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Climate uncertainty and technological innovation shape investments in renewable energy for small off-grid islands

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ABSTRACT

In this paper, we propose a methodological framework for assessing the influence of climate uncertainty and technological innovation on renewable investments in small off-grid islands.

At the core of the framework, an energy system model calculates the system performance in terms of Present Value of Cost. Through reiterate simulation of the model under different system designs, including photovoltaic, wind turbines, and wave energy converters, and future scenarios, the framework allows to identify the key climate drivers and technological parameters of system performance, and the most robust investments. The framework is demonstrated in the case study of Ustica Island, Italy.

Results highlight wind speed as the key climate driver affecting system performance. The effects of technological innovation are instead strictly dependent on the technology considered and the level of risk aversion of the decision maker.

With respect to the technology competitiveness, photovoltaic is nowadays the most robust investment irrespective of the future uncertainty on natural resource availability and technological innovation. The competitiveness of wind and wave technologies is instead strictly affected by climate and technological uncertainty. Although wind technology is currently more competitive than wave, except for high-risk averse decision-makers, results show that the wave improvement estimated for 2030 and 2050 could make this technology an effective investment in the short/medium term. This suggests the importance of carefully deciding the timing of the investments reducing current investments in the wind for installing higher wave capacity in the future could in fact lead to more effective investments over the entire planning horizon.

1. Introduction

Worldwide, more than 2000 small inhabited islands, from 1000 to 100,000 inhabitants, are completely disconnected from the mainland's electricity grid and rely on off-grid, stand-alone power systems to provide energy services [1]. Among them, more than 100 Mediterranean islands still use carbon-intensive diesel generators to produce electricity, thus depending upon the remote supply of fuel and contributing to greenhouse gas emissions and air pollution [2,3]. Common peculiarities of these islands are also the high seasonal variability of the electricity demand due to summer touristic fluxes and the use of energy-intensive desalination technologies for producing potable water. All significantly impact on the energy system operations and, ultimately, on the economic and environmental sustainability of the energy system [4–6]. In an energy transition context, small off-grid islands have recently assumed a key role in testing advanced and ambitious clean energy solutions, and, at the same time, to serve as showcases of carbon neutrality at a wider scale [7–10]. The European Union (EU), in particular, has recently issued several decarbonization policies, such as the Clean Energy for EU Islands Initiative [11], the European Islands Facility, and the political declaration on clean energy for EU Islands of May 2017.

However, due to the intermittent nature of renewable energy sources (RES) and the high variability of the electricity demand, a complete transition from fossil fuel to renewable technologies is still a little practicable solution. Therefore, the adoption of hybrid energy systems, combining RES (e.g., photovoltaic, wind turbines, wave converters) with conventional power sources (e.g., diesel generators) and storage technologies (e.g., batteries), represents a promising alternative to guarantee high levels of economic and environmental sustainability and, at the same time, to assure the energy security of the system [12–15].

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Designing hybrid energy systems for off-grid islands consists of planning investments whose benefits in terms of reduction in operational costs and greenhouse gas emissions over the medium term (i.e., from 10 to 30 years) overcome the capital costs for introducing new renewable and storage technologies. Nevertheless, the identification of robust investments is extremely challenging as it implies making decisions considering the joint effects that climate uncertainty and the rapid technological innovation could have on the RES power potential and, ultimately, on the system performance throughout the entire investment horizon [16].

On the one hand, the characteristics of the different technologies (i.e., cost, efficiency) directly influence both the capital costs and the RES power potential [17,18]. Although these parameters are known at the time of the decision, considering the uncertainty associated with technological innovation could suggest temporal shifts in the interventions to benefit from more efficient or less costly technologies, which may become available in the short-medium term. The technological improvement is, in fact, evolving extremely rapidly: in the last decade (2010–2019), we observed a remarkable reduction in the Levelized Cost of Electricity (LCOE) of 83% for photovoltaic and 49% for onshore wind, resulting from a combination of lower capital costs and higher capacity factors (e.g., the efficiency of photovoltaic monocrystalline modules increased from 17.5% in 2010 to 21.1% in 2019) [19].

On the other hand, the uncertainty in the natural resource availability (e.g., wind speed, solar radiation, wave climate) could strongly influence RES power potential and, consequently, the planning of robust and effective investments [20]. Here, investment planning becomes strictly dependent on the level of risk aversion of the decision-maker, namely the attitude of this latter towards the climate uncertainty affecting the decisions. For instance, a high-risk averse decision-maker would probably prefer a more conservative solution maximizing the system performance in the worst-case scenario (e.g., low natural resource availability). Conversely, a low-risk averse decision-maker would adopt a solution maximizing the system performance in the best-case scenario (i.e., high natural resource availability), eventually risking making an oversized, non-optimal investment if a different scenario actually occurs.

From a more general perspective, choosing interventions, which would reveal effectiveness over the whole investment horizon, assumes even wider importance in relation to the environmental, aesthetic, socio-economic constraints that characterize most of the Mediterranean Islands [15].

Even if climate change and technological innovation could strongly affect renewable investments, the state-of-the-art studies, aiming at supporting decision-makers in the identification of the best intervention strategies for small off-grid islands, usually over-simplify the real decision-making problem by considering stationary climate conditions and by neglecting hypotheses of technological innovation [3,5,21–25]. In practical terms, they adopt a least-cost approach that identifies the capacity of each power/storage technology that minimizes the Present Value of Cost (PVC) over a given project horizon [26,27]. Although based on a linear model, PVC is one of the most comprehensive metrics for evaluating investments as it accounts for all the costs occurring during the project horizon, namely the capital costs for installing the different technologies, the operational costs and the costs for replacing the installed technologies when reaching the end of their life. In addition, this indicator allows identifying sustainable solutions also from an environmental point of view by penalizing greenhouse gas emissions with additional operational costs. According to this approach, PVC is calculated by simulating the energy system dynamics considering fixed technological (e.g., efficiency and costs of power and storage technologies) and economic (e.g., interest rate, inflation rate) parameters, and a 1-year stationary trajectory of electricity demand and each climate variable affecting renewable power (e.g., solar radiation, wind speed, wave climate).

In this paper, we want to extend the above-mentioned approach by proposing a methodological framework for evaluating how climate uncertainty and rapid technological innovation could influence renewable investments in small off-grid islands, with the ultimate goal of providing useful insights for supporting the decarbonization decision-making process. Even if potentially affecting investment evaluation, we did not instead consider in this first version of the framework the uncertainty related to the socio-economic conditions (e.g., electricity demand, interest rate, inflation rate), due to the difficulties in generating reliable scenarios over the medium term. The core of the framework is represented by an energy system model, which simulates the energy system dynamics for a given system design and a specific climate and technological scenario, eventually calculating the system performance in terms of PVC. Through reiterate simulation of the model for different system designs and future scenarios, the framework has been adopted to perform different experiments.

These experiments focus, on one hand, on the identification of the key climate drivers and technological parameters that mainly affect the system performance, and, on the other hand, on reproducing a real decision-making process for identifying the most robust investments with respect to climate and technological uncertainty.

The framework has been applied to the real case study of Ustica (Sicily, Italy), which represents a paradigmatic example of a small off-grid Mediterranean island, where severe spatial constraints require sound and long lasting RES development plans. We focused on hybrid energy systems composed of diesel generators, wind turbines (WTs), photovoltaic systems (PV), and wave energy converters (WECs), considering climate scenarios of wind speed, solar radiation and wave climate, and technological scenarios of future changes of capital cost and efficiency of each renewable technology.

