


Case Report

Planning of Aegean Archipelago Interconnections to the Continental Power System of Greece [†]

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Abstract: This paper presents the results of a thorough planning investigation carried out by the Transmission System Operator (TSO) and the Distribution Network Operator (DNO) in Greece in order to study the interconnections of the Aegean Islands with the mainland power system. The feasibility of interconnecting islands is based on the need for a reliable power supply to isolated and autonomous islands, reducing the operating costs of the power generation system through the withdrawal of high-cost oil-fired generating units, and the further ability to increase renewable energy source (RES) penetration in the country’s energy mix, according to directions imposed by the National Energy and Climate Plan. Among the alternative topologies and interconnection technologies considered, the final selection of the interconnection scheme selected for inclusion in the development plans of TSO and DNO was based on their detailed comparative evaluation, considering financial and other technical criteria.

Keywords: transmission planning; island interconnections; security analysis; energy simulation; economic assessment

1. Introduction

A special characteristic of Greece is the large number of islands located in the Ionian Sea as well as the Aegean Sea. While most of the islands near the continental coast have been connected to the mainland grid via 150 kV and medium voltage (MV) connections, there is a great number of autonomous and isolated island systems (either single islands or complexes of islands connected to each other via local MV subsea cable lines) that represent about 10% of the total electricity demand of Greece. The main problems related to the operation of non-interconnected islands (NIIs) are:

- Lack of alternative supply in case of autonomous power station (APS) fault
- High cost of energy produced by the APS compared to the continental system
- High variation of frequency due to low system inertia
- High variation of voltage due to low short-circuit power level
- Short margin of system stability
- Restricted penetration of RES

The interconnection of the NIIs has been a priority of the Greek state, as well as a research objective, for many years [1–6]. Recently, the isolated systems of northeastern

Cycladic Islands (Syros, Paros, Mykonos, and Naxos) have been interconnected to the mainland system [7,8], while the interconnection of Crete via 150 kV HVAC (high voltage alternating current) and HVDC (high voltage direct current) interconnectors is in progress. Moreover, the integrated interconnection of the southwestern Cycladic Islands (Thira, Folegandros, Milos, and Serifos) has been decided to be implemented in the following years [9,10]. A very long and high depth of laying subsea cable lines introduces a wide range of challenges that need special studies, design, and technology [11–17]. For example, the Crete–Peloponnese double circuit interconnection, which consists of a 135-km-long subsea part and a 43-km underground part on the Crete side, recently became the longest cable HVAC interconnection constructed in the world. The project also constitutes the deepest (1 km maximum depth) HV interconnection in the world using a three-core cable with cross-linked polyethylene (XLPE) insulation. In addition, significant innovations in the cable design (lighter and stronger) as well as in its laying have been applied [18–21]. Moreover, the operation of parallel HVAC and HVDC interconnectors in Crete needs a special control and protection strategy [22–25]. A current view of the power system of Greece (Hellenic Transmission System, HETS) is presented in Table 1 and depicted in Figure 1.

Table 1. Main characteristics of the interconnected power system of Greece (2020 data).

Total Annual Peak Load (MW)	9547
Annual Peak System Load—Losses are included (MW)	8631
Total Net Energy Demand (GWh)	49,932
Net System Load (GWh)	44,403
Total Net Installed Thermal Generation Capacity (MW)	8314
Total Net Installed Hydropower Generation Capacity (MW)	3171
RES Generation (MW)	7341
RES Generation (GWh)	13,881

The operation of autonomous thermal power plants that exist on islands as well as further local conventional generation development are restricted by environmental constraints, further enhanced by the European Commission (EC) emissions directives 2010/75/EE and 2015/2193/EE, applicable from 2020 onward. It is noted that the current variable generation cost of NIIs varies from 100 to over 500 EUR/MWh [26], while the weighted average market price is about 65 EUR/MWh (data from the first quarter of 2021). Moreover, the power supply of the NII consumers is set at the same price tariff per consumer category as that applying to the country’s mainland, as part of the Services of General Interest (SGI). Additionally, the target model—the wholesale electricity market model—aims to gradually harmonize, through coupling, different national electricity markets, so that a unified EU electricity market can be established. These different electricity markets include the wholesale market of forward electricity products (renamed the energy financial market), the day-ahead market (DAM), the intraday market (IDM), and the balancing market (BM). The Hellenic Energy Exchange (HEEnEx) has been established, and the IPTO carries the responsibility of managing the aforementioned markets and balancing the system in real time.

Furthermore, the new islands’ interconnection will enable the development of new onshore and offshore RES capacity in the Aegean Sea area, considering the rich wind, solar, and geothermal potential on the islands [27–29].

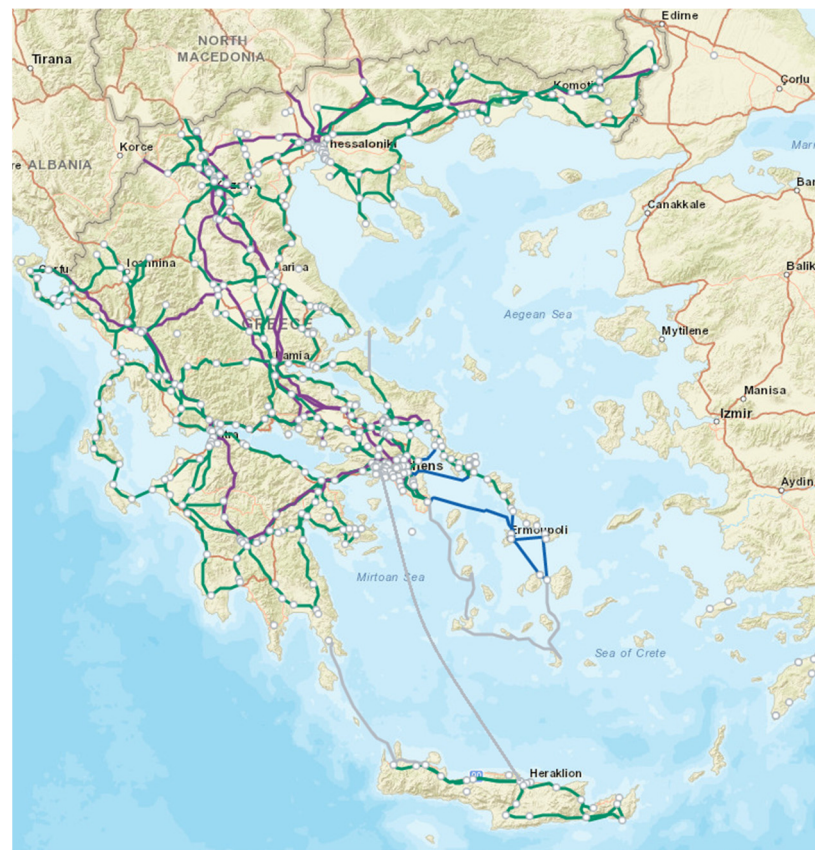


Figure 1. Map of the interconnected Hellenic Transmission System (HETS). Projects in progress are noted (grey lines), e.g., dual interconnection of Crete, a 150 kV/AC double circuit and a bipolar voltage source converter HVDC (VSC-HVDC), and southeastern Cycladic Islands (under planning/permitting licensing).

