GREEN ENERGY AND STORAGE INTEGRATION – THE CASE STUDY OF IKARIA

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Abstract

Recently there is a global effort to reduce carbon dioxide emissions and modernize the electric power systems (EPS) in order to provide green and stable energy to consumers, while also taking cost minimization into account. To achieve this, production from Renewable Energy Sources (RES) in tandem with Energy Storage Systems (ESS) is being proposed and integrated to EPS around the world. However, the dispersed and intermittent nature of RES, the differing ESS technologies, the variety of landscapes on a local level and the fact that those solutions must be incorporated into the existing infrastructures, impose the need for further studying the optimal implementation of those new technologies without power disruptions, while ensuring grid stability through the provision of ancillary services. The Hellenic Electricity Distribution Network Operator (HEDNO) is responsible for the wider Greek distribution network, as well as the Non-Interconnected Islands (NIIs). The NIIs in particular can be considered excellent test beds for new technologies and innovative solutions, since they are insular microgrids and therefore, can provide immediate feedback on implemented changes. This paper will focus on the island of Ikaria; mainly on the effort of modernizing the grid management as well as the possibility of expanding upon the lessons learned to the rest of the Greek electricity grid.

1 Introduction

With the recent focus on decarbonization efforts on a global scale and in conjunction with advancements in RES and ESS technologies, HEDNO is already in the process of restructuring and developing plans to ensure the optimal operation of the electricity distribution network (DN) and the electrical grids of the NIIs, while reducing the overall environmental impact. To expand upon these premises, HEDNO also promotes the utilization of Hybrid Production Plant (HPP) facilities on the NIIs. Such cases are the recent projects in the islands of Tilos (project Tilos 2.0) and Ikaria (project Naeras), as well as the proposed solutions on the islands of Astypalaia and Agios Efstratios. In further detail, the proposed HPP in Astypalaia will combine photovoltaic (PV) production with a battery energy storage system (BESS) solution, in order to achieve RES penetration of 50% with the existing PV parks and up to 80% with the integration of future PV expansions [1]. The HPP in Agios Efstratios is planned to achieve RES penetration greater than 85% while minimizing the energy loss from unexploited RES production during low demand periods [2]. In the island of Tilos, the local HPP consists of PV and wind installations in combination with $NaNiCl_2$ batteries, equipped with an optimal control system for operation in the existing smart grid with the ability to support multiple services. It should be noted that the HPP of Tilos existed before the project Tilos 2.0 but could not and was not able to function without the support of thermal generators (diesel and mazut). The project's goal was to achieve the autonomous operation of the HPP without the genset when the interconnection cable with the larger island complex of Kos – Kalimnos - Tilos is cut, while also providing auxiliary services, like grid forming and voltage/frequency control. Also, another challenge was to reduce the time required by the HPP's inverter to provide primary frequency regulation via droop control. So far, the HPP of Tilos is able to function and solely provide for the load demand of the island, while offering voltage control services [3]. Lastly, an HPP plant is already integrated in Ikaria's grid and HEDNO has similar plans as in the Tilos project for this HPP. Currently, research projects like [4] regarding the theoretical structure for the HPPs operation and provision of voltage and frequency control to the upstream transmission system have been concluded and HEDNO is in the process of realizing and expanding those plans.

As a DN Operator (DNO), HEDNO has a set of goals in conjunction to the projects. Those goals can be summarized as such; (a) to increase hydropower production, (b) to utilize the HPP for the provision of auxiliary services, (c) to improve the efficiency of Ikaria's grid operation and (d) to gain environmental benefit through Increased RES penetration and Hydro-pumped storage (HPS) utilization. Lastly, an important future goal is (e) to evaluate future interconnection plans between Ikaria and Samos in accordance with [5] that could further increase HPP penetration in lieu of the interconnected grids energy demands, and also affirm the cost effectiveness of the interconnection plan. To further bolster the efforts, HEDNO participates in European or global projects with similar goals towards the transition to green energy. One such programme is the Storage INNOovations for Green ENErgy Systems, abbreviated as SINNOGENES, a project focused on ESS integration and digital tool development.

