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# The Clean-Green Decarbonization of Remote Islands: The GReco-Islands Concept †

**John K. Kaldellis * and Panagiotis Ktenidis**

Laboratory of Soft Energy Applications & Environmental Protection, University of West Attica, P.O. Box 41046, 12201 Athens, Greece; pktenidis@uniwa.gr

* Correspondence: jkald@uniwa.gr

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**Abstract:** Climate change due to extended fossil fuel utilization strongly affects islands all over the world. Greece has a large number of islands of various sizes. As far as the electrification status and the climate surcharge of Greek islands is concerned, the current work is concentrated on the non-interconnected group of islands that cover their electricity demand on the basis of local oil-based thermal power stations. In this context, the EU-originated effort to drastically change the local electricity generation fuel mix was examined. More specifically, under the recent Territorial Just Transition Plan for the islands, a variety of actions is proposed in view of the "GReco-islands" initiative. Applying the proposed clean-green solution on a representative island (e.g., Patmos island), one may estimate the expected carbon dioxide emissions reduction. Finally, the necessary investments cost may be estimated due to the clean-green decarbonization actions implemented.

**Keywords:** climate change; local society; green investment; wind energy; solar energy; fuel mix

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## 1. Introduction

A remarkable number of islands around the globe have experienced historic under-development and relatively narrow employment bases, while limited job opportunities encourage outmigration among younger generations and population decline. This situation is more severe for the several very small Greek islands (see also 2021 census), which are gradually being abandoned by their permanent population [1]. Moreover, climate change due to extended fossil fuel utilization strongly affects islands all over the world [2], with small-scale islands perceived as the most vulnerable environments.

Greece has a large number (~227) of islands of various sizes [3]. As far as the electrification status and the climate surcharge of Greek islands is concerned, Greek islands are divided into two large categories, i.e., those electrically interconnected to the mainland and the non-interconnected ones. The current work is concentrated on the second, non-interconnected group of islands, which covers its electricity demand using small- or medium-sized (~30), autonomous power networks. All these autonomous systems operate on the basis of local oil-based thermal power stations; thus, currently, the equivalent specific carbon dioxide emissions of the non-interconnected islands' electricity generation is slightly above that of the mainland (i.e., 0.6 kg $CO_{2eq}$), being approximately 0.64 kg $CO_{2eq}$ for each kWh consumed. Moreover, the result of the above-mentioned remote islands' electrification status is that the electricity requirement is hardly fulfilled by the existing, usually outdated autonomous power stations, at very high fuel consumption (e.g., SFC ≈ 300 gr/kWh$_e$) [4].

On the other hand, the majority of Aegean and Ionian Archipelagos islands have excellent wind potential (annual average wind speed between 8.0 and 9.5 m/s) and very high solar potential (up to 1900 (kWh/year)/m$^2$; see also Figure 1). Unfortunately, several electrical grid stability constraints [5] substantially limit the real contribution of the wind and solar power to the load demand fulfilment of all these islands at the level of 17% (see also Figure 2). Despite this quite difficult situation, and under the recent Territorial Just Transition Plan for the islands, a variety of actions are proposed for these islands, including energy transition and climate neutrality, circular economy and efficient use of resources, sustainable mobility, etc. The current work analyzes the implementation of a new EU-supported initiative for the "decarbonization" of small- and medium-sized Greek islands, the so-called "GReco islands" initiative, and its application in representative islands in order to estimate the necessary effort per $CO_{2eq}$ emissions avoided.