The Ministry of Energy and Climate Change, alongside the Regulatory Authority of Energy (RAE) in Greece, set up a joint task force (TF) with members from the Transmission System Operator (IPTO), Distribution Network Operator (HEDNO), and Natural Gas System Operator (DESFA), supported scientifically and technically by two project teams from the National Technical University of Athens (NTUA). The role of the TF was to examine the best and most economical option for electrification of the NII clusters as depicted in Figure 2; specifically, several scenarios were examined for autonomous operation based on natural gas or interconnection to the mainland grid. Finally, three deliverables were published [9,10]:

The Rest of the Cycladic Islands, which are Serifos, Milos, Folegandros, and Thira, are promoted to be interconnected to the mainland via HVAC cables. It is noted that Syros, Paros, Naxos, Mykonos, Andros, and Tinos have already been interconnected in the past. The rest neighboring islands, specifically Kythnos, Sifnos, Anafi, Astypalea, Donousa, Amorgos, and Schinoussa, will be interconnected via MV cables to the nearest island Substation.

- i. *The Dodecanese islands*, which are the Kos–Kalymnos complex, Rodos, and Karpathos, are promoted to be interconnected to the mainland. Apart from Kastellorizo, which will remain an autonomous system, the rest of the neighboring islands, specifically Patmos, Arkoi, and Symi, will be interconnected via MV cables to the nearest island substation.
- ii. *The Northeast Aegean Sea islands*, which are Skyros, Lemnos, Lesvos, Chios, and Samos, are promoted to be interconnected to the mainland via HVAC cables. Apart from

Ag. Efstratios (Ai Stratis), which will remain an autonomous system, Ikaria and Agathonisi will be interconnected via MV cables to the Samos substation.

It is noted that the rest of the Aegean islands, which are mentioned above, are currently interconnected through 68 operating links in which more than 160 subsea MV cables of 1000 km in total length are installed.



Figure 2. Map of island clusters: (a) Cycladic, (b) Dodecanese, and (c) Northeast Aegean Islands. Connection points are noted: Nea Santa, Aliveri, Lavrio, and Korinthos Extreme High Voltage Centers (EHVC) on the mainland as well as Atherinolakkos SS on Crete (under interconnection).

According to this conclusion, TSO and DNO conducted more detailed studies afterward in order to determine the necessary projects for the optimized implementation of the proposed interconnections. The preliminary studies at this stage were organized as follows:

- Project specification studies
 - Finalization of the Master Plan regarding the islands' electrical connections
 - Preliminary investigation of land planning of high voltage (HV) installations (e.g., substations and compensation devices) at the islands as well as the landing points of the submarine cables
 - Investigation of subsea routes in the sea sections of the interconnections based on an in-office survey regarding the existing sea depths
 - Investigation of overhead or alternatively underground routes over the land sections of the interconnected islands or the mainland system
- Technical specification studies
 - Appropriate selection and dimensioning of submarine and underground cables and overhead lines (OHL) in order to satisfy the necessary transmission capacity

- Appropriate selection and dimensioning of HVDC interconnector equipment [30,31]
- Selection and dimensioning of an optimal compensation scheme of subsea-underground transmission lines (TLs) [32,33]
- Selection and dimensioning of dynamic compensation instruments, e.g., static VAR compensation (SVC) or static synchronous compensators (STATCOM)
- System-related studies
 - Selection and sizing of reserves capacity
 - Energy analysis with hourly operation simulation and detailed loss calculation
 - Investigation of the possibility of developing new RES units on the interconnected islands
 - Static security analysis of load flows (LFs) under conditions of permanent operation as well as under conditions of contingencies for characteristic snapshots throughout the examined period [34]
 - Calculation of short-circuit currents
 - Investigation of the needs of necessary conventional thermal power stations on the islands as well as the needs of emergency reserves that arise under conditions of serious contingencies on the interconnection circuits
- Scheduling of projects for their inclusion in the Ten-Year Network Development Plan (TYNDP) of the IPTO for implementation

Subsequently, two alternative scenarios were examined. The first scenario, which is based on pure HVAC 220/150 kV technology, investigated a vertical subsea loop corridor that starts in North Greece and ends interconnecting Crete, reinforced by a horizontal subsea branch from Central Greece to Lesbos. The second scenario investigated an HVDC interconnector from Peloponnese to Kos combined with HVAC 150 kV subsea interconnection branches to the system as well as between the islands. The scope of this article is to inform on basic planning techno-economic variables. It does not present the results of the detailed contingency analyses ($N - 1$) and short-circuit current calculations that have been conducted. Moreover, electromagnetic transient (EMT) analyses have not been performed at this preliminary stage of the study.

The general description of the interconnection diagrams and the basic technical characteristics of the equipment are presented in Section 2. Furthermore, the results of the static security analysis and the new RES development capacity are presented in Sections 3 and 4, respectively. Energy simulation results are the focus of Section 5, and the economic assessment is presented in Section 6. Qualitative benchmarking is performed in Section 7, while the Conclusions section is devoted to a discussion on the advantages and disadvantages of each solution.

2. Interconnection Scenarios

The design and study of alternative interconnection scenarios were based on meeting the following criteria:

- *Network-centric approach to the island interconnections of all NIIs*: The scope was to holistically deal with the interconnections of the Aegean Sea islands, in contrast to the separate study per cluster of islands (Cyclades, Crete, Dodecanese, and North Aegean).
- *Creation of a unified grid of island interconnections*: We attempted to interconnect the complexes apart from the HETS and between them.
- *Reliable operating schemes*: We aimed to ensure uninterrupted operation under conditions of critical contingencies.
- *Ensuring scalability and interoperability*: It is necessary to ensure the possibility of future extensions without requiring extensive projects and high costs.
- *Economics and benefit of interconnections*: The aim was to maintain the economy of the alternative scenarios, in comparison with the reference scenario, based on the

proposals of the committee for examining the economics of the electrification method of the NIIs. The optimal exploitation of interconnection projects was sought.

- *Capacity for the development of new RES units:* The aim was to ensure significant margins for the development of new RES units on the interconnected islands.

Based on the above criteria, several alternative topologies were examined with a combination of different interconnection branches. According to the investigation conducted, the following conclusions emerged.

The clusters of the Northeast Aegean and Dodecanese islands should be coupled, especially in the case of a direct HVDC interconnection of HETS-Dodecanese. In this case, the operation of the HVDC interconnector will be based on an operating scheme corresponding with that selected for Crete, i.e., the active flow through the DC link will be controlled to maintain, within desired limits, the interface link to the AC link ending at the corresponding electrical node. In this way, the synchronization conditions will be based on the AC interconnection and the control under normal operating conditions of the HVDC interconnector will be voltage control on the HETS side and power control on the island side.