More specifically, SINNOGENES aims to develop a complete framework of methodologies, tools and technologies that will enable the grid integration of innovative storage solutions beyond the state-of-the art, while demonstrating sustainability, increased technical performance and cost reduction. Through the project, the partners involved will create use cases for green ESS solutions, and later deploy them in existing systems at different scales and timeframes. SINNOGENES will target the effective integration of innovative ESS in the aforementioned use cases, while adhering to the standards set for participation in flexibility markets. Six pilot projects will take place in Portugal, Spain, Germany, Switzerland and Greece while a detailed scalability and replicability analysis will prove the wide impact of SINNOGENES at a pan European level More information can be found at [6].

Specifically, the Greek pilot is the Ikaria Island where a Digital Twin of the grid is being developed in parallel with an optimization tool which aims to solve optimal power flow analysis problems. Furthermore, load forecasting models through the use of Artificial Neural Networks (ANNs) that utilize historical data, mainly production, load and weather data, and in combination with the Digital Twin and optimizer can produce optimal day-ahead and possibly intra-day schedules. Through the SINNOGENES project, HEDNO can not only affirm the propositions in [4], but also optimize the whole systems operation through the combination of the optimizer and forecasting models with the accurate simulation of the Ikarian and the interconnected Ikaria – Samos grids.

2 Ikaria case study

For the Greek demo case, the island of Ikaria was selected since it is an excellent test bed for HPS studies and it incorporates the projects demands fully. Furthermore, this use case can provide invaluable information to HEDNO for the optimized operation of the island's grid in the first phase and accommodate the expansion of such advantages to the management of the expanded Ikaria – Samos grid and also other NIIs in the second phase.

2.1 Ikaria case study advantages

For the selection of the specific island, there are four main advantages. Firstly, there is already an HPP, as well as wind and PV installations already integrated into the island's energy mix. The second one is the prior existence of scientific literature that comes with those installations, such as [4], [7], [8] and [9]. The third advantage is that Ikaria is an insular micro-grid as a NII. As an insular microgrid, the results of different approaches can clearly and effectively be noted. Lastly, the islands of Ikaria and Samos are planned by HEDNO to be interconnected, offering the possibility of performing similar studies but in a larger grid, possibly further taking advantage of the HPS capabilities.

2.2 Ikaria DN description

Ikaria is powered by a combination of thermal production units (mazut and diesel), two Wind Parks (WPs), three PV parks and an HPP. Ikaria's HPP exclusively leverages another Wind Park (Stravokountoura WP), water turbines, hydro pumps, a small-scale PV park, two reservoirs and a Dam to ensure green ESS and production. The islands load demand varies from 2 – 8MW [10] and is heavily dependent on the season.

In more detail, the thermal production is concentrated on an Autonomous Local Fuel Power Station (ALFPS) that includes six (6) mazut thermal generators, two (2) diesel thermal generators and four (4) portable diesel generators that can cover a maximum load of 15.7MW. Furthermore, the distributed RES production consists of two (2) Wind Parks (WPs), Perdiki and Kefales with 385kW and 600kW installed power respectively, and three (3) PV installations, two (2) Medium Voltage (MV) 150kW each and one (1) Low Voltage (LV) with installed power of 100kW. Due to the low PV production with respect to the total load and because of intermittent communication issues, the parks are not included on the day-ahead scheduling.

