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Introduction of optimal photovoltaic and wind power balance algorithm in power systems

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Abstract. Since 2021, Crete has been connected to the mainland's power system grid providing security regarding load peak demand and intra-day fluctuations. The grid provides, also, the opportunity to take full advantage of it in order to alter the island's energy mix, making the island's power system more climate neutral and reduce the emissions produced by conventional power production means. In the current paper, the utilization of mathematical models and a few numerical solution algorithms lead to the optimization of the power production of RES, under certain constraints regarding the system's rejections. The approximation of each optimal solution for all three cases is satisfactory, which is, for the first two cases, an immediate result of the linear properties of the objective function that expresses the annual production of RES in each case. Those linear properties prevent each approximated solution from deviating from the problem's feasible region, while, also, permitting the use of optimization techniques which can be easily implemented and require very little computational time. For the third case, a search algorithm has been designed and implemented, yielding accurate, yet low-precision solutions, which approximate sufficiently the optimal ones.

1 Introduction

For the past years, Crete's energy demands have been satisfied mostly with conventional means of production, as well as renewable energy sources (RES) [1]. However, the RES share was relatively low in the island's energy mix primarily due to their unpredictable output that is dependent on local weather conditions [2]. This causes significant reliability to conventional units that have a highly controllable output yet produce power by consuming fuels (such as mazut, natural gas, etc.) whose prices and means of supply are sensitive to geopolitics and macroeconomic events while contributing significantly to the local area's pollution levels.

The investigation of increasing the RES penetration in the power systems has been examined in the literature taking into consideration several points of view. Luz et al. [3] used the Interactive MOLP Explorer to solve the multi-objective linear problem of minimize the levelized cost of electricity and maximize the generation of non-conventional

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RES. The results show that 90% of the annual load can be covered by renewable sources and that solar power can play a significant part in the power share. In the same topic from a different perspective, the authors in [4] estimated an increase of RES penetration with energy storage system at the point of 60-90% of the total energy of islands can be feasible a project. The authors used 'Response Optimization' tool within the Simulink model to minimize the levelized cost of the system. In [5] the authors estimated that up to 90% of the electricity demand of Dia island, which is located in Greece, can be supplied by RES. In [6] an increase of 65.5% of RES was estimated in a protentional interconnection between Pico and Faial islands. It is used the EnergyPLAN tool to evaluate the increase of RES and the installation of energy storage system to the power system of the two islands. A similar work is performed in [7], where the authors concluded that the interconnection of the Lesbos island with the mainland can increase the share of wind turbines and make the interconnection a more feasible scenario.

The interconnection of Crete's power grid connection with the mainland has provided an opportunity to redesign the current power system allowing higher RES penetration in the energy mix providing economic and environmental benefits [8]. This can be achieved by optimizing the penetration of photovoltaics and wind turbines under certain constraints regarding the rejection of energy by the system. The goal is to reduce the dependence on conventional means of power production, reduce the import of energy through the interconnection with the mainland, and turn the island into an energy exporter for certain hours of the year.

In this paper, mathematical models are designed in order to determine the functions that relate the nominal powers of the photovoltaics and wind turbines to be installed with the annual energy produced by RES, the annual amount of energy imported, and the annual amount of energy rejected by the system. Numerical solution algorithms are also used to determine the optimal nominal powers for each case.

2 Power system study

For the purpose of this study, data from the beginning of 2022 until the end of the same year regarding hourly demand (load), RES production, power import/export from the interconnection, production from the generators, as well as normalized power output of solar panel and wind turbine parks has been provided. For the year 2022, nearly 2/3 of the energy mix of the island was consisted of energy originating from conventional means of production, while production of RES was 23.16% and the contribution of the interconnection 12.80%. There are three distinct cases under study in this paper:

Case 1: Increasing RES by installing additional solar panels.

Case 2: Increasing RES by installing additional wind turbines.

Case 3: Increasing RES by installing additional solar panels and wind turbines.

In all cases the same constraint is enforced, which dictates that the percentage of rejections of the system does not exceed 10%.

