

Overview of insular power systems under increasing penetration of renewable energy sources: opportunities and challenges

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Abstract

Insular electricity grids are considered to have a more fragile structure than the mainland ones due to several factors such as the lower inertia because of lower number of generation facilities connected to the system, absence or insufficient interconnection with the main grid, etc. The recent trend of integrating large portions of environmentally sustainable power generation units that have a significantly volatile nature in the generation mix (such as wind and solar energy conversion systems) within this fragile structure, poses profound challenges that need deeper and specific analysis. This study aims to provide an overview of insular power system structures and operational requirements, especially under increasing penetration of renewable energy sources. Firstly, a general evaluation of insular power systems is presented. Then, potential challenges are thoroughly discussed together with opportunities to tackle them. Future technological developments, as well as innovative applications are also given special attention. Hence, this paper contributes to the scarce literature regarding insular power systems by providing a critical overview of issues regarding their operation and possible solutions.

Keywords: Demand response; energy storage; insular power systems; renewable energy; smart grid.

1. Introduction

The term “island” has a basic meaning as a sub-continental land that is surrounded by water, which implies a physical total insularity (that basely means isolation and/or dispersion) from the mainland. Thus, insular power systems correspond to electric power grid structures in physically isolated geographical areas that are mainly islands [1].

It was stated in The Treaty of Amsterdam that “*insular regions suffer from structural handicaps linked to their island status, the permanence of which impairs their economic and social development*” [2]. In other words, insular areas have limitations that need to be identified. Limited range of resources, inability to achieve economies of scale, often seasonal change of population, higher infrastructure costs, distance from the mainland, climatic conditions and microclimates within the insular area are examples of such constraints. These limitations lead to several negative outcomes including overseas trade dependency, economic weakness that reduces the chance of gaining access to conventional markets, need of oversizing infrastructure including power systems, etc. [3].

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Among the mentioned limitations, priority should be given to the fact that insular areas are among the most vulnerable places regarding climate change as the frequency of natural disasters (mostly tropical storms, typhoons, etc.) that has increased because of climate change are a more important threat for insular areas than for the mainland [4]. Climatic effects such as sea level rising, climate variability, abnormal climatic conditions etc. also affect the environment of islands [3].

Thus, the general problems of insular areas can mainly be categorized as dependence on imported fuel, availability of fresh water, management of wastes and other problems related to climatic conditions, etc. [3,5], which are affected by many factors including the components of insular economies.

The economies of most of the insular areas rely on tourism, which is specifically an advantage driven by their geographical added value. For European Islands, a research concluded that dependency ratio of these insular economies on tourism is nearly 70%. Apart from tourism, insular economies mainly depend on agriculture and fishery, since industry development is very limited in islands due to scarce resources, high infrastructure and transport costs, limited competitive markets for companies, etc. [3]. Nearly all the imported goods at many insular areas are shipped over very long distances, a fact which has a serious impact on their economic sustainability. Many islands around the world rely nearly 100% on imported fuel for many activities such as energy production, transportation, heating, etc. Such dependence on imported fuel is a major issue that has economic, technical and social results. Many critical industries like fisheries are highly vulnerable to fuel prices [4].

Tourism is a high-quality water and energy consuming activity. Generally, tourism is mostly seasonal and leads to a significant increase in the island's population for a few months. Tourism also increases waste and the waste management especially in such high population periods is a serious problem due to limited area, high cost and scale of recycling processes, etc. If high-quality water is not available within the own resources of an island, there are two ways to fulfil this requirement: water import from another area or desalination of sea water, both fuel and energy consuming activities. As seen, the mentioned waste management and quality water preparation increase the need of energy together with the fact that the other daily energy needs (air-conditioning, other daily consumptions, etc.) in high population periods are significantly greater than rest of the year. This leads to oversizing infrastructure in all fields as systems sized to accommodate the requirements of the summer period are significantly underutilized in winter time.

The mitigation of dependence on imported fuel especially for electricity production is an important parameter for the economic sustainability of insular areas. The fuels (gasoline, oil, LPG-liquefied petrol gas) required for conventional energy sources are generally carried to islands by tankers which creates both an unsustainable service model especially during peak times and a problematic strategy from environmental point of view. Besides, the energy production from fossil fuels is costly especially due to transportation costs. Thus, the utilization of local resources mainly in form of renewable energy systems (RES) is a pivotal aim of many energy policies especially during the last decade and the structures of electric power grids have started

to significantly change with the recently increasing interest in RES. Comparatively weaker electricity grid structures such as insular grids are more sensitive to power quality issues such as frequency and voltage deviations especially if the penetration level of RES is high due to the volatile nature of such units. Insular grids with a lower inertia due to reduced number of generating units connected to the system are more vulnerable to large frequency and voltage deviations, which in turn reduces system reliability and security. Thus, the policies aiming to improve the penetration of RES especially in insular areas are limited by insular power system deficiencies. As a result, insular power systems are considered as a “laboratory” for testing the impacts of such new technologies and strategies including the target of higher RES penetration [3], which underlines the need for deeper examination of insular areas and insular power systems in terms of current status, challenges and opportunities for future technological advancements also ultimately including “smartification” of all operations.

There are many literature studies dealing with the impact of high RES penetration and methods to overcome the drawbacks related to the integration of such systems. Lund et al. [6] presented an analysis on the impacts of high solar and wind power penetration and demand and production side options to mitigate their variability. Luthra et al. [7], Tigas et al. [8] and Eshchanov et al. [9] realized country scale regional analyses for high RES implementation considering respectively India, Greece and Uzbekistan cases. A review of many policies to increase RES penetration considering also methods to overcome existing barriers based on lessons learnt from real cases in different countries of the world was presented in [10]. There are also some studies focusing specifically on different topics related to insular areas and relevant power system operations. Diagne et al. [11] introduced a review of solar forecasting methods specifically to aid insular power system operations. Brito et al. [12] presented the details of an imaginary insular power system that was assumed as carbon free and also discussed the pros/cons of integrating sustainable energy resources and ways to overcome the possible drawbacks. Georgiou et al. [13] examined the technical applicability and possible outcomes of interconnecting insular areas with the mainland in terms of possibility for increasing RES penetration considering a specific Greek case. In a very recent study, Notton [14] firstly highlighted the problems related to grid integration of RES in insular power systems and then analysed the current status of eleven French islands. However, [14] treated the topic only from the perspective of RES integration and relevant storage requirements neglecting other issues linked with insular areas.

This study presents an overview of insular power system structures including high RES penetration and discusses the challenges and opportunities, emphasizing on real examples from different insular areas all over the world. Although the aforementioned studies have provided useful insights into the challenges faced in insular areas, none of them has addressed these problems in the general framework of insular power system structures from the perspective of economy, sustainability and reliability. Besides, this paper provides a discussion on different challenges and opportunities dealing also with high RES penetration apart from simply focusing on the opportunity of energy storage as in many review studies on the topic.

The rest of the study is organized as follows: Section 2 deals with evaluation of insular power system structures generally from system size, economy, sustainability and reliability point of view. Then, in Section 3 the possible challenges and opportunities in insular power system structures are discussed. Finally, conclusions are presented in Section 4.

2. Evaluation of Insular Power Systems: Analysis of typical insular grid structures

2.1. System size and typical infrastructure

According to their peak power demand (MW) and annual energy consumption (GWh), insular areas are classified into four groups [15]:

- Very small islands (<1 MW & <2 GWh)
- Small islands ([1-5 MW] & [2-15 GWh])
- Medium islands ([5-35 MW] & [15-100 GWh])
- Big islands (>35 MW & >100 GWh)

Over the last few decades, the electric power loads have significantly increased with the investments in new transmission and distribution system construction to enable nearly all citizens in insular areas to access electricity apart from the people living in significantly rural areas where geographical conditions prevent the possibility of installing power lines, etc. Table 1 gives brief information on power loads of sample insular areas geographically located in different parts of the world.