The remainder of this paper is organized as follows. Section 2 introduces the case study of the Ustica island. Section 3 presents the proposed methodological framework, providing details on the energy system model, the climate and technological scenarios, and the decision criteria considered in our analysis. Section 4 describes the performed experiments and Section 5 shows the numerical results. Finally, Section 6 provides conclusions and suggestions for further research.

2. Study site

Ustica is a small Italian island with an area of 8 km^2 and is located about 50 km north of Sicily in the Mediterranean Sea (Fig. 1a). It has a resident population of around 1300 inhabitants, which nearly doubles during the summer touristic months.

Electricity is produced entirely by 5 diesel generators with a total installed capacity of 4.6 MW and an average yearly electric production of around 6500 MWh. Household consumption accounts for nearly 70% of the annual electricity demand, with the remaining 30% covered by the desalination plant, built in 2016 to satisfy the entire water demand (Fig. 1b). Due to the high touristic fluxes, electricity and water demand have high seasonal variability. To guarantee energy supply security, the diesel generators are over-sized to cater to the summer peaking demand, avoid supply deficits, and make up for possible engine faults. Energy efficiency and thus unit carbon emissions are much worse than those of the mainland centralized power plants whilst electricity costs are normally much higher [15].

Combining diesel generation with RES and storage technologies has been considered in the last years as a potential solution to improve the sustainability of all the Italian small, off-grid islands (Ministerial Decree February 14th 2017 [28]). For this case study, we have considered the exploitation of solar, wind and wave resources through the installation of wind turbines (WTs), photovoltaic systems (PV), and wave energy converters (WECs), coupled with storage technologies, in order to produce clean energy at lower costs (Fig. 1b).

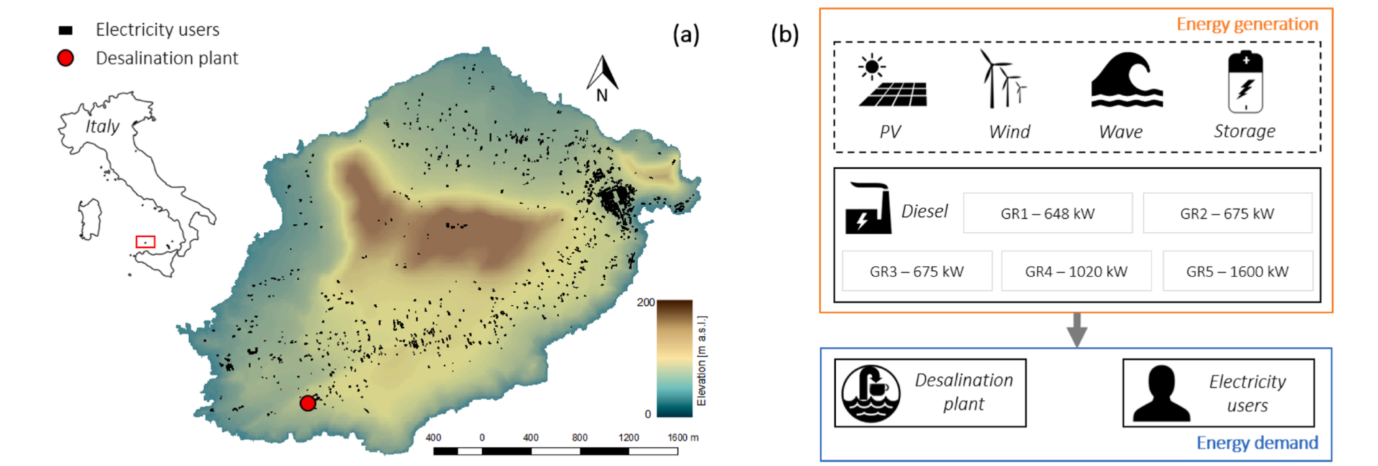

Fig. 1. (a) Location and map of Ustica island with the desalination plant and the electricity users highlighted. (b) Schematization of existing and planned energy system of Ustica.

3. Material and methods

The proposed methodological framework evaluates the performance of different hybrid energy system designs over a large set of future scenarios of climate change and technological innovation with the ultimate goal of identifying the most robust investments over a medium/long term horizon (Fig. 2).

The future scenarios have been generated by combining different plausible climate conditions of wind speed, solar radiation and wave climate with different values of efficiency and investment cost characterizing each renewable technology, set according to different hypotheses of technological innovation from now (2020) to 2050. The energy system designs are composed of different combinations of PV capacities and numbers of WTs and WECs of fixed nominal capacity. The energy system model of the Ustica island [3] represents the core of the framework and can simulate the energy system dynamics of a given system design for a specific scenario, calculating the system performance in terms of PVC.

Through repeated simulations of the energy system model, the framework identifies the ideal optimal system design (i.e., the design attaining the lowest PVC) for each future scenario considered. In addition, given a specific hypothesis of technological innovation (i.e., fixing the technological scenario), it allows identifying robust investments by filtering the uncertainty associated with the climate variables (represented by the climate scenarios) through different decision criteria reflecting different levels of risk aversion of the decision-maker.

In the following paragraphs, more details on the energy system model, the energy system designs, the future climate and technological scenarios, and the decision criteria considered in this work will be provided.

3.1. Energy system model

The proposed methodological framework is based on the reiterated simulation of the energy system model of the Ustica island for different pre-specified system designs under different scenarios of climate change and technological innovation. The reader can refer to Refs. [3,20]. for a detailed description of the equations governing the electricity production from PV, WTs, and diesel generators as well as the strategy adopted for simulating the electricity storage system and the micro-grid dynamics.

WECs (not included in our previous studies [3,20]) are modelled

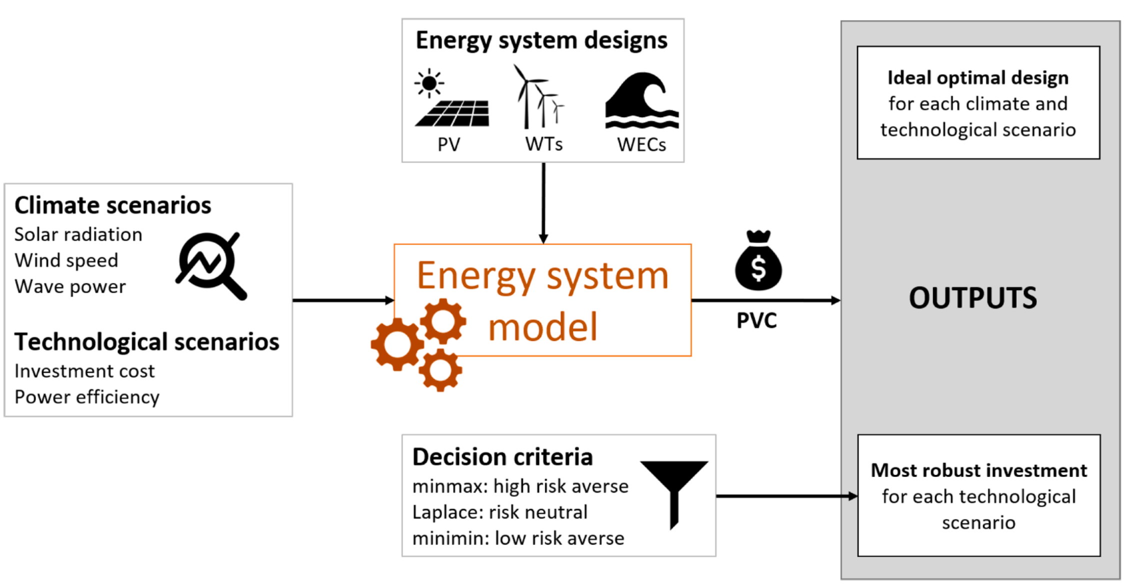

Fig. 2. Methodological framework adopted for evaluating the effects of climate uncertainty and technological innovation on the renewable investments in small off-grid islands.

assuming to deploy downscaled Pelamis wave energy converters with a nominal capacity of 8.18 kW. The choice and the size of the device are based on a preliminary analysis aimed at finding the best wave power technology for the Ustica offshore. We evaluated the mean annual energy production of eight of the most promising WECs off the coasts of Ustica, optimizing the device scales to match the local wave climate, as described in Refs. [29,30]. The results showed that the technology with the highest performance for the Ustica wave climate is the Pelamis device with a size equal to one third of the full WEC size. This device would have a mean annual energy production of 22 MWh, a mean annual power of 2.5 kW and a capacity factor of 30%.

