



## Transition towards decarbonisation for islands: Development of an integrated energy planning platform and application

Andrew Barney<sup>a,\*</sup>, Heracles Polatidis<sup>a</sup>, Marko Jelić<sup>b,c</sup>, Nikola Tomasević<sup>b</sup>, Gobind Pillai<sup>d</sup>, Dias Haralambopoulos<sup>e</sup>

<sup>a</sup> Uppsala University, Dept. of Earth Sciences, Cramérgatan 3, 621 57 Visby, Sweden

<sup>b</sup> School of Electrical Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11120 Belgrade, Serbia

<sup>c</sup> Institute Mihajlo Pupin, University of Belgrade, Volgina 15, 11060 Belgrade, Serbia

<sup>d</sup> School of Computing, Engineering and Digital Technologies, Teesside University, Middlesbrough, Tees Valley TS1 3BX, UK

<sup>e</sup> University of the Aegean, Dept. of Environment, University Hill, 81100 Mytilene, Lesvos, Greece

### ARTICLE INFO

#### Keywords:

Decarbonisation  
Energy planning  
Islands  
Levelized cost of energy  
Renewable energy, Energy storage

### ABSTRACT

This paper presents REACT-DECARB, an energy planning decarbonisation platform employing renewable energy sources coupled with storage for islands. The paper implements the energy scenario creation and economic evaluation steps of the platform on eight geographic islands in seven countries within the EU. Twenty-one technologically feasible energy scenarios, applicable to the specific conditions of each island, are specified and their economic assessment via a levelized cost of energy (LCOE) calculation is then performed. The main aim of this application is to verify the noted steps of the platform as well as to test its flexibility across geographically, socially and dimensionally disparate islands with various scenario generation methods. The results of the economic analysis show a wide variation of LCOE depending primarily on whether full island autonomy is assumed. In some cases the islands' scenarios' costs approach current market prices but are never below them; some scenarios are, however, below the current price of the island's thermal generation. The sensitivity and uncertainty of the economic performance results' and the variables used to calculate them are evaluated and discussed for two of the islands. The overall analysis and application has shown that the REACT-DECARB platform is suitable for different islands, regardless of location and size and can be useful for island energy planners.

### Introduction

High emissions of greenhouse gases linked to imminent climate change and depletion of fossil fuels for power generation have necessitated the search for alternative solutions to energy supply. For the case of islands this situation is exaggerated due to often autonomous electricity grids and difficulty in balancing supply and demand. To tackle these issues Renewable Energy Sources (RES) coupled with battery or other storage could offer a cost-effective and sustainable energy supply for both large and small islandic energy systems.

At the same time many islands also have economies based on touristic activities that are usually seasonal in nature. This short-term influx of visitors often means that islands' energy systems must be greatly overdimensioned from what would be needed if only considering permanent residents [1]. This is coupled with the other sustainability issues that

local energy planners must also take into consideration, such as the need for the decarbonisation of energy systems, the impacts on local communities and groups of these new systems as well as the economic feasibility of the emerging energy projects [2].

Put succinctly, energy planning for the decarbonisation of islands necessitates the following:

- RES coupled with energy storage (supply side)
- Modern smart grids (energy transport infrastructure)
- Optimized energy scenarios (energy planning)
- Demand side management strategies (user perspective, individual and collective behaviour).

To this end, an innovatory energy planning decarbonisation platform, REACT-DECARB, for islands is developed within the context of the

\* Corresponding author.

E-mail address: [andrew.barney@geo.uu.se](mailto:andrew.barney@geo.uu.se) (A. Barney).

REACT<sup>1</sup> Horizon 2020 EU project and is applied on a number of case studies.

The REACT-DECARB platform fills the research gap that exists between selecting and placing energy production technologies on islands, generating techno-economically optimized energy scenarios, assisting users via demand response measures and evaluating social perceptions on potential energy futures. It enables energy planners to develop scenarios that include economic, technical, social and environmental criteria while also assessing risk and allowing them to maintain flexibility in selecting the specific tools that best fit their island's unique circumstances for real world projects. The structure and flow of analysis of the REACT-DECARB platform and the results of a levelized cost of energy (LCOE) assessment for a number of islands in the EU are presented in this paper.

The remainder of this article is structured as follows: Chapter 2 presents a literature review on island energy planning and increased RES penetration research. Chapter 3 presents the steps of the REACT-DECARB platform applied, including data gathering and energy scenario generation with some of them assuming full island autonomy, as well as economic and sensitivity and risk analyses. Subsequently, Chapter 4 introduces the islands studied and the specific energy scenarios developed for them along with the economic results for all and sensitivity and risk analyses for two of the island scenarios. Chapter 5 is composed of a discussion of the results. Chapter 6 provides the conclusions on the paper's findings.

## Literature review

The unique and varying set of problems on geographic islands has led to a range of different approaches, scopes and goals having been used in literature to account for the special circumstances in island energy planning. Many researchers have employed methods focused on techno-economic optimization to develop and plan energy systems for islands. The cost optimal sizing of solar PV and battery systems on an isolated island in India is studied in [3] to determine if such systems could potentially serve as economical and technically reliable alternatives to fossil fuel-based power generation. An optimal energy mix is determined using techno-economic analysis on the Italian island of Lampedusa in [4] and finds that when 40% of the island's current demand is replaced with renewable production the costs for electricity production could be reduced. The potential for economic savings from a hybrid solar-diesel power generation system in comparison to a diesel only system for an isolated island in the Philippines is studied in [5]. In [6], the potential for developing a reliable and least-cost RES-based electrification systems is assessed for a number of un-electrified islands in the Philippines.

The techno-economic feasibility of integrating differing amounts of renewables into Russia's Popova Island's energy system is considered in [7] and it is found that a penetration shares above approximately 46% cause system costs to begin to increase and finds a 95% penetration to be nearly three times as costly. In [8] the techno-economic impacts of the use of electric vehicles on the Portuguese island of Porto Santo's is investigated and finds decreased periods of renewable curtailment and of thermal plant operation. Six geographically varied islands are investigated in [9] for how their cost-optimal hybrid renewable energy system configurations' change with increasing renewable energy production, to find the final optimal RES penetration ranges for each of the islands. The system's reliability and the cost savings of a number of combinations of hybrid solar PV and wind power projects coupled with battery storage on an island in China are presented in [10]. The technical, economic and environmentally optimal configurations of the Italian island of Favignana's energy system with high renewable