Generally, the power systems of insular areas comprise a single or a few, typically conventional fuel based generators, especially in very small and small islands. Thus, the inertia of the total system is significantly low and the current status of insular power systems can be considered unreliable due to possible outages and fuel shortages for such a small number of generating options. Moreover, most of the generating units as well as other electrical infrastructure components are old and need maintenance more than newly installed systems, an issue that reduces the reliability and economic sustainability.

The technical and nontechnical losses in insular areas are considered to have a higher percentage in comparison with the bulk power system that promotes the increase of fuel utilization and also the unit cost of electricity [4]. Thus, the overall power system operating efficiency is significantly lower compared to mainland that adds further economic burdens on energy serving companies (ESCOs) and accordingly end-user customers.

2.2. Economical framework of insular power system operation

During the last decades, the organization and regulation of the electricity sector has substantially changed in many countries around the world where vertically integrated companies and monopolies have been or are being replaced by competition and market structures. In favour of these profound changes, supporters of deregulation claim that competition among an increasing

number of firms will permit cost and price reductions [16]. Practically, restructuring of the electricity sector entails the introduction of several new entities and agents that operate in all levels of the production-to-consumption chain [17]. Although there are several examples of successful liberalization around the world, the power systems of islands pose challenges towards the implementation of market structures and competition because of their peculiarities. The main barriers are:

- In contrast with continental grids, a generator in an island cannot have significant capacity due to system security reasons.
- More reserve capacity is required than in the mainland networks on account of absence of interconnections.
- Provision of electricity is more expensive in insular power systems owing to high fuel transportation costs.
- Limited space, public opposition and local factors (e.g. the island is a tourist resort) do not allow vast investments in conventional power plants.
- RES are alternative candidates for electricity production, promising economic efficiency and sustainability. Nevertheless, network security issues and the interruptible nature of such resources limit the penetration of RES.

Until recently, most insular power systems were managed by a public vertically integrated company that was socializing the higher cost of producing electricity in islands in order to achieve social fairness and boost the economies of the islands.

There are several models to introduce competition in electricity markets [16]:

- The Single Buyer model,
- Bilateral contracts,
- Wholesale markets (pools).

The single buyer model and bilateral contracts are considered the most suitable structures for non-interconnected insular power systems [18]. All the insular power systems share the aforementioned limitations. However, the organization of the electricity market may differ significantly from island to island. In Malta, a small-sized island, there exists only a national corporation (Enemalta) that acts as a generator, distributor and retailer. In Malta, the market structure follows the single buyer model since independent producers may sell electricity to Enemalta. Furthermore, consumers have to buy energy from the same corporation since there does not exist any other retailer [19]. In Cyprus, a non-interconnected island country, the market is based around bilateral contracts. Legislation allows the 67% of the island's electricity consumers to choose their electricity supplier and also foresees for competition in generation. Nevertheless, Electricity Authority of Cyprus remains the only power producer and supplier [20]. In Canary Islands (Spain), Red Eléctrica de España (REE) acts as a single buyer using a minimum cost generation scheduling procedure [16,21]. The island of Crete offers the opportunity of having a pool market structure given the load's demand and its size [18]. It is obvious that although the legal framework regarding insular power systems in many cases allows competition, in practice it is not operational. In order to attract investors' interest and overcome the practical barriers in

insular power systems, several alternatives should be considered such as hybrid portfolios (e.g. combining energy storage and RES) and investigating possible interconnections with other nearby islands or the mainland.

2.3. The need for sustainability

In general, it is evident for many islands that it is technically hard or economically unviable to have a direct interconnection with the mainland. This leads to the necessity of supplying all the energy demand by production on site. The insular electricity grids generally rely on a single type of energy resource that is typically conventional type and dependent on imported fuel with price volatility. This issue is likely to hamper the economical sustainability for insular areas. The utilities in these areas suffer dramatically from the increase of cost for the imported fuel that in turn has a major impact on unit cost of electrical energy. As a real example, the electrical energy prices reflected to end-users within insular areas were varying between 25-34 cents per kWh while the same cost was in the range of 10-14 cents per kWh in the mainland for United States in 2005 [4]. The cost of electricity for residential and commercial end-users was approximately 31 cents per kWh in September 2010, 40 cents per kWh in December 2012, and 42 cents per kWh in the third quarter of 2013 for American Samoa [22]. It is clear that the price has been significantly volatile in a short time period for insular areas. This was mainly caused by the higher and variable cost of fuel per barrel, due to additional costs such as transportation (as all imports are shipped over very long distances to most of the islands), etc. Another major reason for this cost difference is the increasing percentage of maintenance within total costs and decreasing efficiencies of employed engines and turbines, all caused by aging of electric production facilities as investment in new technologies with surely significant capital costs is not regular for insular areas as opposed to the bulk power system renovations [4]. Some insular areas have their own bulk fuel facilities and can purchase fuel from the bulk market at more affordable prices. Besides, in some countries the difference in prices between insular areas and mainland are supported by public funds to ensure that kWh cost for the customers is the same both in mainland and islands. An apt example is the small islands in Sicily, Italy where the Ministry of Industry gives the mentioned support [23]. However, this is not a common case, since it is an additional burden on the economy of the country.

In some islands (e. g. Pacific Islands of US which depended nearly 100% on petroleum for their energy needs in 2006), the use of local wood, coconut husks and other possible biomass products is also employed for some daily activities such as cooking instead of using electricity. However, the need for fossil fuels, especially petroleum, is also increasing because of other sectors, e.g. transportation, apart from electricity production. Among the transportation facilities, commercial airlines and local airports are major fossil fuel users. Furthermore, fishing fleets and other marine crafts promotes the need of fossil fuel utilization.

This increasing use of petroleum and other kinds of conventional resources not only threatens the insular economies, but also significantly contributes to the environmental degradation that can have serious results. First of all, such an increase in conventional fuel utilization increases the major impacts of global warming similarly to all over the world. However, the

climatic changes related to global warming will have a greater impact on insular areas compared to the mainland. Sea level rise, natural disasters, drought, etc. threaten the natural life in insular areas dramatically. The life quality with such an increase of greenhouse gas emissions will surely worsen, especially in such limited places such as islands where end-users are more closely located to production sites compared to a mainland area. Thus, both economic and environmental impacts of fossil fuel utilization in insular areas should be examined in a more detailed way, aiming to improve the sustainability of insular life.

2.4. Reliability requirements

Given the economic and social aspects the usage of electricity entails, measures have to be taken in order to guarantee the uninterrupted and quality operation of the power system. In this respect, the concepts of power system stability and reserve adequacy should be given importance both for interconnected continental grids and insular power systems.

According to the IEEE/CIGRE Joint Task Force on Stability Terms and Definitions “*power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact*” [24]. Three types of stability have been identified: rotor angle, frequency and voltage stability.

The rotor angle stability indicates the ability of the power system to remain synchronized under severe or small disturbances. Transient stability (ability to withstand severe disturbances) depends on both system properties and type of faults. Generally, systems with centralized and of similar technology synchronous generators have better transient stability. Small disturbances are linked with small signal stability. This means that the system has the properties of damping electromagnetic oscillations and improved frequency response (frequency restores its pre-disturbance value quickly and with no oscillations) [25].

