Novel Storage Concepts to increase RES penetration in autonomous systems. The case of Cyprus

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Abstract

The intermittent nature of RES and the variations between RES generation and demand profiles create a roadblock for the increased RES penetration into electric grids. Scope of this research paper is to examine the immense benefits offered by the application of RES-Storage hybrid technologies on the overall performance, resilience and sustainability of the transmission system of the republic of Cyprus. The RES plants, mainly represented by commercial solar photovoltaic systems, are optimally synthesized with pumped-hydro storage technology and battery energy storage systems, forming the so-called hybrid power park modules. The hybrid power parks are synergistically integrated into the power network aiming to maximize the RES penetration in the system and minimize the conventional power demand by the thermal units. For the specific study, the evaluation of RES potential in Cyprus together with the overview of the island's demand profiles were necessary in order to suggest best suited energy storage technology and most applicable hybridization concepts for Cyprus. The smart Grid approach is summarized in applying methods to smooth the demand side instead of cope generation to the demand only. Smart Grid techniques offer significant benefits if manage to transform the demand curve to cope with the most efficient generation mode. Expected implications to the Cypriot grid and sustainability are also examined through the change of the operation of the conventional units of Cyprus grid when 165 MW of storage capacity is applied and 200 MW of additional PVs are installed.

Keywords: RES, Energy Storage, Pumped hydro storage, Hybrid

1. Introduction

As Renewable Energy Sources (RES) use and development is regarded as a high priority to reach sufficient degree of sustainability, the limitations imposed by the intermittent nature of RES and the variations between RES generation and demand profiles create a roadblock for the 100% renewables goal. This is particularly true for the case of autonomous systems. There are currently several energy

storage approaches and significant effort is being placed in developing electricity storage equipment to meet the need for higher RES penetration into the grids. Additionally, as the multiple power producers entering the grid affect the grid power quality, several approaches based on the smart grid concept i.e. the demand to cope with the generation and not the reverse i.e. generation to meet the demand, have been developed.
The present study focuses mainly on the following:

- Selection of the most appropriate storage and RES coupling approaches that would benefit Cyprus based on the RES availability and the demand profile of Cyprus
- Examine the potential of combination of existing storage and Smart Grid technologies
- Conclude to novel storage and/or Smart Grid concepts or combination of existing technologies that are beneficial for applications in Cyprus

Although Cyprus met their targets regarding RES penetration into the grid, this task will be more complicated in the forthcoming years taking into account the unique characteristics of the island i.e. an autonomous grid with significant demand variation within various time scales i.e. daily, seasonally and yearly.

2. Evaluation of RES potential in Cyprus

The renewable source that is mostly available in Cyprus is the solar irradiation. Wind potential is generally low and the same is valid for other RES sources e.g. Hydro, Biomass. Solar Irradiation can be used to produce electricity mainly via Photovoltaics-PVs-, and Concentrated Solar Power Plants –CSPs- either with parabolic troughs or solar tower configuration. Other methods are in a pre-commercial stage of development.
Figures below show the measured and estimated solar and wind potential in Cyprus.

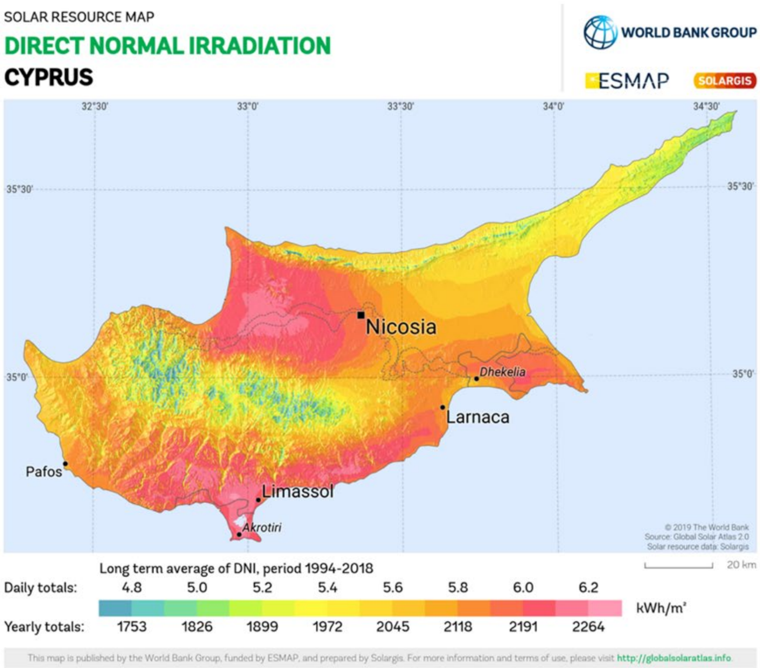

Figure 1: Contour map of the direct normal irradiation in Cyprus. Long term averages for the period 1994-2018 (Global Solar Atlas 2.0)