Furthermore, it is possible to electrify the Northeast Aegean and Dodecanese islands with only AC interconnections, i.e., without the implementation of the HVDC interconnectors. This, however, is possible only by adopting a voltage level higher than 150 kV/AC for the interconnection. Based on relevant investigations, the optimal voltage level for the implementation of this scenario is 220 kV.

The Cycladic and other Aegean island clusters should not be coupled at this stage. This was concluded because of the violations of operational limits in the Cyclades cluster, which may happen for various contingencies. In a later phase, with upgraded interconnections of Cyclades cluster, the scope of coupling the clusters could be reconsidered.

The *Crete–Dodecanese interconnection* is possible under certain conditions for specific topologies. This is a particularly difficult task in terms of implementation because of the high depth and existence of cracks. It also increases the complexity of the control scheme of the Attica–Crete interconnection. Conversely, it also leads to more efficient exploitation of the Attica–Crete interconnection.

Based on the above, two basic scenarios were selected and examined in detail:

- *Interconnections Scenario A.* This plan foresees a 220 and 150 kV AC interconnection of the Northeast Aegean and Dodecanese Islands to the HETS through Nea Santa EHVC, Aliveri EHVC, and Atherinolakkos SS in Crete.
- *Interconnections Scenario B.* This plan foresees one (1) bipolar HVDC interconnector for the interconnection of the Dodecanese Islands directly to the HETS at the future Korinthos EHVC, along with 150 kV/AC interconnections of the Northeast Aegean Islands between islands and to the HETS.

Moreover, several new or reinforcements of MV interconnections are promoted:

- Ikaria and Agathonisi are promoted to be interconnected to the Samos MV grid.
- Patmos and Arkioi are promoted to be interconnected to the existing Kos–Kalymnos MV grid, which will be reinforced in order to securely supply all neighboring islands, e.g., Leros and Leipsoi.
- Simi is promoted to be interconnected to the Rodos MV grid.

The costs of these projects developed by HEDNO are defined as distribution investment costs. Finally, Agios Efstratios (Ai-Stratis) and Kastellorizo are not promoted to be interconnected. On the contrary, there are plans to develop smart hybrid technologies for their electrification transformation with a high penetration of RES, energy storage, and smart energy management (smart islands or green islands).

2.1. Scenario A—HVAC Interconnection Topology

This scenario, depicted in Figure 3, consists of the following new interconnection projects, substations (SS), and transmission lines (TLs):

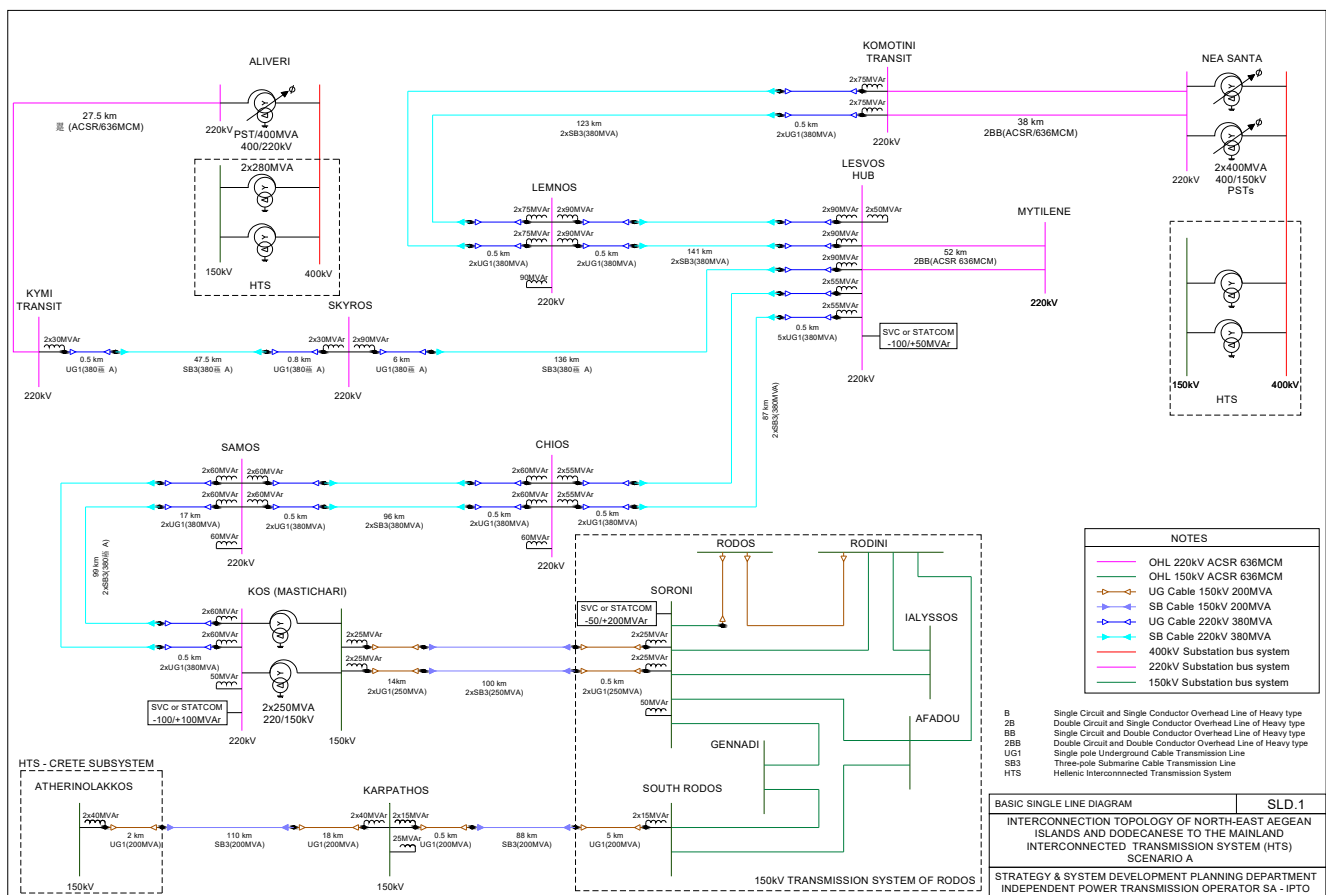


Figure 3. Single line diagram of Scenario A (HVAC interconnection topology).