Frequency should be maintained within acceptable limits around the nominal value. Off-nominal frequency has negative and potentially hazardous results such as resonances in rotating machines that tear them because of mechanical vibrations, change in the speed of asynchronous machines, overheating of transformers and machines because of increased core losses, flickering etc.

To maintain the frequency at its nominal level, the balance between production and consumption of active power balance should be retained. In order to achieve this, an amount of active power is rendered available in order to be able to control frequency through its variation. Despite the fact that the energy stored in the rotating masses of generators compensates energy deficits constantly due to their inertia, control schemes are required in order to guarantee appropriate values for frequency.

The typical procedure in order to control frequency comprises three levels. The first level is primary frequency control which is a local automatic control and is performed by generators that are equipped with a speed governor. It is designed to react instantly (several seconds), stabilizing the frequency after large generation or load changes (outages etc.). Frequency-controlled loads such as induction motors or frequency-sensitive relay equipped loads can also participate in this control. There are two issues regarding this control level. Firstly, the active power provided by several generating units or demand-side resources must

be replaced after some time due to technical or other restrictions. Also, the resources that contribute to this frequency control level should not be concentrated in a specific location of the grid but should be distributed instead. In this way unexpected transit phenomena are avoided and network security is enhanced.

Primary frequency control limits frequency deviations but it is not able to recover its nominal value. For this reason, another level of control, namely secondary frequency control, is used in order to restore the target frequency value. This is a type of centralized automatic control and refers typically only to the generation side. In contrast with the primary frequency control, it is not mandatory for all power systems. Such systems exert frequency control based on primary frequency control and a third level of control, known as tertiary frequency control that comprises manual changes in the commitment and dispatch status of generating units. This is a definite measure to restore both primary and secondary frequency reserves to their normal levels and to re-establish the nominal frequency value.

The control of a power system's voltage can be also organized into three levels. Primary voltage control is a local automatic control that maintains the appropriate voltage level at every bus. This task is can be performed by the automatic voltage regulators of generating units or by static devices such as static voltage compensators. Then, a rather rare level of voltage control is the centralized secondary voltage control that regulates the local reactive power injections. Finally, manual tertiary voltage control re-establishes the reactive power flow through the power system. Naturally, demand-side resources capable of absorbing or generating reactive power have the potential of participating in voltage control [26, 27].

3. Challenges and opportunities for insular power systems under high RES penetration

3.1. General overview

The economic and environmental issues that were examined in detail in the previous sections call for new policies to ensure the sustainable growth of insular life. To reduce the dependency on fossil fuel utilization, energy related policy making and relevant R&D studies are of utmost importance. The energy related R&D studies are driven by four major concerns as [28]:

- “Supply pressures” corresponding to risk in the security of global energy resources
- “Demand pressures” corresponding to economic growth, increasing consumer expectations and industrial demand and limitations of existing infrastructures
- “Environmental pressures” corresponding to actions that should be taken to reduce carbon emissions resulting in global warming
- “Political pressures” corresponding to political actions in energy-key regions such as Middle East, Russia, etc.

One of the leading solutions to partly overcome the supply, environmental and political pressures is the increase of renewable and clean alternative energy production technologies share in the generation mix. Many islands around the world have a good

RES potential (e.g. the Aegean islands including Greek islands [29], the Mediterranean islands including the Canary Islands [3], and different insular areas around the world [30]). Wind and solar resources are the pivotal available resource for many insular areas. Besides, hydro, biomass (also bio-fuels for transportation), geothermal, oceanic energy (wave or tidal), etc. also have found application areas in specific islands. In a report, it is stated that for European islands more than %15 of all imports are energy imports that can be reduced by RES integration [3]. However, the intermittency of RES is especially a core concern for small grid structures such as insular areas [5]. Thus, the major concern for increasing RES penetration is the stability of the grid in terms of frequency and voltage control, reactive power supply, etc.) [31].

Another combined social and technical problem is the limited available capital and human capacity to efficiently operate and maintain such technologies that needs this time the import of human resources. There have been many cases of insular area citizens who have lived in the mainland for some time to gain training and technical skills and have finally chosen to migrate rather than returning to their islands to take part in technical actions. If the local know-how necessity is well managed, it can also create job opportunities with high educational requirements that generally islands lack of.

The natural climatic conditions apart from temperature, wind speed and solar irradiation should also be examined. For example, industrial equipment that works well in normal conditions may fail while used outdoors in tropical environments such as in Pacific Islands. Besides, many insular areas are prone to tropical cyclones that make it harder to protect wind turbines from high winds. In a similar context, from the geographical point of view, one of the problems faced during the electrification of rural areas is the practical difficulty in maintenance after installing an off-grid system based on RES.

Apart from RES integration, many reports have been prepared and many actions have been taken around the world to reduce fossil fuel dependence in insular areas. Demand side actions including responsive demand strategies and energy efficiency actions take the second place recently that is linked to “demand pressures”. Some general issues that have been pointed out in the reports including these facts are as follows [4]:

- Using more efficient devices in all areas, from engines to street lights,
- Developing forums to share experiences of different insular areas in terms of policies, projects, programs, etc.,
- Developing strategies to increase competition among fuel suppliers to reduce prices in the market,
- Examining supply-side and especially demand-side energy issues,
- Evaluating power losses in generation, transmission and distribution systems,
- Re-evaluating the current maintenance practices,
- Examining the power demand pattern in a more detailed way than daily total energy usage profiles with advanced metering systems,
- Examining the reactive power requirements within services and reducing VAr flow within the system,

- Examining the loading ratios of all transformers to reduce no-load losses by loading all transformers at a similar loading ratio,
- Examining the loading of power lines and balance the loads to further reduce neutral currents,
- Taking actions and establish legislation (such as making electricity theft a crime) to reduce non-technical losses caused by meter tampering, etc.,
- Taking supporting actions for large power consumers to employ co-generation technologies for excess power,
- Providing fuel diversity with possible investments on power production technologies based on different conventional fuel resources apart from petroleum such as coal, etc.,
- Providing a public transportation structure to reduce personal automobile based transportation fuel utilization.

Thus, it is obvious there are many challenges but also many opportunities for insular areas to more efficiently and effectively operate insular power systems that should be examined in detail.

3.2. Challenges and opportunities

3.2.1. Generation side

Most islands do not have any exploitable indigenous conventional energy sources (e.g. fossil fuels, hydro-carbons) and they are not connected with any other energy sources such as natural gas pipe networks. Hence, due to their location most islands are highly dependent on external energy sources and mainly oil that is transported by ships at a very high cost. An apt example of this is the case of the Canary Islands, the electricity generation of which depended by 94% on imported fuels in 2010 [32]. Similarly, the island of Cyprus uses heavy fuel oil and diesel for electricity generation almost exclusively [33].

To alleviate the negative economic and environmental effects of fossil fuel dependence, RES are considered as a means of increasing the self-sufficiency of insular power systems. There are many autochthonous energy sources that may be used according to the specific needs and peculiarities of each insular system, in order to mitigate imported fuel dependence and to diversify the production mix.

This sub-section discusses available green energy production options, their current applications in insular power systems and future trends.

Solar energy:

Solar radiation may be used directly in order to produce energy either through direct conversion of the solar energy to electrical (through photovoltaics - PV) or to provide energy for side applications (e.g. water heating, solar drying, solar cooling systems etc.). Essentially, most RES (wind, ocean and biomass energy) are indirect forms of solar energy [34]. Surely, even with different levels, generally decreasing from equatorial areas to polar areas, solar energy is available at least in some periods of the year in many areas of the world that is obviously not distributed universally, equally, and continuously at all times [35].