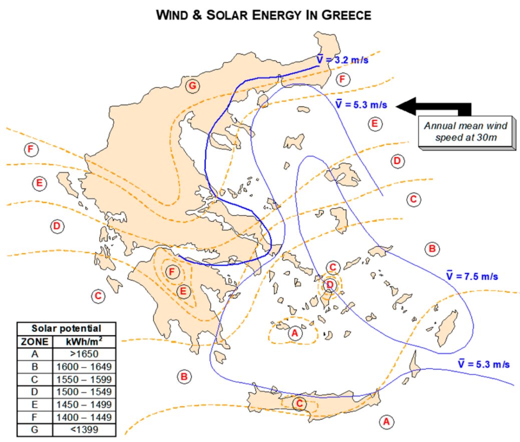


**Figure 1.** Wind and Solar Potential in Greece.

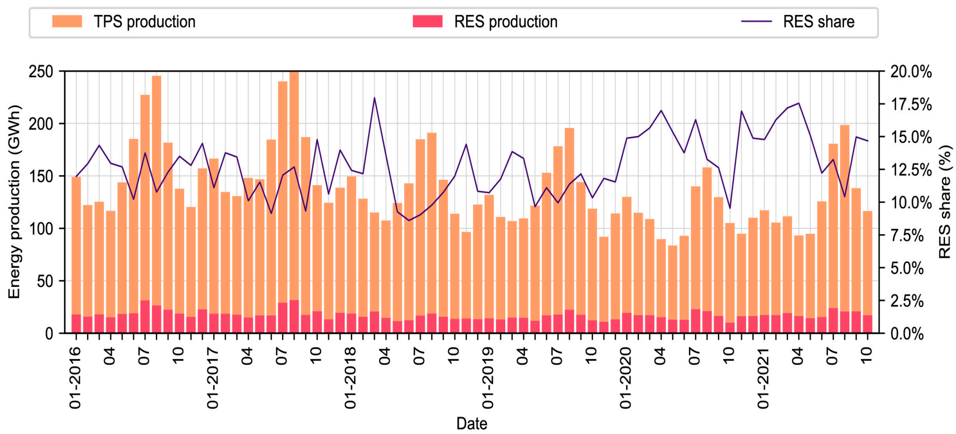


**Figure 2.** RES contribution in the electricity generation mix of remote Greek islands.

## 2. The GReco-Islands Initiative

Since 1990, several attempts have been made to ameliorate the entire electricity generation status of remote Greek islands by trying to drastically change the existing fuel mix in favor of RES [6]. Unfortunately, all the efforts undertaken during recent years did not take into consideration the previous experience of other similar attempts. The GReco-Islands initiative has the potential to combine all this experience and to offer an optimum development occasion for the reviving of several remote medium- and small-sized islands of Greece (and EU) scattered all around the Aegean and Ionian Archipelagos. To address the above challenges related to the quality of life of the local people, radical changes are required in a holistic concept including energy and water consumption, energy production, minimum environmental impact (including zero $CO_2$ emissions and zero air pollution), clean water and sewage management, mobility, waste management, and the available infrastructure.

Following the plans of the Greek authorities on investments to be made within the framework of the forthcoming Operational Programme for the Environment and Energy, there have been encouraging signs in the energy sector to maximize investments in RES, energy efficiency, and e-mobility [7]. A consensus was reached that the opportunities offered by the ERDF and the Cohesion Fund, in combination with the significant budget made available through the Recovery and Resilience Facility [8], offer a unique opportunity for a considerable shift towards sustainable energy production, efficient and rational energy consumption, and zero carbon dioxide emissions.

The concept of the "GReco Islands" aims to make a number of tourism-dependent islands carbon-dioxide-neutral and energy-positive. In combination with decisive actions towards the greening of tourism, state-of-the-art waste and water management, and e-mobility, this would allow for the establishment of a circular economy profile that could also be used as part of the branding and destination management for these islands. In order to develop this integrated zero carbon dioxide roadmap, some representative Greek islands were selected to be analyzed in detail in order to provide real-world examples of realistic green solutions and to estimate the size of the investment required. In the present work, the case study of the island of Patmos is analyzed.

## 3. Patmos Island General Situation

Patmos Island is located at the NW edge of the island complex of Dodecanese (Figure 3) and covers its electricity needs operating an APS of 7 MW. It is the eleventh largest island of the complex, having an area of 34 km$^2$. Despite its small size, the island's population was 3047 inhabitants in 2011, while according to the last census (2021), the population increased to 3217. The equivalent population (also considering island visitors on an annual basis) is estimated at 7000 people, based on which the new infrastructure works are being conceptualized.