The model simulates the energy system dynamics over 1 year using an hourly time step and calculates the system performance in terms of PVC considering a project horizon of 25 years. In particular, PVC is calculated for each system design a and each climate and technological scenario s as follows:

$$J(a,s) = C^{cap}(a,s) + \sum_{y=1}^{H} \delta(y)\left(C^{grid} + C^{oper}(y,a,s) + C^{rep}(y,a,s) + C^{sal}(y,a,s)\right) \quad (1)$$

where $H = 25$ is the number of years of the project horizon, $C^{cap}(a,s)$ are the capital costs, C^{grid} are the costs for the management of the electricity grid, and $C^{oper}(y, a, s)$, $C^{rep}(y, a, s)$, $C^{sal}(y,a,s)$ are the operational, replacement and salvage costs at year y, respectively. All costs, except the capital ones, are discounted using the following time varying coefficient:

$$\delta(y) = \frac{1}{(1+\gamma)^{y}} \quad (2)$$

where γ is the real discount rate, calculated as a function of the nominal discount rate $\gamma^{'} = 2.5\%$ and the inflation rate $\varphi = 1\%$:

$$\gamma = \frac{\gamma^{'} - \varphi}{1+\varphi} \quad (3)$$

The capital costs occur at the beginning of the project horizon and represent the investment to install the power technologies, the replacement costs occur when a technology has to be substituted, and the salvage costs are negative costs that are incurred at the end of the project horizon when one or more technologies have not reached the end of their lifetime. Finally, the operational costs take into account both the cost of operation and maintenance of each power technology, and the cost of fuel (values reported in Refs. [20].). PVC is dependent on both the system design a and the climate and technological scenario s, which is composed of a 1-year hourly time series of each climate variable and a set of technological parameters (i.e., investment cost and efficiency) describing each renewable technology (see next sections for further details on how these scenarios have been generated). In particular, the climate conditions and the efficiency of the technologies directly affect the renewable potential and, consequently, the electricity generation costs, whereas the investment costs influence the capital, the replacement and the salvage costs.

3.2. Energy system designs

The energy system designs evaluated in this work are composed of different combinations of PV capacities and numbers of WTs (fixed capacity of 60 kW) and WECs (fixed capacity of 8.18 kW). In particular, the PV capacities are sampled using a discretization step of 400 kW within the feasibility range [0,2000]. The number of WTs are sampled using a discretization step of 4 units within the feasibility range [0,20]. The number of WECs are sampled using a discretization step of 10 units within the feasibility range [0,110]. The total number of system designs analysed thus results equal 432.

The discretization steps have been selected to capture the effects of different designs on the system performance and, at the same time, limit the dimension of the decision space for reducing the computational time. The upper bound of the feasibility ranges is determined considering the small size of the island and the tight environmental constraints, which strictly limit the maximum installable RES capacity (the whole island is under landscape heritage protection according to the Sicily regional law 29/2015). In addition, a storage system of the same PV capacity is implemented for all the system designs to ensure the PV electricity surplus, potentially generated in the central hours of the day, to be used to meet the required load during the night (see [20] for details on storage system implementation).

3.3. Climate scenarios

Climate scenarios of wind speed and solar radiation have been generated using a hybrid approach [31,32], by first estimating future conditions from climate models and then enlarging the range of plausible future scenarios to stress-test the system of interest.

We first considered climate projections generated by five different combinations of Global Circulation Models (GCMs) and Regional Circulation Models (RCMs), namely ICHEC-CCLM4, ICHEC-RCA4, MPI-RCA4, MOHC-RCA4, MOHC-RACMO22E (see www.euro-cordex.net for details), forced by Representative Concentration Pathways (RCPs) RCP2.6, RCP4.5 and RCP8.5 [33]. These scenarios have a spatial resolution of 0.11 degrees and provide projections for the period 2006–2100. To resolve the mismatch between the spatial resolution of RCMs and that of our study site, we applied a statistical downscaling method based on quantile mapping [34], estimating a correction function between the observations of the climate variables at the local scale and the RCM output over the control period (1971–2005). Since our model simulates the system over a reference year, we considered each projected year as a single climate scenario of hourly values (i.e., 1425 scenarios). It is worth noting that even if this assumption prevents to directly consider inter-annual changes in the climate variables, it allows a considerable reduction of computational costs and represents a conservative hypothesis with respect to the actual evolution of the climate conditions.

Then, we slightly enlarged the mean annual variability of wind speed and solar radiation for stress testing our system under more variable conditions, generating 3125 scenarios. More precisely, for each climate variable (wind speed and solar radiation), we applied a 10% increased/decreased scaling factor to the 425 hourly time series (i.e., 30% of the time series projected by the climate models) characterized by the highest/lowest mean annual values. In the end, we randomly sampled 100 out of 3125 scenarios to limit the computational time of our analyses.

Wave climate scenarios have been generated based on a 40-year hindcast wave data set, which provided the hourly values of significant wave height and the peak period for the Ustica island over the period 1979–2020 [35]. These scenarios have been coupled to wind scenarios, by associating high mean annual wave heights and periods to high mean annual values of wind speed. Then, in order to transform wave height and peak period into a single variable characterizing the wave climate, we calculated the wave power P_{wave} (kW/m) with the following formula:

$$P_{wave} = \alpha \cdot H_s^2 \cdot T_p \quad (4)$$

where $\alpha = 0.5\ \left(\frac{kW}{m^3 \cdot s}\right)$ represents an empirical coefficient depending on water density and gravity, H_s (m) is the significant wave height and T_p (s) the peak period.

It is worth noting that we did not consider future projections of wave climate, due to the high uncertainty and difficulties in modelling the wave resource, especially under climate change, and the lack of existing studies that propose reliable models to perform such wave climate assessments (e.g., EURO-CORDEX project does not provide future wave climate projections).

3.4. Technological scenarios

Technological scenarios have been generated estimating the values of 2 parameters, namely investment cost and efficiency, for each renewable technology at 2020, 2030 and 2050, according to different hypotheses of technological innovation provided by the International Renewable Energy Agency (IRENA).

PV parameters have been estimated according to Ref. [36], considering an increase of PV efficiency from 0.165 in 2020 to 0.24 in 2030 and 0.28 in 2050, and a decrease in the investment cost from 1150 € /kW in 2020 to 575 € /kW in 2030 and 345 € /kW in 2050. Given an observed cost reduction of 74% from 2010 to 2020, future investment costs represent the average installation cost of utility scale PV projects projected by IRENA based on an estimated reduction of solar PV modules prices and the ongoing reductions in balance-of-system costs. Future values of PV efficiency refer instead to the actual efficiency of prototype multi-crystalline (0.24) and mono-crystalline (0.28) silicon solar modules.

