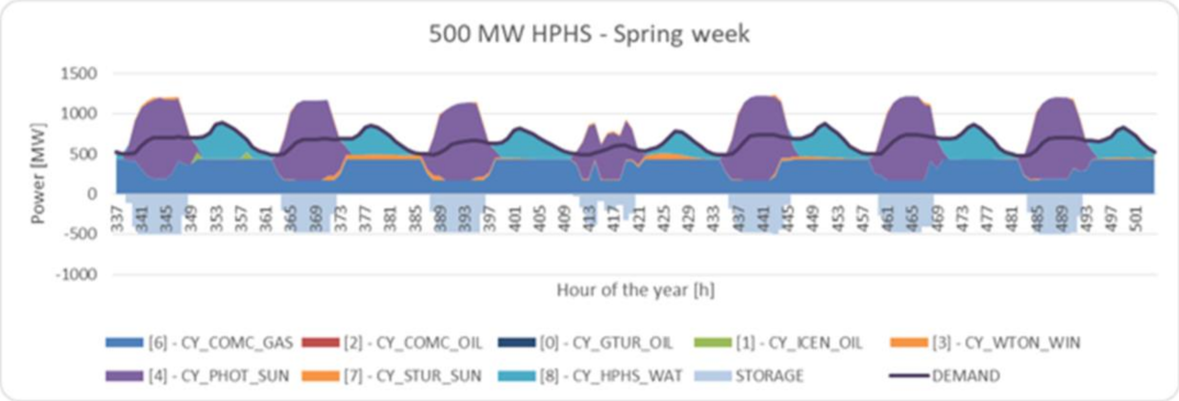

275 MW HPHS - Summer week
Power [MW]
1500
1000
500
0
-500
Hour of the year [h]
4299 4303 4307 4311 4315 4319 4323 4327 4331 4335 4339 4343 4347 4351 4355 4359 4363 4367 4371 4375 4379 4383 4387 4391 4395 4399 4403 4407 4411 4415 4419 4423 4427 4431 4435 4439 4443 4447 4451 4455 4459 4463
[6] - CY_COMC_GAS
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[1] - CY_ICEN_OIL
[3] - CY_WTON_WIN
[4] - CY_PHOT_SUN
[7] - CY_STUR_SUN
[8] - CY_HPHS_WAT
STORAGE
DEMAND


275 MW HPHS - Spring week
Power [MW]
1500
1000
500
0
-500
Hour of the year [h]
2091 2095 2099 2103 2107 2111 2115 2119 2123 2127 2131 2135 2139 2143 2147 2151 2155 2159 2163 2167 2171 2175 2179 2183 2187 2191 2195 2199 2203 2207 2211 2215 2219 2223 2227 2231 2235 2239 2243 2247 2251 2255
[6] - CY_COMC_GAS
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[1] - CY_ICEN_OIL
[3] - CY_WTON_WIN
[4] - CY_PHOT_SUN
[7] - CY_STUR_SUN
[8] - CY_HPHS_WAT
STORAGE
DEMAND


500 MW HPHS - Autumn week
1500
1000
500
0
-500
-1000
Power [MW]
337 341 345 349 353 357 361 365 369 373 377 381 385 389 393 397 401 405 409 413 417 421 425 429 433 437 441 445 449 453 457 461 465 469 473 477 481 485 489 493 497 501
Hour of the year [h]
[6] - CY_COMC_GAS
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[1] - CY_ICEN_OIL
[3] - CY_WTON_WIN
[4] - CY_PHOT_SUN
[7] - CY_STUR_SUN
[8] - CY_HPHS_WAT
STORAGE
DEMAND


500 MW HPHS - Winter week
1500
1000
500
0
-500
-1000
Power [MW]
337 341 345 349 353 357 361 365 369 373 377 381 385 389 393 397 401 405 409 413 417 421 425 429 433 437 441 445 449 453 457 461 465 469 473 477 481 485 489 493 497 501
Hour of the year [h]
[6] - CY_COMC_GAS
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[1] - CY_ICEN_OIL
[3] - CY_WTON_WIN
[4] - CY_PHOT_SUN
[7] - CY_STUR_SUN
[8] - CY_HPHS_WAT
STORAGE
DEMAND


500 MW HPHS - Summer week
1500
1000
500
0
-500
-1000
Power [MW]
4299 4303 4307 4311 4315 4319 4323 4327 4331 4335 4339 4343 4347 4351 4355 4359 4363 4367 4371 4375 4379 4383 4387 4391 4395 4399 4403 4407 4411 4415 4419 4423 4427 4431 4435 4439 4443 4447 4451 4455 4459 4463
Hour of the year [h]
[6] - CY_COMC_GAS
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[1] - CY_ICEN_OIL
[3] - CY_WTON_WIN
[4] - CY_PHOT_SUN
[7] - CY_STUR_SUN
[8] - CY_HPHS_WAT
STORAGE
DEMAND


500 MW HPHS - Spring week
1500
1000
500
0
-500
-1000
Power [MW]
337 341 345 349 353 357 361 365 369 373 377 381 385 389 393 397 401 405 409 413 417 421 425 429 433 437 441 445 449 453 457 461 465 469 473 477 481 485 489 493 497 501
Hour of the year [h]
[6] - CY_COMC_GAS
[2] - CY_COMC_OIL
[0] - CY_GTUR_OIL
[1] - CY_ICEN_OIL
[3] - CY_WTON_WIN
[4] - CY_PHOT_SUN
[7] - CY_STUR_SUN
[8] - CY_HPHS_WAT
STORAGE
DEMAND