**Figure 3.** Patmos location in the Dodecanese Complex.

The municipality of Patmos consists of the Patmos, Marathos, and Arkoi islands as well as numerous islets. In Patmos, there are four municipal districts; Chora is the capital of the island, and it is developed on a hill around of the renowned castle monastery of Saint Ioannis the Evangelist; the second one and the biggest is Skala, which is the port of the island, while there are also two other smaller villages, Groikos and Kampos. The north and south areas of Patmos Island are included in the National Important Areas for Birds in Greece. Finally, the Arkioi Islands, the islets near them, and mainly the southern marine area of Patmos are regions that are included in the Natura 2000 network. The economic activities of Patmos Island are of mild scale and are mainly concentrated around tourism. Actually, the primary sector of Patmos, especially the crop production, is deteriorated due to the geomorphological land type. The farming mainly includes sheep and goat farming as well as apiculture and fishing. Based on data from Region of the South Aegean [9], 14.4% of the Patmos population works in the secondary sector. Very important aspect of touristic development is religious tourism and the Cave of Apocalypse as well as the Monastery of Saint Ioannis at Chora of Patmos. The maximum number of hotel beds in

Patmos is estimated to be 5500, which denotes the touristic development of the island when compared to the 2900 hotel beds in 2013–2014.

## 4. The Main Problems of Medium-Sized Islands: The Patmos Case Study

Similar to the majority of the remote islands of the Aegean Archipelagos, Patmos Island covers its annual electricity demand mainly on the basis of the existing diesel-based thermal power station. According to the official data by PPC [4], in Patmos, the autonomous power station (APS) operates seven diesel-consuming engines with rated power equal to 1100 kW each and $CO_2$-specific emissions coefficient equal to 750–800 gr/kWh$_e$. The corresponding peak load demand of the island is almost 6.1 MW for 2021. The APS is located at the center of the island, near the settlement of Scala. Furthermore, at the northern end of the island, there exist two (2) wind turbines of 1.2 MW (2 × 600 kW), with total $CO_2$-specific emissions coefficient equal to 10–20 gr/kWh$_e$ and 160 kW$_p$ of photovoltaic installations ($CO_2$-specific emissions coefficient equal to 20–40 gr/kWh$_e$). Subsequently, analyzing the most recent data concerning the electricity consumption of Patmos Island [4], one may observe a slightly increasing trend from 17,000 MWh$_e$ during 2014 to almost 20,000 MWh$_e$ during 2021. Moreover, the corresponding annual electricity consumption of the existing water management units is approximately 1300 MWh$_e$, representing 7–8% of the total electricity consumption of the island.

During this period and especially during the last five years, the RES contribution has been approximately 3000 MWh$_e$, i.e., almost 15% of the island's electricity consumption (Figure 4). As far as the electricity production data of the last year is concerned, one may note that the mean variable electricity production cost of the local APS may well exceeded 350 EUR/MWh$_e$. Finally, based on the available data, the electricity consumption of Patmos Island presents the well-known seasonal variation (Figure 4) of the most touristic islands in Greece since the daily electricity demand varies between 30 MWh$_e$ and 120 MWh$_e$.