WTs parameters have been estimated according to Ref.[37], considering an increase in the efficiency of 20% in 2030 and 40% in 2050 with respect to the one of the existing WTs (2020), and a decrease in the investment cost from 3000 € /kW in 2020 to 1240 € /kW in 2030 and 920 € /kW in 2050. In this case, the efficiency values, namely 1 (2020), 1.20 (2030) and 1.40 (2050) represent a multiplicative factor to be applied to the power curve of the WT, without changing the nominal power, which remains equal to 60 kW in all the scenarios considered. Actual investment costs have been provided by the Ustica electricity company; future values represent the global average installation costs of onshore wind projects estimated by IRENA considering different categories of costs (e.g., wind turbine, civil works, planning and project, fees and licences). It is worth noting that wind investment costs are very site and market specific and these projections could significantly deviate from the real costs in contexts such as small Mediterranean islands. Percentage increase in wind turbine efficiency reflects, instead, the increase in the global weighted average capacity factor of new wind turbines projected by IRENA for 2030 and 2050.

WECs parameters have been estimated according to Ref. [38], considering an increase in the efficiency of 20% in 2030 and 40% in 2050 with respect to the current values (2020), and a decrease in the investment cost from 4070 € /kW in 2020 to 3350 € /kW in 2030 and 1750 € /kW in 2050. As for the case of the WTs, the efficiency values, namely 1 (2020), 1.20 (2030) and 1.40 (2050) represent a multiplicative factor to be applied to the power matrix of the WEC, without changing the nominal power, which remains equal to 8.18 kW in all the scenarios considered. Investments costs at 2020, 2030 and 2050 have been estimated by the International Energy Agency (IEA) and refer to the average installation costs of European wave energy projects. The significant decrease in the investment costs (-57% by 2050) is mainly due to very high learning rates and economies of scale observed in this fast-growing sector. With respect to the energy efficiency, due to the lack of available information, we considered an increase of 20% at 2030 and 40% at 2050 with respect to the value at 2020, as for the wind turbines.

Once the parameters for each technology have been estimated, all the possible combinations of investment cost and efficiency values have been computed within every single technology and throughout the different technologies, ultimately generating 729 technological scenarios to be combined with the 100 climate scenarios presented in the previous section.

It is worth noting that we did not consider future changes of the operational and maintenance costs of the different renewable technologies, as they are supposed to have only slight variations in the middle-term future and their effects on the system performance are negligible if compared to the effects of changes in the investment costs [36–38]. The values considered in this work are 50 € /kW/y for PV, 83 € /kW/y for the wind turbines and 126 € /kW/y for the wave converters. In addition, we did not consider changes in the electricity demand as future variations of the resident population and the summer touristic fluxes are not expected due to the small dimension of the island.

3.5. Decision criteria

Given a specific technological scenario, the optimal design (i.e., the most robust investment) can be identified by adopting a decision criterion reflecting the level of risk aversion of the decision-maker towards the climate uncertainty [39].

In this work, we consider three different decision criteria, whose formulation is provided in the following, where a represents the system design, $w \in \Xi$ a specific climate scenario and $J(a, w)$ the performance in terms of PVC of the system design a under the scenario w.

- *minimax*. This criterion identifies the optimal system design a^* that attains the best performance in the worst case:

$$a^* = argmin_a \left(\max_{\Xi} J(a, w) \right) \tag{5}$$

  This criterion, usually associated with a pessimistic point of view, allows the selection of the system design that guarantees at least a certain minimum performance level independently from which scenario will realize in the future [40].
- *Laplace*. This criterion, called the principle of insufficient reason, selects the system design a^* that attains the best expected performance over the n future climate scenarios:

$$a^* = argmin_a \left(\frac{1}{n} \sum_{i=1}^{n} J(a, w_i) \right) \tag{6}$$

  This criterion suggests risk neutrality of the decision-maker and implicitly assumes that each future scenario could be realized with the same probability [41].
- *minimin*. This criterion identifies the alternative a^* that attains the best performance in the best case:

$$a^* = argmin_a \left(\min_{\Xi} J(a, w) \right) \tag{7}$$

  This criterion, usually associated with an optimistic point of view, selects the system design assuming that the best future conditions will be realized [40].

4. Experiment settings

The experiments performed using the proposed methodological framework have the ultimate goal of understanding how the rapid technological innovation and climate uncertainty could influence renewable investments in small off-grid islands. To achieve this goal, we perform the following experiments:

- **Key climate drivers.** The first experiment focuses on the identification of the climate drivers that mainly influence the performance of the optimal energy system design to understand which renewable investments are more sensitive to climate uncertainty. In this case, the system design minimizing the PVC has been obtained for each climate scenario, given three specific scenarios of technological innovation (results discussed in Section 5.1).
- **Key technological parameters.** The second experiment aims at investigating the effects of technological innovation on the system performance to isolate the key technological parameters that mainly affect the future competitiveness of renewable technologies. In this

case, the system designs minimizing the PVC have been obtained by fixing the value of specific technological parameters and by filtering the climate uncertainty using the decision criteria presented in Section 3.5 (results discussed in Section 5.2).

- **Robust investments.** The third experiment allows to directly identify the most robust system design for each scenario of technological innovation and for each decision criterion used for filtering the climate uncertainty (results discussed in Section 5.3). The goal of this experiment is to reproduce a real decision-making process where a decision-maker with a different attitude towards the climate uncertainty (modelled through different decision criteria) have to determine the best investment based on the existing renewable technologies, whose parameters are represented by the different technological scenarios and are supposed to be known at the time of the investment (results discussed in Section 5.3).

5. Results

5.1. Key climate drivers

Results of this experiment clearly show that wind speed and, consequently, wave power are the climate variables that mainly influence the performance of the optimal system design (Fig. 3). An increase in their mean annual values leads to optimal system designs characterized by a lower PVC, which decreases from more than 44 M€ for a low resource scenario associated with the existing power technologies (technological scenario representative of the year 2020) to about 34 M€ (-23%) for a high resource scenario associated to less costly and more efficient technologies (technological scenario representative of the year 2050).

However, although wind speed and wave power are directly correlated in terms of resource availability (i.e., the higher the wind speed the higher the wave power), the decrease in estimated PVC is obtained by system designs characterized by an increasing wind capacity (from light to dark green points) and a decreasing wave capacity (from dark to light blue points). This apparently surprising result is due to the high non-linearities characterizing the WEC power matrix adopted for converting the available wave power to the WEC electricity output. Indeed, differently from the WT power curve estimating a power output that always increases with the wind speed until the cut-off value is reached, the WEC power matrix shows decreasing electricity outputs for high values of wave power, negatively influencing the WEC profitability when the natural resource is too high.

If we focus on solar radiation, changes in this climate variable do not affect the system performance, neither the optimal system design, as no trends can be observed between solar radiation, PVC and PV capacity (from yellow to red points).

From a decision-making perspective, results suggest that the uncertainty associated with the resource availability, mainly in terms of wind speed and wave power, poses great challenges in the identification of the optimal system design. Even if on the one hand the optimal PV capacity is almost insensitive to changes in the natural resource, making investments in this technology low risky, on the other hand, the best investments in wind and wave technologies strictly depend on the wind speed and wave power values. The optimal designs for high resource scenarios are characterized by high wind (dark green points) and low wave (light blue points) capacities, whereas best configurations for low resource scenarios show low wind (light green points) and high wave (dark blue points) capacities, highlighting a clear trade-off between the competitiveness of these two technologies. Since the decision-maker doesn't know the climate scenario that will unfold in the future at the time of the investment, considering such uncertainty within the decision phase through a decision criterion that reflects his level of risk aversion is essential to take robust decisions.

Independently from the resource availability, results also show that the technological innovation would lead to optimal system designs characterized by higher wind and wave capacities and constant/slightly lower PV capacities, confirming the robustness of PV investments also with respect to the future technological innovation.