penetration are assessed in [11]. The benefits of sector coupling to such a system are also considered in [12] where the optimal energy scenarios on the same island, including both battery and hydrogen storage, are techno-economically determined and environmentally analysed. The seasonal variability in population, typical to many islands, is considered in [13], where a range of hybrid RES and diesel projects are evaluated with the goal of finding a cost optimized energy system configuration for a resort island in Malaysia. A methodology seeking to explore the potential of RES integration is applied on the island of Cozumel in Mexico in [14], where techno-economically optimized 50% and 100% renewable hybrid electrical systems coupled with batteries are evaluated. A techno-economic optimization is done to determine the sizing of renewable hybrid power systems both with and without storage for the Nicaraguan island of Ometepe in [15]. The economic and technical feasibility of roof mounted solar PV systems in the Maldives is analysed in [16], while the environmental benefits gained by the reduced usage of diesel generation are also assessed. A stepped decarbonisation of Jamaica using renewables and battery storage is examined using technical and cost perspectives in [17] to find if such a system could eventually phase out fossil fuels from the island's energy production in an economical manner. In [18] the amount of wind and solar PV generation that can be technically and economically integrated on the Japanese islands of Teuri and Yagishiri energy grids without the usage batteries is investigated and found to be nearly 20%. Renewable energy scenarios for the entirety of the Canary Island chain, including transport, heating, and interconnections between the islands are techno-economically analysed in [19] to determine if the islands are able to achieve 100% renewable energy production by 2050 at a lower price than the islands' current fossil fuel dependant energy system. A study of different renewable energy system scenarios on the Island of La Gomera in the Canary Islands in [20] seeks to determine if 100% sustainable energy systems on islands are technically and economically feasible by 2030. On the island of Gran Canaria a cross-sectoral method is applied in [21] and different transition strategies are used to conclude that a nearly 76% renewable energy system could be achieved.

Other authors have prioritized reliability, increased RES penetration or transition and placement optimization of different energy production projects rather than focusing foremost, or only, on the techno-economic optimization. The impact on RES penetration with the interconnecting Pico and Faial islands in the Azores is analysed in [22] and determines an increase of 50% could be achieved while [23] considers the planning paths that can be taken to achieve a 100% RES on the two islands. The potential of a pumped hydro system coupled with wind power to increase RES penetration is examined for the Greek island of Ikaria, where multiple criteria are taken into account in the planning exercise [24]. Increased renewable energy penetration in the context of distributed generation is also considered for the isolated electricity system of the Greek island of Lesbos in [25], whereas the technical and economic feasibility of a hybrid wind and pumped hydro system again for Lesbos is assessed in [26], though with greater emphasis placed on the project economics. Further studies on the Greek islands include an analysis of different planning alternatives for the island of Crete that include environmental and social assessments in addition to techno-economic [27], as well as an analysis of the possibility of increasing the share of renewable energy in the island's energy mix [28]. A methodology for the optimal siting of solar installations is also applied on Crete in [29], where social and environmental criteria are employed along with techno-economic. A spatial planning methodology for offshore wind farm placement is used together with a techno-economic assessment in [30] to evaluate the potential for offshore wind development around the Canary Islands. In [31] a simulation approach using technical, economic and environmental analysis and optimization is applied on the Island of El Hierro in Spain and finds that up to 85% of electricity demands and 79% of thermal demands could be met with through increased RES penetration. A cost, technical and environmentally optimized integration of island energy and water systems is considered in [32] and finds

<sup>1</sup> Renewable Energy For Self-Sustainable Island Communities (REACT), <https://react2020.eu/>

that this method, on the Spanish island of Lanzarote, can result in an increase in renewable contributions by nearly 20%. Social impacts of different sustainable energy system scenarios on the Åland Islands between Sweden and Finland are studied together with scenarios' cost data in [33] to determine if a 100% domestic RES production is possible on the islands by 2030. Different scenarios for renewable energy production are considered for the French island of Ushant using techno-economic, social and environmental indicators in [34], three of those renewable scenarios were found to cover the island's energy demand and those three also outperformed the business as usual case for most considered indicators.

It can be shown from the literature that many researchers of island energy planning have placed a significant emphasis on techno-economic evaluations and/or focus on a single island, or a small chain of nearby islands. This has sometimes left social and, to a lesser extent, environmental questions relatively unanswered and only provided island planners parts of the picture they need when making their decisions. In that way, planners could be unsure of whether or not the developed solutions are applicable to their island's geographic, social, technical and economic circumstances. The development of an integrated energy planning decarbonisation platform and the results from its application to a number of diverse islands could assist them in planning for the energy futures of their islands.

**The REACT-DECARB platform**

The overall structure and basic flow of analysis of the REACT-DECARB energy planning decarbonisation platform for islands is shown in Fig. 1.

The first step of the REACT-DECARB platform is concerned with the gathering of the data that is then used in the creation of energy scenarios. This process requires a significant amount of information on both the location where potential energy projects are to be deployed and about the projects themselves. That is specifically important for geographic islands given the often-high seasonality in electricity demand and the increased costs of transporting technological components and personnel to them [35]. At the same time, a number of other parameters must be evaluated. These are both technical in nature (is there existing infrastructure), as well as legal or social (is the area protected in some way). Once energy potential and limitations have been assessed the technologies feasible for deployment can be determined. In this paper the original data used was obtained from [36].

The next step entails the creation of technologically feasible

scenarios for the island being reviewed. To be most effective, this step requires a technical configuration of systems which are optimized to the specifics of the island and its energy needs. There are a number of modelling and planning tools that can be used to assist in determining energy project techno-economic feasibility and there is no perfect model for all cases. These tools have differing purposes, approaches, methodologies, scales and time steps that provide different functionalities suited for differing applications [37]. For additional information on some available energy modelling and planning tools and methods along with their uses, readers are directed to reviews done by [35,38,39], among others. The different methods used to create the scenarios in this paper are described further in Section 4.2.

Subsequently, the REACT-DECARB platform comprises an analysis part that includes an economic, sensitivity and risk analysis as well as an environmental and social dimension analysis. In this paper, the LCOE is used for the economic analyses. The LCOE tool is commonly used for economic analysis to compare electricity generation technologies and systems. The calculation of LCOE for a project is based on the energy produced by it over its operational lifetime and the life-cycle costs. LCOE determines the minimum a project must receive for a unit of electricity produced to cover its generation lifetime costs [40]. A project's investment cost is the total cost of the construction of its components while the total annual cost can include items such as fuel and operations & maintenance costs. The total annual costs and annual electricity generation, generally including degradation of production [41], are discounted each year to the present value as to make them comparable. There are many different methods for calculating LCOE [42] and two of the most common are critically assessed in [43].

Finally, this paper uses Monte Carlo analysis (MCA) to consider the uncertainties involved when calculating an economic indicator, such as LCOE. MCA uses random sampling from a set of inputs to perform repeated iterations of a process or calculation to provide a distribution of the potential results and the likelihood a range of results will occur. By providing a distribution rather than a single value, the user is better able to assess the uncertainties around indicators. These indicators can be costs, electricity prices, energy production and weather variations [44]. MCA has been used in techno-economic analyses for many years to fill this role [45–47].

Subsequent environmental and social analysis together with a concluding multi-criteria decision analysis (MCDA) are to be presented in a forthcoming paper.

