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Autonomous desalination for improving resilience and sustainability of water management in North Cyprus

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ABSTRACT

The study explored the potential of creating an alternative water resource through autonomous desalination of seawater and/or brackish water based on available renewable energy sources. The evaluation was carried out for different levels of water demand in remote rural areas and tourism activities where water scarcity and lack of electricity infrastructure coincides with availability of renewable energy sources. Abundance of solar power (up to 2,100 W/m^2) in North Cyprus makes autonomous desalination based on photovoltaic (PV) power an attractive and sustainable alternative resource for water supply: 1 MW PV powered reverse osmosis desalination plant in North Cyprus is estimated to produce 1.15 million m^3/year and 0.32 million m^3/year of freshwater from brackish water and seawater, respectively. This suggests that PV-run autonomous desalination process implemented at different sites with varying capacities could supply the total municipal water demand using a total PV panel area of only 0.25 km^2 for brackish water and 0.70 km^2 for seawater. Hence an integrated water management plan should consider PV-run desalination systems along with the current applications in order to improve the resilience and sustainability of its water resources potential.

Keywords: Autonomous desalination; Renewable energy; Water management; Solar energy; Photovoltaics (PV); North Cyprus

1. Introduction

Energy and water supply stay at the heart of public services that require continuous conceptual and technical updating as a result of the challenges faced in terms of sustainability. In view of the predictions made by recent climate models that foresee frequent water scarcity problems for the Mediterranean region, there is urgent need to consider and evaluate non-conventional resources based on renewable energy within comprehensive management plans for water supply [1,2]. This approach would be specifically appropriate for North Cyprus (NC), which houses a population of 377,000 with a total water demand of 84 million m^3/year; human activities including municipal use, tourism and education amount to more than 50 million m^3/year, together with 34 million m^3/year consumed by agriculture and livestock farming [3]. This demand should be evaluated in view of the fact that North Cyprus has long been experiencing the serious constraints of limited water supplies. The two most important aquifers, namely Magosa and Güzelyurt,

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suffer from complete salinization due to over-abstraction [4] while other resources also fail to qualify as drinking water unless they receive proper level of treatment. Hence, Turkey resorted to transporting a massive water supply of 75.5 million m^3/year to North Cyprus for domestic and agricultural use. The project was completed and started to deliver water to the island in January 2018 [3]. Water transfer from Turkey may help mitigate the freshwater shortage in North Cyprus, alternative resources will also play a significant and valuable role for the ultimate sustainable solution for water resources management in the country.

Energy supply in North Cyprus has been depending heavily on fossil fuel powered systems. The electricity generation is dominated by diesel generators that make up 99% (318.27 MW) of the installed capacity and there is a single 1,275 MW photovoltaic (PV) power plant in Serhatköy in the Güzelyurt region that supplies renewable energy to the grid; Serhatköy PV plant produces approximately 2,000 MWh energy per year. As a country blessed with abundance of renewable energy (RE) resources, especially, solar and wind energy, North Cyprus should seek every feasible application to enjoy the benefits RE sources have to offer. In addition, the seasonal variations in water demand require systems that respond well to such demand patterns which also favor implementation of RE run water treatment systems in NC, where high demand coincides with peak RE production potential.

Desalination, a key process in water stressed areas [5], is performed using membrane technologies such as reverse osmosis (RO), nanofiltration (NF), and electrodialysis: The latter using electric current for moving ions through membranes is a costly process, mostly applied only for brackish water desalination (500–10,000 mg/L TDS – total dissolved solids); RO and NF units are the most commonly used desalination units for seawater and brackish water, respectively; the NF technology alone cannot be used for desalting seawater to freshwater, it but can be successfully used to treat mildly brackish water. The RO membrane is operated under a hydrostatic pressure higher than osmotic pressure of the feed; the concentration gradient created across the membrane drives the liquid through the membrane as permeate, while salts are retained and concentrated on the influent side of the membrane. RO membranes are used to treat highly saline waters (TDS: 10,000–60,000 mg/L) and mostly to desalinate seawater (TDS: 30,000–45,000 mg/L) as well as to recover brackish waters [6].

The progress in desalination technology enables water management based on "fit for purpose" concept in which water is produced to meet specific quality requirements, that is, high quality water for drinking purposes (TDS < 400 mg/L) and lower quality water for irrigation purposes (TDS < 1,600 mg/L). Energy consumption for desalination systems depends on the feed pressure and desired flow rate. Typically, the electricity consumption of an RO plant to produce one cubic meter of freshwater from seawater is between 3 and 10 kWh, with an average value of 5.5 kWh/m^3 and between 0.5 and 2.5 kWh/m^3 from brackish water [7].