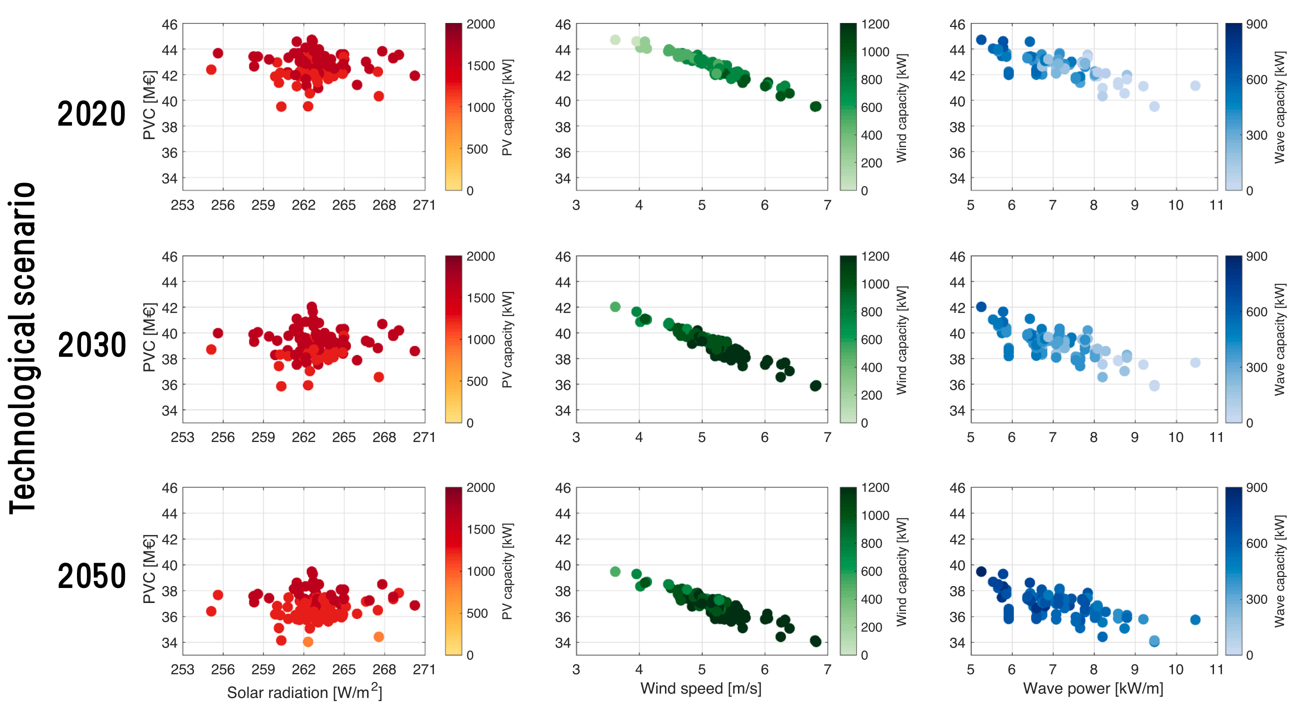

Fig. 3. PVC of the optimal system designs with respect to changes in the mean annual solar radiation (left panels), wind speed (middle panels) and wave power (right panels) for three different technological scenarios characterized by efficiency and investment cost values representative of the year 2020 (upper panels), 2030 (middle panels) and 2050 (bottom panels). Colour represents the capacity of PV (left panels), wind (middle panels) and wave (right panels) associated to the optimal system design.

5.2. Key technological parameters

As already anticipated in the previous section, a decision criterion reflecting the risk aversion of the decision-maker is needed for filtering the uncertainty associated with the climate drivers and thus identifying robust investments. Given a decision criterion, the effects of different hypotheses of technological innovation can be investigated to isolate the technological parameters that mainly influence the system performance.

Fig. 4 shows how the PVC of the optimal system designs (y-axis in each panel) change depending on the decision criterion used for filtering the climate uncertainty (x-axis in each panel) and the values assumed by the technological parameters (i.e., efficiency in the upper panels and investment cost in the bottom panels) of each power technology (PV in the left panels, wind turbines in the middle panels and wave energy converters in the right panels). It is worth noting that, independently from the technological parameters, the PVC decreases by about 6 M€ (14%), from 42 to 36 M€, moving from the minimax to the minimin decision criterion, namely moving from high to low-risk aversion of the decision-maker. However, if in the first case (minimax) the PVC value represents the minimum performance that can be guaranteed irrespective of the scenario that will actually unfold, in the second case, the PVC value is calculated on the best climate conditions, meaning that it will be definitely lower if any other climate conditions will take place.

Focusing on the effects of changes in technological parameters, the PVC of the optimal configurations is not influenced by an increase in the PV efficiency and remains almost constant in all the decision criteria considered (from light to dark orange in the upper-left panel). Conversely, an increase in wind and wave efficiency leads to a different PVC decrease depending on the decision criterion considered (from light to dark green/blue in the upper-middle/right panels). In particular, if we select the minimax criterion, which focuses on the worst climate conditions, the influence of the wave efficiency is higher than the influence of the wind one (median PVC decreases from about 43 to about 41 M€ moving from low to high wave efficiency), whereas, if we select the minimin criterion, which focuses on the best climate conditions, we observe the opposite behaviour (median PVC decreases from about 37 to about 35 M€ moving from low to high wind efficiency). The effects of efficiency changes on the system performance increase in fact when the power potential is high (in the best-case scenario for wind and the worst-case scenario for wave). For this reason, since high wind speed values characterizing the best climate conditions lead to a very high wind power potential, the increase in wind efficiency is more evident in the minimin criterion rather than in the minimax one (upper-middle panel).

As far as changes in the investment cost are concerned, a decrease in the PVC associated with a decrease in investment cost can be observed for all the technologies and all the decision criteria considered (from light to dark colours in the bottom panels). In particular, changes in wave investment cost mostly affect PVC in the minimax criterion (median PVC decreases from about 43 to about 41 M€ moving from high to low wave investment cost - bottom-right panel), instead changes in wind investment cost mostly affect PVC in the Laplace and minimin criterion (median PVC decreases from about 38 to about 35 M€ moving from high to low wind investment cost - bottom-middle panel).

These results clearly show that the effects of technological innovation on the system performance are strictly dependent on the technology considered as well as on the risk aversion of the decision-maker in