Fig. 1 Ikaria island grid and topography

2.3 Ikaria HPP Operation

The HPP's operation can be summarized as such; The overflows of the existing upper dam (Pezi) with 900km^3 capacity are channeled into an intermediate reservoir (Proespera) through a water turbine from a height of 167m. From the intermediate to the lower reservoir (Kato Proespera), two identical 1.55MW turbines utilize the falling water from a height difference of 505m for the production of electricity. Both reservoirs have a capacity of 80 km^3. The water that has accumulated in the lower reservoir is carried through a separate discharge pipeline by raising water from the lower to the intermediate reservoirs, synchronizing the consumption of the pumping station with the production of the 2.7MW Wind Park (Stravokountoura). The pumping station of Kato Proespera is comprised of a combination of fixed and variable speed pumps with total power of 3MW. The specific elements are summarized in Tables 2.3.1 and 2.3.2.

To realize the synchronization between wind generation and pumping, the predicted instantaneous wind generation capacity is used on the basis of which the inclusion of the pumps is decided, while the actual production of the wind farm is responsible for the exclusion of the pumps in operation. This is possible Some components of the station are connected with smart synchronization devices, automatic pump integration/disintegration systems and frequency assistance services help achieve optimal operation with high RES penetration.

Table 1 HPPs hydro pumps locations and nominal power

HPP	HYDRO PUMPS POWER
Pezi to Proespera HPS	1.05MW
Proespera to Kato Proespera HPS	3.10 MW
Stravokountoura WP	2.70MW
Discharge pipeline pumps	3.00MW (12 pumps, 250kW/each)

Table 2 Water reservoirs total capacity

WATER CONSERVATION	CAPACITY
Pezi Dam	900 km^3
Proespera intermediate reservoir	80 km^3
Kato Proespera lower reservoir	80 km^3

The HPS is theoretically able to provide auxiliary services to the network in order to co-assist the thermal units of the ALFPS. For frequency regulation, the correction of underfrequency is done via pump rejection and the correction of overfrequency through the contribution of hydro turbines of Kato Proespera. In particular, in case of an underfrequency fault, the HPP rejects appropriate amounts of pumping power and in case of overfrequency, the integrated hydro pumps of the Kato Proespera station are able to instantly limit their production, utilizing the deflectors of the water beam. According to the rules of operation of the NIIs, there is a requirement that the response should be achieved within a time scale of less than fifteen (15) seconds from the occurrence of the disturbance. The diesel generators have a faster dynamic response, resulting in them completely taking over the necessary power reduction in cases of overfrequency. In order to enable the HPP to participate in the primary frequency regulation, the power control scheme was suitably modified to take advantage of the high-speed operation of the deflectors, in addition to the needles [11].

For voltage control, HEDNO placed three single-phase SIEMENS JFR voltage regulators, with a power of 660 KVA, in a delta connection with ±15% voltage regulation on the load side of the regulator (CO-GEN) [11].

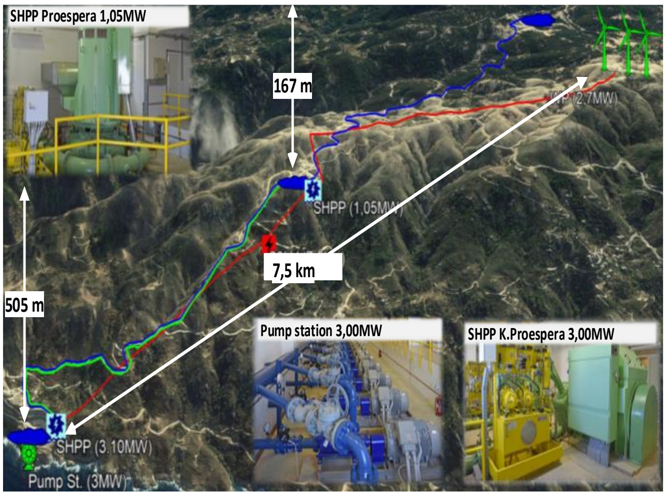

Fig. 2 HPPs geographical location

3 Challenges and current situation

The NIIs are insular micro-systems within the Aegean Sea, and as such, the grid management and operation faces unique challenges. First, there is a great variance in topologies, from mountainous ranges to deep valleys. That can pose a problem in the DN's infrastructure and maintenance, especially considering that the NIIs can be sparsely populated with a lot of small or medium sized villages in need of connection to the grid. Ikaria's topography in particular presents great contrasts, as it displays green slopes and bare cliffs and the majority of the villages are mountainous. The mountainous terrain however also presents height differences, and in combination with the natural existence of clean water presents ideal conditions for HPS.