Autonomous desalination system (ADS) is a concept where saline and/or brackish water treatment is coupled with renewable energy supplies. In literature such systems are often advised for rural areas with no water and grid connection, but have access to non-conventional water resources and having an appropriate level of renewable energy (RE) potential. It is also argued that feasibilities of these systems are satisfied considering the avoidance of the costs for building new network connections for both water and electricity [8]. Many PV–RO desalination units have been installed worldwide with capacities ranging from 0.1 to 60 m^3/d for brackish water and 0.5 to 120 m^3/d for seawater [5]. This concept is perfectly applicable for North Cyprus, which is replete with solar and wind energy at desired proportions, which may be required to create alternative water resources.

In this context, the objective of the study was to explore the potential of alternative water supply through autonomous desalination of seawater and/or brackish water based on available renewable energy sources. The evaluation was carried out for different levels of water demand in rural areas and tourism activities.

2. Current situation in North Cyprus

2.1. Water resources and utilization in NC

Water stress in NC has been an important issue since 1960's. NC has 13 aquifers, the major aquifers being Güzelyurt, Lefke, Girne and Famagusta which used to provide 74.1 million m^3/year whereas surface water resources and reservoirs used to supply 20 million m^3/year. It has been reported repeatedly in literature that water abstraction in NC from aquifers is very well above their safe yields [9,10]. According to data of State Hydraulic Works, total safe yield of aquifers in NC is 74.1 million m^3/year; however, the withdrawals amount to 103 million m^3/year.

Elkiran and Turkmen [4] summarize the historical water stress starting with complete salinization of Magosa aquifer on the eastern part of NC followed by salinization of Güzelyurt aquifer on the western side up to 5,000 mg/L TDS resulting in tap water being unsuitable for drinking. Water delivered to households by the municipalities has between 1,000 and 2,500 mg/L TDS.

Before the massive water transport project from Turkey [1], the freshwater supply of North Cyprus (NC) was consisted of groundwater (75.5%) and dams (20.4%) [9]. Municipal water was delivered from wells and springs, whereas irrigational water was supplied from local aquifers and irrigation dams. The 66.5 km long transportation line to transfer 75.5 million m^3 water per year to NC from Turkey (Alaköprü Dam) has started to deliver water in January 2018. Although water transportation from Turkey is assumed to solve the water shortage problem, currently it is not delivered to the whole island. Only 14 of the 28 municipalities deliver TR water, while others supply TR water and local resources, and Lefke, Akıncılar and Famagusta municipalities still provide water from their own water resources (Fig. 1).

A recent study [3] conducted on the assessment of water requirements of different utilities in North Cyprus indicated that the basic water demand for human activities (including municipal, tourism and education) amounted to 50.6 million m^3/year, of which the overall municipal activities accounted for 40.3 million m^3/year, 80% of the total demand. 72% of the municipal demand was supplied by

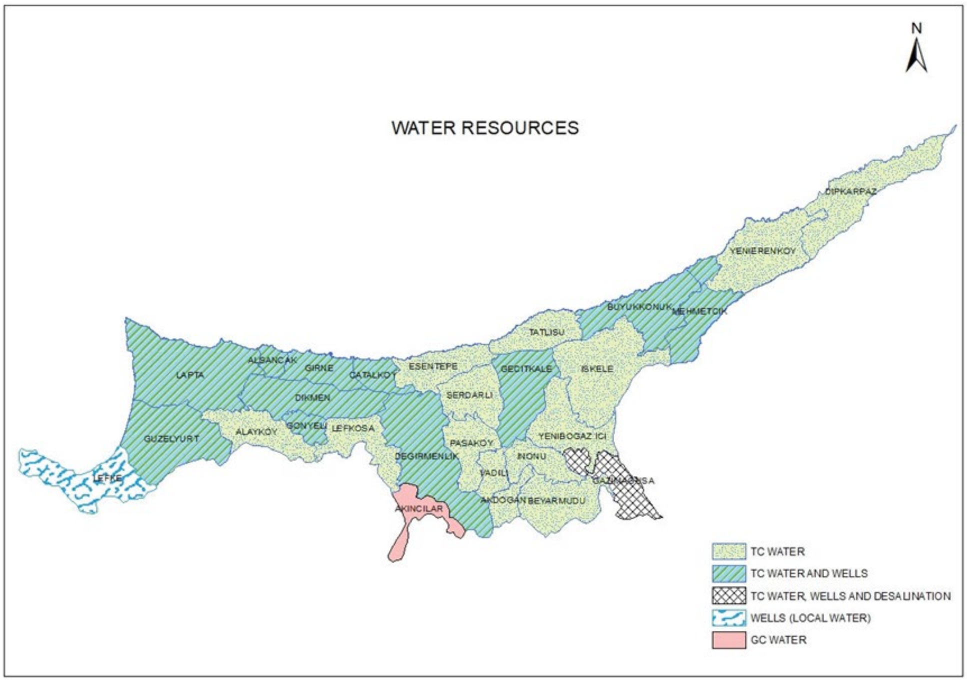

Fig. 1. Water resources distribution in North Cyprus [3].