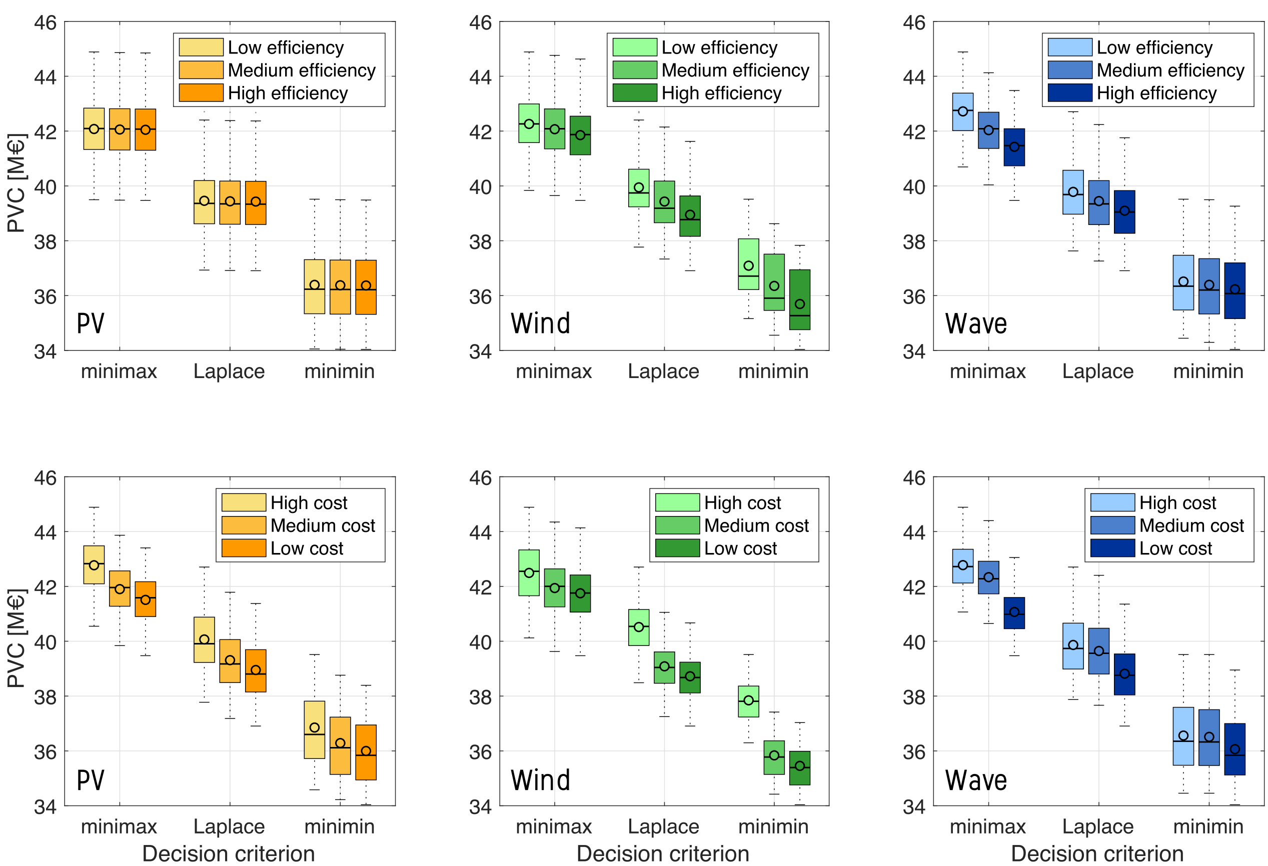

Fig. 4. Box plot of the PVC of the optimal system designs obtained for different technological scenarios and different decision criteria used for filtering the climate uncertainty (i.e., minimax, Laplace, minimin). Colour represents the value of PV (orange), wind (green), wave (blue) efficiency (upper panels) and investment cost (bottom panels). In particular, light colours represents the parameter values estimated for 2020, medium/light colours for 2030 and dark colours for 2050. Box plots identify the 10th, 25th, 50th, 75th, 90th percentiles with the circle representing the mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

filtering the climate uncertainty. In particular, technological innovation in PV would only slightly influence the performance of the optimal system designs, confirming PV as a low-risk investment. Conversely, technological innovation on wind and wave power sources could strongly affect the system performance and their future competitiveness depending on the level of risk aversion of the decision-maker.

5.3. Robust investments

In this section, we analyse how the risk aversion of the decision-maker combined with different hypotheses of technological innovation influence the optimal system design and, consequently, the most robust investments.

On the one hand, the level of risk aversion, modelled with a specific decision criterion, directly characterizes the attitude of a decision-maker towards climate uncertainty.

On the other, evaluating how the optimal system design would change in response to future potential improvement in the power sources performance provides useful insights on how to plan the investments, possibly suggesting temporal shifts of planned interventions to benefit from more efficient technologies, which may become available in the short term.

Results highlighted in Fig. 5 show that the optimal system design is completely independent of the expected increase of the PV efficiency (x-axis) and only slightly dependent on the PV investment cost (y-axis). The expected future decrease of this latter would lead to higher PV capacities (from 1200 kW to 2000 kW moving from yellow to red in the left panels) and slightly lower wave capacities (from 245 kW to 573 kW moving from dark to light blue in the right panels), especially for the minimax and Laplace decision criteria (upper and middle panels), without affecting wind investments (middle panels).

In general, technological innovation in PV is expected to have a very low influence on the optimal system design, meaning that the same investments would be planned also if more efficient PV technologies would e available.

The optimal system design is instead extremely dependent on the level of risk aversion of the decision-maker (from upper to bottom panels in Fig. 5). Moving from the minimax to the minimin decision criterion, the optimal wind capacity increases from 0 to 960 kW (middle panels) and the optimal wave capacity decreases from 654 to 0 kW (right panels).

This result suggests that wave is a more competitive technology for high-risk averse decision-makers, which focus on attaining a minimum guaranteed system performance independently of the future conditions that will actually unfold, whereas wind is a more competitive technology for risk-neutral and, especially, low-risk averse decision-makers, which focus on maximizing the system performance under the best possible conditions. This is due to the very high influence of wind speed on the system performance. As shown in Fig. 3, the best climate conditions (i.e., the ones allowing to achieve the minimum PVC values) are characterized by very high wind and wave resources.

However, if the high wind resource can be effectively exploited increasing the installed wind capacity, the high wave power can not be transformed into high power production and installing wave capacity would thus lead to an increase in capital costs which would not be compensated by a higher renewable power generation and the consequent decrease in the operational costs.