- *Nea Santa–Komotini (Transit)–Lemnos Interconnection.* The 220 kV / AC interconnector is a double circuit with a nominal capacity of 2×380 MVA. It consists of a terrestrial part (Nea Santa EHVC—Komotini) of two 45-km-long single-circuit OHLs and a subsea part (Komotini—Lemnos) of two 125-km-long 3-pole subsea cables. In addition, there is a need for two on-load phase-shifting power transformers of 400/220 kV at Nea Santa EHVC.
- *Lemnos–Lesvos HUB Interconnection.* The 220 kV / AC interconnector is a double circuit with a nominal capacity of 2×380 MVA. It consists of a subsea part of two 140-km-long 3-pole subsea cables. There is a need for one (1) static VAR compensator system (SVC/STATCOM) that will be installed at the Lesvos HUB SS with a capacity of $-100/+50$ MVar.
- *Aliveri–Skyros Interconnection.* The 220 kV / AC interconnector is a single circuit with a nominal capacity of 380 MVA. It consists of a terrestrial part (Aliveri EHVC—Kymi Transit) of one 30-km-long single circuit OHL and a subsea part (Kymi Transit—Skyros) of one 50-km-long 3-pole subsea cable. There is also a need for one on-load phase-shifting power transformer of 400/220 kV at Aliveri EHVC.
- *Skyros–Lesvos HUB Interconnection.* The 220 kV / AC interconnector is a single circuit with a nominal capacity of 380 MVA. It consists of a subsea part (Skyros—Lesvos HUB) of one 140-km-long 3-pole subsea cable.
- *Lesvos HUB–Chios Interconnection.* The 220 kV / AC interconnector is a double circuit with a nominal capacity of 2×380 MVA. It consists of two 90-km-long 3-pole subsea cables.
- *Chios–Samos Interconnection.* The 220 kV / AC interconnector is a double circuit with a nominal capacity of 2×380 MVA. It consists of two 100-km-long 3-pole subsea cables.

- *Samos–Kos Interconnection.* The 220 kV/AC interconnector is a double circuit with a nominal capacity of 2×380 MVA. It consists of two 100-km-long 3-pole subsea cables. There is a need for two power autotransformers of 220/150 kV at Kos SS. In addition, there is a need for one (1) static VAR compensator system (SVC/STATCOM), which will be installed at the Kos SS, with a capacity of $-100/+100$ MVar.
- *Kos–Rodos Interconnection.* The 150 kV/AC interconnector is a double circuit with a nominal capacity of 2×250 MVA. It consists of two 100-km-long 3-pole subsea cables. There is a need for one (1) static VAR compensator system (SVC/STATCOM) that will be installed at the Rodos (Soroni SS) with a capacity of $-50/+200$ MVar.
- *Rodos (South Rodos)–Karpathos Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 200 MVA. It consists of one 90-km-long 3-pole subsea cable.
- *Karpathos–Crete/Atherinolakkos Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 200 MVA. It consists of one 110-km-long 3-pole subsea cable.
- Six (6) new 220 kV distribution substations (Indoor GIS type) in Lemnos, Lesvos, Skyros, Chios, Samos, and Kos, and one (1) new 150 kV enclosed-type distribution substation in Karpathos. Note that numerous HV compensation reactors are located in all substations in order to compensate all cable lines.

2.2. Scenario B—Mixed HVDC and HVAC Interconnection Topology

This scenario, depicted in Figure 4, consists of the following new interconnection projects, substations (SS), and transmission lines (TLs):

- *Nea Santa (HETS)–Komotini (Transit)–Lemnos Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 250 MVA. It consists of a terrestrial part (Nea Santa–Komotini) of one 45-km-long single circuit OHL and a subsea part (Komotini–Lemnos) of one 125-km-long 3-pole subsea cable. There is also a need for one on-load phase-shifting power transformer of 150/150 kV at Nea Santa EHVC.
- *Lemnos–Lesvos HUB Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 250 MVA. It consists of a subsea part of one 140-km-long 3-pole subsea cable. There is a need for one (1) static VAR compensator system (SVC/STATCOM), which will be installed at the Lesvos HUB SS, with a capacity of $-50/+100$ MVar.
- *Aliveri (HETS)–Skyros Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 250 MVA. It consists of a terrestrial part (Aliveri EHVC–Kymi Transit) of one 30-km-long single circuit OHL and a subsea part (Kymi Transit–Skyros) of one 50-km-long 3-pole subsea cable.
- *Skyros–Lesvos HUB Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 250 MVA. It consists of the subsea part (Skyros–Lesvos HUB) of one 140-km-long 3-pole subsea cable.
- *Lesvos HUB–Chios Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 250 MVA. It consists of one 90-km-long 3-pole subsea cable.
- *Chios–Samos Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 250 MVA. It consists of one 100-km-long 3-pole subsea cable.
- *Samos–Kos Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 250 MVA. It consists of one 100-km-long 3-pole subsea cable.
- *Kos–Rodos Interconnection.* The 150 kV/AC interconnector is a triple circuit with a nominal capacity of 3×250 MVA. It consists of three 100-km-long 3-pole subsea cables. There is a need for one (1) static VAR compensator system (SVC/STATCOM), which will be installed at Rodos (Soroni SS), with a capacity of $-100/+100$ MVar.
- *Rodos (South Rodos)–Karpathos Interconnection.* The 150 kV/AC interconnector is a single circuit with a nominal capacity of 200 MVA. It consists of one 90-km-long 3-pole subsea cable.

- *Korinthos (HETS)–Kos Interconnection.* This is a bipolar HVDC interconnector with a 2×450 MW transmission capacity. It consists of two 400-km HVDC subsea cables as well as two 450 MW terminal AC/DC converter stations at Korinthos and Kos.
- Six (6) new 150 kV distribution substations (indoor GIS type) at Lemnos, Lesvos, Skyros, Chios, Samos, Kos, and Karpathos.

Note that numerous HV compensation reactors are located in all substations in order to compensate all cable lines.