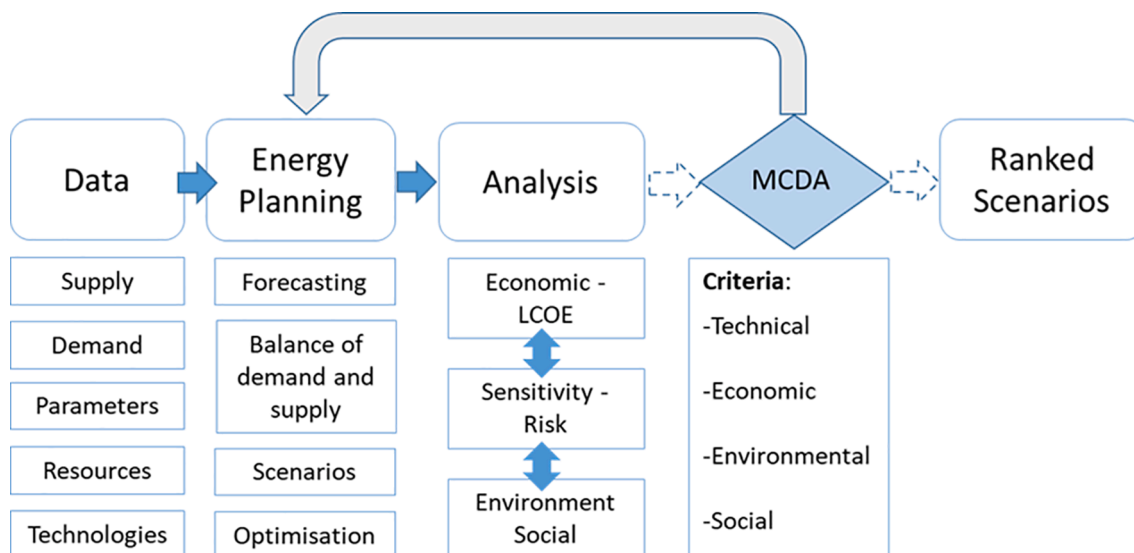


Fig. 1. The REACT-DECARB platform for islands: structure and flow of analysis.

## Results - Case-studies: REACT-DECARB platform application on EU islands

### Island descriptions

The eight EU islands included in the Horizon 2020 REACT project are of differing sizes and have varying local climates. All were evaluated for their tangible renewable energy potentials based on their specific environmental and regulatory conditions [36]. This data was used to create energy system scenarios which were evaluated using different technical key performance indicators to develop combinations of renewable energy projects on the islands. The islands in the REACT project are La Graciosa in Spain, San Pietro in Italy, the Aran Islands in Ireland, Gotland in Sweden, the Isle of Wight in England, Lesvos in Greece, Majorca in Spain and La Réunion in France. The cases of islands of La Graciosa and Lesvos are described in more detail in this paper. For more information on the analysis done for the other islands the reader is directed to [36,48]. The islands' locations are noted in Fig. 2 below.

Table 1 shows the key characteristics of each island. The two islands for which more detailed analysis is given in Section 4.4 are further described below.

The Spanish island of La Graciosa is located in the Atlantic Ocean off the west coast of Africa in the Canary Island chain. The island has a permanent population of about 800 individuals and is separated from the larger island of Lanzarote by only, at its closest point, one kilometre. The island is connected to Lanzarote with a 1 MW underwater cable which provides most of the island's electricity. The island's economy is based primarily on fishing and tourism. La Graciosa has favourable conditions for both wind and solar power [51] but the expansion of both is limited by most of the island's designation as a UNESCO protected site. Some solar PV technology is in place on the island but these installations are limited to rooftops [52].

The island of Lesvos is located in the northeast Aegean Sea and is the third largest of the Greek islands. The island has a permanent population of 110,000 inhabitants and its economy is based on agriculture, farming, handcraft and tourism. The island has no connection to a larger grid and this lack of access requires the island to produce its own electricity using a 75 MW oil-fired thermal facility. Lesvos has favourable conditions for solar, wind, geothermal and some hydro power and has nearly 9 MW of solar PV capacity installed, 14 MW of wind power installed and some geothermal usage which provides limited heating to greenhouses [53,54]. The island currently has a cap on new renewable generation due to grid stability issues.

### Development of energy scenarios

In total twenty-one (21) energy scenarios were developed for the REACT islands that had differing objectives; some scenarios sought complete electricity independence, while others pursued modest increases in the share of renewables in the island's energy mix. From a wide range of possible scenarios with RES and storage configurations, a shortlist was established based on a combination of heuristic and optimization methodologies.

For three islands (La Graciosa, Lesvos, La Réunion) a grid search employing mixed-integer linear programming was used to optimise RES and battery storage capacities [48,55]. The main objective of each optimization was to minimize the operational costs from the standpoint of the island using limited load flexibility and the flexibility given by the energy storage. Different scenarios based on the specific circumstances of these islands were selected from these optimisations for the present analysis to show the impact of diverse battery and production combinations.

The scenarios evaluated for two islands, (San Pietro and Majorca), were generated considering the RES sizing parameters as the variables of the model. The optimisation criteria for these cases are somewhat more diverse and include a depiction of the interaction with the wider grid by

considering:

- Minimizing maximum export and maximum import values,
- Maximizing both daily and yearly correlation values between supply and demand,
- Minimizing both net metering (export) mean value and its standard deviation.

For the remaining three islands (Aran Islands, Gotland and the Isle of Wight) the main criterion for selecting a scenario was to achieve full energy autonomy by 2030. Complementary, non-autonomous scenarios were also included for Gotland and the Isle of Wight.

More details regarding all the considered configurations of the systems and their respective performance parameters used for the short-listing process for economic analysis can be found in [48]. It should also be noted that the used methodologies have a few limitations that should be kept in mind for further studies of a similar type. The selected criteria that were applied largely focus on monetary indicators such as operating costs, however more specific grid interaction indicators of each of the systems could also be analysed. A comprehensive overview of some these grid interaction indicators is given in [56].

The scenarios chosen for evaluation are shown below in Table 2. The technologies deployed include solar photovoltaics, wind power, heat pumps and both thermal and electrical storage. The RETScreen software was used to assist the analysis of the scenarios' economic performances [16,35,57–59].

The environmental and energy profile of the islands differ significantly; three islands (La Graciosa, Aran Islands, San Pietro) are small with significantly lower populations than the rest. This, together with the existence or the absence of mainland grid connection, make direct comparison among the islands difficult and inconclusive.

In Section 4.3 we present a full summary of scenarios' LCOEs for all islands. In Section 4.4 sensitivity and risk analysis of one scenario for the island of La Graciosa (small, interconnected), and one for Lesvos (large, autonomous) are presented.

### Results of the economic analysis

For the economic analysis three methods of LCOE were applied: one on an annuity basis<sup>2</sup>, one on a non-annuity basis<sup>3</sup>, and one based on equity cost with fixed un-degraded annual production<sup>4</sup>.