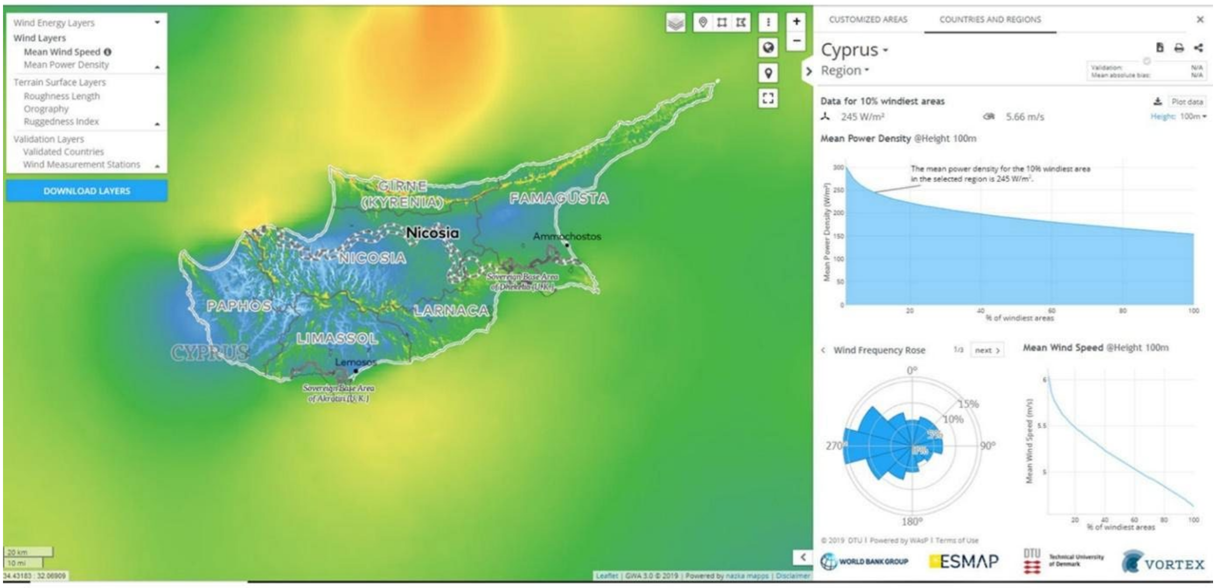

Figure 2: Overview of the Global Wind Atlas model for the whole Cypriot territory. Results at 100m AGL height (Global Wind Atlas 3.0)

Based on presently available data the per kW installed yearly yield of the various renewable energy plants in Cyprus benefits the solar power generation as wind speeds rarely exceed the 6m/s as an mean annual figure giving yearly capacity factors smaller than 25% even with the modern long blade wind turbines.
Solar irradiation can be turned into electricity by PVs and CSPs. The choice between the two methods should be based on several parameters including:

- Maturity of technology
- Storage means
- Ease of construction and maintenance
- CAPEX -Capital Expenditure i.e. cost to build a ready to run plant-
- OPEX -Operating Expenditure i.e. cost to run the plant-
- Local added value
- Grid compatibility
- Demand compatibility
- Suitability to operate in parallel with Smart Grid operations
- Lifetime and LCOE - Levelized Cost of Energy-
- Efficiency, i.e. part of the Solar irradiation turned into useful electricity

An important characteristic of the CSP plants is their storage ability: part of the thermal energy produced during daylight hours can be stored in large tanks where specially developed salts are molten at temperature ranges up to 600 ºC. In this way their latent heat can be used to recover thermal energy during the night hours feeding with steam the plant's steam turbines.
Contrary to CSPs, PVs should collaborate with external storage facilities to store electricity which then can be used when needed by the grid e.g. during the night hours.

3. Overview of Cyprus demand profiles

An important parameter to achieve efficient match between RES generation and RES penetration into the grid is the grid demand profile. Figures below show typical demand profiles of the Cyprus grid. These Figures show typical day profiles all the year round split by season.

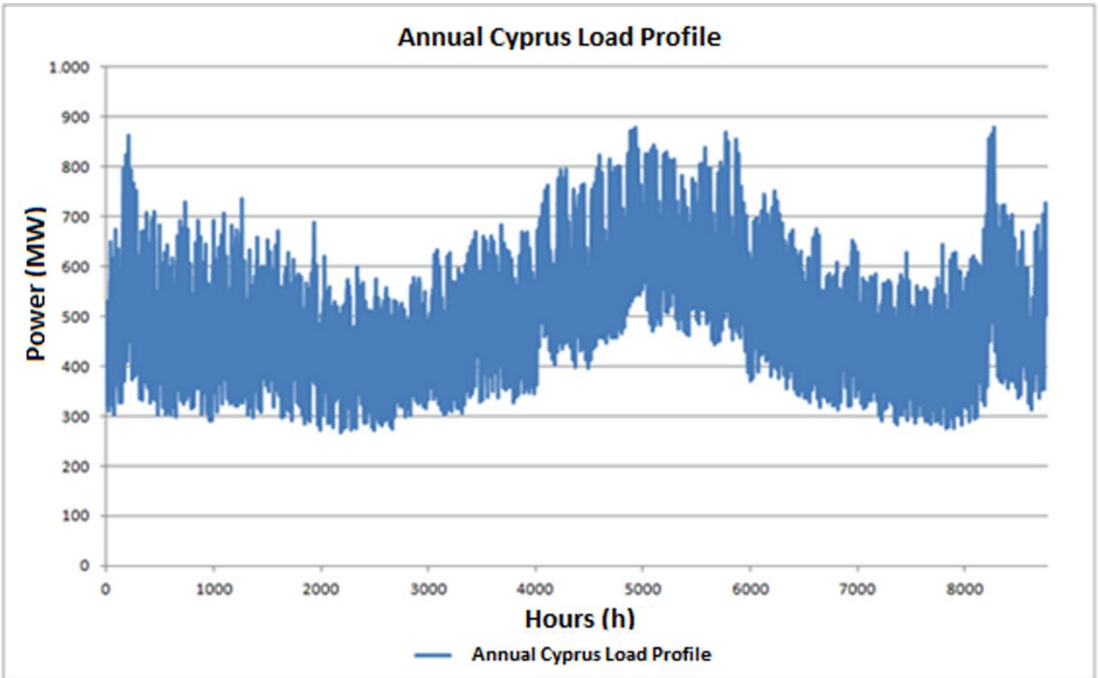

Figure 3: Overview of the yearly demand profile of the Cyprus grid starting from the first of January