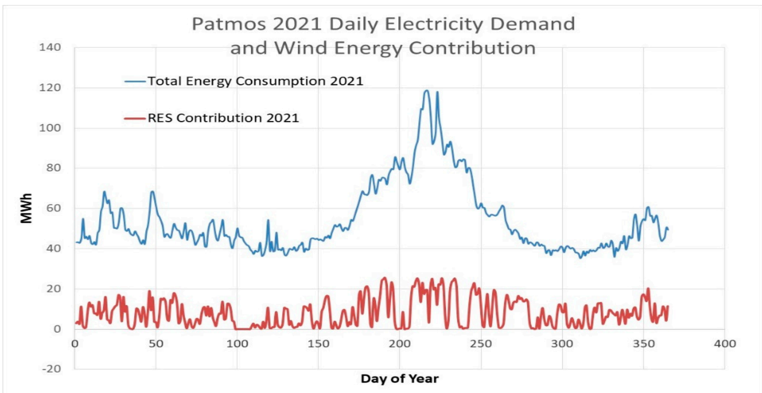


**Figure 4.** Electricity Demand vs. Wind Energy Production for Patmos Island.

On top of the electrification problems, Patmos Island is also facing a chronic shortage of water resources since its annual precipitations are quite limited. More specifically, Patmos Island faces very modest precipitation values since the total accumulative rainfall is about 435 mm (country average 650–850 mm of $H_2O$) (Figure 5). Since 1996, clean water has been imported by water tanks in an ever-increasing amount, offering an unsustainable and economically unprofitable solution. In 2005, the Livadi Dam was completed, providing a capacity of 455,000 m$^3$ that was expected to cover a large part of the irrigation needs. At the exit of this dam operates the Geranos water refinery. At the beginning of June 2017, two desalination units with a capacity of 2 × 600 m$^3$/day of drinking water were completed and delivered in operation. The cost of the two above-mentioned desalination units was in the order of EUR 1 million, while only the annual average cost of transporting water was higher. Thanks to desalination units, the water-needs coverage improved, especially for Skala and Chora of Patmos. Finally, the Geranos water refinery also provides a contribution with an estimated capacity of some 150,000 $m^3$ and a maximum daily production of 500 $m^3$. Taken together, the desalination units and the Geranos water refinery should be sufficient to cover the entire consumption for Patmos even during the summer season, although in some cases limited water shortages have been encountered during August, especially in case of a temporary water desalination unit malfunction. Actually, the local situation is quite intense due to the excessive touristic activity of the island; e.g., during the last August, the number of visitors approached 18,000 people. On the basis of the existing official data (Figure 6), the maximum daily production of the existing two desalination units along with the Geranos water refinery is 1780 $m^3$/day [10]. Moreover, it is important also to mention that the maximum clean water demand coincides with the corresponding peak load demand of the island due to the intense touristic activity of July and August. To this end, one may state that the corresponding average annual electricity consumption of the water management facilities of Patmos Island is almost 1500 $MWh_e$, representing almost 45% of the total electricity consumption of the Patmos municipality. The clean-water-production-related $CO_{2eq}$ emissions may even exceed 1200 tn per year.

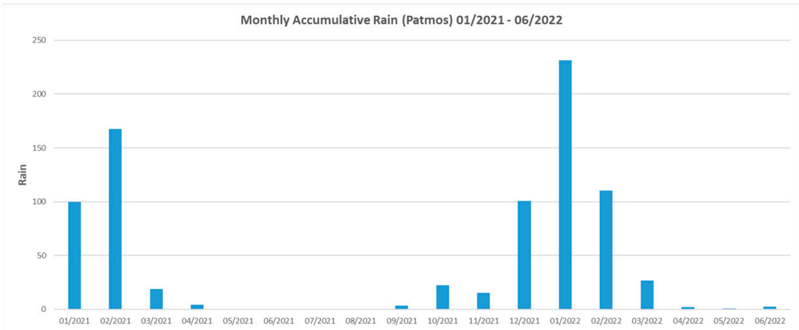


**Figure 5.** Monthly Precipitation values for Patmos Island.

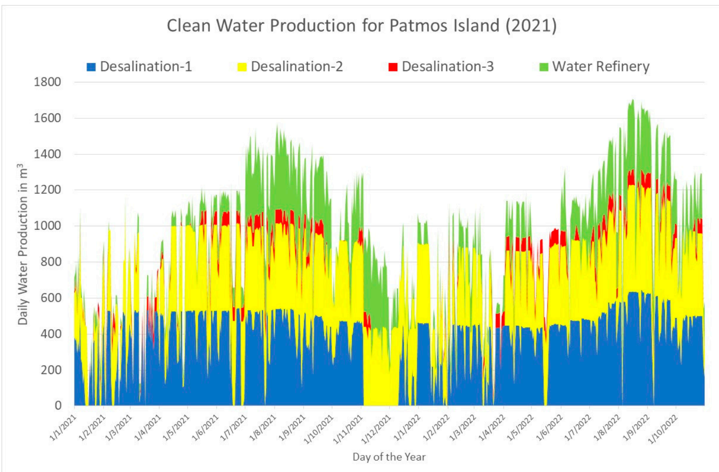


**Figure 6.** Clean Water Production for Patmos Island.

## 5. Proposed Solutions

Patmos Island can be characterized as a windy island; hence, the corresponding capacity factor [11] of the existing WTs is fairly high (more than 30%), taking into consideration the available long-term data by the quite old, existing WTs and the curtailments imposed by the local network manager [12]. Moreover, the cloudy days during the year are estimated at 39.3%, mainly from January to March. Thus, the long-term solar energy potential [13] on an annual basis varies between 1650 and 1800 kWh/$m^2$ on the horizontal plane.