Such solar energy systems may be considered a suitable generation opportunity in different forms for remote islands with considerable solar energy potential. Naturally, according to the location of each island, generation potential differs from place to place. For example, all the Greek islands are characterized by high solar irradiance, varying from 1500 kWh/m² to 1700 kWh/m². Furthermore, the annual variation of the solar potential coincides with the annual variation of the system's load demand [36], rendering it an appealing green energy option.

There are several ways to integrate PV modules. They can be installed on the rooftops of buildings (several kW) or, if larger production is required, collective solar power plants (e.g. municipal), such as concentrated photovoltaic or concentrated solar power plants.

There are two major drawbacks concerning electricity generation using solar energy. Firstly, it is still an expensive technology and subsidies are required in order to render it competitive. However, there are initiatives by leading country governments in order to reduce the relevant costs [37]. Secondly, as a result of its relatively low energy density, significant space is required in order to achieve adequate electricity production from solar potential. This can raise issues of limited space, as well as of environmental impacts. These are especially important parameters for islands the economy of which relies on tourism [32].

Several initiatives regarding the integration of renewable energy sources in islands consider vast investments in solar energy. In 2010, 112MW of solar photovoltaic were installed on Canary Islands, mainly concentrated in PV farms and a small portion on several premises. The Canary Islands Energy Plan aims to have 30% of the electricity produced by RES, mainly solar (160MW) and wind (1025MW) [32]. Most recent data (2013) regarding the RES share in the insular power system of Cyprus suggest that it stands only for the 1.2% of the total electricity production. Production of rooftop PV systems and PV parks amounts only for about 7.7% of this small share. Due to the commitment of Cyprus to comply with the EU 2020 obligations, the country developed a program (National Renewable Energy Action Plan of Cyprus) that among others targets to install 192MW of solar PVs and 75MW of concentrated solar power by 2020 [33]. Furthermore, the island of Crete is expected to have installed 140MW of solar energy by 2030 [38]. Already in 2010, 60GWh were produced in Reunion Island by PV systems installed (80MW) both stand-alone and interconnected [34]. Recently, the Hawaiian islands of Oahu, Maui and Kauai had significant solar resources, reaching a penetration of 10% in Oahu [39]. Finally, the example of the U.S. Virgin Islands where PV installations are considered an economic way to reduce fossil fuel consumption is very important to realize the potential of the solar energy, especially for the electrification of non-interconnected islands [40].

Wind energy:

It is estimated that world's wind resources have the capacity to generate 53000TWh of electrical energy per year which accounts for three times the global energy consumption [41]. Because of the increasing interest (due to national and international targets) in reducing the carbon footprint, many countries motivated the development of this type of RES during the past decade.

Most remote islands are located in favourable locations with exploitable on-shore and off-shore wind potential. As a matter of fact, there are many examples of relevant investments in islands of different sizes across the globe. In the Greek island of Rhodes, approximately 6% of the energy production comes from the 11.7 MW installed wind power [42]. The biggest Greek island, Crete, has an installed wind capacity of 105MW which accounts for 12.5% of the total capacity and the twelve wind farms may instantaneously provide up to 39% of the total generated power (in 2006). However, the total licensed capacity exceeds 200MW [38]. In 1998 Samsø Island was chosen by the Danish Government as a demonstration of a 100% RES electricity production island. As an evidence of this successful endeavour, Samsø Island currently has 23MW of offshore wind power generation and 11MW of onshore wind power generation while all its demand needs are produced by RES. The Spanish El Hierro Island is also subject to an ambitious target of becoming a 100% renewable energy island and currently wind power penetration reaches 30% [43]. The South Korean Jeju Island is also an example of high wind power generation penetration. There is the goal of installing 250MW of wind power and in 2010 88MW of wind power generation was already installed [44]. Finally, plans for increasing the RES penetration in many islands are set by other countries as well. Canary Islands, the American Hawaiian Islands, Germany's Pellworm Island are a few indicative examples.

The major challenge that needs to be addressed when planning to utilize wind energy to produce electricity is the intermittent and variable nature of this kind of production. Intermittency refers to the unavailability of wind for a considerably long period while volatility describes the smaller, hourly oscillations of wind. Due to the reduced control over the wind energy production, some quality characteristics of the power system such as frequency and voltage may be affected. Also, to balance the lack of production during some periods, generation adequacy has to be reserved, leading the power system to a vulnerable state, especially in non-interconnected islands. Nevertheless, intermittency management is performed using sophisticated tools and wind can be considered a reliable source of energy in long-run [45]. Another concern that is associated with the operation of wind-farms and can be significantly important for small islands is the noise pollution near the wind park. This is the case for the island of Faial in Azores, where the wind farm is shut down for several hours during the night in order to cease the disturbance of local houses [46]. Offshore wind farms seem to improve several issues related to the regular onshore wind farms such as the visual and noise impact and the efficiency because of higher speed and less turbulent wind streams [47].

Wave energy:

During the past decades, great effort has been devoted to develop solar and wind energy generation. However, the idea of exploiting the high energy potential of the waves has drawn significant attention recently. Wave energy has been recognized as more reliable than solar and wind power because of its energy density (typically 2-3 kW/m² compared to 0.4-0.6 kW/m² of wind and 0.1-0.2 kW/m² of solar potential). Besides, wave energy offers several advantages in comparison with other RES. First of all, waves can travel long distances without losing much of their energy and as a result wave energy converters can generate up

to 90% of time compared to 20-30% for wind and solar converters. This fact renders wave energy a credible and reliable energy source. Furthermore, there are also specific advantages that make it an appealing choice for the electrification of insular power systems. Firstly, the resource is available in multiple locations (from shoreline to deep waters). Secondly, the correlation of demand and resource (distance between generation and load) is high in islands. Finally, this type of renewable resource has less environmental impacts than other alternatives. This is particularly important for islands with limited space and particularly for islands the economy of which relies on tourism.

The main challenge towards the large scale integration of wave energy is the infant phase of relevant technologies. To provide high quality power to the grid frequency and voltage have to be of appropriate levels. Together with the fact that the wave power is uncertain, special storage systems are needed to support the output of such plants. To exploit efficiently the wave power, especially in off-shore applications where energy flux is greater, infrastructure has to withstand severe stress due to environmental conditions. Regardless of the attractive features of wave energy, lack of funding poses a further hindrance towards the development of the required technology. Other renewable sources are more competitive since their respective markets are mature and still, large investments are required to construct wave energy harnessing plants.

Wave power varies with the location and the season and therefore the placing and the technology of such plants should be carefully considered. Also, the variability of the resource changes significantly according to the same parameters. Nevertheless, measurements regarding the wave energy potential near several islands around the world have provided promising results. In Table 2 relevant information is presented. Based on the previous review of wave power, it is evident that it emerges as an opportunity for ecological and smarter insular grids. Already, for the year 2015, the Canary Islands Energy Plan establishes that 30% of the electricity generation should be supplied by RES, mainly wind and solar. This plan establishes among others that wave energy has to reach 50MW of production [32].

Geothermal energy:

Geothermal energy comes from the natural heat under the crust of earth and is linked to earthquakes and volcanic activity and therefore the thermodynamic characteristics (e.g. temperature, enthalpy etc.) of geothermal resources may significantly vary with the place. However, the available technology to exploit geothermal energy has evolved to adapt to the specific characteristics of a place's resources and it may be considered mature.

