Assessment of Renewable Hybrid Power Plants on Greek Non Interconnected Islands and their Contribution to CO_2 Reduction by Evaluating the Potential Penetration Rates on Different Islands

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***Abstract*—Greece compromises 3,054 islands of which only 113 are inhabited. Of these inhabited islands 60 are not yet connected to electrical system of the mainland and forming therefore 32 isolated electrical systems. 21 of these islands are single island systems while the 11 remaining serving two or more islands. Interconnection plans via undersea cables exist for the most of these islands and implementation started already at Crete a couple of years ago. This so called non-interconnected islands (NII) host 15 % of the Greek population and account for 14 % of the total national electricity consumption. Due to the missing interconnection of these islands their electricity supply is relying to most extend on thermal power plants operated with heavy fuel oil (HFO) or light fuel oil (LFO). This results in not only high production cost per kWh but also on heavy CO_2 emissions. Distributed renewable energy resources (DER) such as wind and photovoltaic (PV) power plants are currently only sparsely distributed over the NIIs although the natural resources to operate such DERs are available on all NII at a huge extend. Expanding of DERs on the NIIs is limited by the fact that the regional grids of the NIIs are not able to cover a considerable percentage of this kind of energy generators, due to their intermittent nature. With increasing penetration rates of DERs in limited grid areas, the risk of grid stability problems increases. To increase the share of renewable DERs on the NII and with that decreasing the cost of electricity generation and emissions they must be combined with battery energy storage systems (BESS) to a so-called Hybrid Power System (HPS). By combining the two items a dispatchable power plant arises and a grid connection of renewable DERs will be possible up to 100 % energy penetration rates in theory. Such HPS are under development since couple of years but only few are in operation to date. For this paper we analyzed the energy demand and supply matrix of the islands Samos, Chios, Rhodes, and Lesbos and set it in relation with the HPS under development at the respective island to find out on which extend an implementation of this HPS will reduce the emissions caused by energy produced from thermal power plants on the island. For this evaluation, our inhouse system modelling approach is used, especially developed to quantify the impacts of the planned Greek NII´s HPSs considering the recent regulations on HPSs for NII´s. We point out current challenges which hinder the rollout of the HPS and as a conclusion the theoretical possible HPS penetration rates shall be displayed. This shall subsume the relevant information which are public available and serve as a basis for starting the discussion whether a future interconnection of the NIIs with the mainland grid system is necessary from energy balance perspective considering the existing project pipeline of the HPS on the four investigated islands.**

Keywords: hybrid energy systems, battery energy storage system, islands, grid, Greece, renewable energies

I. INTRODUCTION

Since more than six years local and international project developers for renewable energy projects working on development of HPSs on the 32 Greek NIIs. According to national law 4414/2016 such systems are to be remunerated based on a subsidized feed in tariff scheme. In 2016 it turned out that this approach was no longer in line with the directives of the European Commission (EC) [1] about state aid for energy remuneration although the NII are not participating at the Greek wholesale energy market. Since that date the Greek Government is working on establishing and introducing a new remuneration scheme according to EC requirements. Due to that, until today there is no remuneration scheme available for HPSs on the Greek NIIs which is the main reason that the majority share of the projects got stuck at the Producer Certification (PC) level of the permitting procedure. The PC is the first out of several licenses and permits a project developer needs to collect before starting project implementation and operation. However, after almost six years of waiting for a new remuneration procedure it seems to be that in 2022 there will be a new scheme introduced, which is approved from EC. Based on the currently available information it will be most likely a competitive tender procedure [2]. Development and implementation of the HPSs in the licensing pipeline of the Regulator for Energy (RAE) would significantly contribute to the decrease of fossil fuel demand on the NII and by that to the decrease of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions. Most recent numbers available on RAE homepage shows that 148 projects with approx. 970 MW of renewable and more than 540 MW of Battery Energy Storage Systems (BESS) power are under development and issued already with a PC (Pumped hydro projects are excluded). According to the Hellenic Electricity Distribution Network Operator S.A.[1] (HEDNO) only 485 MW of renewable DERs are installed on the NII compared with 1,845 MW of thermal power plants [3]. Considering this numbers, it becomes reasonable that the average variable cost (AVC) per produced kWh of electric energy is extremely high compared to the system cost of the mainland. According to HEDNO data the 2020 AVC of the NIIs was 212 €/MWh while the average mainland Greece Day-Ahead-Market (DAM) price was 36 €/MWh in 2020 [4] and the avg. retail price for non-industrial customers was 178 €/MWh [5] including all taxes and levies. **Figure 1** displays the AVC of all NII as well as the continental Greek DAM price and the Greek retail price for electricity.

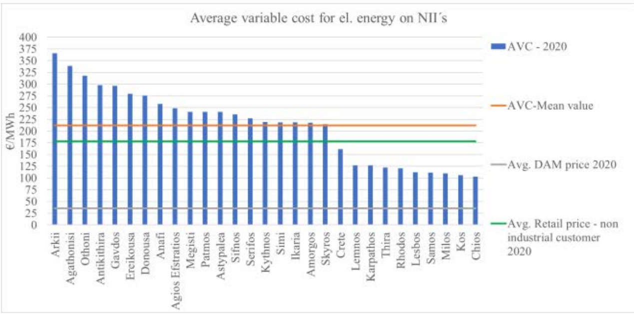

Figure 1. Average variable cost for energy on non-interconnected islands

The use of thermal power plants on the NIIs results not only in high energy production costs, but also in very high GHG emissions such as CO_2. Referring to this, on the one hand, the Greek government is under pressure from cost and environmental perspectives to reduce the operating hours of thermal power plants and, on the other hand, from the EC side through directives 2010/75/EU and 2015/2193/EU on allowed industrial emissions of amongst other thermal power plants. According to these directives approx. 99 % (1,830 MW) of the installed thermal power plants needs to be dismantled or refurbished until 2030. To achieve the national target of 95 % GHG reduction until 2050 [6] and to comply with the EU directives Greece must drastically expand DERs on the NIIs but at the same time HEDNO must take care about the security of electricity supply on the NIIs since they are not interconnected with the mainland grid and therefore lacking high inertia especially in times of high penetration through intermittent DER. To achieve cost and emission reduction as well as increased system stability there are only the two reasonable options available. Either through NII-interconnection or by enrolling HPS on the NIIs. Both options can be combined but must be decided based on a cost-benefit analysis. It is hypothesised that rolling out HPS across the NIIs is a faster and more cost-efficient way to achieve national climate targets, EU targets, as well as a reduction in the cost of power generation on the NIIs. This thesis is supported by the large number of HPS projects already under development (with and without issued PC), which would take approx. one to two years at most to implement (once all permits have been obtained). By enrolling HPS the security of supply will remain stable or will even improve through the BESS part of the HPS as the BESS is able to deliver ancillary services such as voltage and frequency control. A connection of the NII with the mainland can further increase the security of supply but should be (re)assessed under consideration of an area-wide expansion of HPSs on the NIIs. To point out the importance of HPS installation roll out on NIIs, referring to cost and GHG emission reduction, four out of 32 NIIs are assessed in this paper. These four islands are Samos, Chios, Rhodes, and Lesbos.