Table 3 summarizes the basic economic assumptions used in all scenarios.

These calculated LCOEs for the 21 scenarios on the eight islands of the REACT project are presented in Fig. 3.

There exists a wide variation for the calculated LCOE depending mainly on whether an autonomous electricity grid is sought, and in those cases, the calculated LCOE is significantly higher. It can be seen that generation costs for the 100% renewable electrical autonomy scenarios which relied on significant battery capacity, Gotland Scenario II and Isle of Wight Scenario I, range from 0.45 to 0.58 euros/kWh whereas the remaining islands range from 0.09 to 0.31 euros/kWh.

### Results of the sensitivity and risk analyses for La Graciosa and Lesvos

A sensitivity analysis is conducted to evaluate the impact that the changes in estimated energy production and initial investment cost have on the scenarios' LCOE. Additionally, a risk analysis is used to determine the distribution of LCOE at a given risk level. The main inputs needed to

<sup>2</sup> As used by U.S. National Renewable Energy Laboratory (NREL); <https://www.nrel.gov/>

<sup>3</sup> As used by International Renewable Energy Agency (IRENA); <https://www.irena.org/>

<sup>4</sup> As used in RETScreen, Natural Resources Canada; [www.etscreen.net](http://www.etscreen.net)



Fig. 2. Locations of the REACT islands have been boxed in red, [49] edited. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

perform the economic evaluation of these scenarios include the procurement cost, the cost of installation of energy generation and storage systems, the operations and maintenance costs, replacement costs and decommissioning costs [60].

The results, for La Graciosa Scenario I and Lesvos Scenario II are presented below in Table 4. The LCOE varies slightly between the three different calculation methods for the same input data but are within a range of  $\pm 10\%$  of each other.

For La Graciosa Scenario I the sensitivity of the LCOE to changes in the initial cost of the new system as well as the amount of electricity produced was tested and the results are presented in Table 5 below.

Combinations of changes in initial cost and production for which the project is economically viable are shown in white, while the orange areas indicate LCOE where the given combination of initial cost and production amounts are not viable at the given price of electricity. At the initial cost and income assumptions, La Graciosa Scenario I's LCOE is greater than the current local price of electricity of 150€/MWh. A decrease in the initial costs of the system by 25% results in the system approaching a breakeven point in economic viability, while a 30% decrease results in project viability. At initial cost estimates, the system requires a 30% increase in production to become viable.

The sensitivity analysis above is complemented by a Monte Carlo risk

**Table 1**  
REACT islands summary information.

	La Graciosa	San Pietro	Aran Islands	Gotland	Lesvos	Isle of Wight	Majorca	La Réunion
Island population (approx.)	800	6200	1300	60,000	110,000	140,000	880,000	860,000
Interconnected	Yes	Yes	Yes	Yes	No	Yes	Yes	No
Existing grid stability issues	No	No	No	Yes	Yes	Yes	Yes	No
Köppen-Geiger climate classification [50]	Sub-tropical desert	Hot summer Med.	Temp. oceanic	Warm summer continental	Hot summer Med.	Temp. oceanic	Hot summer Med.	Tropical monsoon
Favourable RES technologies	Wind, Solar	Wind, Solar, Geothermal	Wind	Wind, Solar	Wind, Solar, Geothermal	Wind, Solar	Wind, Solar	Wind, Solar, Geothermal
Area (km <sup>2</sup> )	29	51	46	3183	1633	380	3640	2511
Scenario targeted 100% RES electricity autonomy	No	No	Yes	Yes	No	Yes	No	No

**Table 2**  
Selected technical energy scenarios for the REACT islands.

			La Graciosa	San Pietro	Aran Islands	Gotland	Lesvos	Isle of Wight	Majorca	La Réunion
I	Photovoltaics	MW <sub>p</sub>	0.5	0.4	0.12	–	30	663	221	800
	Wind power	MW	–	2.3	2.22	310	–	–	289	–
	Battery – electric	MWh	0.4	–	0.3	–	80	1 731	–	600
	Battery – thermal	MWh	–	–	0.09	–	–	–	–	–
	Heat pump	MW	–	–	1.77	–	–	–	–	–
II	Photovoltaics	MW <sub>p</sub>	0.5	4.3	–	96	30	30	405	400
	Wind power	MW	–	–	–	200	30	20	187	–
	Battery electric	MWh	–	–	–	2 100	80	–	–	400
III	Photovoltaics	MW <sub>p</sub>	0.3	–	–	96	40	–	–	100
	Wind power	MW	0.2	6	–	200	–	–	–	–
	Battery – electric	MWh	0.4	–	–	–	80	–	–	50
IV	Photovoltaics	MW <sub>p</sub>	–	13	–	–	–	–	–	–
	Wind power	MW	–	–	–	–	–	–	–	–
	Battery –electric	MWh	–	–	–	–	–	–	–	–

**Table 3**  
Key assumptions used for the economic analysis of all scenarios.

Assumption type	Amount	Unit
Inflation rate	2	%
Nominal discount rate	10.7	%
Project lifetime	20	Yrs
Solar PV system lifetime	20	Yrs
Solar PV module production degradation	0.5	%/yr
Wind turbine lifetime	20	Yrs
Wind turbine production degradation	1.5	%/yr
Battery system lifetime	15	Yrs
Electricity price increase	2	%/yr
Equity share	30	%

analysis for Scenario I with a 10% level of risk and 5000 possible variations of the given inputs used in calculating LCOE within a range of  $\pm 25\%$  to provide a frequency distribution. The distribution is shown in Fig. 4 where the height of each column indicates the frequency which the LCOE values occur within a given range around the shown value on the x-axis. The distribution shows that LCOE values are relatively near, but still above, an electricity price of 150 €/MWh in only about 2% of the 5000 different input combinations for the scenario.

The sensitivity of Lesvos Scenario II's LCOE to changes in the initial cost of the installed system as well as the amount of electricity produced was also tested. Table 6 below shows that, at the initial cost and production assumptions, Lesvos Scenario II's LCOE is unattractive at the given local electricity price of 100 €/MWh. The sensitivity analysis shows that, unlike the La Graciosa scenario above, no combination of adjustments to these key inputs within a range of  $\pm 30\%$  results in a viable LCOE. The price of the initial investment would need to be reduced by more than half or the production increased by more than 90% before the scenario's LCOE nears the estimated electricity prices on the island.

The sensitivity analysis above is complemented by an LCOE distribution for Lesvos Scenario II with the same level of risk and number of variations and uncertainty range for the variables as described for the La Graciosa case. The distribution is shown in Fig. 5 and finds that none of the LCOE values in any of the 5000 different input combinations for the scenario approach the local electricity price of 100 €/MWh.