3 Methodology

3.1 Case 1: Installation of additional solar panel nominal power

In this case, for each hour i the island's load (Load[i]) is satisfied with power production from RES (RES[i]), conventional generators (Conv[i]) and, if needed, from imports coming from the mainland's grid (Link[i]). If the production from RES and conventional generators suffices, then the surplus is exported through the interconnection to the mainland. Using mathematical notation, the above can be symbolized as:

$$Load[i] = Conv[i] + RES[i] \pm Link[i]. \qquad (1)$$

With the increase in RES production (NewRES[i]), the new contribution of RES each hour i is:

$$NewRES[i] = RES[i] + x*PV_{norm}[i], \qquad (2)$$

where x is the nominal power of the additional solar panels to be installed, and PVnorm[i] the normalized energy produced by the solar panels.

In an effort to reduce the system's dependency on conventional generators and locally-produced emissions, the RES output has been prioritized overall and the imports have been prioritized over fuel-consuming production. Which means that:

$$\pm NewLink[i] = Load[i] - NewRES[i] = Load[i] - RES[i] - x*PV_{norm}[i]. \qquad (3)$$

By adding each term i for all 8760 hours of the year, the above equation becomes:

$$\sum_{i=1}^{8760} \pm NewLink[i] \; = \; \sum_{i=1}^{8760} Load[i] - \sum_{i=1}^{8760} RES[i] - x*\sum_{i=1}^{8760} PV_{norm}[i]. \qquad (4)$$

The summed terms in equation (4) are the annual energy imported/exported to/from the system, the annual energy consumed by the power system's users and the annual energy produced by RES and conventional production systems.

In an ideal scenario the generators wouldn't be needed at all. However, there is a limit to the amount of power that can be imported/exported each hour, meaning that if the RES production and the maximum imported energy do not suffice, then the use of the generators is obligatory. With that in mind, each term NewLink[i] is calculated using the flowchart depicted in Figure 1:

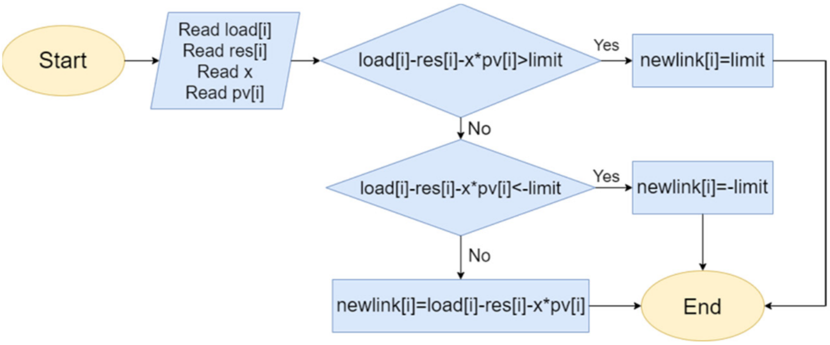


Fig. 1. Calculation of NewLink[i] flow chart.

The export limit presents a different problem. If the RES production is more than a specific hour's need (in this case during sunny hours), then the remaining is exported through the interconnection. If the amount of power to be exported exceeds the interconnection's capacity, then the rest is discarded completely. The discarded energy is called the rejection of the system and plays an important part in the optimization problem. The algorithm for the calculation of rejection Rej[i] is described in the following flow chart in Figure 2:

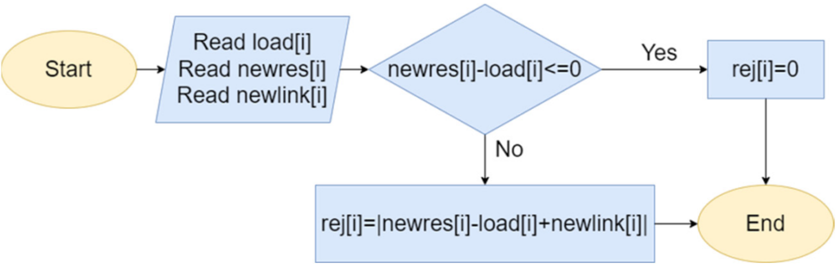


Fig. 2. Calculation of Rej[i] flow chart.

Using the flow charts in Figure 1 and Figure 2, the annual Rejections sumRej(x) is plotted and a polynomial function f(x) is fitted to them. Applying the constraint that annual rejections should not exceed 10% of energy produced by RES, which is described by the inequality:

$$\frac{sumRej(x)}{sumNewRES(x)} \leq 0.1, \tag{5}$$

where:

$$sumNewRES(x) = sumRES + x*sumPV_{norm}. \tag{6}$$

The optimal x value is being searched that maximizes sumNewRES(x). SumNewRES(x) increases linearly with x, so the optimal solution is expected to be found where the inequality becomes an equation, meaning g(x)=0.