Geothermal energy has a potential to be used for electric energy generation in insular power systems. For example, based on several studies, a 2.5MW geothermal power plant may be considered to be installed in the Island of Pantelleria (Italy). It may be possible to achieve a production of 20000 MWh/y that stands for about the 46% of the island's consumption [48]. Also, Government of Azores has launched an ambitious plan to achieve 75% by 2018 of sustainable electricity production, on average of all islands. The Electricity of the Azores (EDA) strategy, among others, includes additional investments in geothermal plants

in the major islands (São Miguel) [49]. In February 2009 approximately 20.6% was produced by geothermal energy in Hawaii Island (Big Island) [50]. Significant geothermal power is installed in Jeju Island (South Korea) where 130.1 MW of geothermal energy contribute to the total RES generation by 15% [44].

Geothermal plants are characterized by high capital investments (exploration, drilling, plant installation). However, operation and maintenance costs are low and thus, geothermal plants may serve as base load units [51]. Recently, several hybrid systems combining geothermal energy have attracted research interest in order to achieve a more efficient usage of this resource. Hybrid fossil-geothermal plants have been developed but they led to a compromise of the environmental benefits that standalone geothermal plants have to offer because of the increased greenhouse gases emissions. To maintain the advantage of sustainability, combining other renewable energy sources (e.g. solar and biomass) with geothermal energy production has been proposed [52].

Biomass:

Biomass is considered a mature and promising form of RES. It offers the advantages of controllability and the possibility of creating liquid fuels and the flexibility to adapt to any raw material available locally (agricultural and livestock residuals, urban garbage etc.). The major challenge is that the installation should be strategically considered near a populated area in order to guarantee the constant availability of the resource.

A recent study [38] indicates that based on agricultural residues (olive kernel, citrus fruits etc.) and forestry material Crete has the potential to develop up to a total of 60MW of biomass power plants around the island. In Hawaiian Islands operate two biomass stations with installed capacity 57MW and 46.1MW. Currently, two more are under construction and have a rated capacity of 24MW and 6.7MW. Especially, the 6.7MW station that is being constructed in Kauai Island will provide the 11% of the island's annual energy needs [53].

Small hydroelectric power plants:

Small Hydroelectric Power Plants (SHEP) have small installed capacity (e.g. below 10MW in Europe) and do not generally use large reservoirs and therefore the interference with the environment is minimal. Such units exist in several islands. In the island of Crete there exist two SHEPs, while a third one is being considered to be built [38]. In Faial (Azores) a 320kW hydro power unit exists [46]. In El Hierro Island, 9.9MW of hydropower capacity is installed with pumping capability. In this way, excessive wind power is used to pump water in the upper reservoir in order to achieve energy storage and cope with the intermittency and variability of wind power generation [43].

3.2.2. Energy storage systems

On the way to “smartification” electrical power system, many factors should be taken into account. In this regard, a specific part of the smart grid definition of DoE should be given importance: “*All generation and storage options should be considered*

in a smart grid structure" [54]. Thus, the role of energy storage in new smart and sustainable power grid structures cannot be neglected.

There are many roles storage systems can have in a power grid. Fast storage units that offer short duration (seconds, minutes) storage option can be used for power quality sustaining including frequency regulation, etc. while middle duration (hours) storage systems can be used for load levelling, peak shaving, etc. actions for load pattern reshaping. On the other hand, storage units offering long duration (days) of storage are generally used for providing autonomy to the system also by levelling output of intermittent RES with a considerable penetration within the relevant grid structure.

Energy storage technologies can be electrical or thermal. An electrical input-output is available for electrical energy storage systems while similarly there is a thermal input-output for thermal systems. Electrical energy storage systems can be in the form of electrochemical systems (battery, etc.), kinetic energy storage systems (flywheel, etc.) or potential energy storage system (pumped-hydro, compressed air, etc.). Recently, large-scale storage options such as compressed air (CAES) or pumped-hydro based storage systems have been utilized with a growing ratio. Such energy storage options can be utilized for storing hundreds of MWh of energy. However, the geographical dependence of such systems is a major drawback especially for insular areas as a suitable underground storage space and an inclined land with multiple water storage options in different levels are necessary for compressed gas and pumped hydro systems, respectively. Large-scale new types of battery units are also considered as an option especially for smoothing the fluctuating power output of large power WTs. A 245 MWh Sodium Sulfur (NaS) battery system is available in Japan for ensuring the dispatch of a 51 MW wind farm [21]. New generation lithium-ion batteries for EVs will also be a significant option of energy storage, particularly when the penetration of EVs on road transport reaches a considerable level.

As another storage option, the flywheel technology has already been employed in different areas, especially for rapid response to frequency deviations caused by the fluctuating nature of non-dispatchable renewable energy sources. With their significantly high power density, superconducting magnetic energy storage (SMES) and ultracapacitors can also play similar role in short period rapid response requirements. As a promising technology, the hydrogen storage systems composed of electrolyzer-large scale hydrogen tank-fuel cell (FC) combinations have been given importance in the research studies realized, especially on the cost reduction and reliability improvement of the mentioned systems. The generated hydrogen can also be utilized directly for powering FC based hydrogen vehicles, which is also a topic of research for more than a decade. A concise summary of the specifications of main energy storage systems provided by [55] is given in Tables 3 and 4.

The role of energy storage systems in insular power grids is gaining more importance especially since RES investments have become more important towards reducing dependence on imported fuels to ensure sustainable growth of insular areas. The RES are highly dependent on the conditions of nature. Thus, the energy produced by these resources can significantly vary monthly,

daily, or even instantly. This leads to the fact the produced energy may not exactly match with the energy demand. In order to supply the load demand in every condition, energy storage units show great potential. The excess energy produced by alternative resources is transferred to energy storage units, and this stored energy is used to supply the load demand when the main sources are non-existent or are not sufficient. Besides, the rapid unavailability of RES units especially during high RES penetration may force the conventional units to reduce their power ratings below an allowable lower limit [55]. Here, storage systems can effectively be employed to meet this discrepancy in production and consumption to ensure safe operation of main power units. This issue is especially significant for small systems like insular areas where the number of available generators is tightly limited that offers nearly zero flexibility. Energy storage units with different characteristics come into action at this point to add different levels of flexibility in required points of the low inertia insular power system.

Especially, research and examination of energy storage units for stand-alone applications is also significantly important [56]. With the usage of energy storage systems in such applications, the need for energy transmission lines that have a high investment cost is highly reduced that is an important issue especially for the most secluded areas of insular grids [57]. From this point of view, different applied energy storage systems in sample insular areas are given in Table 5.

3.2.3. Operational and system planning aspects

The abundance of RES in combination with the high fossil fuel prices has led to a significant penetration level of such technologies in order to produce electricity in insular networks. Although leading RES technologies such as wind and solar are mature and able to compete conventional power plants, they are linked with variability due to their intrinsically stochastic nature. Therefore, integration of such levels of non-dispatchable resources in relatively small sized insular systems poses operational and economic challenges that need to be addressed. The magnitude of the problem depends on the penetration of RES in the production mix, while its mitigation is reflected on the “flexibility” of the power system.

There are several issues that need to be considered in the operational practice of insular networks. Firstly, RES production such as wind and solar depend on wind and irradiation values, which in turn fluctuate according to climatic changes and spatial characteristics. As a result, instantaneous, seasonal and yearly fluctuations affect the generation output. In case of wind power production, power quality is also affected by these fluctuations (especially by very short term- turbulences) depending on network impedance at the point of common coupling and the type of wind turbine used.