Conversely, the very low wind resource associated to the worst

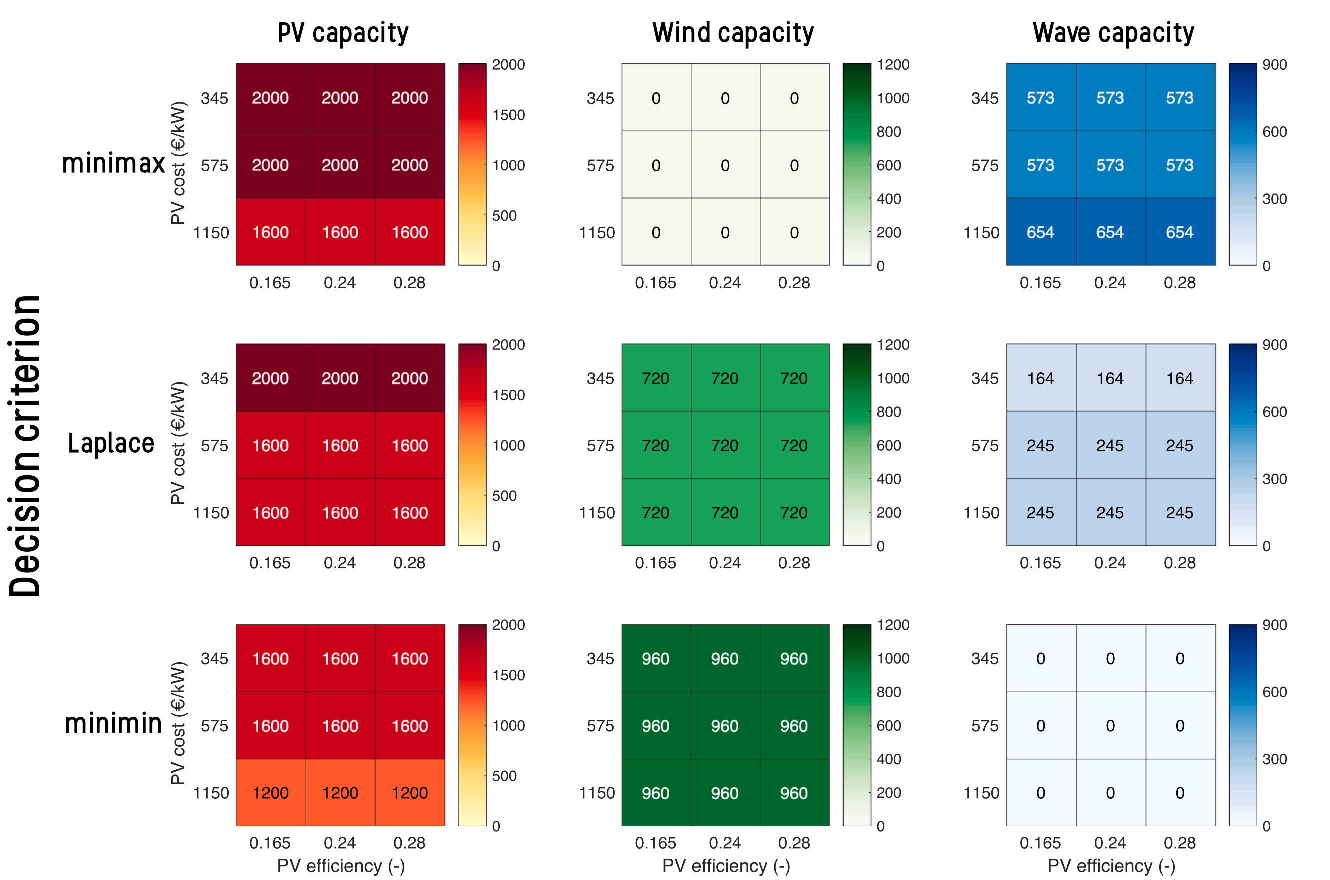

Fig. 5. Optimal PV (left panels), wind (middle panels) and wave (right panels) capacity (kW) calculated for different scenarios of PV efficiency and investment cost and different decision criteria used for filtering the climate uncertainty, namely minimax (upper panels), Laplace (middle panels) and minimin (bottom panels). From left to right, efficiency values refer to the year 2020 (0.165), 2030 (0.24) and 2050 (0.28), respectively. From bottom to top, investment cost values refer to the year 2020 (1150 € /kW), 2030 (575 € /kW) and 2050 (345 € /kW), respectively.

climate conditions negatively affect the profitability of the wind technology, which becomes less competitive than wave. However, Fig. 6 and Fig. 7 show that the estimated future improvement of wind and wave technologies could significantly change the competitiveness of the different power sources and thus the optimal system design. In particular, it is worth noting that if wind efficiency increases to the value estimated for 2050 (1.4 on the x-axis of each panel of Fig. 6) or both wind efficiency and wind investment cost reach at least the values estimated for 2030 (1.2 on the x-axis and 1240 € /kW on the y-axis of each panel of Fig. 6), wind becomes more competitive than wave (i.e., optimal wind capacity higher than the wave one) for high-risk averse decision-makers (minimax criterion - upper-middle and upper-right panels of Fig. 6).

For neutral or low risk averse decision-makers (Laplace and minimin criteria, an improvement in the wind technology would further increase its competitiveness with respect to the wave technology, becoming also more competitive than PV when considering the minimin criterion (middle and lower panels in Fig. 6).

Wave technological innovation (represented in Fig. 7) confirms the competitiveness of the wave technology for high-risk averse decision-makers (minimax criterion), with the optimal wave capacity that mainly increases according to the estimated increase of the wave efficiency (from 654/736 kW to 900 kW in the upper-right panel), and allows wave technology to become more competitive than wind also for neutral and low-risk averse decision-makers (Laplace and minimin criteria - middle and bottom panels).

In particular, for the Laplace criterion, wave technology becomes more competitive than wind only if wave efficiency or wave investment cost reaches the values estimated for 2050, or if both wave efficiency and wave investment cost reach the values estimated for 2030 (i.e., when the optimal wind capacity is equal to 480 kW, the wave capacity is always higher - middle-middle and middle-right panels in Fig. 7).

For the minimin criterion, the wave technology would become more competitive than wind if wave efficiency reaches the values estimated for 2050 and wave investment cost at least the value estimated for 2030 (i.e., when the optimal wind capacity is equal to 720 kW, the wave capacity is always higher - bottom-middle and bottom-right panels in Fig. 7).

6. Discussion and conclusions

Climate uncertainty and rapid technological innovation pose great challenges to the identification of robust investments in renewable energy, especially for critical and vulnerable systems such as off-grid small islands. Here, the decision-making process should be based on a robust assessment of the optimal energy mix configurations, to evaluate potential investments in relation to i) specific decision criteria reflecting the attitude of the decision-makers towards the future uncertainty in the natural resources, and ii) different hypotheses of technological innovation, which could suggest temporal shifts of planned interventions to benefit from more efficient technologies, which may become available in the short/mid-term.

In this paper, we propose a methodological framework for evaluating how climate uncertainty and rapid technological innovation could influence renewable investments in small off-grid islands, to provide an effective tool for supporting the decision-making process.

Our analyses for the case study of the Ustica island highlight that PV represents the most robust investment, as its optimal capacity is only