Once the equation g(x) is determined, the root is calculated using the Newton-Raphson method. This method is best suited for finding the roots of differentiable, continuous functions. The method is applied in a range of the variable [a,b], usually with f(a)*f(b)<0. Starting from an initial point x0 ∈ [a, b], the value f (x0) is calculated and its first derivative $f'(x_0)$. The new approximation, x1, is the intersection point between y = 0 and the straight line determined by f'(x0), so $y=f'(x_0)*(x-x_1)$. For $x=x_0$, $f(x_0)=f'(x_0)*(x-x_0) \Rightarrow x_1=x_0-\frac{f(x_0)}{f'(x_0)}$. The method iterates until a value $x_n=x_{n-1}-\frac{f(x_{n-1})}{f'(x_{n-1})}$ is found, ideally with $f'(x_{n-1}) \neq 0 \ \forall \ x_{n-1}$ with $f(x_n) \leq \epsilon$, or until two consecutive x values, x_n, x_{n-1}, satisfy $|x_n-x_{n-1}| \leq \epsilon$, where ϵ the specified by the user error.

3.2 Case 2: Installation of additional wind turbine nominal power

Similar to the previous case, the optimal value y is searched, where y the nominal power of the wind turbines to be installed. The current model, in comparison to the previous one, has slight changes to the NewRES[i] formula:

$$NewRES[i] = RES[i] + y*WT_{norm}[i], \tag{7}$$

where WTnorm the normalized output of the wind turbines. The imports/exports from the interconnection are equal to:

$$\pm NewLink[i] = Load[i] - NewRES[i] = Load[i] - RES[i] - y*WT_{norm}[i]. \tag{8}$$

The algorithm described in Figure 1 changes slightly to the one in Figure 3:

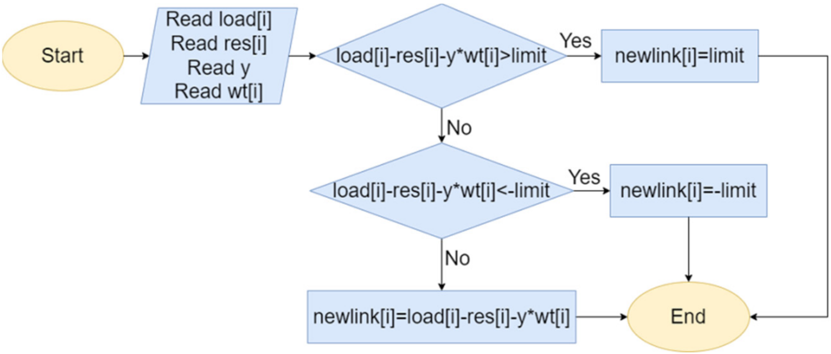


Fig. 3. Calculation of NewLink[i] flow chart.

The algorithm described in Figure 2 remains the same, the Newton Raphson method that maximizes sumNewRES under the constraint described in Case 1 is, once again, used to determine the optimal value of y that satisfies g(y) = 0.

3.3 Case 3: Installation of additional solar panel and wind turbine nominal powers

In this case, both the solar panel and wind turbine parks are reinforced, resulting in the NewRES[i] formula:

$$NewRES[i]=RES[i]+x*PV_{norm}[i]+y*WT_{norm}[i]. \tag{9}$$

The algorithm for the calculation of NewLink[i] changes once more to Figure 4:

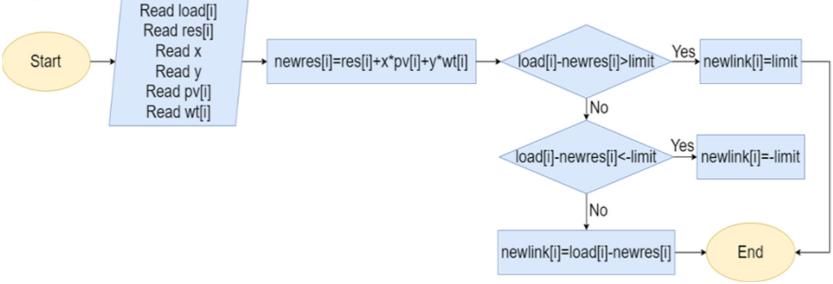


Fig. 4. Calculation of NewLink[i] flow chart.