As shown in the figures below, there does exist significant daily and seasonal variation all the year round. Peak values are reached during summer and the Christmas and New Year Holidays while demand drops during spring and autumn. The daily variation is considerably high and is smaller during spring and autumn. It is obvious that air conditioning and heating are driving factors as far as demand side concerns plus the increased users during the summer vacancies. As is the case most heating is based on heat pump equipment thus consuming power from the grid.
The low daily demand occurs during the early morning hours all the year round while the peak demand occurs in the late afternoon during winter days at about 19-20 hours every day. As environmental temperatures grow up approaching summer a second peak develops around noon. This peak becomes higher than the one existing in the evening all the year round. The reason should be the air conditioning units and the increased demand due to increased users in the vacancies period.

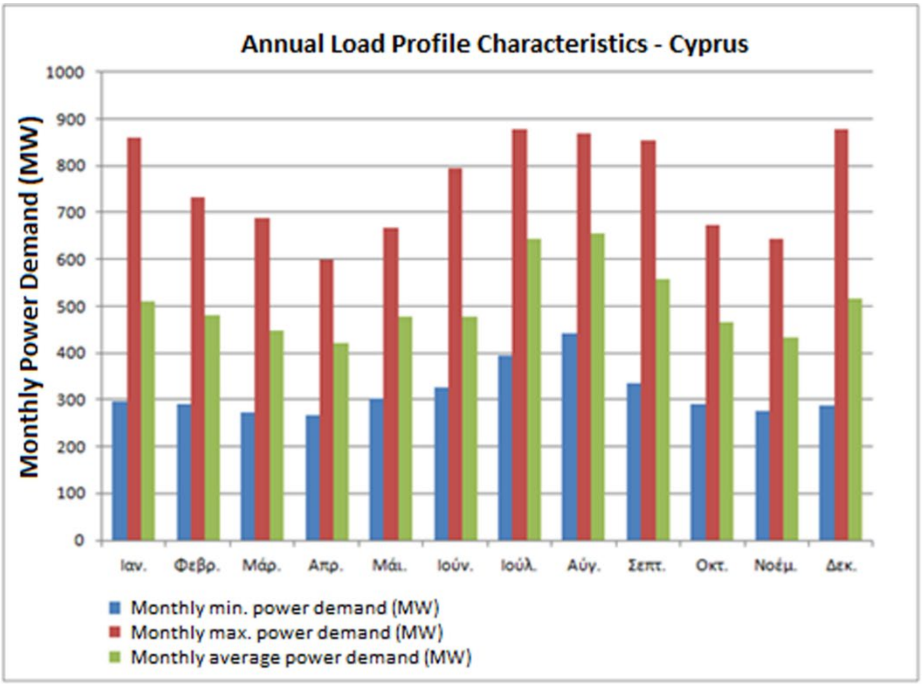

Figure 4: Monthly variation of demand profile of the Cyprus grid

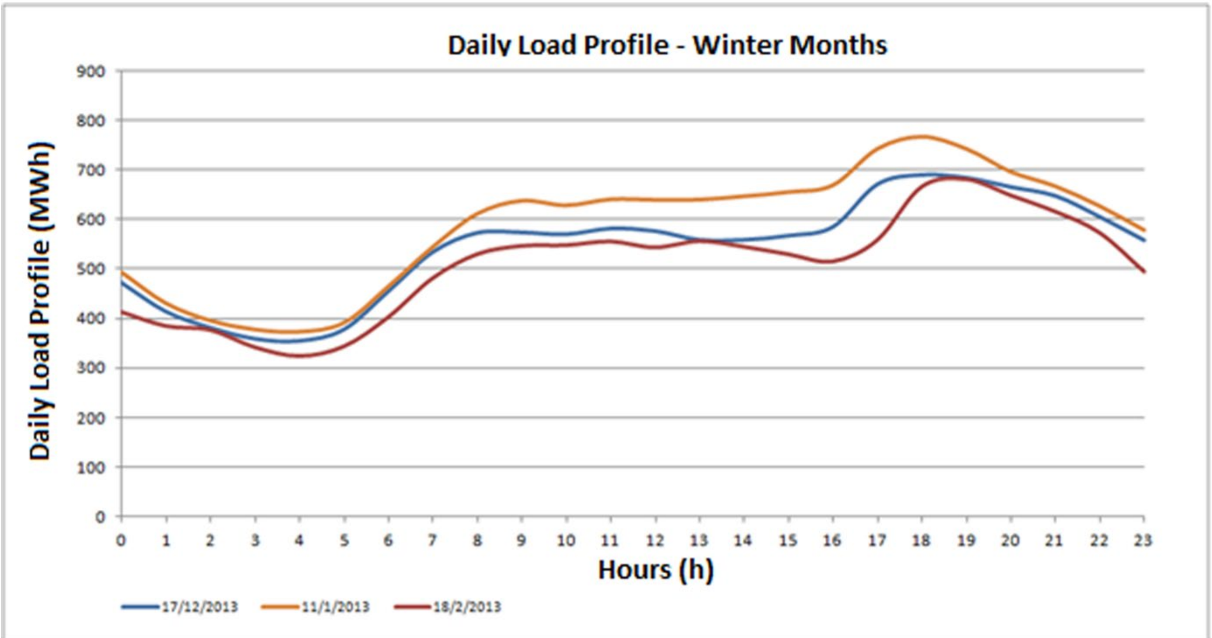

Figure 5: Specimen typical day demand profiles during winter

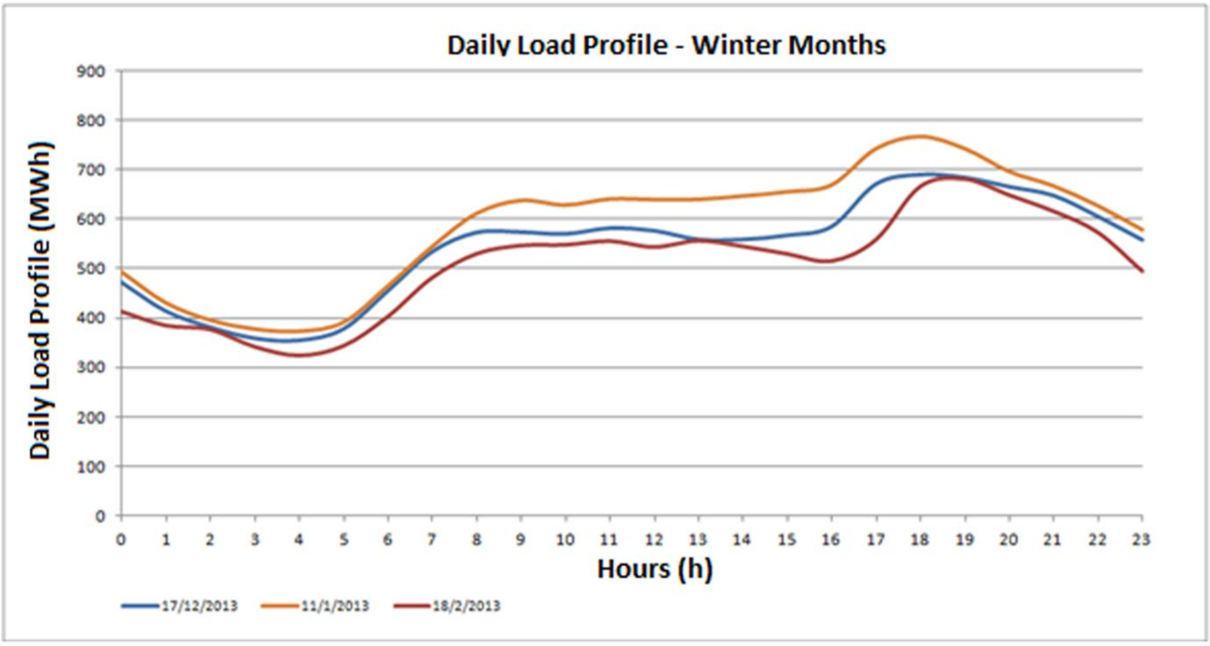