Variable RES production affects the operation of conventional generators [58-60]. Under high penetration conventional units are likely to operate in a suboptimal commitment. Fluctuation of RES output power leads to cycling of conventional units and shortens the life of their turbines, while causing increased generation costs. Emission reduction potential is also suppressed. Reserve needs are also increasing with the penetration of RES and especially ramping requirements (load-following) because of the uncorrelated variation of wind generation and load demand. A case study for the insular power system of Cyprus [61]

concluded that the available reserve is not adequate to balance the real-time fluctuations of wind, while higher penetration of wind power generation would further constrain the downward ramping capability of the island's system due to the part loading of generators.

An indispensable tool in the decision making process taking place in insular power systems is the accurate modeling of uncertainty factors using advanced forecasting and scenario generation techniques. It has been reported [62] that modern forecasting methods commercially available are able to provide up to 80% of the benefits perfect predictability would have for wind power integration. Accurate forecasting may improve the results of unit commitment and minimize the operational costs. Besides, sophisticated scheduling tools should be employed in order to accommodate uncertainty at different time scales. In [63] a multi-step approach is proposed for the short-term operation of insular networks under high RES penetration. It comprises a day-ahead scheduling model, an intra-day dispatch scheduling model and a real-time economic dispatch model. It also considers through appropriate forecasts and scenarios several uncertainty sources such as wind and solar power production, load variation and unit availability. This model is developed based on the insular power system of Crete.

Apart from the aforementioned solutions, demand-side and electrical energy storage [64, 65] technologies offer a great opportunity for increasing the flexibility of insular power systems. Flexibility will enable a most efficient utilization of the RES production that in an inflexible power system may be curtailed to maintain the generation-demand balance (or to avoid congesting transmission lines) and thus decreasing the environmental and economic potential of wind power production. Given that investments in fossil fuel fired power plants are neither motivated by policy makers and governments, nor cost-effective because of the increased fuel prices in islands, flexibility is not possible to be increased by generation-side resources. A study for the power system of Cyprus [61] suggested that in order to accommodate the fluctuations of the wind power generation, load-shedding and extensive wind power curtailments are necessary. The potential of the active demand-side participation in several time-scales of the grid's operation is illustrated in Fig. 1. In [66], a study concerning the demand response integration is conducted for the insular power system of Gran Canaria in order to assess the benefits on the operation of the power system and the cost savings. Also, a new type of load that can act as a means of energy storage integration, namely the electric vehicle (EV), is considered a factor of flexibility in power systems. A study concerning the island of Flores (Azores) has concluded that through appropriate control schemes the current distribution system can support the penetration of EVs that apart from transportation they are also able to provide services to the system in order to accommodate the interruptible RES but also to reduce distribution system losses etc. [67].

When planning the integration of RES in insular power systems, system operators should consider the following aspects:

- RES based power plants may reduce or increase the transmission line capacity requirements (and subsequently active power losses) according to their location and their distance from the load.

- Voltage quality may be improved because of the capability of several RES technologies (such as DFIG wind turbines) to control their reactive power. As a result, connecting renewable energy sources to weak parts of a power system may contribute to the voltage stability of the system.
- The RES installations should be as much geographically dispersed as possible in order to avoid further requirements in transmission capacity.
- Demand of loads that contribute to peaks (such as air-conditioning) may be correlated with the peak production of several RES (such as solar energy). This is a fact that should be recognized during the sizing and connection procedure.

3.2.4. Reliability

Challenges concerning the reliability of insular power systems are a result of both their structure and the increasing penetration of RES.

Insular power systems have low system inertia and therefore, are highly sensitive to frequency deviations. Renewable energy sources such as PVs that use an inverter interface further reduce the inertia of the system. Furthermore, lower inertia implies that after a disturbance in the network large frequency deviations are expected since there is not enough active power to mitigate the rate of frequency's change. The fact that insular power systems, especially in small islands depend on a few conventional fuel fired generators further jeopardizes the security of the system. Generators tend to be large in comparison with the system size and during off-peak hours, a single generator may represent a large proportion of the system's total generation. It is then evident that the sudden loss of this unit will lead to significant frequency deviations [68].

Another problem that is caused by increasing renewable penetration in combination with the typical insular power system described above is the inability of conventional generators to reduce their output when non-dispatchable RES production is high. Typically, diesel-fired generators have a minimum output limit of 30% of their installed capacity. Forcing a load-following unit to shut-down in order to retain the generation and demand balance may compromise the longer-term reliability of the power system. In order to avoid such deficit in system's inertia, RES generation is normally curtailed in order avoid switching off synchronous generators at the expense of economic losses [69].

The penetration of RES may also affect voltage stability because power sources such as fixed-speed induction wind turbines and PV converters have limited reactive power control. Also, high system loading and inductive loads such as air conditioning have a serious impact on the voltage stability.

Surely, operational reserves (spinning or non-spinning) are required in insular power systems as well. Apart from frequency regulation, load-forecasting error, sudden changes (ramps) in the production of RES units, equipment forced or scheduled outages need also to be confronted. To deal with these issues adequate generation or demand-side capacity should be kept.

In order to improve frequency and voltage stability several measures can be taken:

- The reduced inertia in isolated power systems with inverter interfaced RES can be replenished by energy storage that keeps the power balance [70]. Grid code changes have been proposed and many different applications of energy storage systems in island systems already exist [15, 71, 72].
- Demand-side resources can be used in order to provide frequency stabilization reserves. According to [73], there are two ways of controlling consumed power. Either there can be continuous control if the load is supplied by power electronics based power supply, or the loads can be switched on and off for specific periods of time. The first group of loads is rare and expensive, while the second is linked with minimal inconvenience of consumers. Heating, ventilation, air conditioning, dryers, water heaters and pumps are loads of this group. Using frequency relays they can be switched on or off according to the frequency swifts. This is a particularly promising opportunity for islands that primarily serve residential load.
- A relatively new concept that may prove indispensable is the inertial-control of wind turbines. “Virtual” wind inertia is created through utilizing the kinetic energy stored in the rotating mass of wind turbines in order to respond to frequency drops. Variable speed wind turbines may accept wide speed variations and as a result the inertial response of wind turbines is greater (more kinetic energy can be transformed to electrical energy) than of the regular synchronous generators given the same inertia value [69,74,75]. Power control of wind farms with respect to frequency can complement the frequency control schemes of the insular power system.
- Solar and wind power plants have the ability of controlling their reactive power. Doubly-fed induction generators (DFIG) and permanent magnet (PM) synchronous generators are capable of injecting or consuming reactive power. Power electronics that interface solar power plants have the same ability. Therefore, regulating voltage at the common connection point is possible [74]. Connecting wind-farms and solar power plants to weak network points can thus improve the overall stability of the system.

Finally, regarding transient and small-signal stability no major concerns are expressed for insular systems under high penetration of RES. As it has already been stated, transient stability from the system’s perspective is linked with the type of controllers and the dispersion of synchronous generators and therefore it is not possible to draw general conclusions since each single insular power system is a unique case. However, several studies indicate that moderate presence of RES (~40%) does not seem to have severe impacts on transient stability [76]. Besides, given a specific insular network one could suggest a maximum penetration limit for RES in order to avoid affecting transient stability. Regarding small-signal stability, it is not generally considered a concern for insular power grids [25].