While the algorithm for the rejections remains the same. Using those algorithms, the percentage of the amount of rejections from the amount of energy produced by new RES is calculated for x in range [0,1650] and y in [0,1800] and a contour map of those values is created and depicted in Figure 5:

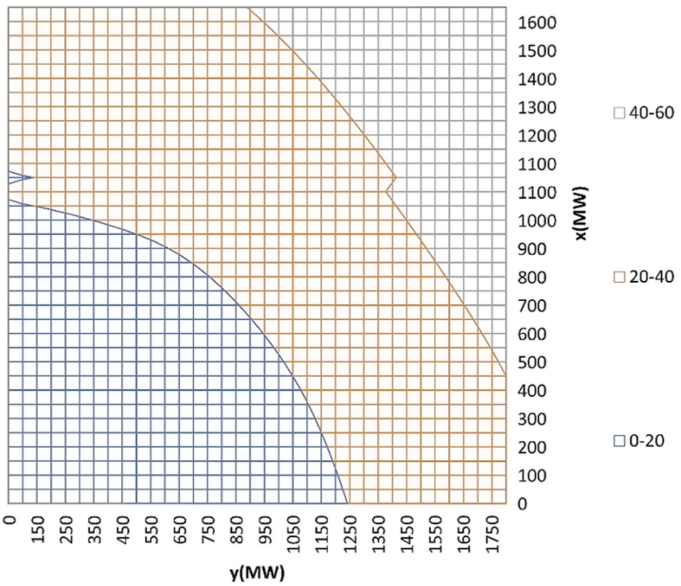
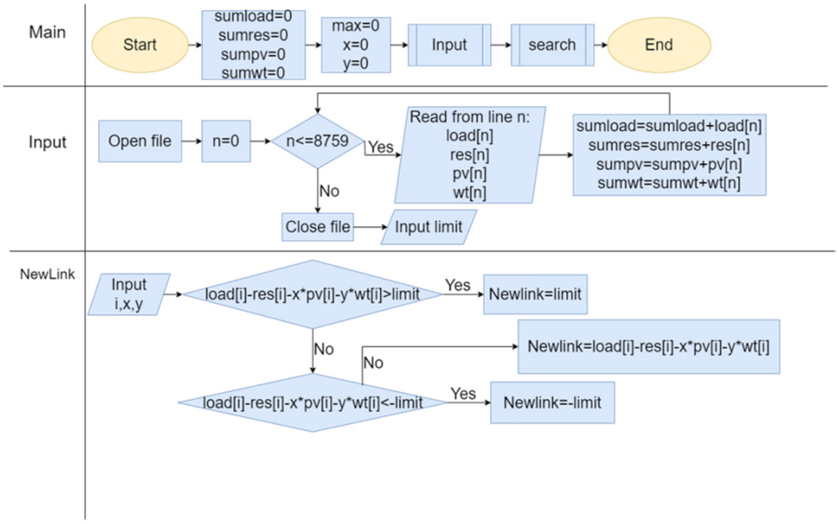


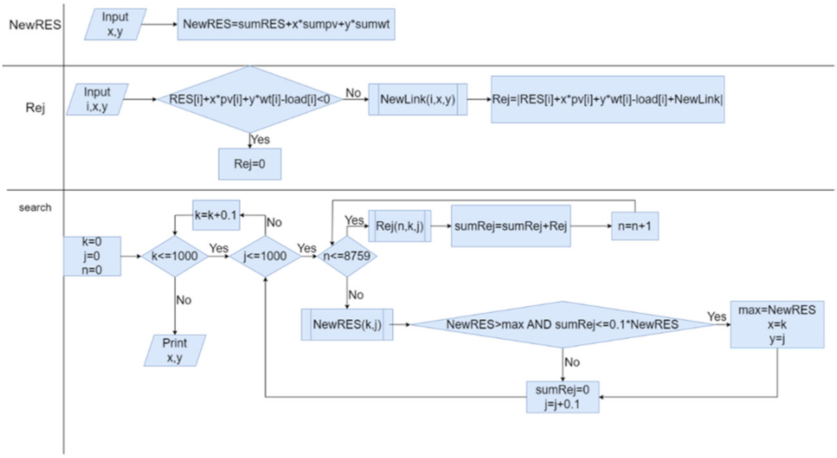
Fig. 5. Contour map of sumRej(%) for link limit=150MW per hour.

In Figure 5, it is apparent that the (x,y) pair that assures maximum RES energy production with rejections less than 10% of the produced energy is located in [0,1250] for both x and y.