II. Status Quo

According to HEDNO reports[2] the 2019 annual electricity energy demand of the four islands accounts for 1,300.85 GWh of which the distribution across the four islands is shown in **Table 1**. Furthermore, the same table shows the CO_2 emissions caused by the el. energy produced by the thermal power plants of the assessed islands. For CO_2 emission calculation a factor of 690.87 t/GWh is here used.

Table 1. Annual el. energy demand of Samos, Rhodes, Chios and Lesbos

	Chios	Samos	Rhodes	Lesbos
Energy demand in 2019 in GWh	204.3	138.8	665.9	292.0
Thermal share[3]	88.64 %	80.4 %	84.14 %	84.86 %
CO_2 emission in t	125,111	77,098	387,086	171,191

In the following subchapters of Chapter II, a closer look on the current el. systems of the four islands should be done and the load patterns of the same should be briefly discussed.

A. Installed Power Plants

Finding out the amount of installed nameplate power of the thermal and DER power plants on the NIIs in general and at the four islands in particular is a difficult task as only power plants above one MW nominal power are registered in the public available data rooms of HEDNO. Depending on the

[1] HEDNO secures operation, maintenance and development over the whole country. Furthermore, on the NIIs HEDNO is responsible for the whole O&M of the NIIs electrical systems as well as the proper operation of the energy market on the NIIs.

[2] Referring to law 3468/2006 Article 6 part 3 HEDO is obliged to deliver technical reports of NII to interested developers of HPSs. These reports are available on request.

[3] Own calculation based on HEDNO input data of installed DER and HPS on the islands.

source referring to the total installed nominal power on the different islands the obtainable information is different. According to [7] a total installed thermal power of 455.22 MW and 116.5 MW of renewable DERs are installed. However, referring to the technical reports of HEDNO which refers to law 3468/2006 Article 6 part 3 the installed amount of thermal power on the four islands accounts for 535.43 MW while the number of MW for DERs sum up to a value of 121.7 MW of which 43.81 MW are PV installations and 77.89 MW are wind farms with one or more wind turbines installed. To be as accurate as possible all further calculation results base on modelling input parameter which refers to the data of the official HEDNO techno-economic reports from 2020. In **Table 2** the current power plant park of the four investigated islands is presented.

Table 2. Installed power plant capacity by source in MW

	Chios	Samos	Rhodes	Lesbos
Thermal power	77.8	49.63	327	81
PV	5.2	4.77	25	8.84
Wind	8.2	5.74	50	13.95
HPS	0	0	0	0

Currently at none of the four islands HPSs are installed at the one hand and at the other hand in avg. the renewable to thermal installed capacity ratio is already 22 %. However, as this value is calculated on the installed thermal power it has no real value while looking at stability concerns on the four island grids. To get a better understanding it must be taken the relation between installed RE power and the real maximum, minimum and average load demand of the island of which the values are shown in **Table 3**.

Table 3. Power demand and RE to power ratios

	Chios	Samos	Rhodes	Lesbos
Max. demand [MW]	45.87	28.93	153.79	64.19
Min. demand [MW]	11.13	7.55	33.73	16.61
Average demand [MW]	23.32	15.84	75.83	33.34
RE ratio on max. demand	29 %	36 %	49 %	36 %
RE ratio on min. demand	120 %	139 %	222 %	137 %
RE ratio on avg. demand	57 %	66 %	99 %	68 %

The ratios shown in **Table 3** for sure are not representative to clearly prove that grid instabilities might occur in the respective grid, but they give a first glimpse about the limitation of connecting new DERs to the grid. On all four islands RE penetration rates of above 50 % on the avg. load demand are already achieved and in low time windows max. penetration values of up to 222 % can be reached in theory. Considering this it could be assumed, that the already installed DERs on the island phases times with heavy curtailment to not causing voltage and stability problems in the grids. Unfortunately, it is not possible to get proper data on the amount of the curtailed energy of the DERs on the islands. To execute a proper system modelling the limits on minimal operation output of the thermal generators installed on the islands was considered in the modeling tool. This data on the minimal load output of the generators were collected from the technical reports of HEDNO. Although with the results shown in **Table 3** no quantitative statement about potential stability problems on the islands grid can be made the results however could be considered as the limiting factor of expanding more DERs on the islands as it would cause even more curtailment and the risk of grid instabilities. To avoid stability problems but also expanding DERs on the islands there is only the possible way of enrolling HPS projects on them. As the HPS contain a BESS they can be considered as dispatchable renewable power plants which can be steered and controlled according to the needs of the grid in a respective time step. A HPS is therefore comparable to a thermal plant with the benefit of being sustainable at the one hand and at the other hand the BESS can significantly participate in securing the grid stability due to the fast reaction times and the capability of delivering active as well as reactive power when needed.

B. HPSs under Development

As mentioned in the previous chapter and in Chapter I already 148 HPS projects are equipped with a PC and waiting for final regulations in force which enable further development. This is however just the sum of projects which already managed to receive the PC. According to RAE register for HPS projects some of applications for PC dates back until 2007 while the majority share of them applied in 2016 and 2017. Most projects received the PC in 2020. Besides the 148 projects already equipped with a PC there are additional 124 projects under investigation to either receive PC or being rejected. Only two out of these projects are HPS with pumped hydro as storage facility. The other 122 are wind or PV combinations with BESS. The most surprising number is the number of HPS which are in operation to date. Only two projects are in operation of which one is a PV (0.16 MWp), wind (0.8 MW) and BESS (0.8 MW / 2.88 MWh) combination installed on the island of Thilos developed by Eunice Energy Group[4]. The other one is a wind farm (2.7 MW) combined with pumped hydro storage (3 MW charging / 3.8 MVA discharging; approx. 85 MWh)[5] on the island of Ikaria developed by PPC Renewables[6]. In **Table 4** the HPS projects under development on the four investigated islands are shown.