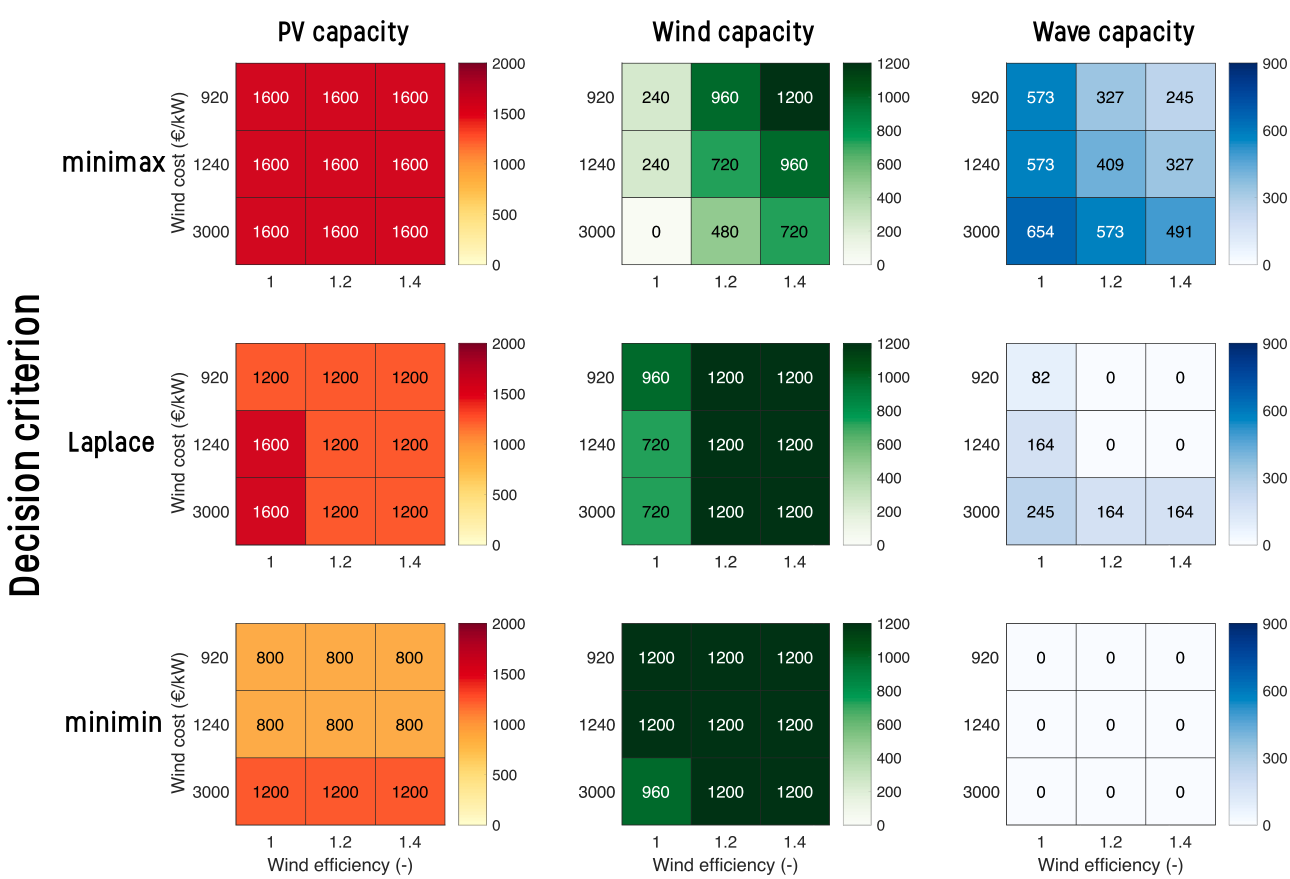

Fig. 6. Optimal PV (left panels), wind (middle panels) and wave (right panels) capacity (kW) calculated for different scenarios of wind efficiency and investment cost and different decision criteria used for filtering the climate uncertainty, namely minimax (upper panels), Laplace (middle panels) and minimin (bottom panels). From left to right, efficiency values refer to the year 2020 (1), 2030 (1.2) and 2050 (1.4), respectively. From bottom to top, investment cost values refer to the year 2020 (3000 € /kW), 2030 (1240 € /kW) and 2050 (920 € /kW), respectively.

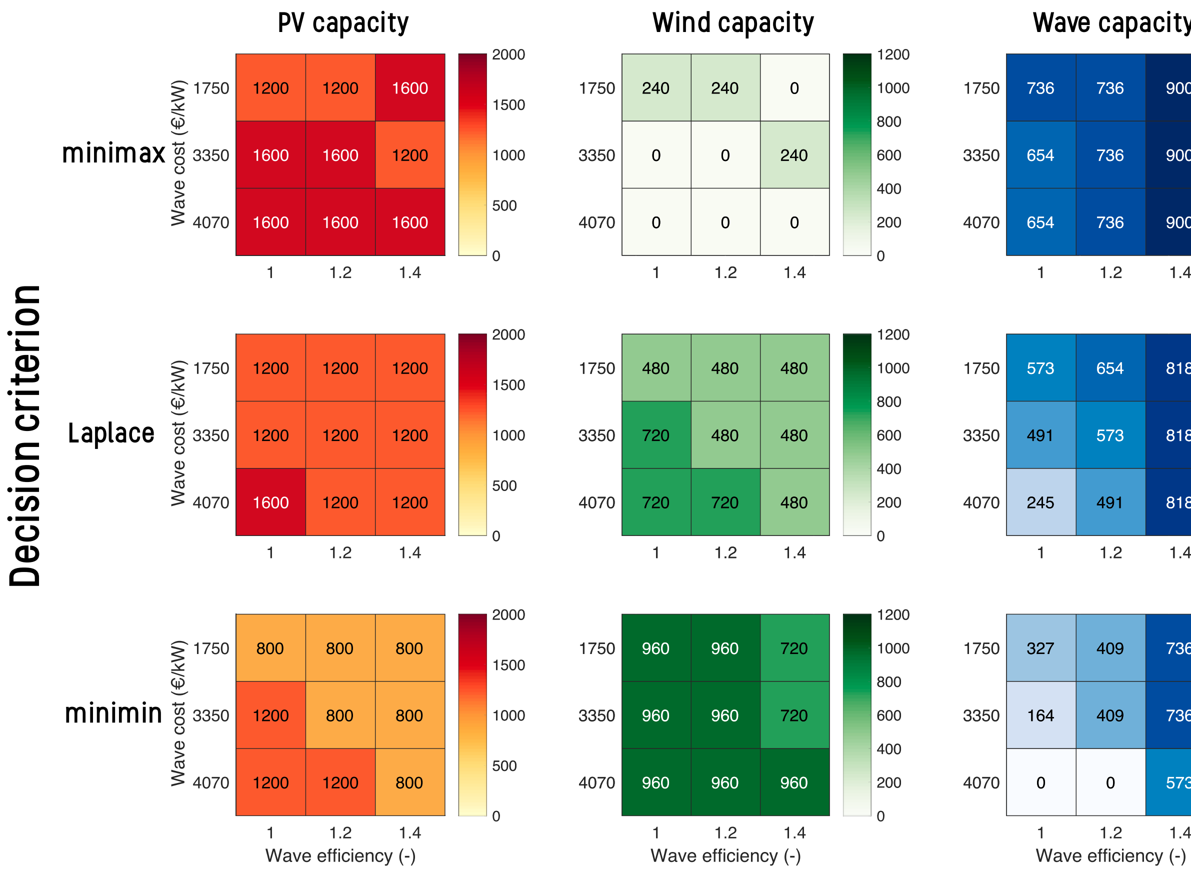

Fig. 7. Optimal PV (left panels), wind (middle panels) and wave (right panels) capacity (kW) calculated for different scenarios of wave efficiency and investment cost and different decision criteria used for filtering the climate uncertainty, namely minimax (upper panels), Laplace (middle panels) and minimin (bottom panels). From left to right, efficiency values refer to the year 2020 (1), 2030 (1.2) and 2050 (1.4), respectively. From bottom to top, investment cost values refer to the year 2020 (4070 € /kW), 2030 (3350 € /kW) and 2050 (1750 € /kW), respectively.

slightly dependent on changes in the climate variables as well as on the technological innovation expected from now to 2050. This suggests that installing PV represents nowadays a robust and sustainable investment irrespective of the level of risk aversion of the decision-maker and the potential technological improvement that may occur in the near future.

The competitiveness of wind and wave technologies is instead dependent on the attitude of the decision-maker towards the climate uncertainty, as wind speed and, consequently, wave power represent the climate drivers that mainly influence the system performance. In particular, due to lower investment cost and higher efficiency, wind currently results more competitive than wave, except for high-risk averse decision-makers. In this latter case, wave constitutes a more conservative investment that allows guaranteeing a minimum (even if low) system performance independently of the climate conditions that will unfold. However, the improvement of wind and wave technologies estimated for 2030 and 2050, if not occurring simultaneously, could strongly affect the optimal system design, potentially inverting the competitiveness of these technologies. This implies that investments planned considering the existing technologies could lead to useless interventions or oversized system designs, which would likely perform poorly even after few years. For coping with this, the decision-maker should carefully decide the timing of the investments for maximizing the system performance over a medium/long term horizon. For instance, a risk-neutral or low-risk averse decision-maker could slightly reduce the current investments in the wind for installing a higher wave capacity as soon as this technology becomes competitive. This results in saving money today to be used for more effective investment in the near future.

However, it is worth highlighting that deciding the timing of the investments constitute itself a decision-making process, which needs to be modelled based on decision criteria reflecting how the decision-maker trusts the scenarios of technological innovation. Further developments of this study will go in this direction by considering the timing of the investments as a decision variable and adopting different decision criteria for representing the attitude of the decision-maker towards the future technological uncertainty. In addition, further research will focus on exploring the uncertainty related to the socio-economic conditions in order to provide deeper and more comprehensive insights for guiding and supporting robust renewable investments.

In conclusion, with the ultimate goal of succeeding in the energy system decarbonization, considering the risk attitude of the decision-maker towards climate uncertainty and the rapid technological innovation taking place is essential for planning effective investments over a medium term horizon. Results obtained for the specific case study of the Ustica island in Italy can be qualitatively generalized to most of the small islands in the Mediterranean Sea, which are characterized by the same peculiarities in terms of energy system structure, variability of the electricity demand and natural resource availability [35,42].

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.

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