Figure 6: Specimen typical day demand profiles during spring

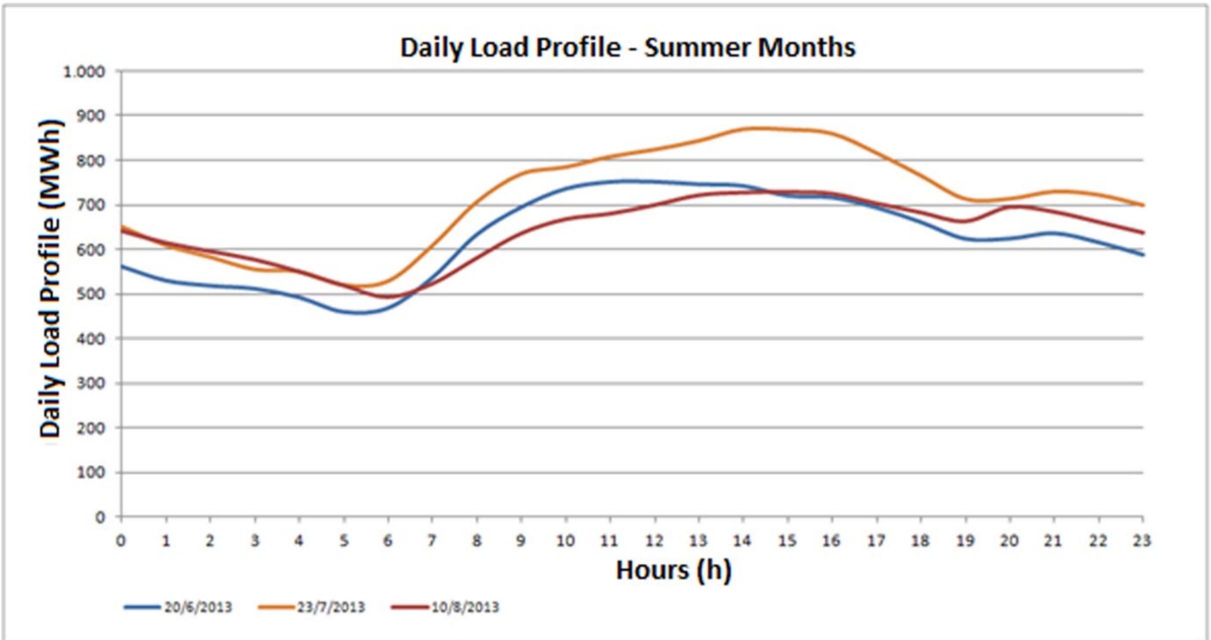

Figure 7: Specimen typical day demand profiles during summer

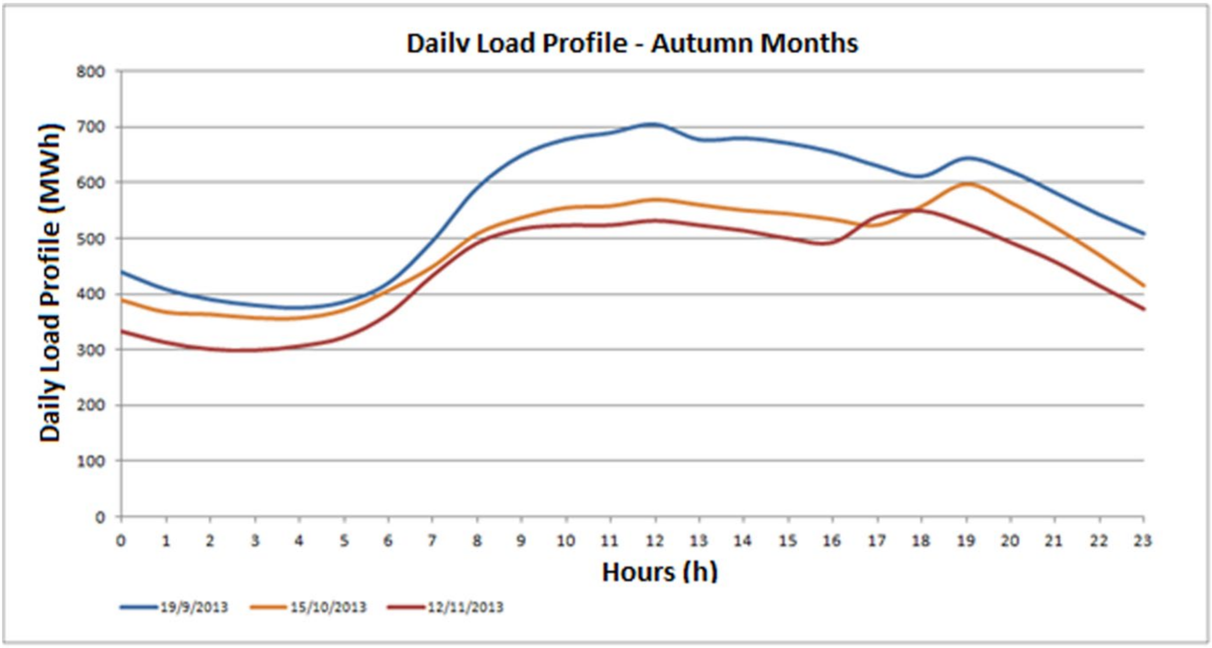

Figure 8: Specimen typical day demand profiles during autumn

If a typical solar irradiation daily curve -the main RES existing in Cyprus- is placed on figures 5-8 it is easy to show that in the lack of storage, penetration of power generated by Solar irradiation or any other means of non-stable RE sources will create difficulties in the operation of the conventional units.

Taking into account the above figures and performing the calculations a need of 400- 800 MWh of daily storage is needed to smooth the operation of the conventional units of Cyprus grid or similarly to use efficiently with the less possible curtailment the RES electricity to be produced by solar power plants either PVs or CSPs. Additionally taking into account the daily and seasonal variation of power demand a total of at least 200 MW of stored electricity is needed to cover the demand differences between day and night and the seasonal variation.

Based on the above the following parameters should be met by the potential storage systems in Cyprus:

Table 1: Capacity characteristics of the storage systems for Cyprus

Parameter	Capacity
Total energy content of electricity storage	800 MWh
Daily storage system discharge time	Up to 8 hours
Daily storage system recharge time	Up to 16 hours
Max power available from the electricity storage system	200 MW

Figures may change depending on the power demand or on developments related with other sectors e.g. if penetration of electric vehicles take place then a dramatic change on the demand side of electricity may occur affecting also the daily demand profile.

Although storage can be applied at various system levels it is more efficient, as a first step, to be controlled centrally by the operator. This means that initial target should be to install few centrally controlled storage systems. Widely distributed storage can be applied at a second stage either at medium or small scale with the main goal to change the demand system curves under a Smart Grid approach.

4. Novel hybridization and/or storage concepts applicable in Cyprus

Based on the data recovered and presented above, the following results are concluded regarding novel hybridization and storage concepts applicable in Cyprus:

4.1 Best suited storage technology for Cyprus

In the following figure the classification of existing storage methods is classified against their nominal size and maturity.