[4] For more information: https://eunice-group.com/projects/tilos-project/

[5] Pumping power is 3 MW. The power of the el. generators is 3.8 MVA while the two hydro turbines deliver 3.1 MW. Capacity calculated based on available information about the altitude of the reservoirs (555 & 65 m) and the water volume of the lower reservoir of 80.000 m² as well as with an estimated efficiency of 80%.

[6] For more information: https://www.ppcr.gr/en/projects/current-projects

Table 4. Overview on HPS under development on the assessed islands

	Chios	Samos	Rhodes	Lesbos
Number of HPS with PC	3	4	22	5
Number of HPS waiting for PC	3	3	0	6
PV share on HPS with PC [MW]	18	2.4	53.22	23
PV share on HPS waiting for PC [MW]	10.17	7.24	0	30.4
Wind share on HPS with PC [MW]	0	0	156.35	0
Wind share on HPS waiting for PC [MW]	0	0	0	0
BESS share on HPS with PC [MW]	7.75	1.2	51.15	14.7
BESS share on HPS waiting for PC [MW]	6.75	6.75	0	27.25
BESS share on HPS with PC [MWh]	15.5	6.0	625	29.4

Table 4 contains all HPS projects currently under development and for which sufficient public data are available. In total there is a sum of 68 projects under development but according to the RAE register at 20 of them no sufficient data about MW under development and source of energy as well as storage technology are available. Additional two projects were excluded from the list as they refer to wind combined with pump hydro storage. They applied for PC in 2006 and 2008 and got the PCs in 2010 and 2011 respectively. In the modelling of the future energy landscape of the assessed islands, which will be tackled in chapter III, these two projects are excluded as it reasonable to assume that the projects will not become reality in very short term. The 20 projects of which no proper data are available are also excluded from the modelling as it is not possible to make reasonable assumptions about the size of this very HPSs. All these projects are under evaluation for getting PC. It could be reasonable assumed that due to the lack of proper information the projects will be rejected from RAE and with this neither will get PC nor will they become reality in the future.

C. Electric Load pattern of the Islands

The main island characteristics of the 32 isolated energy systems are in general that the load demand of most of the NIIs presents a high seasonal variability due to the tourism industry. For the four considered islands this turns out in load profiles as shown in **Figure 2** below. During summer times which least from June to August the energy demand is at highest point on all islands. In general, it could be seen that the lowest energy demand is reached in the months from February to May.

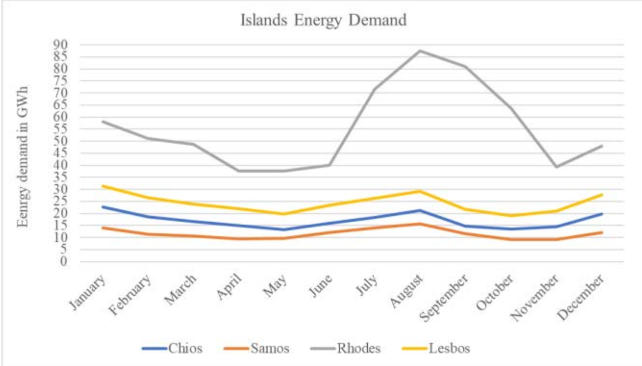

Figure 2. Monthly energy demand profile of the islands

Especially on Rhodes the high seasonal variability in the load demand could be seen while looking at **Figure 3**. Between the four islands Rhodes is the most touristic one which is reflected by an increase in max. load demand of 121.54 MW in the month of February (off-season) to 153.79 MW in the month of September (high season).

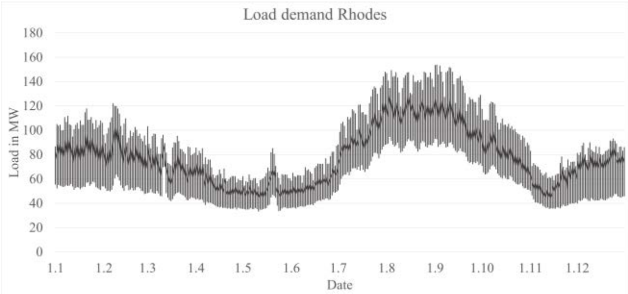

Figure 3. Annual load profile of Rhodes

For the other three islands it could be stated that an increase of peak demand due to seasonal variability caused by heavy tourism is not reflected while locking on 2019´s load demand profile (**Figure 4**). Within the 32 NIIs of Greece Chios, Samos and Lesbos are the islands which have comparable low tourism numbers during high season [8].

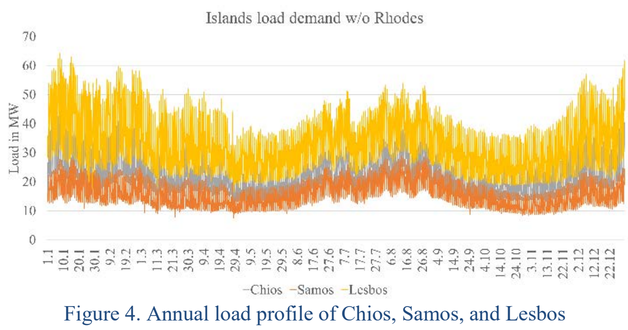

Figure 4. Annual load profile of Chios, Samos, and Lesbos

At Lesbos the highest load demand of 64.19 MW is in January while the peak demand during touristic season (June to August) is only 53.86 MW at the middle of August. On Chios and Samos, one sees a small increase of load demand in the touristic season with a max. demand of 39.34 MW (August, Chios) and 28,93 MW in Samos in August too. However, at Chios the max. power demand occurs in wintertime as it is on Lesbos. At beginning of January power demand on Chios reaches the max. value of 45.87 MW. Considering the min. and max. power demand of the islands (**Table 1**) it could be seen that Rhodes has the highest increase step in power demand with a value of 120 MW while the other three reaches 34.74 MW (Chios), 21.38 MW (Samos) and 47.58 MW (Lesbos). As displayed in **Table 2** already some renewable DERs are installed on the islands which contribute to the electric energy supply of them. **Figure 5** shows the energy supply matrix of the four islands assessed.