Before closing this sub-section, it is worth mentioning that the concepts of security and reliability may as well have a localized component because of geographical or other peculiarities of the specific island. For example, we will refer to the interesting case of the tropical island of Guam that has an area of 542 km² and 157 thousand residents and is a major tourist destination reaching 1.5 million visitors per year. Like in many other tropical islands, there is an increased need for maintenance due to corrosion, rapid growth of tropical vegetation that threatens distribution lines and storms. However, what makes the case of Guam different is the increased population of the brown tree snakes that are the reason for at least 1658 power outages from 1978 to 1997 and most recently approximately 200 outages per year. Outages span the entire island and last eight or more hours and cost over 3 million dollars. Excluding repair costs, damage of electrical equipment and lost revenues, the damage on the economy of the island exceeds 4.5 million dollars per year over a 7-year period [77]. This example confirms the fact that each insular power system's operational requirements are directly linked to the geographical and other local factors.

3.2.5. Demand-side management

The demand side in power systems was formerly referred to as consumption level due to the fact that the consumers were just consuming energy without power producing facilities. However, as the applications of small scale grid tied renewable RES (roof top PVs, small wind turbines, pico-hydro systems for areas located near a small river, etc.) recently increased, the consumers have gained the chance of also selling energy back to the grid in low demand-high production periods. For instance, PV based power production is at the highest level during noon times when generally the consumption is at the lowest due to the fact that most people are out of their home (working hours). Besides, on-site energy storage facilities and additional new generation consumer appliances such as EVs have also changed the demand side structure and made the demand side more flexible, able to respond to power system requirements.

The demand side of a power system surely includes different kinds of end-users. These end-users can be listed under three main types: residential, commercial and industrial end-users. The demand side management actions that can be taken to change the load pattern considering the requirements can be basically classified into two groups: energy efficiency actions and demand side participation programs.

Energy efficiency actions mainly focus on reducing the total energy consumed for realizing a particular amount of work. One of the widely known energy efficiency actions is to change the old light bulbs with new generation energy efficient bulbs to obtain a particular lighting level with a reduced amount of energy consumption. Many different actions can be taken in order to improve the efficiency of energy usage in all areas of a power system from production to consumption. Energy policies on insular areas within the last decade give specific importance to energy efficiency actions. Firstly, it is proposed to make investments in new generating facilities instead of old technology based polluting generating units that contribute to imported fuel consumption significantly, which is the most critical issue for sustainable growth of insular areas. Apart from the generation

level, also investments in transmission and distribution levels such as proper sizing of assets, reduction of reactive power flows, etc. are also proposed in order to improve system efficiency similar to such investments on mainland. There are also policies for energy efficiency actions in demand side to reduce consumption levels, especially for common areas. For example, the replacement of street light bulbs with more efficient ones was strongly recommended for many islands in US territories to reduce the impact of such a consumption component in a detailed report on recommendations for insular areas [4].

Demand side participation programs generally focus on shifting the energy usage to off-peak periods to reduce the need of extra electrical infrastructure investment requirements to cover the peak load conditions. Demand side programs have successfully been applied in industrial area in the last decades, but new technologies also provide opportunities to apply such programs in other end-user areas. Individual residential or industrial end-users have their own appliances/devices that can be classified under three main categories [78]:

- Thermostatically controllable appliances.
- Non-thermostatically controllable appliances.
- Non-controllable appliances.

Controllable appliances provide the leading opportunity for new generation demand side programs. The thermostatically controllable devices include heating and ventilation air conditioners, water heaters, etc., for residential end-users that can be switched from on to off position and vice versa and curtailed during peak periods of power demand, also considering the comfort settings of the residents. Besides, non-thermostatically controllable appliances can be controlled by positioning the appliance to work consuming a higher or lower power value without just totally opening or closing the appliance.

Washers, dryers, etc., for residential areas may be given as an example for such kind of appliances. On the other hand, the non-controllable appliances are called "non-controllable" due to the fact that these appliances, such as TVs, lights, etc. have a comfort lowering impact on consumers if controlled without the permission of the end-user. It is well known that there is a chance of automatic dimming for the lightening of an end-user unit, but this is considered in the concept of energy efficiency investments.

As a new type of end-user appliance/load, EVs have recently gained more importance as electrification of the transportation sector that is a major fossil fuel consumer, is a hot topic of environmental sustainability. EVs have a different structure with challenges/opportunities that should be examined in detail. As a load, the energy needs of EVs can reach to the levels of new power plant installation requirements. The recommended charging level of a Chevy Volt as a small sized EV is 3.3 kW [79], which can even exceed the total installed power of many individual homes in an insular area.

Thus, special importance should be given to EV charging with smart solutions, especially with the consideration of high level EV penetration. On the contrary to the charging power challenge of EVs, the opportunity of using EV as a mobile storage unit

with the vehicle-to-grid (V2G) concept may provide some opportunities, especially for shaping the demand without adding stress to transformers and accordingly to the bulk power system. Analysis of EVs is expected to have an important place in a better deregulation of electric power systems.

Demand side management activities especially in the context of new generation smart grid vision mainly lies on demand response (DR) strategies employed in end-user local areas. DR is a term defined as “*Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*” by DoE and is composed of incentive based programs and price based programs (time-of-use, critical peak pricing, dynamic pricing, and day head pricing) [80].

The utilization of DR strategies is considered as mature for industrial customers, but this is a relatively new concept for employing in residential areas responsible for nearly 40% of energy consumption in the world [81]. There are many supporting devices/technologies for DR activities in residential areas. Especially, home energy management systems (HEMs) and smart meters have the leading role for effectively applying DR strategies.

Smart meters are new generation electronic meters that have the capability of two-way communication with the utility/system operator. For DR activities, smart meters can receive signals from the system operator, such as the maximum allowable level of power in a certain period (especially reducing the possible foreseen stress on the relevant transformer) or price signals determined in a dynamic way, and can share this information with HEMs. HEMs also receive information signals from smart appliances and/or smart plugs, if available, including state of the appliance, power consumption, etc. Also, the power production information of available renewable generation facilities is received by HEMs.

For insular areas that have limited industrial facilities, such DR applications in residential and possibly in commercial (hotels, etc. for more touristic islands) areas may come into prominence in order to improve the economic and technical sustainability of insular power systems. Such flexibility in demand side is likely to overcome the high inertia structure of generation system in insular areas. In this regard, many projects and investments have been ongoing in all over the world to provide an enabling infrastructure for DR activities in insular areas. For Caribbean islands which mostly depends on imported diesel fuel for energy production and has a system loss of 27%, it is announced that 28,000 smart meters will be installed in a close future to provide a basis for future smart grid activities by the Caribbean Utilities Company, Ltd (CUC) [82]. Utility Hawaiian Electric, the local operator of Hawaiian Insular Power System declared to have 5,200 customers with smart grid facilities by smart metering. Other islands in US Virgin Islands also have a similar plan of improving the number of smart metering facilities with different deadlines between 2016 and 2018 [83]. Another project in EU is conducted with a similar aim for Bornholm Island of Denmark [84] while many different insular areas are considered in this regard in a different research project [85]. There are many

activities, incentives and policies in different regions of the world for insular areas for reducing the dependence on imported fuel and losses in the system in insular areas where demand side actions play and will surely play a leading role in efficient and effective balancing the production and consumption.

3.2.6. Other innovative approaches and possible future developments

The discussion conducted in the previous sections has highlighted several opportunities to address the issues of reliable, cost-effective and efficient operation of insular power systems. Complimentary, there exist several other innovative approaches that can further boost the goal of sustainability in all aspects of insular power system operation.

Desalination process employed in many islands in order to fulfil the needs of high-quality water may be embodied in a general operational scheduling of the islands power-consumption portfolio. For example, excess of wind power generation that would be in other case spilled, can be used to desalinate sea water [86]. Waste management in insular areas can also be turned into an opportunity by producing energy from wastes for covering self-needs of the waste treatment procedure. Furthermore, locally available resources such as plantation can be used in order to produce bio-fuels that together with the opportunity EVs offer will reduce the dependence on imported fuels of the transportation section. Moreover, similar to the areas with low solar potential but high solar energy use such as Germany, all the available solar energy can be procured also in insular areas with high or low solar potential by the combination of all different civil, architectural, engineering methods within the concept of “energy neutralization”.