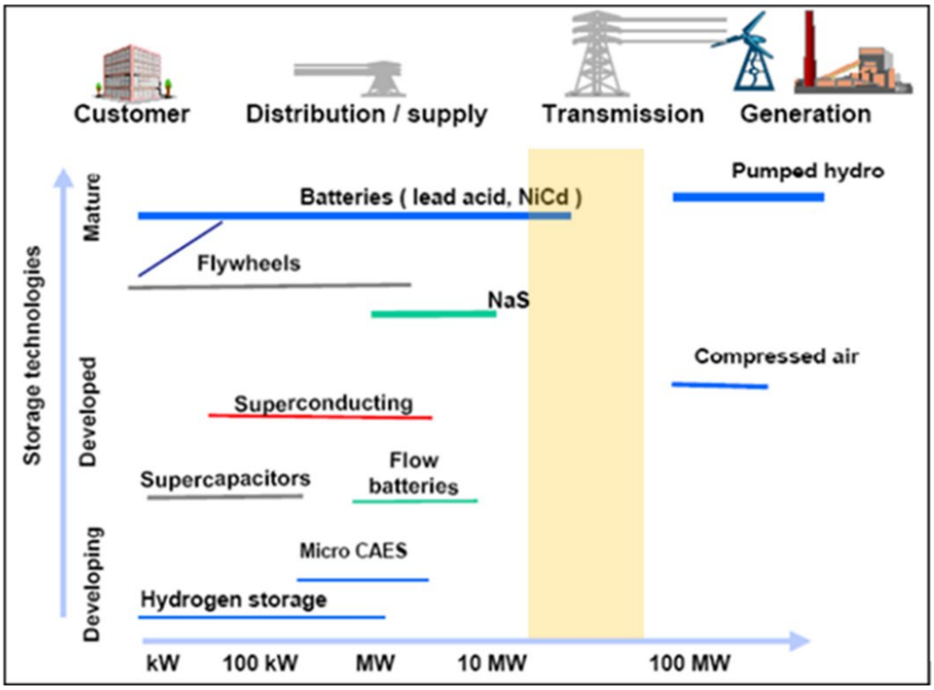

Figure 9: Classification of storage technologies against their maturity. Orange belt shows the range of capacity of storage needed in Cyprus grid and is added by the authors

It is shown that when selecting mature technologies for the size of storage needed in Cyprus Pumped hydro is better suited. If smaller units are planned then the use of batteries is also possible.
Non matured technologies might be useful to examine but for application within a longer timeframe.
If storage is planned for the management of the deviation of the demand and the increase of RES penetration in Cyprus grid, then the following figure is helpful. It is shown that pumped hydro is suitable for operation within the scale of hours whereas batteries are better suited for the management of the characteristics of the distribution grid i.e. operating for minutes or seconds -frequency correction etc.- see figure below.
Based also on the real operational data of existing commercial plants it is shown that the most suited storage applications in Cyprus should be based on a big part of Pumped hydro storage to manage the shift of the demand curve and permit RES penetration together with a smaller part of Battery storage to handle the needs of the grid in terms of stabilization and smooth operation.

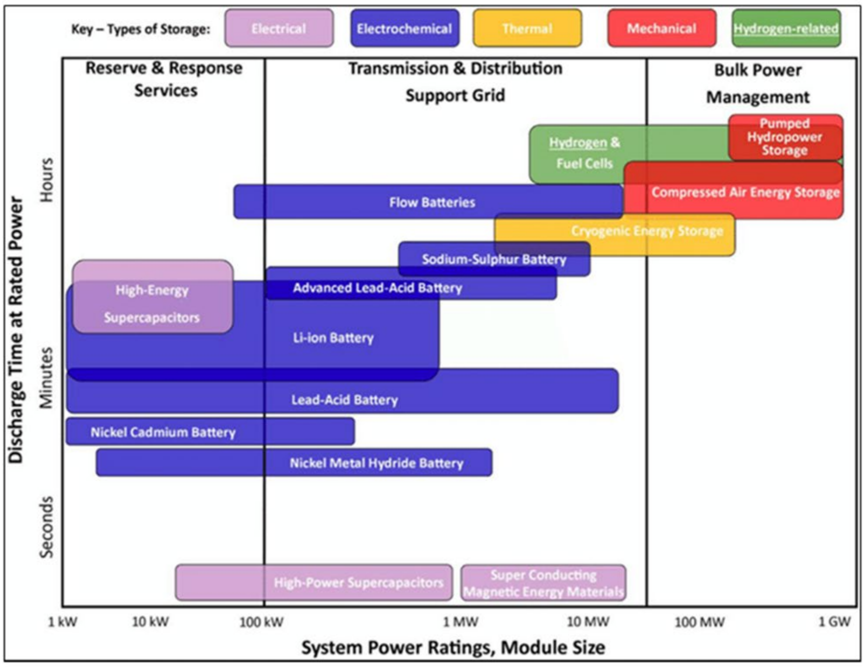

Figure 10: Classification of storage technologies against their time response parameter

The size and the distribution of the systems will be concluded by a joint approach taking into account technical and financial parameters.

Battery plants can be located anywhere however the pumping storage plants should use the existing reservoirs to save CAPEX costs and improve the water availability with all other positive side effects.

To decide for the potential locations of pumped hydro plants all existing reservoirs in Cyprus were examined taking into account various parameters. The results show that a storage capacity exceeding 400 MW of power lasting for up to 12 hours is possible using only the existing reservoirs thus minimizing CAPEX costs.

The figure below presents the location of the existing reservoirs which could be the lower reservoir in a potential pumping storage application together with the proposed location of the upper reservoir which could be built.

Figure 11: Potential locations of pumping storage power plants in Cyprus

In all cases there are suitable areas to build the upper reservoir at acceptable distances from the lower existing reservoir achieving heads well exceeding the 200 meters.

Although there are dry seasons in Cyprus there are years where existing reservoirs are full and excess rain water is guided to the sea. Pumping storage will add positive side effects by increasing the stored water volume of the present reservoirs by the volume of the upper reservoirs to be used primarily as energy storage means.

Existing reservoirs were classified in priority order taking into account several parameters. Results are shown in the table below. An initial of more than 200 MW of storage capacity is available with reservoirs that even during the driest years contain more than 60% of their nominal water volume. Additionally the water circulated between the upper & lower reservoir is less than 1/10 of the driest content of the lower reservoir which is used for irrigation purposes i.e. safety factor in terms of water availability is extremely high.

The table below presents the potential of pump-hydro systems based on existing reservoirs in Cyprus. They are classified using a system of ranking which takes into account several parameters including water availability, capacity, CAPEX, proximity to the grids, environmental issues etc.