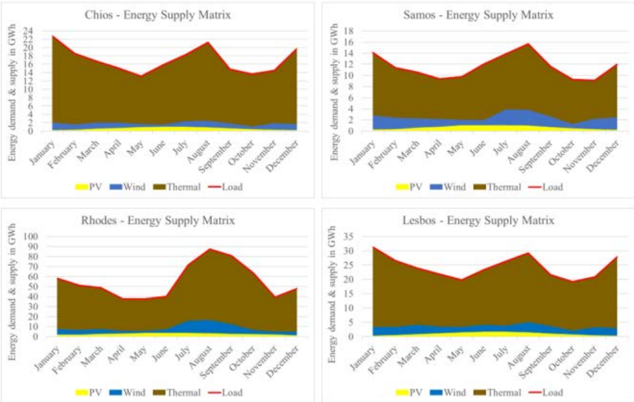

Figure 5. Energy supply matrix of the assessed islands

Although the renewable share on the total energy demand of the islands is in average at a low level of 16 % there are also times of high penetration looking into the hourly load and supply data of the islands. Based on the available data of thermal power plant and wind farm production the highest penetration per hourly time step is reached on Samos with a value of 82 %[7]. On Lesbos and Chios, a max. penetration rate of 58 % could be reached while on Rhodes the max. value is not exceeding 45 %. However, with this temporary high penetration rates it is theoretically possible that grid stability problems could occur. To avoid this circumstance the NII systems operator HEDNO will secure stable system operation by curtailing the renewable DERs after the penetration passes a certain threshold limit. This limit is different from island to island but according to HEDNO whenever penetration rates are as high that not only one thermal generator of the islands thermal power plant fleet is able to produce equal or more than approximately 50 % of its rated capacity the DERs must be curtailed to secure stable grid operation. Summarizing this operation strategy while considering the technical challenges caused by high DER penetration rates it is reasonable that RAE together with HEDNO is setting limits for new additional DERs permitted to be connected to the NIIs grids. As shown in Chapter I the Greek government is however under pressure reducing cost of energy production and GHG emissions on the islands. To achieve this renewable based DERs must be expanded which is only be possible by adding storage (e.g.: BESS) to them and by interconnecting the NIIs with the mainland. For the latter already approved plans of interconnection exists, which shall be briefly discussed in the following subchapter D.

D. Islands Interconnection

Interconnection of the NIIs with the mainland by undersea cables started already in 2018 with signing the implementation contracts for the Crete interconnection – Phase I project. The aim of the project is the interconnection of Crete Island with the mainland Greece electrical system at the connection point on the Peloponnese. Estimated budget for the two times 135 km cables (150 kV AC; 400 MVA capacity in total) is 330 million Euros with an initial planned project completion by mid-2020 [9]. However, the project was delayed by one year as completion was reached in May 2021 with increased cost of 50 Mio. € compared to the initial budget calculation [10]. The Crete interconnection consist of a second phase which completion is to be intended by the 3rd quarter of 2022. Estimated cost for the second phase is approx. one billion € [9]. However, as the implementation contracts for the phase two project were signed in June 2020 [11] the project suffers already a delay of one year. According to [12] interconnection of the NIIs via undersea cable is the most cost and time efficient way forward of reaching high renewable penetration on the NIIs as well as significant GHG emission reduction. Furthermore, island interconnection was explored to be the most efficient way to reach high security of supply due to reaching N-1 level ones the interconnections are operating, and it is stated that with interconnection it is no longer necessary to operate the thermal plants on the islands. From technical point of view, there seems to be no leverage to challenge the N-1 finding but whether all the thermal power plants must not operate anymore after islands interconnection must at least be questioned as there could be still times of transfer limits either from the islands to mainland or vice versa. Especially in times of high renewable penetration which could then cause again stability problems on the island's distribution grids. However, from time and cost perspective and by referring to the cost increases and time delays of the Crete interconnection projects it could be also reasonable to open again the discussion whether the interconnection of all NIIs with the mainland should be the first step to increase renewable penetration and with that GHG emission and cost reduction on the islands or if it should be the other way around and the starting point should be the proper and efficient roll out of HPS on the same. In the results of the cost-benefit analysis for island interconnections the roll out of HPS were not considered [12] which is from cost and technical perspective at least to be questioned. From market perspective this approach seems not adequate as especially BESS, but also renewable energy source experienced a drastic decrease in cost during last years. As the average project implementation time for HPS (after receiving all relevant permits) is not longer than two years it seems obvious to discuss the point of interconnection again. The latest ten-year national development plan (TYNDP) of Greeks independent power transmission operator (IPTO or ADMIE as it is abbreviated in Greek) was recently approved by RAE and with that the way was pathed for starting the interconnection of all Greek NIIs. In **Figure 6** the interconnection plan of the NIIs is shown. Referring to [12] the four assessed islands of this paper shall be interconnected latest in year 2029. Estimated interconnection costs for the islands of Dodecanese (including Rhodes) are expected to reach 1.47 billion € while the estimated cost for the north-east Aegean islands (Chios, Samos, and Lesbos) are expected to reach 935 Mio. € [13]. According to [12] and [13] the expected

[7] Wind energy production values were given from HEDNO techno-economic reports, while PV energy produced was calculated based on the available data on installed power and with irradiation data as further explained in Chapter III of this paper.

cost for a complete interconnection of the NIIs sums up to 4.195 billion €. With this amount of money 3 GW of HPS could be installed in theory by assuming investment costs of 1,500 €/kW.