Another challenge is the harsh weather conditions. In Ikaria, high speed winds and storms with lightning strikes are especially common, and that creates telecommunication issues, faults in transport lines and pylons and greater difficulty in traveling to and from the island, as well as within.

In addition, there are some problems with the existing grid that can be summarized as; aging equipment, lack of smart meters and metering points and lengthy transmission lines which create hurdles with the smooth grid operation, power loss mitigation, accurate data acquisition for live control and historical database maintenance and the setup of secondary and tertiary auxiliary and support services.

Another issue is the large margins on the islands load variability. As a NII, in winter months the daily demand is somewhat low, since the grid provides services for the permanent population, and heating is accomplished mostly by natural gas. On the other hand, in the summer period the island experiences heavy increase in the load demand due to tourism and air condition usage. As a result, the grid should be able to provide stable energy that covers the high summer demand, while most of the production capabilities remain idle in the winter, leading in increased operational and maintenance costs.

Finally, technical limitations imposed by conventional units, such as higher spinning reserve requirements, adherence to thermal plant technical minima and stability considerations, restrict the penetration of intermittent power sources as RES in the generation mix in small isolated systems [12]. As a result, HEDNO is forced to adopt more conservative procedures and reject some of the available resources since they have restricted control skills. Implementing and improving sophisticated management systems and algorithms with strong control capabilities is necessary to get around this restriction [12], [13].

The issues described above are known to the Greek DNO, and the organization has already taken steps towards solutions, while also taking an active role in further expanding its problem mitigation capabilities. For instance, HEDNO currently has the ability of active surveillance of the NIIs through Supervisory Control and Data Acquisition (SCADA) systems, that offer a live feed of the electrical grids characteristics (P, Q, V, I), thermal and RES production and other operational data, as well as live connection to HEDNO's Database for data storage. Moreover, HEDNO has partly automated grid management processes in ways such as algorithmic Wind Park Set point management according to factors like weather conditions, system stability and RES penetration limits, and an automated day ahead energy planning programme. Also, HEDNO runs local departments on the islands that are responsible for the smooth day to day operation, maintenance, and customer service that cooperate with the central NII Department in Athens responsible for SCADA management and operation, day ahead scheduling, grid expansion planning and overall supervision of the NIIs. The analysis of the SCADA systems and their implementation on the side of HEDNO are analyzed in [14], [15].

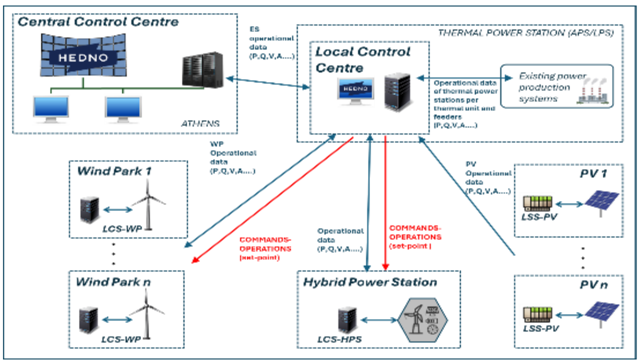

Fig. 3 SCADA systems architecture [15]

In summary, the system operates with a mixture of automated processes and human intervention as follows; the SCADA systems include surveillance systems on the ALFPS, WPs and PV parks with the ability to impose changes in the system such as curtailment commands. Moreover, an internally developed algorithm in conjunction with the SCADA systems and historical data can provide day ahead scheduling plans. The algorithm and its predictions are validated through a team of HEDNO engineers responsible for its development and optimization, while twenty-four (24) hour shifts are conducted to supervise the SCADA systems and also intervene when needed.