The possible future developments should not just focus on technical aspect of addressing the problems of insular power systems, but also should aim towards reshaping the way governments, energy producers and end-users consider sustainability as a key-stone of their daily life.

4. Conclusions

Insular areas have naturally different characteristics compared to mainland a fact that is also reflected to power system structures. The insular power systems that generally rely on nearly 100% imported and fossil-based fuels lack of sufficient characteristics for sustainability of insular economies and natural life. Thus, the mitigation of the dependence on imported and polluting fuels is pivotal. Some energy efficiency measures, policies, renovation based new technological investments, demand side strategies, and pivotally higher levels of RES integration are all proposed as viable opportunities. However, the challenges such as the geographical limitations of insular areas, the technical limitations of small size grid structures with low inertia like insular grids, etc., are all barriers to overcome in order to seize these opportunities for ensuring a sustainable insular power system. Many policies and many reports have been announced, specifically focusing on insular power systems. Besides, many largely funded R&D projects have just been finalized or still continue. All of these efforts have resulted in specific applicable

solutions and also have shown that some pre-proposed possible solutions are not applicable or not feasible to apply in real-life. In this regard, a worldwide cooperation between insular areas, policy makers and researchers is strongly required to share valuable experiences to overcome such drawbacks of insular structures. Agencies and organizations such as United Nations and European Union that are active in each region of the world may take responsibility in this regard to ensure sustainable continuity of insular life.

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Figure Captions

Fig. 1. Potential of active-demand side participation into the operation of a power system.

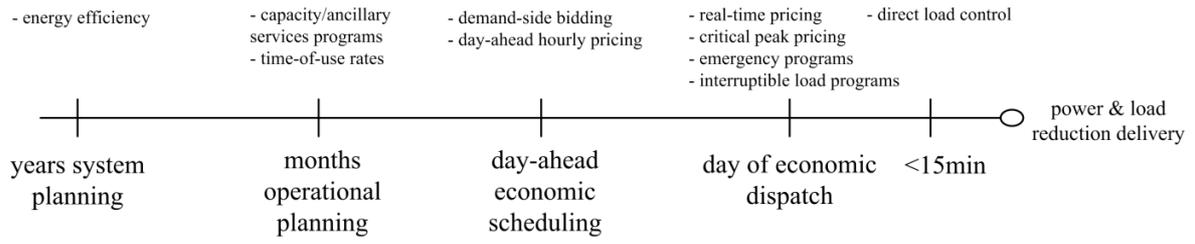


Fig. 1. Potential of active-demand side participation into the operation of a power system.

Table Captions

- Table 1. The power loads of sample insular areas.
- Table 2. Wave energy potential in different islands.
- Table 3. Ranges for concise specifications of storage technologies [55].
- Table 4. Concise specifications of different major storage technologies [55].
- Table 5. Different applied energy storage systems in sample insular areas.

Table 1. The power loads of sample insular areas.

Location	Population	Installed Capacity	Peak Load	Reference
Guam	~170,000	550 MW	280 MW (40,000 customers)	[4]
St. Thomas-St. John (US Virgin Islands)	~53,000--~4,000	199 MW	86.3 MW	[4]
St. Croix (US Virgin Islands)	~55,000	120.8 MW	55 MW	[4]
Cyprus	~860,000	990 MW	775 MW	[87]
Crete	~600,000	1085 MW	650 MW	[85]
Gran Canaria	~840,000	860 MW	552 MW	[87]
S. Miguel (Azores Islands)	~140,000	160 MW	65 MW	[85]
La Graciosa (Canaria Islands)	~1,000	1.3 MW + 1.5 MW from main island	1.2 MW	[85]
San Juanico, Mexico	~640	205 kW	167 kW	[88]

Table 2. Wave energy potential in different islands.

Location	Estimated Wave Energy	Reference
Madeira Archipelago	20 kW/m (Madeira) , 25kW/m (Porto Santo)	[89]
Hawaii	60kW/m in winter time, 15-25kW/m throughout the year	[90]
El Hierro	High energy: 25 kW/m, 200MWh/m (annually) Low energy: 13kW/m, 150MWh/m (annually)	[91]
Lanzarote	Over 30kW/m, 270MWh/m (annually). Seasonal variation: energetic winter and spring, mild summer.	[92]
Menorca	8.9 kW/m, 78MWh/m (annually)	[93]
Canary islands	25kW/m	[94]
Azores	Peak power 78kW/m, minimum 37.4 kW/m	[95]
Vancouver island	34.5kW/m 7km from shore	[96]

Table 3. Ranges for concise specifications of storage technologies [55].

	Very low-very weak	Low-weak	Medium	High	Very high
Energy density [Wh/kg]	0.01<X<10	10<X<30	30<X<50	50<X<150	150<X
Power density [W/kg]	10<X<25	25<X<50	50<X<150	150<X<1000	1000<X
Storage duration	Seconds to minutes	Seconds to hours	Minutes to hours	Minutes to days	Hours to months
Self-discharge per day	X<0.1%	0.1%<X<1%	1%<X<10%	10%<X<30%	30%<X
Capital cost [€/kW]	-	100<X<600	600<X<1500	1500<X	-
Charge-discharge cycle efficiency	-	X<60%	60%<X<90%	90%<X	-
Lifetime [years]	X<1	1<X<5	5<X<15	15<X<50	50<X
Technological maturity	Developing -	Developing +	Developed -	Developed +	Mature

Table 4. Concise specifications of different major storage technologies [55].

	Energy density	Power density	Storage duration	Self-discharge per day	Capital cost	Charge-discharge cycle efficiency	Lifetime	Technological maturity
Pumped-hydro	Very weak	-	Very long	Very weak	High	Medium	Very high	Mature
CAES	Medium	-	Very long	Weak	Medium	Medium	High	Developed +
Battery (lead-acid)	Medium	High	Long	Weak	Weak	Medium	Medium	Mature
Battery (NaS)	High	High	Short	High	High	Medium	Medium	Developed +
Battery (Li-ion)	High	High	Long	Weak	High	High	Medium	Developed +
Hydrogen	Very high	Very high	Very long	Very weak	High	Weak	Medium	Developing +
SMES	Very weak	Very high	Medium	High	Weak	High	High	Developed -
Flywheel	Weak	Very high	Very short	Very high	Weak	High	Medium	Developed +
Ultracapacitor	Very weak	Very high	Short	Very high	Weak	Medium	Very high	Developed +

Table 5. Different applied energy storage systems in sample insular areas.

Location	Type	Rating	Reference
Bella Coola, Canada	Hydrogen	100 kW	[88]
	Flow battery	125 kW	
Bonaire, Venezuela	Nickel-based battery	3 MW	[88]
King Island, Tasmania, Australia	Vanadium redox battery	400 kW	[88,97]
Metlakatla, Alaska	Lead-acid battery	1 MW	[88]
Ramea Island, Canada	Hydrogen	250 kW	[88]
El Hierro, Canary Islands	Pumped-hydro	Hydro 11 MW, Pumping 6 MW	[98]
Gran Canaria, Canary Islands	Li-ion battery	1 MW/3 MWh	[98]
La Gomera, Canary Islands	Flywheel	0.5 MW	[98]
Ventotene	Li-ion battery	300 kW/600 kWh	[98]