the transported water from Turkey, 23% by groundwater and 5% by desalination systems. The study assessed the actual overall water demand of NC as 84 million m^3/year, where agriculture and livestock farming amounted for 40% of this demand. The current available water resources in the country were assessed as 109 million m^3/year, mainly greater than the overall water demand. However, available water did not exceed so far 20–25 million m^3, due to poor operation of the system.

It is also important to note that the water consumption per capita ranges between 180 and 600 L/d at different parts of the island mainly depending on residential density and concentration of tourism and agricultural activities. Consumption rates below 300 L/ca.d mainly belong to residential areas and above this value belong to areas with high population density due to tourism activities (Girne and Iskele), university campuses (Lefkoşa, Girne and Famagusta) and areas of agricultural (barley, wheat, oat, potato, citrus; cattle and sheep) and industrial (dairy) activity.

2.2. Energy generation in NC

Electricity production in NC almost entirely depends on fossil fuel–powered generators. There are three active energy plants of 362 MW installed capacity that burns Fuel Oil No.6 to produce 1,615 GWh electricity in 2017. The energy consumption has increased by 11.9% and 4.5% in 2017 compared with 2015 and 2016, respectively. Energy consumption peaks in July and August reaching up to 178,036 kWh/month.

2.2.1. Renewable energy potential and utilization

An assessment of solar and wind power generation in urban regions of NC, namely Girne and Lefkoşa was recently reported by Kassem et al. [11]. Based on data collected on wind speed, sunshine duration and solar global radiation over 9 years for each location, their analysis has shown that mean wind speeds at Girne and Lefkoşa were both over 2 m/s at 10 m height (2.505 and 2.536 m/s, respectively) and the annual mean sunshine duration and global solar radiation were higher than 7 h/d and 15 MJ/m^2/d at a height of 2 m for all studied regions, respectively. Kassem et al. [11] claim that Girne and Lefkoşa have huge solar potential and actual market opportunities for investors to develop grid-connected PV projects compared with wind farm projects.

Kassem and Gokcekus [12] reported that maximum solar radiation potential in Lefke was observed during July averaging 315 kWh/m^2 followed by August 300 kWh/m^2, which are also the months with peak energy demand. They also estimated yearly electricity production of a grid-connected 1 MW PV power plant in Lefke to be between 1,804 and 2,498 kWh depending on the tracking modes applied and two-axis tracking system to be the most economical option.

2.2.2. Serhatköy PV plant

The only grid-connected renewable energy power plant in NC is the 1,275 MW PV power plant in Serhatköy. The plant was commissioned with the financing received from the EU environmental sustainability program and started to deliver electricity to NC grid on May 2011. Serhatköy PV plant costed about 3.7 million EUR.

The plant consists of 6,192 panels made up of polycrystalline solar cells and 86 group inverters. Total area of the solar park is 21,600 m^2 (L: 120 m and W: 180 m). The electricity generating area of the park is 8,412 m^2. The solar park is made up of two columns of 21 and 22 rows of PV panels [13].

The tilt angle for the plant is 24.84° with annual solar radiation of 2,000 kWh/m^2. Serhatköy PV plant produced between 1,720 and 2,053 MWh energy between 2013 and 2017, yielding capacity factor (CF) values ranging between 15.4% and 18.2%, which is considered efficient in view of the industry standard for PV (15%–25%).

A 900 kW capacity PV power plant was installed very recently (May, 2019) by a private telecommunication company in Vadili district of NC. The plant is expected to produce 1.5 GWh electricity per year. The PV plant costed about 1 million EUR.

2.3. Desalination practice in NC

Desalinated water takes up only 3.8% of the total water supply in NC. Seawater desalination for public water supply is practiced in Famagusta (5,500 m^3/d) and certain other tourism units (9,400 m^3/d). Elkiran and Turkman [4] reported that cost of desalinated water was between 0.7 and 0.84 USD/m^3 for two coastline desalination plants having capacities between 1,000 and 2,000 m^3/d.

Poor quality (TDS: 1,000–2,000 mg/L) water delivered to households in NC has led to the use of energy intensive roof-top reverse osmosis (RO) desalination units for drinking water production or buying water from water vendors (0.14 USD/L). However, the cost of electricity (0.7 USD/kWh) in NC has made RO unattractive for the users.