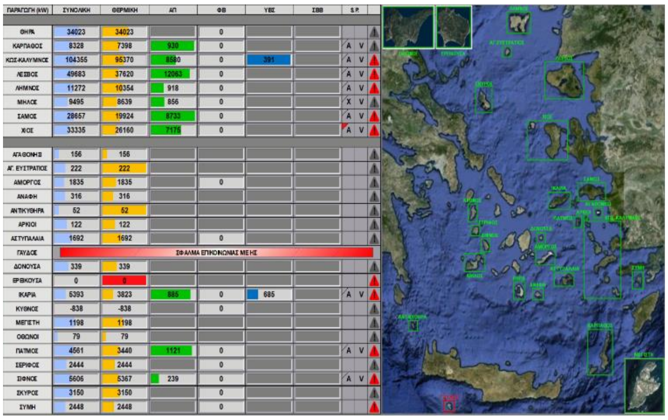
Fig. 4 SCADA supervision of NIIs

4 SINNOGENES toolkit

As mentioned in the introduction, part of HEDNO's efforts are focused on European projects like SINNOGENES. Through this, a list of useful tools is being developed that form the toolkit named SINNO Toolkit. The SINNO toolkit encompasses a Digital Twin of Ikaria's DN, an optimizer and a load forecasting ANN model.

The digital twin is a digital representation of the island's grid which performs power flow analysis through operational data as input. This tool is actively being co-developed by the Center of Research and Technology Hellas (CERTH), the Independent Power Transition Operator of Greece (IPTO) and HEDNO on CERTH's INTEMA platform. This tool will generate the digital replica of an HPS plant, along with the connected power system. It will also enable the investigation of both operational aspects, by collecting data from the physical assets of the HPS and the transmission system, or from mathematical models that mimic the physics of its different components. In that manner, the fully enabled digital model of the plant and the connected power system will be created, providing opportunities for the system operators to conduct feasibility studies to strengthen or reject network planning and development activities. Specifically, the tool will create a digital profile of historical and current HPS based on virtual and real-time data and feedback to optimize relevant operations [16]. Since HEDNO is responsible for the supervision and operation of the grid, the organization is able to offer expert opinions on the tool's scope and operation, as well as to provide crucial data for its development. In this digital environment, different operational models can be tested with the aim of maximizing the use of the HPP for energy production, storage, and auxiliary services. In addition, potential changes to the grid can be tested, such as grid expansion operations.

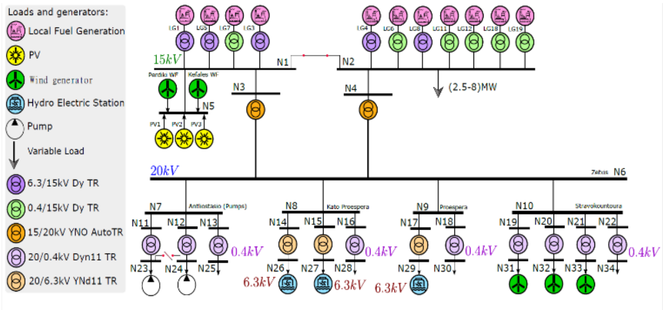

Fig. 5 Ikaria's grid single line diagram [16]

The optimizer tool is co-developed by CIRCE technology center, IPTO, CERTH and HEDNO. This tool takes into account efficiency KPIs, gas emissions and operational costs in order to produce optimal solutions to power flow problems which are executed in the Digital Twin. It is the mathematical framework that takes advantage of the imported data. Through objective functions and power flow solutions, it produces the best result depending on the DSO's needs. The optimal solution is currently developed to be single variable, for instance to maximize RES penetration or to minimize the production and operational costs. At later stages, either through the SINNOGENES project or through HEDNOs departments, it is possible to expand the optimal solutions to focus on multi-variable analysis such as a combination of maximum RES penetration and minimum production cost than can output a variety of solutions for the DSO to decide upon.