## Discussion of results

The energy situation on islands presents several particularities to the energy planner, especially in the process of decarbonisation. Islands vary in area, population, climate, economic structure, available energy resources, grid capacity and connection or lack of it to mainland grid, energy demand patterns, electricity pricing schemes, regulations regarding environmental and aesthetics along with other specific restrictions. The scenarios developed in this study encompass the majority of the aforementioned particularities and show a number of interesting points for the energy planning exercise.

Three LCOE methods were employed on the same scenario data, i.e., non-annuity LCOE, annuity LCOE and equity based LCOE. The non-annuity LCOE provided the highest value in all scenarios. The annuity LCOE normally provided the lowest value. The equity based LCOE was somewhere in between. The small differences shown, indicate that, according to the particular scheme of discounting and funding basis, the energy planner should adopt the most appropriate method. The scenarios' LCOE are higher than the average LCOE for either wind or solar PV given by the International Renewable Energy Agency (IRENA) at 0.051 €/kWh and 0.078 €/kWh, respectively [61], but are in line with those found for systems containing renewables and, often times, storage in other island energy planning research [7,9,10,13–15].

One complete electricity autonomous scenario for the Isle of Wight (Scenario I) and one for Gotland (Scenario II) were included. These two scenarios required significant battery capacity to be able to rely solely on

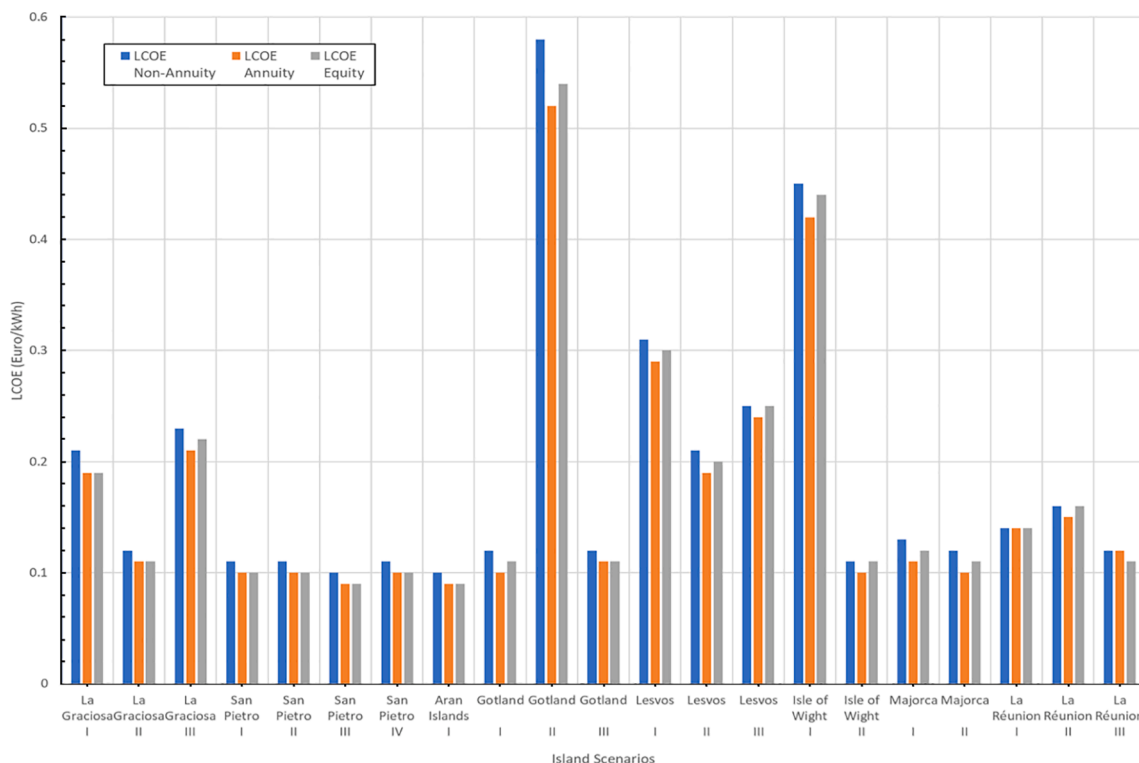


Fig. 3. Variation of LCOE for the twenty one scenarios on the eight islands of the REACT Horizon 2020 EU project.

Table 4  
LCOE values for two islands.

	LCOE (€/kWh)		
	Non-Annuity	Annuity	Equity
La Graciosa Scenario I	0.21	0.19	0.19
Lesvos Scenario II	0.21	0.19	0.20

variable renewable energy production sources. The costs of these independent, entirely renewable electricity systems were prohibitive and are the worst performing of all scenarios. That noted, less aggressive scenarios for the two islands, where complete electricity independence wasn't achieved, performed much better. This finding is in line with other research where increasing autonomy levels and usage of renewables together with storage can result in higher and costs [7,9,10,15].

For Lesvos and La Réunion, the two islands without a connection to a mainland grid and the former with existing stability issues, the stochastic nature of RES means that production increases must be followed by an increase in storage capacity to ensure stability. Beyond a certain point, however, the cost of batteries results in excessive system costs.

Table 5  
La Graciosa Scenario I LCOE (€/MWh) sensitivity analysis.

- Remove analysis		Initial costs					€
Electricity exported to grid		849 142	1 031 101	1 213 060	1 395 019	1 576 978	
MWh		-30,0%	-15,0%	0,0%	15,0%	30,0%	
615,89	-30,0%	209,93	241,28	272,63	303,99	335,34	
703,87	-20,0%	183,69	211,12	238,55	265,99	293,42	
791,86	-10,0%	163,28	187,66	212,05	236,43	260,82	
879,84	0,0%	146,95	168,90	<b>190,84</b>	212,79	234,74	
967,83	10,0%	133,59	153,54	173,49	193,45	213,40	
1 055,81	20,0%	122,46	140,75	159,04	177,33	195,61	
1 143,79	30,0%	113,04	129,92	146,80	163,68	180,57	

Decreasing the amount of storage while keeping increased production from variable sources may increase the likelihood that stability issues will persist, or possibly worsen, but employed effectively may also prove sufficient to address these issues at a competitive cost.

In many cases islands benefit from unsustainable subsidised electricity prices. Had higher electricity prices been assumed, several scenarios would have been much nearer breakeven amounts. A number of the islands' scenarios, particularly those without or with only moderate amounts of storage in the system mix, are potentially competitive when compared to the high cost of thermal power generation on the islands. This is the case, for example, on the islands of Majorca and Lesvos where the historical costs of producing electricity from thermal sources has been more than twice the market price [62–64].