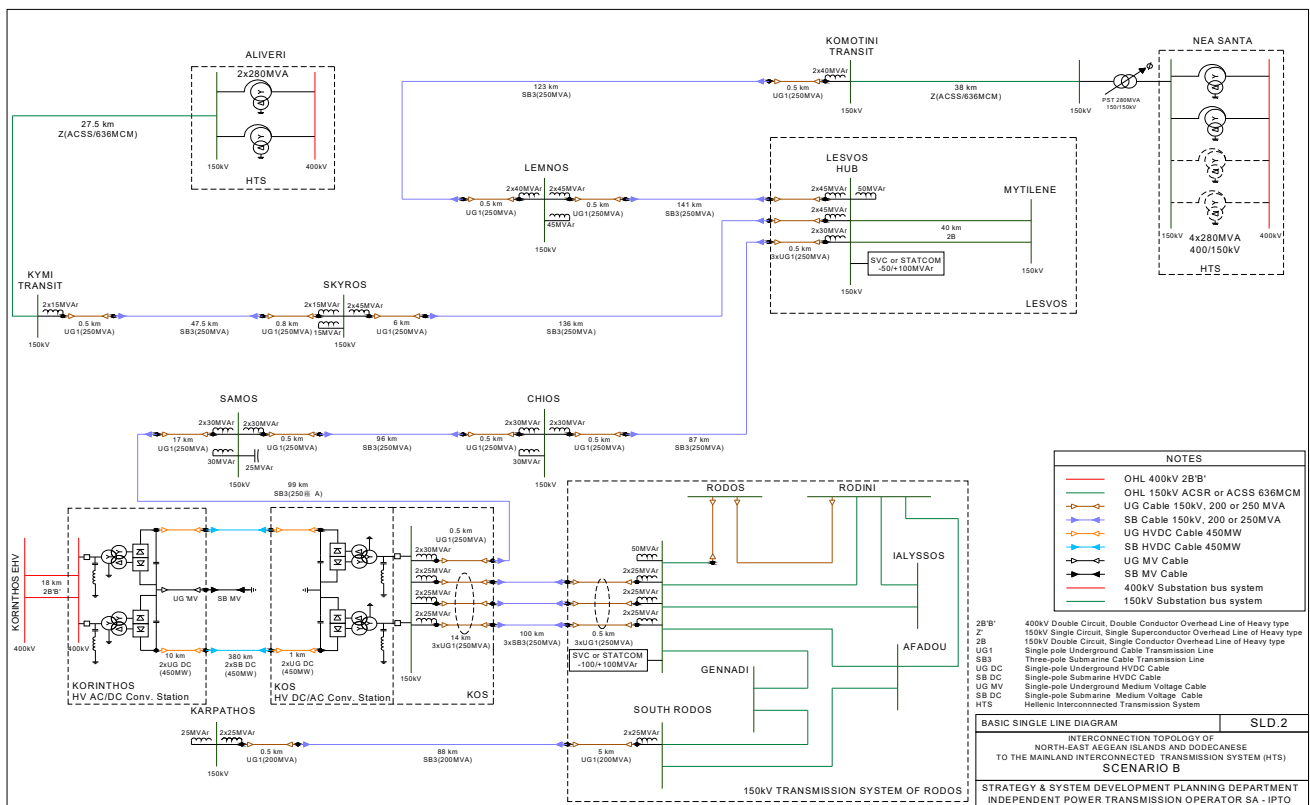


Figure 4. Single line diagram of Scenario B (mixed HVDC and HVAC interconnection topology).

3. Static Security Analysis

This section presents the results of the static analysis, which includes load flow analysis under normal and abnormal operating conditions. The criteria considered for the static safety analysis were:

- Satisfaction of thermal limits of the equipment
- Satisfaction of voltage limits, in accordance with the provisions of the HETS grid code, for normal and abnormal operating conditions during contingencies or errors in the system
- Satisfaction of $N - 1$ reliability criterion. The system must be transiently capable of withstanding all critical contingencies without the risk of collapse (e.g., due to low voltages) or the risk of equipment damage (e.g., unacceptable overloads and surges).
- Overloads on AC cables were only accepted temporarily according to the emergency overload capacity of the cables based on their technical characteristics.
- To check the satisfaction of the $N - 1$ reliability criterion, all possible contingencies were examined, including either the loss of an interconnection circuit, the loss of one of the poles or cables of the DC interconnector, or the loss of a static (reactor) or dynamic (SVC/STATCOM) compensation device. For this purpose, technical aspects of the coordination between HVDC and HVAC links were also considered [20,22,25].

- Common-mode faults on parallel cables were not considered because of the separate routing assumption that was considered to be the case for the interconnections studied.

3.1. Scenario A—HVAC Interconnection Topology

For Scenario A (150–220 kV/AC), the following main conclusions emerged:

- Under normal operating conditions at peak-load conditions for the time horizon investigated in this study (until 2050), there are no violations of operational constraints, and the operation of the interconnections ensures the supply to the islands without the need for local production operation.
- Under abnormal operating conditions at peak load conditions for the time horizon investigated in this study (until 2050), which include simple loss ($N - 1$) of interconnections, transient overloads of up to 25% for the year 2025 and up to 50% for the year 2050 are observed. To deal with these transient overloads, it is necessary to maintain local reserves set in operation after the outage in order to restore the loads within the permitted limits. The most critical contingencies are losses of the connections of Lesvos–Chios and Chios–Samos.
- Under minimum load conditions, the operation of the additional reactors in the substations of the interconnected SS is required in order to have no violations of operating limits in both normal and emergency operating conditions.
- The total required emergency reserves that need to be maintained on the interconnected islands is defined up to 220 MW, distributed as follows: 120 MW at Rodos and 100 MW at Chios or alternatively at Samos. With these reserves, the system can cope with all the expected contingencies.

3.2. Scenario B—Mixed HVDC and HVAC Interconnection Topology

Based on the results regarding Scenario B (mixed HVDC and HVAC interconnection topology) the following main conclusions emerged:

- Under normal operating conditions at maximum loads for the time horizon investigated in the study (until 2050), as well as in contingencies involving simple loss ($N - 1$) of AC interconnections, no violations of operating limits are observed, and the operation of the interconnections ensures the supply to the islands without requiring the operation of local production.
- The most critical contingency is the loss of one of the poles or cables of the HVDC interconnector. During the first years of operation of the interconnections (2025–2035), with half-loading (450 MW) of the HVDC interconnector (before fault occurrence) in the transitional state just after the loss of the pole, there are transient overloads within acceptable limits on the cables of Samos–Chios, Lesvos–Chios, and Skyros–Lesvos (higher transition overload at the Lesvos–Chios interconnection, up to 20%) while with a 530 MW loading (before a fault occurrence), there are no violations of operational limits during the transitional state. In the years after approximately 2035 (based on the predicted evolution of the loads), in order for the system to be able to cope with contingencies leading to pole loss of the HVDC interconnector, local reserve generation of about 70 MW must be set into operation/dispatching (pre-contingency). Reserves should be located at least at Rodos; otherwise, load rejection of 70 MW may be executed.
- In case of minimum load conditions, additional reactors in the substations of Lemnos and Karpathos are required to be set in operation so that there are no violations of operation restrictions in either normal or emergency conditions.
- The total required emergency reserves that need to be maintained on the interconnected islands are approximately 130 MW, distributed as follows: 70 MW at Rodos and 60 MW at Chios or alternatively at Samos. If these reserves are available, the system can cope with all the expected contingencies, except in the case of the total loss of the HVDC interconnector.

3.3. New MV Islands Interconnections

Beyond the HV interconnections of the abovementioned main islands, the rest of the small and isolated islands are studied to be interconnected or reinforced (for those that are already interconnected) via new submarine MV cable lines. Therefore, it is noted that:

- Ikaria and Agathonisi are promoted to be interconnected to Samos.
- Patmos and Arkoi are promoted to be connected to the Kos–Kalymnos MV complex. It is noted that numerous islands neighboring Kos and Kalymnos are already interconnected, e.g., Leipsoi, Leros, Pserimos, Nisiros, and Telos. In addition, additional MV lines are proposed for the reinforcement of the inter-island MV grid.
- Simi is promoted to be connected to the Rodos complex via MV subsea cable lines, while Chalki is already connected.
- Kasos is already interconnected to the Karpathos complex.

Moreover, it is mentioned that the new MV interconnection projects are the same for both Scenarios A and B. Of course, the current thermal power plants of the above deisolated islands will be withdrawn.