Taking into consideration the excellent solar potential of Patmos Island, PV systems can operate either as connected to the Hellenic Electricity Distribution Network Operator

(HEDNO) grid system or as autonomous installations. For the second option, a suitable energy storage system (ESS) (or reserve system) should complement the PV system in order to ensure load demand satisfaction even in the case of sunshine absence [14]. Applying well-documented methodology [13,14], the expected solar electricity generation exceeds 1500 $kWh_e$ per $kW_p$ as installed on Patmos Island; thus, the corresponding annual capacity (or utilization) factor CF has been calculated as equal to 18.8%. Nevertheless, the specific energy requirements could be satisfied with PV installations spread throughout the entire island's territory and not only with a PV installation concentrated in a specific location. To this end, Patmos Island could cover its electricity needs with 13 $MW_p$ PV modules in the case that the proposed solution is based exclusively on PV panels. As a first urgent application and in order to find a potential clean-green energy solution for the energy consumption of Patmos Island's potable water infrastructure, the possibility of exploiting the high solar potential of the island near the Livadi water reservoir (located in the NE part of the island) is under investigation. Actually, by installing 600 $kW_p$ to 1000 $kW_p$ PV panels, they may produce annually 1000 to 1600 $MWh_e$ by covering only 8000 to 12,000 $m^2$, while the expected (current) investment cost varies between EUR 0.9–1.2 million.

As already mentioned, the wind potential of the island is quite high, while the WTs operate during the entire 24-h timeframe with sufficiently high capacity factor "CF" (leading to approximate energy generation in the range 2000 to 3000 $MWh_e$ per MW installed) [11]. Furthermore, one should also take into account their complementary nature as related to photovoltaic (PV) systems (winter–summer). Thus, for the Patmos Island case, one may need six (medium–small-sized) 900 kW WTs on top of the 2 × 600 kW already in operation in order to meet the current electricity demand. However, the number of these WTs can be decreased in the case that rational PV installations are implemented in parallel.

Finally, for each one of the available RES technologies (solar energy and wind energy), a number of different energy scenarios may be selected in order to satisfy the all of Patmos Island's energy needs—including the seawater RO desalination units (see Table 1). Moreover, the gradual introduction of electro-mobility to the island of Patmos, not examined here in detail, improves even more the green transition concept of the GReco-Islands initiative. Using the experience by analogous projects in other similar-sized islands, the electricity consumption expected by a typical private electric vehicle (EV) is approximately 2 $MWh_e$ per year. On the other hand, the fuel savings are almost 1000 lt of petrol or diesel oil, and the expected $CO_2$ emissions avoided approach the 1.2 tn per year [15].

**Table 1.** Proposed RES-based solutions and the corresponding $CO_2$ emissions savings.

| Number and Size (kW) of WTs | Wind Farm Rated Power (kW) | PV Plant Rated Power ($kW_p$) | Total Hybrid Power Plant Energy Generated ($MWh_e$) | Annual $CO_2$ Emissions Savings (tn/Year) |
|---|---|---|---|---|
| 2 × 900 | 1800 | 1000 | 6890 | 5512 |
| 2 × 900 | 1800 | 2000 | 8280 | 6624 |
| 2 × 900 | 1800 | 5000 | 12,450 | 9960 |
| 2 × 900 | 1800 | 9000 | 18,000 | 14,400 |
| 4 × 900 | 3600 | 1000 | 12,400 | 9920 |
| 4 × 900 | 3600 | 2000 | 13,800 | 11,040 |
| 4 × 900 | 3600 | 5000 | 17,950 | 14,360 |
| 4 × 900 | 3600 | 9000 | 23,500 | 18,800 |
| 6 × 900 | 5400 | 1000 | 17,900 | 14,320 |
| 6 × 900 | 5400 | 2000 | 19,300 | 15,440 |
| 6 × 900 | 5400 | 5000 | 23,450 | 18,760 |
| 6 × 900 | 5400 | 9000 | 28,990 | 23,192 |

One of the most interesting solutions implemented in remote islands, as they are characterized by plentiful RES resources, is the installation of hybrid power plants or hybrid renewable energy systems (HRES) [16]. These specific power plants are comprised of various configurations of the considered constituents (for example, PV systems with WTs, etc.), whereas their target is the complete exploitation of the available RES potential. To this end, several configurations of potential RES-based hybrid power solutions may be examined in order to satisfy the island's total energy requirements given the constraints (e.g., minimum land use) and the targets of the analysis (e.g., max autonomy with rational investment cost or/and zero carbon dioxide emissions). In Table 1 are presented some potential RES-based solutions for the island of Patmos, covering a remarkable electricity consumption load along with the annual $CO_2$ emissions savings in comparison with the current situation.