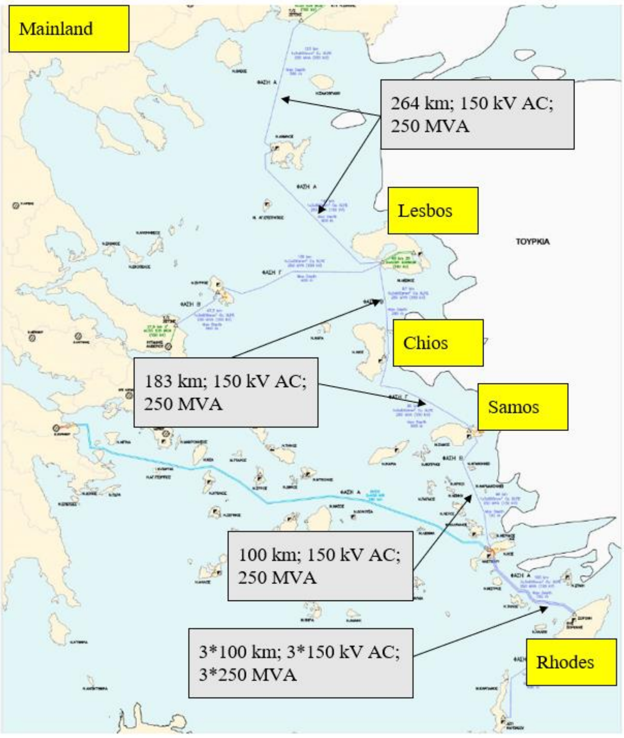

Figure 6. Overview of islands interconnection plan according to IPTO´s TYNDP

III. Modelling Approach

In this section a description of how the modelling was performed for all the islands in this study is provided. The model is created as to balance the energy flow in the island. Here no considerations on grid stability nor constraints are modelled, so energy can flow and be distributed freely amongst all the sources to attend the load at any time. The primary goal of the proposed HPSs is to attend the island loads when they need it most, therefore additional information of these loads is provided below; furthermore, the HPSs units in combination with the DERs units are decreasing the production from fossil fuels. Therefore, a description of the thermal units as well as their dispatch is also showcased. Finally, the DERs are shown as well as consideration on the dispatch of all these sources.

A. Inputs

The inputs considered for the model are obtained from both HEDNO and from market analysis. HEDNO provides documents, such as the techno-economic reports introduced in Chapter II, with several information on the different islands. This section will address the inputs, such as island electrical load, generator data and wind as well as PV production, of the overall model. Following that the submodules for the PV generation and the dispatch of the different types of generation is discussed.

1) Island Loads

From the HEDNO Technical Reports the information on the islands loads in hourly resolution is retrieved. The peak load hours can be derived from the power time series as shown in **Figure 4**. In each case, it is noted that the peak hours are divided in two different windows of hours[8]. High Demand Hourly Window (HDHW) during the day and night and distributed during winter and summer:

Table 5. High Demand Hourly Windows (HDHW)

Season	Day Hours	Night Hours
Summer	10 – 14	18 – 23
Winter	11 – 14	18 – 21

2) Generators

Every island comes with a description of their thermal generators as well as a dispatching list. In this section, an example of a generator from the Island of Lesbos is provided. One sees in **Table 6** that this generator outputs electrical power only in the region between 5 MW and 7 MW, which are its boundaries for technical minimum and maximum possible production, in this order. This generator runs with Mazut, here simplified as HFO. The information on the fuel consumption is given by HEDNO´s reports at different loadings as well as during the generator's start-up operation.

Table 6. Example of generator data, given for Lesbos Island.

	Lesbos	
Generator Type	CEGIELSKI 9RTAF58	
$Pgen_{max}$	7 MW	
$Pgen_{min}$	5 MW	
Fuel Type	HFO	
Dispatch Order	1st	
Start-up Consumption	**Status**	**[kg of Fuel]**
	Cold	350
	Intermediate	200
	Hot	50
Fuel Consumption	**Loading**	***[kg/MWh]***
	50 %	210
	75 %	202
	100 %	207

3) Wind and PV

Wind and PV generation data is usually given by HEDNO as the generation fed into the grid. A differentiation between the modelling of the generation of these two sources is provided in the next section.

4) HPSs

In **Table 4** it was displayed a list with the HPSs that have received PC. Only two out of these projects are HPSs with pumped hydro as storage facility. The other 122 are wind or PV combinations with BESS. Their storage capacity is not always publicly available, so the BESS capacity of these HPSs that have received production certificate are based on a market analysis estimate.

[8] Approximately, the proposed energy of the hybrid system will be dispatched at peak hours of each day. It is noted that the hours that the controlled units of the HPSs are going to produce energy are not specific for each day but are decided by HEDNO on a case-by-case basis, considering the producer's energy offer. More on that during the description of the HPSs dispatch under III.B.3).

B. Generation Dispatch and Modelling

In this section, the dispatch of the generators as well as the modelling approach for the PV DERs (when not given) is explained. It is proposed to start with the thermal generators, since they are the ones that will serve the unmet load from the DERs.

1) Thermal Generators

In the following, it is explained how the generators are called to be dispatched depending on the remaining electrical load of the island.

a) Selection of the must run Generators

The must run generators are selected in the following fashion: Fist the minimum yearly demand of the island is taken. From **Table 3** one sees the following data:

	Chios	Samos	Rhodes	Lesbos
Min. demand [MW]	11.13	7.55	33.73	16.61

This minimum demand (e.g.: 16.61 MW for Lesbos) is supplied by the minimum technical capacity of the first generators in their dispatch order. These are then the must run generators, which will be running for the whole year. The remaining generating capacity of these generators ($Pgen_{max} - Pgen_{min}$) is kept as spinning reserves.

b) Dispatch of remaining Thermal Generators

Apart from the must run generators, the next thermal generator (NTG) starts its operation when the current required island demand ($Load[i]$) is higher than the minimum demand ($Min(Load)$) in such a way that $Load[i] - Min(Load)$ is higher than the next generator's technical minimum P_{min}^{NTG}. When $Load[i] - Min(Load) < P_{min}^{NTG}$, this is covered by the must run generators at the expense of their spinning reserve. In the rare cases that the remaining load is less than P_{min}^{NTG} and higher than the spinning reserves, then the generator runs and the excess is modelled as losses.

2) PV Generator Model

For the selection of the PV generation model, this work is based on already published literature and considers factors such as dirt de-rate, module mismatch, cable loss, and maximum efficiency of inverter [14]. These aforementioned factors are all given in p.u. and their values and summarized as follows:

Table 7. Description of used factors on the PV production simulation.

Factor	***Short***	***Value***
Dirt de-rate	f_{dirt}	0.97
Module mismatch	f_{mm}	0.95
Cable loss factor	f_{cable}	0.99
Maximum efficiency of inverter	f_{inv}	0.95
Temperature coefficient for pmp (%/°C)	$\%\gamma_{pmp}$	0.45

$$P_{AC,p.u.}^{Estimate} = \left\{\frac{G[i]}{1000}\right\} \times \left\{1 + \frac{\%\gamma_{pmp}}{100} \cdot (T[i] - 25)\right\} \times F \quad (1)$$

Where:

- $G[i]$ Solar Irradiation in W/m^2 during hour i;
- $T[i]$ ist he module temperature during hour i;
- F is given below and its components in **Table 7**:

$$F = f_{dirt} \cdot f_{mm} \cdot f_{cable} \cdot f_{inv} \quad (2)$$

When considering the installed PV capacity, one uses

$$P_{AC,Total}^{Estimate} = P_{STC}^{Array} \times P_{AC,p.u.}^{Estimate} \quad (3)$$

Where P_{STC}^{Array} is the installed PV capacity in Wp.