On a higher level, the review of the eight islands showed a number of patterns. No matter the size of the island, its climate or renewable resources, there were always some areas prohibited for development of some or all types of renewable generation. The reasons for the areas being off-limits varied, ranging from environmental and preservation of landscape concerns to military and touristic ones. The size of the area being excluded was generally quite high. In the cases of La Graciosa, the Aran Islands and San Pietro, nearly all the islands' lands were closed to

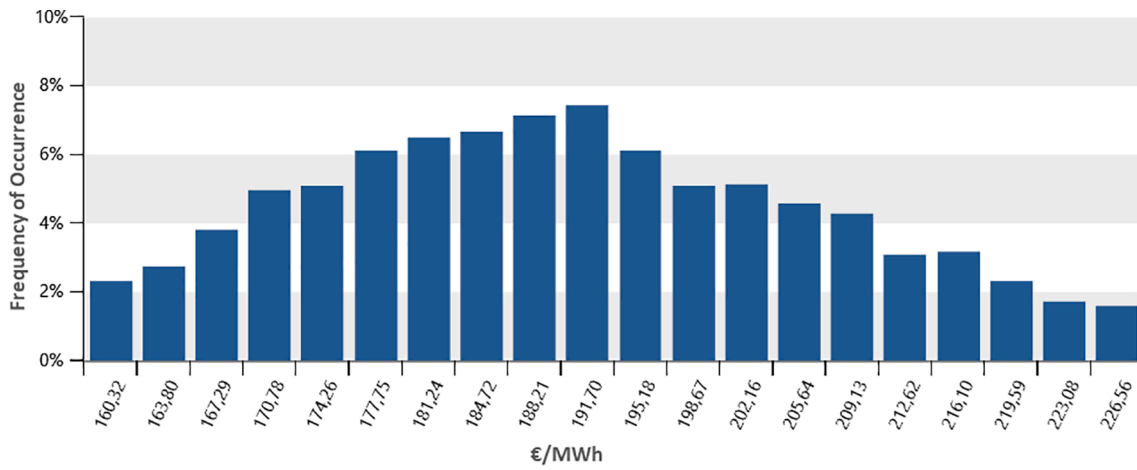


Fig. 4. La Graciosa Scenario I LCOE (€/MWh) energy production cost distribution.

Table 6  
Lesvos Scenario II LCOE (€/MWh) sensitivity analysis.

- Remove analysis		Initial costs					€	-	+
Electricity exported to grid		123 594 713	150 079 295	176 563 876	203 048 458	229 533 039			
MWh		-30,0%	-15,0%	0,0%	15,0%	30,0%			
87 690,31	-30,0%	219,96	252,01	284,06	316,11	348,16			
100 217,50	-20,0%	192,46	220,51	248,55	276,60	304,64			
112 744,69	-10,0%	171,08	196,01	220,94	245,86	270,79			
125 271,87	0,0%	153,97	176,41	<b>198,84</b>	221,28	243,71			
137 799,06	10,0%	139,97	160,37	180,77	201,16	221,56			
150 326,25	20,0%	128,31	147,00	165,70	184,40	203,09			
162 853,44	30,0%	118,44	135,70	152,96	170,21	187,47			

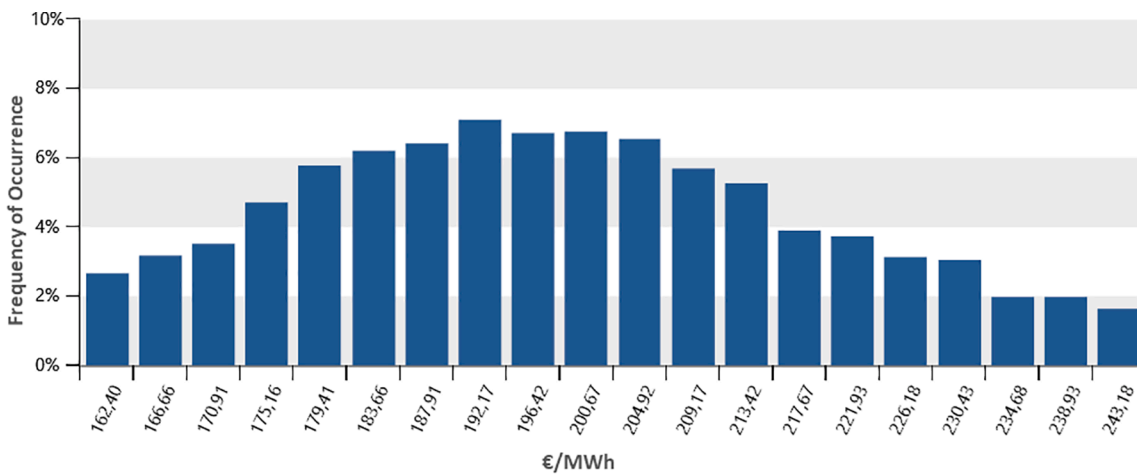


Fig. 5. Lesvos Scenario II LCOE (€/MWh) energy production cost distribution.

development and large swathes of the other REACT islands were also closed. Furthermore, the impact tourists had on an island’s demand was island specific, even within the same climate zones [36].

Unsurprisingly, local climate had a leading role in determining which renewable sources were appropriate for potential development but the specifics of the islands, including topography, population and legal requirements were also strong determinants. These findings point to the implication that any methodology developed for the specifics of a single island is likely to need revision before it can be applied to another. The REACT-DECARB platform was developed with this need for

flexibility in mind and can provide guidance to planners on any island as they fit the framework’s steps to their needs and abilities. Application of the REACT-DECARB platform for energy planning on islands outside the Horizon 2020 REACT project may be warranted to further assess the platform’s general applicability and value.

No concessions were granted in this analysis for any decreases in technology costs when replacements were expected. The impact of this was not evaluated in depth but, at currently predicted price decreases for the relevant technologies, the effects on project economic viability are expected to be minor when compared to initial investment costs and



energy production amounts. Furthermore, the study does not attempt to estimate the value of any external benefits provided by the scenarios, such as reductions in air pollution and greenhouses gas emissions.

## Conclusions

This paper has introduced and described the structure and flow of analysis of an innovatory energy transition platform, REACT-DECARB, for the decarbonisation of islands. The techno-economic analysis, i.e. development of energy scenarios and economic assessment, have been applied to renewable energy production and storage scenarios on eight geographic islands within the EU's Horizon 2020 REACT project and were presented in this paper. The flexibility of the REACT-DECARB platform has been assessed by using a diverse set of methods for scenario generation, economic assessment and risk analysis. Scenarios seeking complete energy autonomy on islands based on RES and storage, e.g. the case of Gotland Scenario II and Isle of Wight Scenario I, are far from economic feasibility. Less aggressive transition scenarios on these islands, on the other hand, are within the realms of both technical and near economic feasibility and indicate that investments into such systems could provide positive returns in certain conditions. At the same time, it was determined that the economic performance shown by LCOE depends strongly on the ratio between the stochastic RES production and the need for sufficient battery storage. Overall, conclusions and insights for the energy planning of eight differing EU islands are drawn through usage of the REACT-DECARB platform which can assist planners with the task of decarbonising their islands.