Table 2: Ranking of potential pumped -hydro storage potential in Cyprus

Existing Reservoirs (Dams)	Water availability (M3) Lower Reservoir -1-	Upper Reservoir -2-	Capacity % 2/7/2014	Head ΔH - 1-2 (m)	Hybrid Power Station Capacity (MW)	Ranking [0 - 7.5]
Priority projects						
Arminou	4.300.000	800.000	62,0	580	60	7,50
Asprokremmos	52.375.000	1.500.000	72,7	320	60	4,75
Kannaviou	17.168.000	700.000	63,2	400	35	5,25
Evretou	24.000.000	1.200.000	62,6	400	60	6,25
Kalopanagiotis	363.000	180.000	90,4	550	13	5,25
TOTAL					**228**	
Other projects						
Dipotamos	15.500.000	500.000	15,0	220	15	5,75
Lefkara	13.850.000	500.000	16,2	400	20	5,75
Kouris	115.000.000	1.800.000	33,1	250	60	5,75
Germasogeia	13.500.000	450.000	34,3	250	20	4,75
Kalavasos	17.100.000	750.000	10,9	350	35	5,75
Mavrokolympos	2.180.000	700.000	54,3	435	37	6,25
Argaka	990.000	300.000	26,2	400	15	2,00
Pomos	860.000	200.000	17,6	420	13	1,00
Ksiliatos	1.430.000	250.000	33,1	300	10	3,00
Lefkas	368.000	200.000	50	400	8	2,75
Klirou	2.000.000	300.000	50	280	15	5,25
Palaiochori	620.000	200.000	50	300	8	4,25
TOTALS	**183.398.000**	**6.150.000**			**256,0**	

4.2 Novel hybridization concepts

As already mentioned above, solar irradiation is the RES to be used with the storage facilities in Cyprus.

Currently there are two methods when turning the available solar irradiation into electricity: Photovoltaics -PVs- and Concentrated Solar Power Plants - CSPs-.

The following figure shows typical CAPEX data for both of them. Today the margin between PVs and CSPs increased more as PVs cost dropped considerably to less than 700 Euro/kW nominal installed, while CSP’s including storage is still at the range of 4.500 Euro/kW installed.

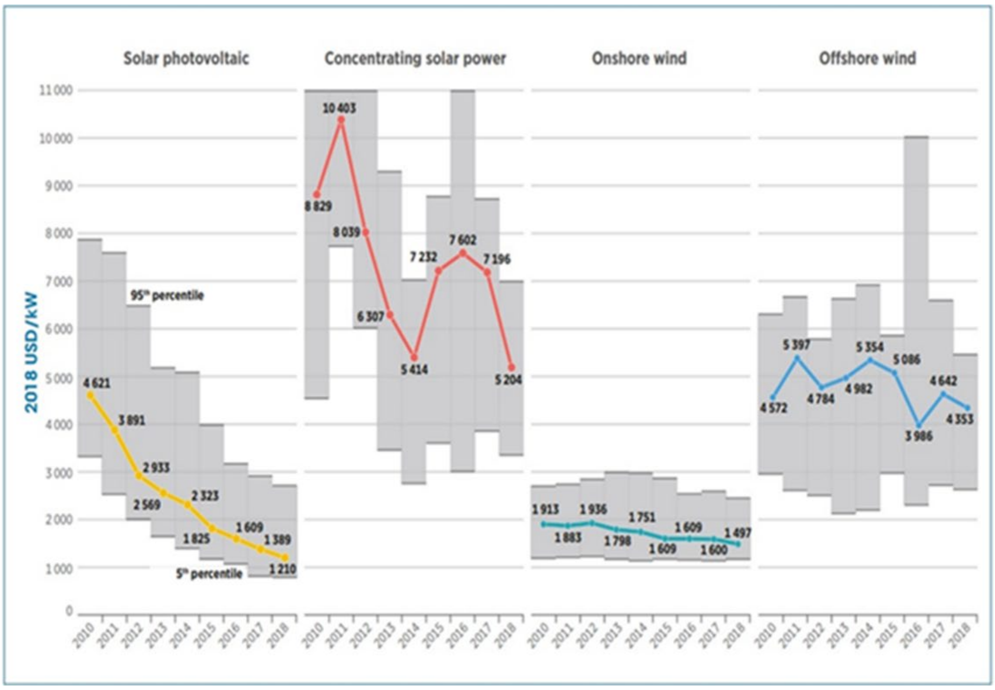

Figure 12: Comparing costs of well proven technologies until 2018

Taking into account that PV plant efficiency -electricity output/solar irradiation input per m^2 of collector- is about 50% of a modern CSP plant efficiency the use of PVs is three times cheaper compared to CSP's. This assumption is based also on the fact that PVs can also utilise the diffused solar irradiation while CSP's only the direct one. Meteorological data show that in Cyprus total irradiation is about 10-15% higher than the direct one.

When adding the storage parameter i.e. to assign the storage cost to PVs only then the cost of PVs with pumping storage or batteries is going up to around 1.700 Euro/kW which is still a third of the hybrid CSP/storage cost.

Based on the above, PV development with pumped-hydro and batteries storage is more financially sound compared to CSP development, if the goal is to increase RES penetration in Cyprus.

The combined use of PV's with pumped-hydro storage has not been used elsewhere. Typical scheme includes the use of wind as a primary RES. However, as in Cyprus wind resources are modest while solar irradiation is high, the hybridization of PVs with pumped-hydro storage creates significant benefits including lower CAPEX, local added value, water storage enhancement etc. Despite the novelty of this combination i.e. PVs with pumped-hydro, both technologies are well matured and present significant benefits compared with other approaches. One of them is the ability of the decentralization of the PV plants.