4. RES Development Capacity

The assessment of the development of new RES capacity on the interconnected islands was based on the following methodology:

- In conditions of minimum load, RES power is gradually increased in all interconnected islands. In the examined scenario, the total load on the interconnected islands amounts to approximately 115 MW.
- The new RES development capacity is distributed on all islands according to each island's geographic area (km²), as well as according to the average annual wind speeds.
- The criterion for finding the limits of maximum absorption capacity per island is the secure operation of the overall interconnected network in normal (N) and emergency (N – 1) operating conditions.
- The violation of operating limits leads to a redistribution of the power of RES units distributed to the islands (with the result that the final distribution is not necessarily based on the initial percentages) in order to maximize the total capacity of new RES plants to be developed in the Northeast Aegean and Dodecanese Islands.
- The penetration limit resulting from the above methodology corresponds to simultaneous generation. Considering a simultaneity rate of 90%, the total acceptable installed capacity of new RES units per island is obtained.

Table 2 presents the results grouped by scenario for the clusters of the Northeast Aegean and Dodecanes Islands. Based on this clustering, it is possible to develop more RES units on some islands compared with others belonging to the same cluster.

Table 2. New RES development capacity per island cluster after interconnections.

Island	Scenario A HVAC Topology	Scenario B Mixed HVDC & HVAC Topology
Lemnos Lesvos Chios Samos	480 MW	360 MW
Skyros	130 MW	100 MW
Kos Rodos Karpathos	390 MW	570 MW
Total	1000 MW	1030 MW

5. Energy Simulation

For the calculation of the energy supplied by HETS for the electrification of the interconnected islands, an hourly energy simulation of the operation of all the islands was performed based on each interconnection scenario. In this context, the following information was considered:

- Time series of the average demand for electricity of the islands for all the years of the examined period (indicated as $P_{Load,k}^h$ for island k at hour h). These time series are based on reports considering the predicted increase in demand for the following years. Table 3 presents the maximum demand forecasting per cluster for the 2025–2050 period.
- Time series of the average hourly generation of existing RES units (indicated as $P_{PV,k}^h$ and $P_{W,k}^h$ for PV and wind generation, respectively)
- Technical and economic data of conventional thermal generation units considered to be maintained on the islands of Rodos, Chios, and/or Samos as emergency reserves
- Characteristics of power transmission and losses of the interconnections. Regarding the power losses for a cable connecting node k and node n P_{loss}^{kn} , a polynomial approximation was used following Equation (1):

$$P_{loss}^{kn} = a \cdot P_{kn}^2 + b \cdot P_{kn} + c \quad (1)$$

Table 3. Peak (maximum) demand forecasting per cluster for the period of 2025–2050.

Cluster Peak Demand (MW)	Year					
	2025	2030	2035	2040	2045	2050
Dodecanese Islands <i>Rodos, Karpathos, Kos–Kalymnos complex</i>	389	424	454	476	498	520
N.E. Aegean Islands <i>Lemnos, Lesvos, Chios, Samos–Ikaria complex, Skyros</i>	190	203	214	224	233	243

Notes: Ai-Stratis and Kastellorizo are not promoted to be interconnected and are not included, while solutions will be examined for the transition to smart/green islands. The clusters include all neighboring islands, which are either connected or are going to be interconnected via subsea MV lines.

At the connection points to the HETS, the system was modeled as an equivalent generation unit with a capacity equal to the capacity of the transmission cables and an energy cost equal to the anticipated SMP. A DC optimal power flow (OPF) approach was adopted to dispatch power to the interconnections and local generation units [35].

According to the DC power flow, the power transfer between node k and node n of the system was calculated by Equation (2):

$$P_{kn} = b_{kn} \cdot (\delta_k - \delta_n) \quad (2)$$

in which b_{kn} is the susceptance of the line(s) between bus k and bus n , and δ_k and δ_n are the voltage angles.

The objective function of the optimization problem was defined by Equation (3):

$$\min \sum_{h=1}^{24} \sum_{i=1}^{NGEN} \left(C(P_{gen,i}^h) + VOLL \cdot P_{Load,curt}^h \right) + C_{penalty} \quad (3)$$

where $C(P_{gen,i}^h)$ is the cost of generation of active power $P_{gen,i}^h$ by unit i at hour h , $NGEN$ is the number of generation units and points of interconnection to the HETS, $C_{penalty}$ is the penalty cost incurred by wind curtailments, $VOLL$ is the value of the lost load, and $P_{Load,curt}^h$ is the load curtailment at hour h

The objective function was minimized subject to the following constraints:

- *System power balance constraints.* Total generation from local units, interconnection points, and RES shall be equal to the total load of the system and the losses of the interconnections cables:

$$\sum_{i=1}^{NGEN} P_{gen,i}^h + P_W^h + P_{PV}^h = P_{Load}^h + P_{loss}^h - P_{Load,curt}^h \quad (4)$$

- *Power balance constraint at each node.* The net power injected at node k by all cables connected to this node, local generating units, and RES, shall be equal to the load demand of node k (subtracting any load curtailment at this node) and the losses attributed to node k ($P_{loss,k}^h$) as expressed in Equation (5):

$$\sum_{i=1}^{NGEN_k} P_{gen,i,k}^h + \sum_{n \in A(k)} P_{kn}^h + P_{W,k}^h + P_{PV,k}^h = P_{Load,k}^h + P_{loss,k}^h - P_{Load,curt,k}^h \quad (5)$$

- *Cable capacity constraints.* ($|P_{kn}| \leq P_{kn}^{max}$)
- *Angle constraints.* ($\delta_k < 90^\circ$)
- *Generation unit constraints.* This includes the technical minimum and maximum constraints, as well as ramp-up and ramp-down constraints and minimum up and down time.

Applying the mentioned methodology of hourly energy simulation, the calculated outputs are shown in Table 4. Based on the results, we observed:

- For Scenario A (HVAC Topology), most of the demand of the islands is covered through the interconnection with the HETS in the north (Nea Santa) at a rate of about 40%, while the energy supplied by Aliveri EHVC (central HETS) and Atherinolakkos SS in Crete is 20% and 21% of the demand of the islands, respectively.
- As expected, in Scenario B (Mixed HVDC and HVAC Topology), most of the island demand is covered through the DC link at a rate of about 63%, while the energy supplied to the islands via HETS from the AC interconnections with Nea Santa EHVC and Aliveri EHVC is 10% and 12% of the demand of the islands, respectively.
- The weighted average energy loss rates on the interconnected energy is between 4.8% and 5.1% for Scenario A and between 6.2% and 6.9% for Scenario B throughout the period considered.

Table 4. Energy simulation results.