For the implementation of such drastic changes as the ones related with the GReco-Islands concept, in similar isolated communities, it is vital to communicate with the local authorities and the local society as well as with the major stakeholders in order to facilitate and support the entire procedure. According to long-term discussions, the local authorities are interested in participation in the GReco-Islands initiative, also supporting the mild introduction of RES applications in their areas. Furthermore, the local societies of remote islands are usually optimistic towards similar clean-green electricity and water production efforts; however, they express their concern about the size of the necessary interventions and whether this concept is going to really improve their lives and their economic status.

## 6. Investment Cost and Carbon Dioxide Elimination

Taking into account that the electricity consumption needs of Patmos Island range between 20,000 and 25,000 $MWh_e$, one may need a total investment of approximately EUR 30 million in order to cover the electricity needs of almost 25,000 $MWh_e$ per year (using both PVs and WTs), to provide 450,000 $m^3$ of clean water on an annual basis, and replace 500 private cars based on internal combustion engines (ICE) with an equivalent number and type of EVs. Moreover, the installation of an appropriate energy storage system depends on the carbon dioxide target to be adopted since Patmos already operates the local autonomous thermal power station that may assist the energy system in cases of low production of the RES-based hybrid power station. Note also that the majority of the solutions offered in Table 1 are modular; thus, one can easily provide additional power if required.

At this point, it is important to mention that in case of the RES-based electricity and water-needs autonomy of the island, the maximum $CO_{2eq}$ emissions avoided approach 16,000 tn per year plus almost 1000 tn due to the replacement of the old-technology cars (Table 1). The proposed solution will be in operation for the next 15 to 20 years; hence, the corresponding $CO_2$ reduction cost for Patmos Island on a life-cycle basis varies between EUR 90 and 120 per tn, a value completely comparative with the current $CO_2$ emissions tax.

Furthermore, the annual operation and maintenance cost of the proposed solution may require an additional EUR 500,000 at maximum. Note that this is the amount paid by the Patmos municipality during 2020 for covering only its own electricity consumption. For the entire island, the annual electricity consumption cost is more than EUR 2.5 million. In this context, one may also create additional new job positions for the operation of the proposed hybrid power solution, the safe and reliable operation of the water management system, and in order to provide service for the new EVs of the island.

In the course of time, an attempt should be made for Patmos Island to replace the local boat fleet with new boats operating with clean electricity or with green hydrogen. The important issue here is that the proposed solution is modular, while some parts of the proposed integrated solutions have already safeguarded state subsidization.

## 7. Conclusions and Proposals

After a thorough analysis of Patmos Island's status as a representative, small–medium-sized Greek island, it is clear that currently, the contribution of RES is less than 15%. However, using the excellent RES potential (e.g., solar/wind) of the Aegean Archipelagos, one may reverse this situation, increasing the RES contribution in the range of 80% during the next 3 to 5 years and minimizing the corresponding $CO_2$ emissions. Moreover, taking into consideration the strong water deficit of almost 450,000 $m^3$ for Patmos Island, the utilization of RES-based desalination and the improvement of local water networks will minimize the oil-based electricity consumption, especially during the summer period. Finally, taking into account the limiting size of the corresponding road network, the introduction of electro-mobility based on green electricity production will significantly reduce (by 30% to 50%) the corresponding oil consumption and the corresponding $CO_2$ emissions.

Finally, the proposed RES-based solution's initial investment cost, for an integrated green-clean energy solution, is in the order of EUR 5000 per capita (including visitors) or approximately less than EUR 10,000 per capita (permanent population). This capital invested will be amortized in less than five years by simply taking into account the electricity production cost of Patmos island and the corresponding potable water production cost. On top of these financial savings, the corresponding $CO_2$ reduction cost for Patmos island, on a life-cycle (15–20 years) basis, can exceed EUR 1.5 million per year by simply taking into consideration the current value of $CO_2$ emissions tax.

To this end, it is clear that the implementation of the GReco-Island concept will drastically improve the energy and water supply security for similar small- and medium-sized islands, improving the quality of life of the local habitants and eliminating the carbon dioxide emissions at a rational investment cost.

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