Finally, the predictive load models in development focus on the state-of-the-art Artificial Neural Network (ANN) deep learning algorithms, namely the Convolution Neural Nets (CNNs) in order to perform load prediction. Through the project it will be shown that CNN based models can also provide efficient solutions for the electric load forecasting problem and under certain conditions, such as applying proper data preprocessing and analysis, they could even outperform the Long Short-Term Memory-based models which is the common solution for electric load forecasting [17].

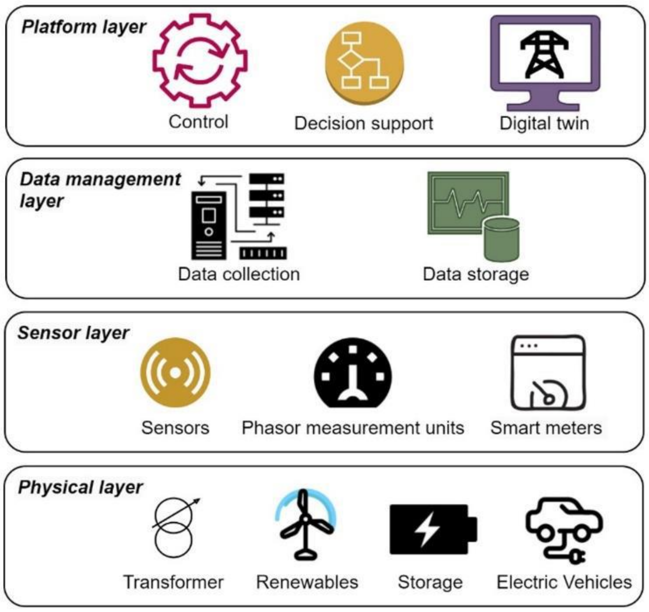

Fig. 6 Sinnogenes smart grid architecture [8]

5 Proposed improvements

Considering all the challenges mentioned, HEDNO has developed a set of measures and plans to achieve its future goals. Those include

-Expanding SCADA and management algorithm capabilities and improved datasets for machine learning.

-New methodologies of validating historical data and new complete and validated database

-Replacement of older energy metering models that require HEDNO technicians on site to read with remote telecommunicating ones, accessible through an existing interface

-Introduction of smart meters for enhanced communication and metering capabilities, exceedingly useful for the planning of auxiliary support services and more accurate prediction modeling

-Implementation and integration of the SINNOGENES toolkit in the planning and operational procedures

6 Conclusions

In this paper, the current situation of the NIIs management and surveillance is described and possible solutions in order to aid HEDNO's decarbonization, modernization and service optimization efforts are discussed through the case study of Ikaria. Furthermore, apart from optimizing the operation of the network, HEDNO's expansion upon existing auxiliary services, such as voltage and frequency regulation, ability to black start, grid congestion relief and improvement of the dynamic response on load fluctuations through the utilization of existing and planned HPPs infrastructures is focused on. The proposition is the combination of RES and batteries can offer the similar control as conventional units, with comparable or even lower cost and with less of an environmental impact. Especially through the SINNOGENES toolkit, differing solutions to existing problems or possible grid expansion plans can be proposed, studied and practically tested in the digital twin environment at increased speeds and zero further cost, without affecting the grid's normal operation. Through the use of Digital Twin technologies, and the ability to replicate real components, better studies can be carried out about component efficiency, cost and expected operation in realistic conditions

The case of Ikaria and the theoretical and practical conclusions drawn and tools developed from the effort of via internal effort and external cooperation through projects could also be expanded to the management of the other NIIs, especially considering the future HPP installations that will take place, and possibly at a later stage to the Greek DN. The digitization of the transmission systems and distribution networks is a priority in many countries, and this demo can act as an applicable guideline about the process and the tools needed. Furthermore, RES, ESS and HPP technologies are on the rise due to the global decarbonization goals and the testing in a close environment that includes all of the above is a great first step towards meaningful progress.

7 Acknowledgements

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