4.3 Smart Grid suggestions

The Smart Grid approach can be summarized in applying methods to smooth the demand side instead of cope generation to the demand only.

Smart Grid techniques play an important role when generation side consists of power plants having an optimum operation mode. In such cases smart grid techniques offer significant benefits if manage to transform the demand curve to cope with the most efficient generation mode.

In cases of high RES penetration which is vastly intermittent and stochastic, smart grid approaches are very useful when conserving the grid stability and power quality under conditions of "chaotic" operation of the intermittent RES generators.

As presented in the previous paragraphs the most proven smart grid technique in this case is the ability to store power and cope with short time scales - seconds or milliseconds - to the implications of generators stoppage or ramping which affect the grid stability. It has been shown in several real life cases that this can be offered with battery storage although there is ongoing research to achieve those benefits also with modern pumped-hydro storage equipment.
Other smart grid approaches include actions to develop consumer behavior that might be beneficial for the grid e.g. apply local cool storage in medium and large consumers to shift the cooling load from day time to night. In any case all those are related to incentives or variable charging of consumed power around the day because all these methods typically require more CAPEX compared to common equipment.

5. Expected implications to the Grid and sustainability

Following the previous developed approach the implication of the selected technologies to the grid of Cyprus were examined.
An excel based code has been developed to examine the implications of storage in the operation of the conventional units taking into account RES generation through a stochastic approach related mainly with the climatic characteristics of Cyprus and able to change the installed RES capacity.
Several scenarios were examined. Figure below presents the change of the operation of the conventional units of Cyprus grid when 165 MW of storage capacity is applied and 200 MW of additional PVs are installed.

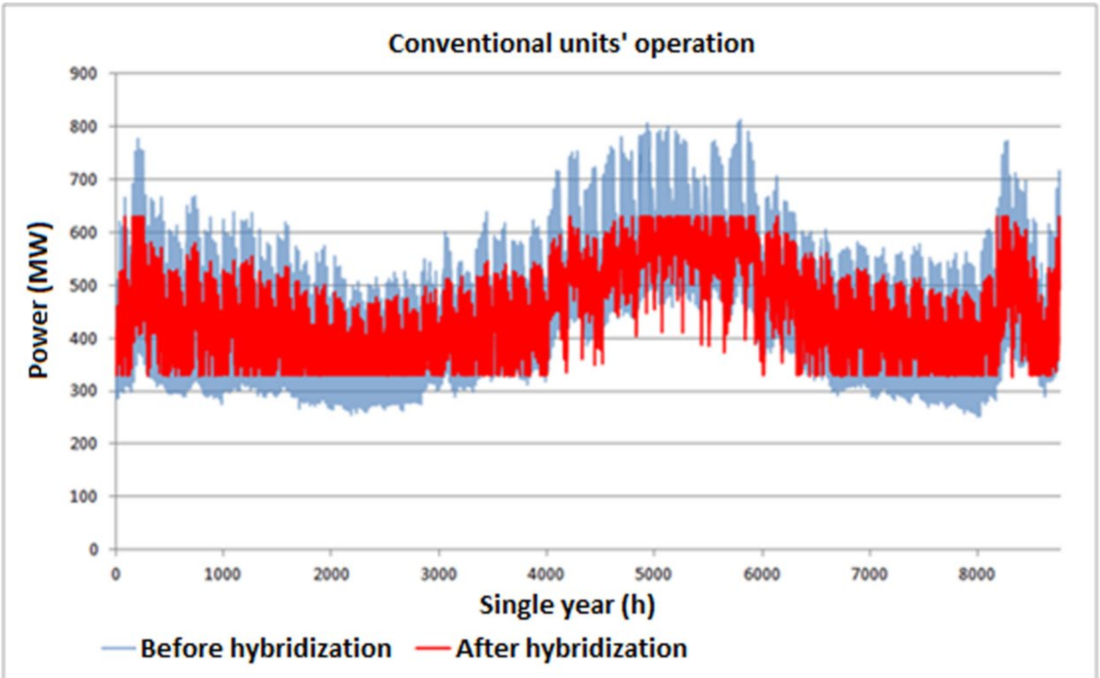

Figure 13: Results of applying storage with PVs on the typical yearly operation of the conventional units. Blue line: before hybridization - Red line: after hybridization. Peak saving and power variation is significant

Important peak saving occurs. Low grid demand is increased minimizing the curtailment of the RES plants as power is needed to recharge the storage units. The big variation between day and night load demands is significantly reduced. Figures show that this variation is reduced up to 50%. Additionally the RES penetration is increase more than 100%. Power safety supply is also enhanced significantly as there is a back-up of 165 MW of power to meet emergency needs. Idle run of conventional units can be significantly reduced saving costs.

6. Conclusions

According to the present study and in order to reach the goal of increased RES penetration and grid stability in Cyprus the following steps could be followed:

- Apply storage including pumped-hydro storage of around 150 MW using the existing reservoirs and battery storage of about 60 MW to stabilize the grid.

- Based on the existence of storage capacities increase the PV installations over Cyprus thus provide RES power to charge the storage facilities and minimize the operation of the conventional units.

- CSP installations are more expensive today. If their costs drop in the future then this technology could be examined again in terms of financial competitiveness compared to PVs.

- Other storage technologies are either more expensive to apply in Cyprus - e.g. Compressed air storage or sea water hydro pumping storage - or in a non-matured stage regarding commercial applications - e.g. gravity based solutions, flying wheels etc.-.

Acknowledgement

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