Basic Energy Characteristics	Year					
	2025	2030	2035	2040	2045	2050
Net demand at S/S level (GWh)	2120.9	2223.2	2330.1	2441.7	2555.7	2677.0
Thermal generation on islands (GWh)	0.0	0.0	0.0	0.0	0.0	0.0
Rodos local generation	0.0	0.0	0.0	0.0	0.0	0.0
Lesvos local generation	0.0	0.0	0.0	0.0	0.0	0.0
RES generation (GWh)	444.4	465.0	489.6	510.7	533.2	560.7
Wind generation	288.3	303.7	318.2	333.7	349.7	366.3
Rest RES	156.1	161.3	171.4	177.0	183.5	194.4
Scenario A (HVAC interconnection topology)						
Energy supplied from HETS by HVAC interconnectors (GWh)	1761.1	1847.4	1934.6	2030.8	2128.3	2228.5
HVAC interconnector from Nea Santa EHVC	868.5	910.7	953.4	1001.5	1048.8	1098.9
HVAC interconnector from Aliveri EHVC	421.1	446.1	470.6	498.5	524.9	553.9
HVAC interconnector from Atherinolakkos SS	471.5	490.7	510.6	530.8	554.7	575.7
Transmission losses (GWh)	84.5	89.2	94.0	99.8	105.8	112.2
Average losses factor	4.80%	4.83%	4.86%	4.91%	4.97%	5.03%
Scenario B (Mixed HVDC and HVAC topology)						
Energy supplied from HETS by HVAC interconnectors (GWh)	1800.9	1885.3	1970.5	2064.2	2256.6	2256.6
HVDC interconnector from Korinthos EHVC	1341.1	1406.3	1470.4	1542.0	1615.4	1688.1
HVAC interconnector from Nea Santa EHVC	204.0	213.0	222.1	231.7	241.0	251.7
HVAC interconnector from Aliveri EHVC	254.8	266.0	278.0	290.6	302.8	316.8
Transmission losses (GWh)	124.4	127.1	130.0	133.2	136.6	140.3
Average losses factor	6.91%	6.74%	6.59%	6.45%	6.33%	6.22%

6. Economic Assessment

This section presents the results of the cost analysis of the solution as well as the preliminary economic evaluation (prefeasibility) of the interconnection scheme with a combination of HVDC and 150 kV/AC interconnectors. It should be noted that cost estimation of interconnection projects is usually difficult because of the special specifications and uniqueness of each project, specifically the HVDC projects [36].

In particular, the following items were calculated:

- Total investment cost of the necessary new transmission and distribution projects (CAPEX) for the implementation of the new offshore grid
- Net present value of the total cost of electricity (Energy Cost, NPV) of the interconnected islands for the 2025–2050 period considered
- Levelized cost of energy (LCOE).

The calculation of the NPV assumed a duration of investment payback of 35 years, a discount rate of 8%, system marginal price (SMP) of 74.5 EUR/MWh, and a 25-year period for the calculation of the total cost of electricity.

Based on the above assumptions, Table 5 presents the results of the economic computations for scenarios A and B.

Table 5. Economic analysis.

a. Results for Scenario A (HVAC Interconnection Topology)						
Economic Characteristic	Year					
	2025	2030	2035	2040	2045	2050
Transmission Total Investment Cost, CAPEX (M EUR)	2304.343					
Transm. Annual Capital Cost (M EUR)	197.720	197.720	197.720	197.720	197.720	197.720
Transm. Annual Oper. & Maint. Cost, OPEX (M EUR)	23.043	23.043	23.043	23.043	23.043	23.043
Distribution Total Investment Cost, CAPEX (M EUR)	49.503					
Distr. Annual Capital Cost (M EUR)	4.248	4.248	4.248	4.248	4.248	4.248
Total Annual Cost Transmission & Distribution	240.378	240.378	240.378	240.378	240.378	240.378
Annual Cost of Reserves (M EUR)	15.4	15.4	15.4	15.4	15.4	15.4
System Marginal Price (EUR/MWh)	74.5					
Cost of Energy Generated by System (M EUR)	131.199	137.633	144.129	151.296	158.560	166.024
Total Cost of Supplied Energy (EUR/MWh)	371.577	378.012	384.507	391.674	398.938	406.403
NPV of Scenario A (M EUR)	4470.832					
LCOE of Scenario A (EUR/MWh)	210.35					
b. Results for Scenario B (Mixed HVDC and HVAC Topology)						
Economic Characteristic	Year					
	2025	2030	2035	2040	2045	2050
Transmission Total Investment Cost, CAPEX (M EUR)	2342.142					
Transm. Annual Capital Cost (M EUR)	200.963	200.963	200.963	200.963	200.963	200.963
Transm. Annual Oper. & Maint. Cost, OPEX (M EUR)	23.421	23.421	23.421	23.421	23.421	23.421
Distribution Total Investment Cost, CAPEX (M EUR)	49.503					
Distr. Annual Capital Cost, (M EUR)	4.248	4.248	4.248	4.248	4.248	4.248
Total Annual Cost Transmission & Distribution	238.804	238.804	238.804	238.804	238.804	238.804
Annual Cost of Reserves (M EUR)	10.2	10.2	10.2	10.2	10.2	10.2
System Marginal Price (EUR/MWh)	74.5					
Cost of Energy Generated by System (M EUR)	134.168	134.168	134.168	134.168	134.168	134.168
Total Cost of Supplied Energy (EUR/MWh)	372.971	372.971	372.971	372.971	372.971	372.971
NPV of Scenario B (M EUR)	4483.958					
LCOE of Scenario B (EUR/MWh)	210.96					

In conclusion, based on the results, the following could be ascertained:

- The total cost of the interconnection projects for the electricity supply of the islands (CAPEX) is about EUR 2.3 B for the investigated scenarios.

- The levelized energy cost (LCOE) is about 211 EUR/MWh for scenarios considered, considering that the LCOE value of the NIIs is currently up to 500 EUR/MWh.

7. Discussion: Qualitative Benchmarking of the Scenarios

The main advantages of Scenario A, with 150 kV/AC and 220 kV/AC interconnectors, are summarized as follows:

- Development of a “meshed” offshore grid with four connection points to the HETS (one of them with Crete)
- Capacity for development of new RES units on the interconnected islands
- Reduced transmission losses
- However, this interconnection scheme has the following disadvantages:
- Requirement to maintain higher emergency power reserves
- Requirement for new equipment specifications for the 220 kV level (currently not operated in Greece)
- Long distance from the load center
- First application of 220 kV voltage equipment for the HETS
- Asset management issues of new equipment that arise with the introduction of a new voltage level
- Complexity of the control operation strategy of the HVDC interconnection of Attica–Crete because of the connection of Crete with the Dodecanese Islands

The main advantages of interconnection scenario B, with a combination of HVDC and 150 kV/AC links, are summarized as follows:

- Direct power supply corridor of the load center from HETS
- Capacity for the development of new RES units on the interconnected islands
- Technical and engineering readiness regarding equipment specifications
- However, this interconnection scheme has the following disadvantages:
- Great dependence of the whole project of the interconnection of the Northeast Aegean and Dodecanese Islands from the implementation of the Korinthos–Kos HVDC project
- Increased transmission losses

Moreover, new trends on offshore RES connection can be enabled with the HVDC technology [37,38] jointly with HVAC cutting-edge equipment.