For the location of the wanted x and y, a searching algorithm is implemented which reads all the hourly values of load, res, pv and wt from a .txt file, all the (x,y) possible combinations are tested in order to locate the pair that insures the maximum RES production under the forementioned constraint. The first three subroutines are presented in Figure 6.a, and the rest in Figure 6.b:



a)



b)

Fig. 6. Optimal values search algorithm for x and y of scale 1 flow chart.

4 Results

4.1 Case 1

In the first case, the relation between the solar panel nominal power and the annual amount of energy that is rejected is presented in Figure 7:

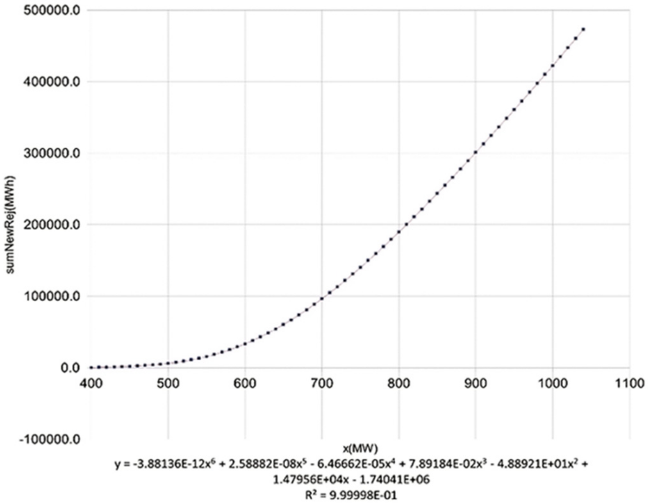


Fig. 7. The sumRej(x) plot for link limit=150MW per hour.

The constraint from equation (5), therefore, turns into:

$$-3.88136*10^{-12}*x^6+2.58882*10^{-8}*x^5-0.0000646662*x^4+0.0789184*x^3-48.8921*x^2 +14625.2*x-1.81528*10^6\leq 0. \tag{10}$$

Applying the Newton-Raphson method in the range [0,850] with $\epsilon = 10-10$, the optimal solution found is x = 824.126MW with $g(x) = -1.6415 * 10^{-9}$MWh. Applying this solution x for link limit=150MW per hour and the same load, the energy mix would be as presented in Figure 8:

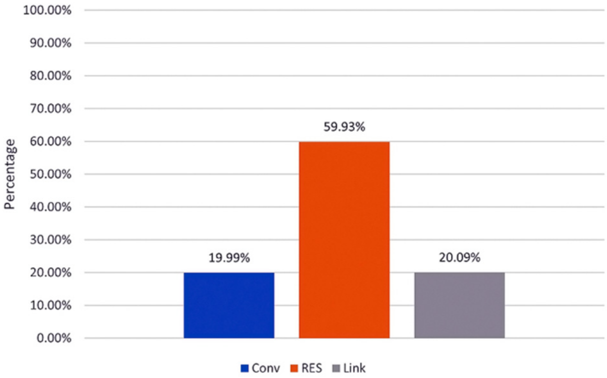


Fig. 8. Energy mix for optimal x and annual Rejection percentage equal to 10.0022%.

It is apparent from Fig. 8 that installing extra nominal power of photovoltaic parks alone increases RES penetration to a little less than 60%, with a significant reliance on both conventional means of power production and imports through the interconnection, with a total annual amount equal to 40.08% of annual load demand.

4.2 Case 2

Similarly, for the newly installed wind turbines, the plot that presents the annual rejections of the system related to y is shown in Figure 9:

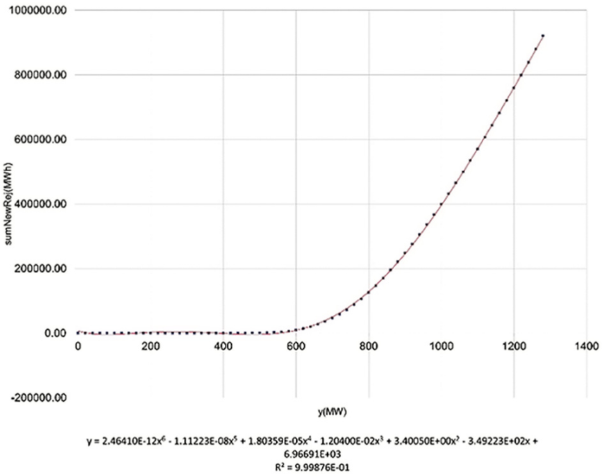


Fig. 9. The sumRej(y) plot for link limit=150MW per hour.