$G[i]$ values are taken from NASA Surface meteorology and Solar Energy database and $T[i]$ are values taken from the software *Meteonorm* (V8.0.4.21990).

3) HPSs Dispatch Model

The most important power parks of this paper are the HPSs. This is because besides offering clean energy via the DERs, they are also dispatchable because of their BESS component. The HPSs dispatch model is presented after the PV generator model because the DER section of the HPSs take the PV model as its PV production, scaling $P_{AC,p.u.}^{Estimate}$ to the PV AC production via the installed HPS power (P_{STC}^{Array}).The energy storage part of the BESS is modeled here as a Lithium – Ion battery. Their state of charge (SoC) varies between 100 % and 10 %; the remaining 10 % are kept as a reserve by the distribution system operator (DSO).

Table 8. HPS parameters

BESS Parameters	
Efficiency AC to DC	94 %
Efficiency DC to AC	94 %
Max SoC	100 %
Min SoC (Reserve)	10 %
Min SoC	0 %
Self-Discharge	0 %
PV to BESS power ration (Wp/VA)	1.2

Now that the DERs part of the HPSs is shown, a presentation of the BESS dispatch is given. First a list of parameters is presented.

- Max Production Power of the HPSs (P_{HPS}^{max}):

The HPSs tries to export its power as predictably as possible. When the DERs' PV power ($P_{AC,Total}^{Estimate}$) is beyond P_{HPS}^{max}, there are three cases:

1) The exceeding PV power is used to charge the BESS
2) The exceeding power is fed into the grid if possible
3) If export to the grid is not possible, then the exceeding power is curtailed.

In terms of the general battery behavior, the BESS works as follows:

Table 9. BESS simplified dispatch. No SoC limits nor interaction with other HPSs considered.

		$P_{AC,Total}^{Estimate} < P_{HPS}^{max}$	$P_{AC,Total}^{Estimate} \geq P_{HPS}^{max}$
Inside HDHW	Day	Discharge $P_{HPS}^{max} - P_{AC,Total}^{Estimate}$	Charge $P_{AC,Total}^{Estimate} - P_{HPS}^{max}$
	Night	Discharge SoC Based (Remark 1)	Charge $P_{AC,Total}^{Estimate} - P_{HPS}^{max}$
Outside HDHW	Day	Remark 2	Charge $P_{AC,Total}^{Estimate} - P_{HPS}^{max}$
	Night	Discharge SoC Based	Discharge SoC Based

Remark 1: Here the discharging power is going to be calculated according to the remaining SoC in the BESS. Because there is no available template on the dispatch from the DSO, the BESS discharges its remaining total capacity equally during the HDHW. This is also done to have the BESS at lowest possible SOC (10 %) during the night-time. The remaining 10 % SOC is reserved for emergency operations performed by the DSO.

Remark 2: If the HPS receives a curtailment signal from the DSO, the BESS should charge to avoid curtailment from the PV. If for some issue more power in the grid is needed, the BESS could also potentially discharge. In all the other situations, the BESS would be dormant.

For the SOC considerations, of course the battery will be always respecting its maximum and minimum energy boundaries. For instance, if a request to discharge some energy is higher than the available energy in the BESS, the same is only going to discharge the remaining energy. The same goes for charging: if there is some energy left for charging, the BESS is going charge this energy and the rest is going to be either exported to the grid or curtailed.

Here one sees that the lower the (P_{HPS}^{max}), the closer the HPS is to a non-intermittent generation. $P_{AC,Total}^{Estimate}$. However, this would lead to larger sized BESS, which might not be economically feasible.

4) *Wind generation*

Wind generation data is usually given by HEDNO as the generation from the Wind parks fed into the grid. When there is a need to simulate a generation from Wind, this generation is proportionally compared with the data given by HEDNO.

C. *Generators Dispatch and Priority*

As mentioned, the islands count with a generation matrix composed by thermal units, Wind, PV and HPSs. These energy sources have different levels of production priority. The thermal units have the lowest generation priority, given their associated high costs to produce and their emitted pollution. To account the priority order of the different energy sources in the island, **Table 10** is proposed:

Table 10. Generation priority by energy source and type

Energy Source	Order of Priority
BESS	1
Wind HPS	2
Solar HPS	2
Wind	3
Solar PV	4
Thermal Units	Substituted by DERs up to the Island's minimum demand

Here one sees that the thermal units have the least priority. However, their generation is capped only during the region above the island's lowest demand. At the hour when the island reaches its lowest demand, it is fully supplied with thermal gensets.

Following the thermal units, stand-alone solar parks and wind parks are going to be curtailed in this order. PV plants are curtailed before wind turbines because doing so does not incur in the same rear and tear experienced by the wind turbines. At the end, the DERs at the HPS are going to be curtailed if need be. The BESS are never curtailed, because they are supporting the grid during the times when the load request is higher. The BESS dispatch will be explained further in the paper.

One must bear in mind here, that in this paper the redispatch from thermal units is the most significant. The curtailment of renewable energy sources would happen when there is a competing situation of excessive DERs in the system.

IV. IMPACT OF HPS IN THE ISLANDS ENERGY MATRIX

The fuel and CO_2 reduction are calculated following the below logic: The CO_2 emission of diesel generators is given as an estimation between 2.4-2.8 kg CO_2 per liter of diesel. This range is dependent on the characteristics of both the engine and the fuel [15]. One takes the average CO_2 production value (2.6 kg/L) as a starting point: taking into consideration a fuel density of 970 kg/m3, or 0.970 kg/L, one calculates that the CO_2 production per kg of diesel spent is approximately given by $\frac{2.6\frac{kg_{CO_2}}{L_{Diesel}}}{0.970\frac{kg_{Diesel}}{L_{Diesel}}} = 2.68\frac{kg_{CO_2}}{kg_{Diesel}}$.