## CRedit authorship contribution statement

**Andrew Barney:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Heracles Polatidis:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Project administration. **Marko Jelić:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Nikola Tomasević:** Methodology, Investigation, Writing - review & editing. **Gobind Pillai:** Validation, Writing - original draft, Writing - review & editing. **Dias Haralambopoulos:** Conceptualization, Methodology, Formal analysis, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgment

The authors would like to thank four anonymous reviewers for providing constructive comments on a previous version of the paper.

The authors would like to express their thanks to the REACT project partners.

## Funding

The research presented in this paper is partly financed by the European Union (Horizon 2020 REACT project, Grant Agreement No.: 824395).

## References

- [1] Blechinger P, Cader C, Bertheau P, Huyskens H, Seguin R, Breyer C. Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands. *Energy Policy* 2016;98:674–87.
- [2] Cardinaletti M, Di Perna C. Tools and concepts for the local energy planning. *Intelligent Energy Europe* 2009.
- [3] Bhakta S, Mukherjee V. Performance indices evaluation and techno economic analysis of photovoltaic power plant for the application of isolated India's island. *Sustainable Energy Technol Assess* 2017;20:9–24.
- [4] Curto D, Favuzza S, Franzitta V, Musca R, Navarro Navia MA, Zizzo G. Evaluation of the optimal renewable electricity mix for Lampedusa island: The adoption of a technical and economical methodology. *J Cleaner Prod* 2020;263:121404.
- [5] Lozano L, Querikol EM, Abundo MLS, Bellotindos LM. Techno-economic analysis of a cost-effective power generation system for off-grid island communities: A case study of Gilutongan Island, Cordova, Cebu, Philippines. *Renewable Energy* 2019;140:905–11.
- [6] Bertheau P. Supplying not electrified islands with 100% renewable energy based micro grids: A geospatial and techno-economic analysis for the Philippines. *Energy* 2020;202:117670.
- [7] Uwineza L, Kim HG, Kim CK. Feasibility study of integrating the renewable energy system in Popova Island using the Monte Carlo model and HOMER. *Energy Strategy Rev* 2021;33:100607.
- [8] Torabi R, Gomes L, Morgado-Dias F. Energy transition on islands with the presence of electric vehicles: a case study for Porto Santo. *Energies* 2021;14(12):3439.
- [9] Gioutsos DM, Blok K, van Velzen L, Moorman S. Cost-optimal electricity systems with increasing renewable energy penetration for islands across the globe. *Appl Energy* 2018;226:437–49.
- [10] Javed MS, Song A, Ma T. Techno-economic assessment of a stand-alone hybrid solar-wind-battery system for a remote island using genetic algorithm. *Energy* 2019;176:704–17.
- [11] Groppi D, Nastasi B, Prina MG, Astiaso Garcia D. The EPLANopt model for Favignana island's energy transition. *Energy Convers Manage* 2021;241:114295.
- [12] Groppi D, Astiaso Garcia D, Lo Basso G, Cumo F, De Santoli L. Analysing economic and environmental sustainability related to the use of battery and hydrogen energy storages for increasing the energy independence of small islands. *Energy Convers Manage* 2018;177:64–76.
- [13] Basir Khan MR, Jidin R, Pasupuleti J, Shaaya SA. Optimal combination of solar, wind, micro-hydro and diesel systems based on actual seasonal load profiles for a resort island in the South China Sea. *Energy* 2015;82:80–97.
- [14] Mendoza-Vizcaino J, Raza M, Sumper A, Díaz-González F, Galceran-Arellano S. Integral approach to energy planning and electric grid assessment in a renewable energy technology integration for a 50/50 target applied to a small island. *Appl Energy* 2019;233-234:524–43.
- [15] Canales FA, Jurasz JK, Guezgouz M, Beluco A. Cost-reliability analysis of hybrid pumped-battery storage for solar and wind energy integration in an island community. *Sustainable Energy Technol Assess* 2021;44:101062.
- [16] Ali I, Shafiullah GM, Urmee T. A preliminary feasibility of roof-mounted solar PV systems in the Maldives. *Renew Sustain Energy Rev* 2018;83:18–32.
- [17] Chen A, Stephens A, Koon Koon R, Ashitine M, Mohammed-Koon Koon K. Pathways to climate change mitigation and stable energy by 100% renewable for a small island: Jamaica as an example. *Renew Sustain Energy Rev* 2020;121:109671.
- [18] Obara S, Fujimoto S, Sato K, Utsugi Y. Planning renewable energy introduction for a microgrid without battery storage. *Energy* 2021;215:119176.
- [19] Gils HC, Simon S. Carbon neutral archipelago – 100% renewable energy supply for the Canary Islands. *Appl Energy* 2017;188:342–55.
- [20] Meschede H, Child M, Breyer C. Assessment of sustainable energy system configuration for a small Canary island in 2030. *Energy Convers Manage* 2018;165:363–72.
- [21] Cabrera P, Lund H, Carta JA. Smart renewable energy penetration strategies on islands: The case of Gran Canaria. *Energy* 2018;162:421–43.
- [22] Alves M, Segurado R, Costa M. Increasing the penetration of renewable energy sources in isolated islands through the interconnection of their power systems. The case of Pico and Faial islands, Azores. *Energy* 2019;182:502–10.
- [23] Alves M, Segurado R, Costa M. On the road to 100% renewable energy systems in isolated islands. *Energy* 2020;198:117321.
- [24] Polatidis H, Haralambopoulos DA, Bruinsma F, Vreeker R, Munda G. Decision aid with the MCDA-RES software: a wind-hydro energy application for an island of the Aegean, Greece. *Energy Sources Part B* 2009;4(4):407–19.
- [25] Tegou L-I, Polatidis H, Haralambopoulos DA. A multi-criteria framework for an isolated electricity system design with renewable energy sources in the context of distributed generation: the case study of Lesbos Island, Greece. *Int J Green Energy* 2012;9(3):256–79.
- [26] Kapsali M, Anagnostopoulos JS, Kaldellis JK. Wind powered pumped-hydro storage systems for remote islands: A complete sensitivity analysis based on economic perspectives. *Appl Energy* 2012;99:430–44.
- [27] Tsoutsos T, Drandaki M, Frantzeskaki N, Iosifidis E, Kiossos I. Sustainable energy planning by using multi-criteria analysis application in the island of Crete. *Energy Policy* 2009;37(5):1587–600.
- [28] Giatrakos GP, Tsoutsos TD, Zografakis N. Sustainable power planning for the island of Crete. *Energy Policy* 2009;37(4):1222–38.
- [29] Giamalaki M, Tsoutsos T. Sustainable siting of solar power installations in Mediterranean using a GIS/AHP approach. *Renewable Energy* 2019;141:64–75.
- [30] Schallenberg-Rodríguez J, García Montesdeoca N. Spatial planning to estimate the offshore wind energy potential in coastal regions and islands. Practical case: The Canary Islands. *Energy* 2018;143:91–103.
- [31] Barone G, Buonomano A, Forzano C, Giuzio GF, Palombo A. Increasing renewable energy penetration and energy independence of island communities: A novel dynamic simulation approach for energy, economic, and environmental analysis, and optimization. *J Cleaner Prod* 2021;311:127558.