Now, the constraint from equation (5) becomes:

$$2.4641*10^{-12}*y^{6}-1.11223*10^{-8}*y^{5}+0.0000180359*y^{4}-0.01204*y^{3}$$
$$+3.40050*y^{2}-628.14*y-67899.7\leq 0. \tag{11}$$

Applying the Newton-Raphson method once more in the range [500,1000] with $\in = 10^{-10}$, the optimal nominal power for wind turbines is y = 968.266MW with $g(y) = -1.44064 * 10^{-9}$MWh. Applying this solution for link limit=150MW per hour, the energy mix would be as depicted in Figure 10:

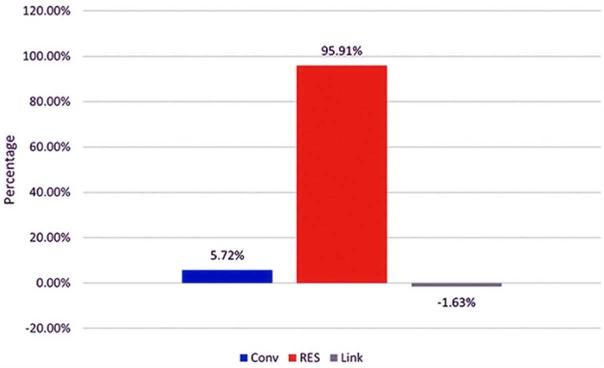


Fig. 10. Energy mix for optimal y and annual Rejection percentage equal to 10.1010%.

In contrast to the previous case, the installation of added wind turbine park's nominal power, as can be seen in Figure 10, increases greatly the annual RES production, while the reliance to greenhouse gas emissions-producing means decreases to considerably low levels of 5.72% of annual demand. It should, also, be noted that the annual exports through the interconnection exceed the annual imports, contributing to the system's self-reliance.

4.3 Case 3

Implementing the algorithm from Figure 6, the optimal solution is x = 345.6MW for the solar panels and y = 808.1MW for the wind turbines. Applying these findings, for link limit=150MW per hour, the energy mix would be as shown in Figure 11:

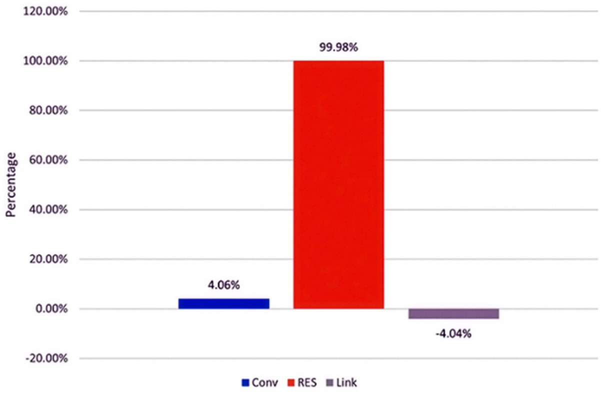


Fig. 11. Energy mix for optimal x and annual Rejection percentage equal to 9.99885%.

From a technical perspective, the search algorithm lacks precision of the approximated solutions, yet it is quite accurate, yielding annual rejection percentage of the system close to the 10% which the optimal solution provides. For this output of the algorithm, Figure 11 clearly dictates that the production of RES reaches nearly 100% of the annual system's demand, with a direct result being the low levels of dependency on fuel-consuming production methods, and the increase of the annual exports through the interconnection to 4.04% of the annual island's demand.

5 Conclusions

The goal of this paper was to study the energy system of Crete as an example of an interconnected island system in order to optimally maximize the penetration of RES energy production in the system's energy mix. This was pursued by designing a mathematical model for three distinct cases and use numerical analysis algorithms to determine the optimal solution for each case under a specific constraint regarding the energy rejections of the system (≤10%). The first case was the installation of extra solar panel nominal power which achieved additional 36.77% penetration of RES to the mix, the second case was the installation of extra wind turbine nominal power to the system, resulting in 72.75% increase in RES penetration to the energy mix, and the final case of increasing both solar panel and wind turbine nominal power that increases RES penetration by 76.82%. It is noteworthy that in the last case the contribution of RES surpasses 99%, since both power-production technologies are taken advantage of, enabling the system to produce power originating from renewable sources for more hours of each day.

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