From **Table 6**, at 75 % loading, this generator consumes 202 kg of fuel per MWh of electricity generated. Therefore, the amount of CO_2 produced is given by:

$$CO_2^{Produced} = 2.68\frac{kg_{CO_2}}{kg_{Diesel}} \cdot 202\frac{kg_{Diesel}}{MWh_{Elt}} = 541.36\frac{kg_{CO_2}}{MWh_{Elt}} \quad (4)$$

Following similar rationality, in the worst case, a different type of generator, which is not a must run, fuelled by diesel and located more down in the dispatching order would produces more CO_2 per MWh of electricity, reaching staggering numbers of 1232.3 $\frac{kg_{CO_2}}{MWh_{Elt}}$, for a consumption of 360.9 $\frac{kg_{Diesel}}{MWh_{Elt}}$.

A similar rational was applied for the generators run by HFO, with values adapted to this type of fuel.

A. Operation and CO_2 reduction and System Non Synchronous Penetration (SNSP)

The operation of the HPSs with PCs in the islands of Chios, Lesbos Rhodes and Samos was tested. The overall energy distribution in the islands is given in **Figure 7**.

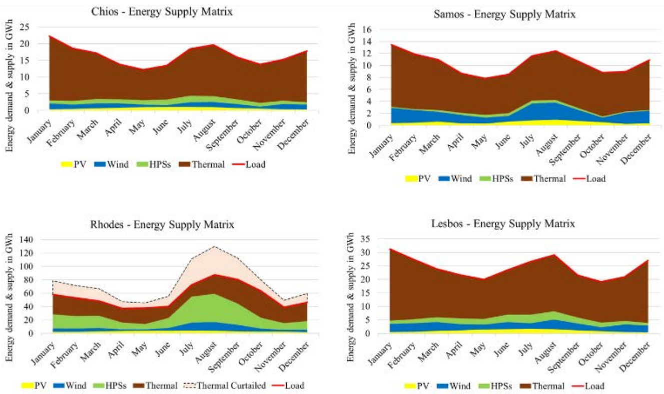

Figure 7. Impact on the island energy consumption after installing HPSs

Table 11. CO_2 reduction from HPS and system max SNSP values

Island	CO_2 Before HPSs in Ton	Max SNSP no HPS	CO_2 After HPSs in Ton	CO_2 Reduction
Chios	116,765	42 %	109,658	6.1 %
Lesbos	177,454	47 %	161,244	9.1 %
Rhodes	385,939	45 %	267,878	31.0 %
Samos	64,073	43 %	62,422	2.6 %

In **Table 11**, one sees that there are differences in the CO_2 reduction in each island. The maximum SNSP lays between the 42 % and 47 %. The maximum CO_2 reduction is perceived in Rhodes, reaching incredible 31 % reduction if all the HPS would be installed. If one takes the times of overproduction in Rhodes and distribute this energy across the other islands (assuming the existing 250 MVA connection in **Figure 6**, a further reduction of 13.74 % of the carbon production on those islands could be expected. This corroborates with the proposition that both initiatives should be performed at the same time and one does not necessarily mean that the other should be avoided.

In all the islands, except for Rhodes[9], a 1.2 MWp PV system was modeled. Consequently, the BESS power is automatically calculated as 1.0 MW, because it should be at least 1.2 the PV installed AC capacity divided by 1.2. As depicted in **Table 8**. The value of P_{HPS}^{max} is set as 0.6 $P_{AC,Total}^{Estimate}$. For all the islands, three values of BESS capacity are tested. One value is no BESS at all, which shows the behavior of the PV alone (considered as HPS though). The other values are two MWh and four MWh.

[9] Rhodes is not assessed, because the projects that have already received PCs would be already enough to cover much of the island needs.

Table 12. Proposed HPS contribution to carbon reduction and new SNSP values after the proposed HPS addition to the energy matrix.

Island	MWh	CO_2 Reduction in Ton	CO_2 Reduction in %	Max SNSP in %
Chios	0	431	0.37	74
	2	564	0.59	73.9
	4	683	0.68	74.0
Lesbos	0	1,039	0.64	71.3
	2	1,136	0.70	71.3
	4	1,182	0.73	69.4
Samos	0	231	0.39	69.6
	2	370	0.51	70.9
	4	423	0.62	70.9

By reading **Table 12,** one sees that increasing BESS size does not necessarily increase the maximum SNSP, which is linked to the fact that the BESS shifts the PV power production from noon to the regions at night where more power is needed. This is depicted in **Figure 8**, **Figure 9** and **Figure 10.** Furthermore, HPSs, as expected, increased the maximum RES penetration in all cases as well CO_2 reduction.

Up to now, the numbers only show an equivalent of a total energy delivered by the system, which provides a poor description of the support of the HPS to the grid. In Figure 9, Figure 10, and Figure 11, one can see the energy shifting to times at night. In the following figure, an explanation on the following graphs meaning and operation of the HPS is provided.

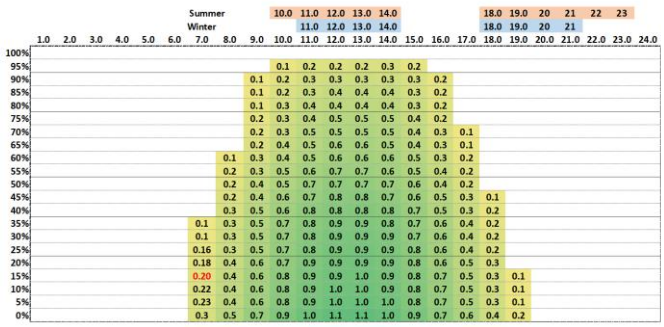

Figure 8. HPS operation in Samos without a BESS (PV only)

Figure 8 shows the HPS without a BESS, which is mainly a PV system. On the Y axis, it is given the percentage of time that the system outputs more than the power given inside the graph area. In the x axis there are the hours of the day. At 7 am, for instance, as a reference for discussion a cell is purposefully marked in red. The meaning of this cell is that the system will output during the whole year at 7 am more than 0.2 MW between 15 % and 20 % of the time. As another example, the system is outputting more than at least 0.1 MW from 10 am until 2 pm for at least 90 % of the time. At 7 pm, the system outputs more than 0.1 MW not more than 15 % of the time and at 8 pm the system never outputs more than 0.1 MW per year.