Evaluating all the study findings, especially the disadvantages of Scenario A (220 kV/AC interconnectors) regarding the requirement to maintain more reserves, the long distance of the connections from the load center, and the complexity in the control scheme of the Attica–Crete HVDC interconnection due to the connection with the Dodecanese Islands, Scenario B (HVDC interconnection of Korinthos–Kos and 150 kV/AC interconnections of the other islands with each other and with the HETS at N. Santa and Aliveri EHVCs) was adopted for implementation by the TSO [39], while the new MV interconnections and reinforcements will be planned by the DNO. Figure 5 presents the system development plan of island HV interconnections (MV interconnections are not depicted). The new interconnections will enable the deisolation of islands and energy transition to reliable, resilient, and economic power delivery. Moreover, the rich RES potential will be utilized where possible.

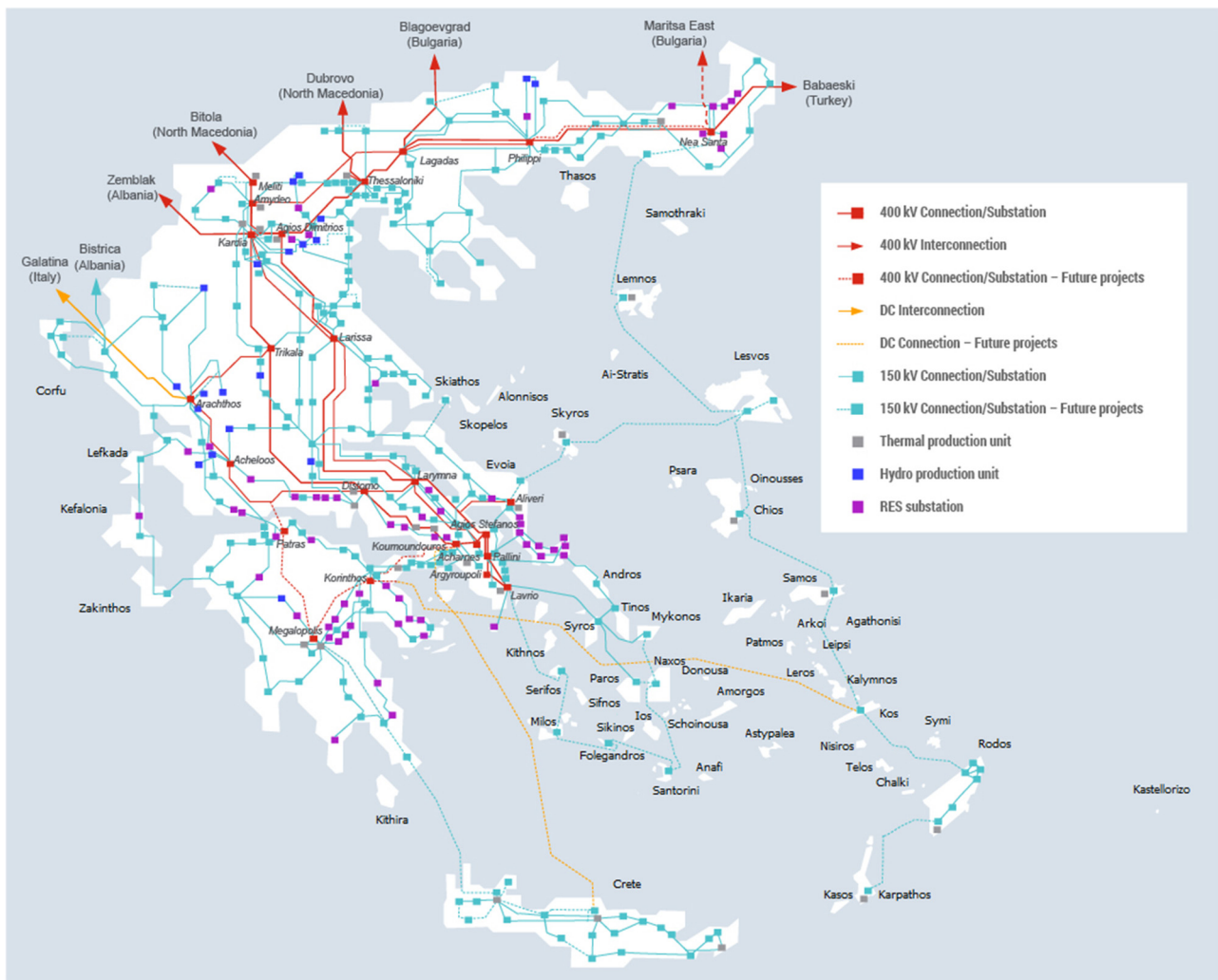


Figure 5. System development planning of the Dodecanese and Northeast Aegean Islands interconnection in the case of scenario B. The rest of the Cycladic Islands and Crete interconnections are currently projects in the implementation process.

8. Conclusions

This article presents a holistic approach to the Aegean archipelago NII interconnections to the continental power grid of Greece. During the network-centric investigation that was carried out, numerous network topologies and cutting-edge transmission technologies were examined in order to promote an optimal economic, secure, and resilient network architecture. Finally, the authors extensively studied and compared two interconnection scenarios: Scenario A, based on pure HVAC (220 kV and 150 kV) technology, and Scenario B, based on a bipolar HVDC interconnector from the mainland to Kos island and 150 kV/AC subsea cable transmission lines. The main conclusions of the investigation initially conducted in the present study can be summarized as follows:

- The clusters of the Northeast Aegean and Dodecanese Islands should be interconnected, while at this stage it is not appropriate to interconnect them with the Cycladic Islands.
- It is possible to interconnect the Northeast Aegean and Dodecanese Islands exclusively with AC interconnectors, but only with the adoption of voltage levels higher than 150 kV.
- The Crete–Dodecanese interconnection is possible under certain conditions for specific topologies.
- Based on the investigation, two main scenarios were selected and examined in depth:

- Scenario A, with interconnections at AC voltage levels of 220 kV and 150 kV for the interconnection of the Dodecanese and Northeast Aegean Islands to the HETS via the Nea Santa EHVC, Aliveri EHVC, and Atherinolakkos SS in Crete.
- Scenario B, with a bipolar HVDC interconnection of the Dodecanese Islands with HETS at Korinthos EHVC and 150 kV/AC connections for the Northeast Aegean Islands.

According to the static security analysis of the abovementioned scenarios, the secure electricity supply to the islands is ensured in normal and emergency operating conditions. For this purpose, it is required to maintain in cold reserve status some local reserves on the islands of Rodos and Chios or Samos of about 130 MW for Scenario B (HVDC and 150 kV/AC) and of about 220 MW for Scenario A (150–220 kV/AC).

From an economic point of view, the scenarios yield equivalent results, with the total investment/capital cost (CAPEX) of the interconnection projects for the electricity supply of the islands amounting to approximately EUR 2.3 B and the levelized energy cost (LCOE) to approximately 211 EUR/MWh. In addition, the scenarios are practically equivalent in terms of the capacity for developing new RES units of about 1000 MW in the interconnected islands.

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