- [32] Cabrera P, Carta JA, Lund H, Thellufsen JZ. Large-scale optimal integration of wind and solar photovoltaic power in water-energy systems on islands. *Energy Convers Manage* 2021;235:113982.
- [33] Child M, Nordling A, Breyer C. Scenarios for a sustainable energy system in the Åland Islands in 2030. *Energy Convers Manage* 2017;137:49–60.
- [34] Kouloumpis V, Yan X. Sustainable energy planning for remote islands and the waste legacy from renewable energy infrastructure deployment. *J Cleaner Prod* 2021;307:127198.
- [35] Ma W, Xue X, Liu G. Techno-economic evaluation for hybrid renewable energy system: Application and merits. *Energy* 2018;159:385–409.
- [36] European Commission, WP2 - Pilot infrastructure planning Deliverable 2.1: Assessment of RES potential at pilot sites, 2019a. [Online]. Available: <https://react2020.eu/publication-results/project-deliverables/>.
- [37] Hall LMH, Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. *Appl Energy* 2016;169:607–28.
- [38] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl Energy* 2010;87(4):1059–82.
- [39] Ringkjøb H-K, Haugan PM, Solbrenke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renew Sustain Energy Rev* 2018;96:440–59.
- [40] Kost C, Shammugam S, Julch V, Nguyen H-T, Schlegl T. Levelized cost of electricity renewable technologies. Freiburg: Fraunhofer Institute for Solar Energy Systems ISE; 2018.
- [41] Georgitsiotti T, Pearsall N, Forbes I, Pillai G. A combined model for PV system lifetime energy prediction and annual energy assessment. *Sol Energy* 2019;183:738–44.
- [42] Tran TTD, Smith AD. Incorporating performance-based global sensitivity and uncertainty analysis into LCOE calculations for emerging renewable energy technologies. *Appl Energy* 2018;216:157–71.
- [43] Aldersey-Williams J, Rubert T. Levelised cost of energy—A theoretical justification and critical assessment. *Energy Policy* 2019;124:169–79.
- [44] Pereira EJdS, Pinho JT, Galhardo MAB, Macédo WN. Methodology of risk analysis by Monte Carlo Method applied to power generation with renewable energy. *Renewable Energy* 2014;69:347–55.
- [45] Darling SB, You F, Veselka T, Velosa A. Assumptions and the levelized cost of energy for photovoltaics. *Energy Environ Sci* 2011;4(9):3133. <https://doi.org/10.1039/c0ee00698j>.
- [46] Sommerfeldt N, Madani H. Revisiting the techno-economic analysis process for building-mounted, grid-connected solar photovoltaic systems: Part two - Application. *Renew Sustain Energy Rev* 2017;74:1394–404.
- [47] Gabra S, Miles J, Scott SA. Techno-economic analysis of stand-alone wind micro-grids, compared with PV and diesel in Africa. *Renewable Energy* 2019;143:1928–38.
- [48] European Commission, WP2 - Pilot infrastructure planning Deliverable 2.2: RES/storage enable infrastructure planning, 2019b. [Online]. Available: <https://react2020.eu/publication-results/project-deliverables/>.
- [49] European Union, The European Union, European Union, 2020.
- [50] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Köppen-Geiger climate classification updated. *Meteorol Z* 2006;15(3):259–63.
- [51] Cabildo de Lanzarote, Plan de Acción Insular para la Sostenibilidad Energética, March 2013. [Online]. Available: [http://www.datosdelanzarote.com/Uploads/doc/Plan-de-Accion-Insular-para-la-Sostenibilidad-Energ%C3%A9tica-para-La-Graciosa-\(2012-20\)-20131122094841448130425\\_-Aprobado-PIAES-La-Graciosa.pdf](http://www.datosdelanzarote.com/Uploads/doc/Plan-de-Accion-Insular-para-la-Sostenibilidad-Energ%C3%A9tica-para-La-Graciosa-(2012-20)-20131122094841448130425_-Aprobado-PIAES-La-Graciosa.pdf).
- [52] endesa, “La Graciosa, la isla de energía inteligente,” 2019. [Online]. Available: <https://www.endesa.com/es/proyectos/a201701-la-graciosa-isla-energia-inteligente.html>.
- [53] Regulatory Energy Authority, 2018. [Online]. Available: <http://www.rae.gr/site/portal.csp>.
- [54] Mendrinos D, Chorapanitis I, Polyzoou O, Karytsas C. Exploring for geothermal resources in Greece. *Geothermics* 2010;39(1):124–37.
- [55] Jelić M, Batić M, Tomašević N, Barney A, Polatidis H, Crosbie T, et al. Towards self-sustainable island grids through optimal utilization of renewable energy potential and community engagement. *Energies* 2020;13(13):3386. <https://doi.org/10.3390/en13133386>.
- [56] Salom J, Marszal AJ, Widén J, Candanedo J, Byskov Lindberg K. Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data. *Appl Energy*, 2014;119:131.
- [57] Natural Resources Canada, “RETScreen,” [Online]. Available: <https://www.nrcan.gc.ca/energy/retscreen/7465>. [Accessed 21 February 2020].
- [58] Owolabi AB, Nsafon BEK, Roh JW, Suh D, Huh J-S. Validating the techno-economic and environmental sustainability of solar PV technology in Nigeria using RETScreen Experts to assess its viability. *Sustainable Energy Technol Assess* 2019;36:100542. <https://doi.org/10.1016/j.seta.2019.100542>.
- [59] Ioakeimidis C, Polatidis H, Haralambopoulos D. Use of renewable energy in aquaculture: An energy audit case-study analysis. *Global NEST* 2013;15(3):1394–404.
- [60] European Commission, WP2 - Pilot infrastructure planning Deliverable 2.3: Techno-economic impact assessment, 2020. [Online]. Available: <https://react2020.eu/publication-results/project-deliverables/>.
- [61] IRENA, Renewable Power Generation Costs in 2018, International Renewable Energy Agency, Abu Dhabi, 2019.
- [62] Govern de les Illes Balears, Energías renovables y eficiencia energética en las Islas Baleares: Estrategias y líneas de actuación, Govern de les Illes Bale, 2015.
- [63] Deligiannis C, Electroshock the cost of electricity production for islands, naftemporiki, 25 August 2017. [Online]. Available: <https://m.naftemporiki.gr/story/1269824/ilektrosok-prokalei-to-kostos-paragogis-reumatos-gia-ta-nisia>. [Accessed 12 September 2020].
- [64] Fintikakis G, On islands we pay up to 6,000 euros per household for electricity, e-mc2, 30 June 2020. [Online]. Available: <https://www.e-mc2.gr/en/node/7698>. [Accessed 12 September 2020].