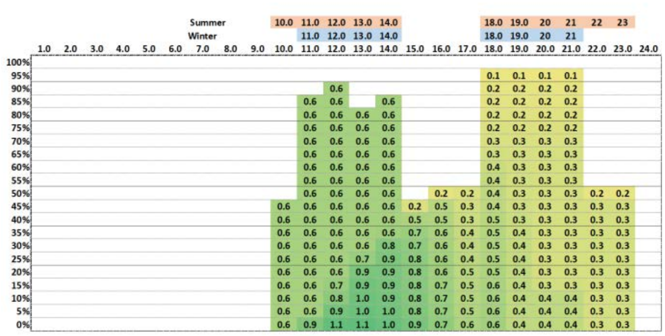

Figure 9. HPS operation in Samos with a 2 MWh BESS

Figure 9 shows the HPS with a two MWh BESS. Here one has a better impression on the BESS behavior and support of the system. The BESS tries to bring more predictability on the power dispatch, and one sees that the targeted output power P_{HPS}^{max} is more probable to be reached after more energy is added to the HPS. At noon, now it is expected to have a power output higher than 0.6 MW for more than 90 % of the year. Here one also sees a clear shift of energy from the interval between 3 pm and 5 pm to the night hours, when the consumption is higher. Also, there is energy available even at the latest hours of the Summer HDHW (10 pm, 12 pm).

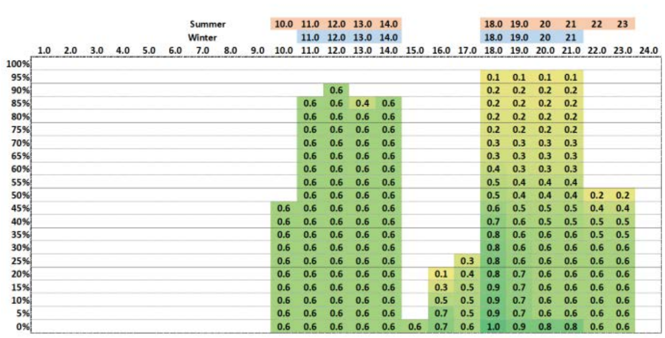

Figure 10. HPS operation in Samos with a 4 MWh BESS

With a four MWh BESS, the energy shift is much more pronounced, as shown in **Figure 10.** Here one sees that there is a probability to have at least 0.6 MW of power dispatch at late summer hours. In at least 35 % of the hours, the system will output more than 0.6 MW at these hours.

In **Figure 8**, **Figure 9** and **Figure 10** one sees that sometimes the exported power goes above the before mentioned value given by $P_{HPS}^{max} = 0.6$ MW. This happens when the PV generation is at its peak and the BESS is full and there is no impediment to export this energy to the grid. The higher the installed BESS capacity, the lower the likelihood of these higher exportation power, because of the energy shifting provided by the BESS.

At last, **Figure 11** shows a full energy shifting. There is no benefit for the energy shifting for BESS sizes over 8 MWh because all the energy produced by the PV is already shifted and the BESS is not importing from the grid.

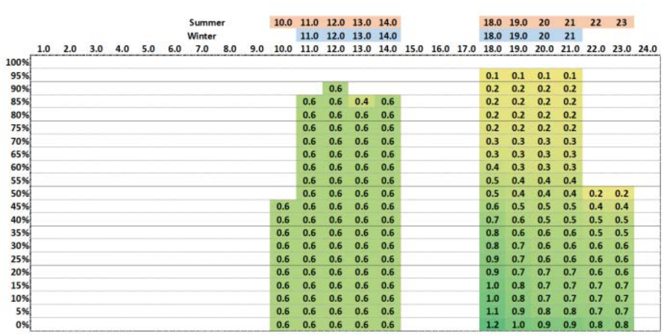

Figure 11. HPS operation in Samos with a 8 MWh BESS

V. Conclusion

In this paper, the authors wanted to share their assessment on the impact of HPSs with PCs on the CO_2 reduction on some Greek non-interconnected islands. In this regard, it was shown that these HPSs could reduce significatively the CO_2 emissions of these islands, almost reaching double digits in percentage reduction in all islands assessed. Furthermore, in the case of Rhodes, there are so many HPSs that they could even export a great sum of electricity production to the other islands analyzed in case they are interconnected and still reducing Rhodes island's CO_2 production by almost one third. It was also graphically shown the benefit of having RES generation with a BESS attached in terms of energy shifting and the cases where increasing the BESS size is no longer beneficial.

It was shown that increasing the BESS capacity of a proposed common HPS increases the CO_2 reduction in the island, since this system is shifting the energy production to time zones where they are mostly needed. Increasing the BESS capacity of the HPSs has not shown great impact in the maximum SNSP values. The proposed HPs systems in those islands would mean reaching SNSP values in the order of 70 %, considering curtailment of renewable energy from PV and Wind. 100 % SNSP could also be easily reached in Rhodes taking into consideration the installed HPS capacity and no thermal generators running at some times.

VI. Discussion and Next steps

In this paper it was shown to what extent the installation of HPSs can reduce CO_2 emissions caused by the thermal power plants on the islands under consideration. These findings can be transferred to all NIIs as the power production landscape is comparable. In the paper, attention was drawn to the issue of potential stability problems caused by excessively high SNPS rates, but the probability of occurrence was not assessed quantitatively. Therefore, the results of this work should now be used to find out in further calculations, including load flow analyses, to what extent stability problems are to be expected in real operation if the theoretical installation of all HPSs considered in this paper is used as a basis. Furthermore, based on these results, it should be evaluated whether it is not more expedient to start installing HPSs as soon as possible, i.e. to create an investor-friendly environment, and not to wait too much for the NIIs to be connected to the mainland.

VII. ABBREVIATIONS

Abbreviation	Description
AVC	Average Variable Cost
BESS	Battery Energy Storage System
CO_2	Carbon Dioxide
DAM	Day Ahead Market
DER	Distributed Energy Resources
DSO	Distribution System Operator
EC	European Commission
EU	European Union
GHG	Greenhouse Gases
HDHW	High Demand Hourly Window
HEDNO	Hellenic Distribution Grid Operator
HFO	Heavy Fuel Oil / Mazut
HPS	Hybrid Power System
IPTO	Independent Power Transmission Operator of Greece
LFO	Light Fuel Oil
NII	Non-Interconnected Island
PC	Producer Certification
PV	Photovoltaic
RAE	Regulation Authority for Energy
SNSP	System Non-Synchronous Penetration
SoC	State of Charge
TYNDP	Ten-Year National Development Plan

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