Contribution of desalination plants to freshwater supply on the southern part of the island, on the other hand, is very high. Currently there are four seawater desalination (RO) plants in operation in the region, at Dhekelia, Limassol (Episkopi), EAC Vassilikos and Larnaca, while the construction of a desalination plant in Paphos is in progress, which is expected to start operating at the end of 2019. The total amount of freshwater production from these plants is yearly about 65 million m^3. Average unit cost for desalination was reported as 1.08 EUR/m^3 whereas the average specific power consumption was 4.0 kWh/m^3 [14].

3. ADS as a sustainable solution for water management

3.1. ADS worldwide

Autonomous desalination system (ADS) is gaining more attraction in many regions as a tool to balance the progressive dependence on fossil fuels and considered as a highly innovative trend [15]. Application and performances of ADS have been reported worldwide [16–18]. PV–RO plants have been treating seawater with TDS values up to 45,000 mg/L in Abu Dhabi with 11.25 kW PV power to produce freshwater at 20 m^3/d; and brackish waters of 3,480 mg/L TDS in Southern Cyprus with 10 kW PV power to produce 50.4 m^3 of freshwater daily. Other PV–RO plants have been successfully operated in Spain (SW-ADS, 1.24 m^3/d 4.8 kW PV), Tunisia (BW-ADS, 10.5 m^3/d 7 kW PV), Brasil (BW-ADS, 6 m^3/d 1.1 kW PV) and Jordan (BW-ADS, 58 m^3/d 16.8 kW PV). The unit costs for PV–RO treatment were reported between 35.9 and 2.5 USD/m^3 [16].

Two small-scale ADS plants were installed and operated in Turkey to demonstrate the ADS potential supported by a EU-financed project in 2007. A 7 m^3/d PV-NF plant was installed at a public school to desalinate brackish water (TDS: 1,500 mg/L) (Fig. 2a) and a 2 m^3/d PV–RO plant was installed at a tourism complex to desalinate groundwater with high seawater intrusion (TDS: 7,500 mg/L) ((Fig. 2b) [19]. Both plants were run by PV panels each having 2.88 kW installed power (36 panels, each with 80 W installed power). The energy demand for these small-scale research project units of NF and RO plants was 3.19 and 15.82 kWh/m^3, respectively, with an average capacity factor of 19% for PV panels.

The data obtained from the small-scale ADS in Turkey and the reported PV performance in North Cyprus can be combined to simply estimate the freshwater output from an ADS with the same installed PV power in North Cyprus. It is estimated that a 2.88 kW PV powered NF type small-scale ADS (<25 m^3/d) unit in North Cyprus is able to produce 1,500 m^3 of freshwater per year [20,21]. The same PV area can produce minimum of 3,140 m^3 of freshwater per year in the case of a medium to large-scale ADS (25 m^3/d up to >1,000 m^3/d), which is equivalent of the seasonal freshwater demand of a 60 bed tourism complex or that of 290 students in a public school (Table 1).

It should also be considered that costs of both membrane and renewable energy technologies are decreasing over time. The major cost component in desalination is the power requirement and this has dramatically decreased (down to 2 kWh/m^3 for seawater) due to development of more efficient membranes, the use of energy recovery systems, new materials with less friction and variable speed engines [15].

In principle, the discharges from small communities will essentially require a well-engineered disposal system to the marine environment. The outfalls with properly designed diffuser systems will ensure adequate initial dilution and dispersion which will match the salinity level of the environment.

3.2. ADS for Cyprus

NC is a suitable candidate for implementation of ADS concept. Huge solar power availability (Serhatköy 1,275 MW PV plant; average: 244 GWh/year km^2) and mostly urban character in NC, suggests PV panels as the renewable energy component of the ADS that can be built readily in urban environments without loss of efficiency and residential disturbance [23]. Desalination, on the other hand, could be implemented through appropriate filtration units, that is, RO and/or NF, depending on the quality of the feed, that is, sea and/or brackish water and the intended use (drinking water, tap water, irrigation, etc.) for the desalinated water. In NC, water resources are almost entirely non-potable groundwater resources with high salinity (TDS = 5,000 mg/L). Brackish water desalination (BW-RO) requires considerably lower investment and operational costs compared with seawater desalination (SW-RO). NF membranes can be used in desalination of brackish waters that have lower operating pressures and energy requirements [24].

ADS also offer some other advantages in renewable energy utilization. One of the challenges in grid-connected renewable energy supply systems is that these systems cannot perform constant and stable energy supply to the grid. A PV system will produce electricity during sunshine hours and will cease electricity production soon after sunset.

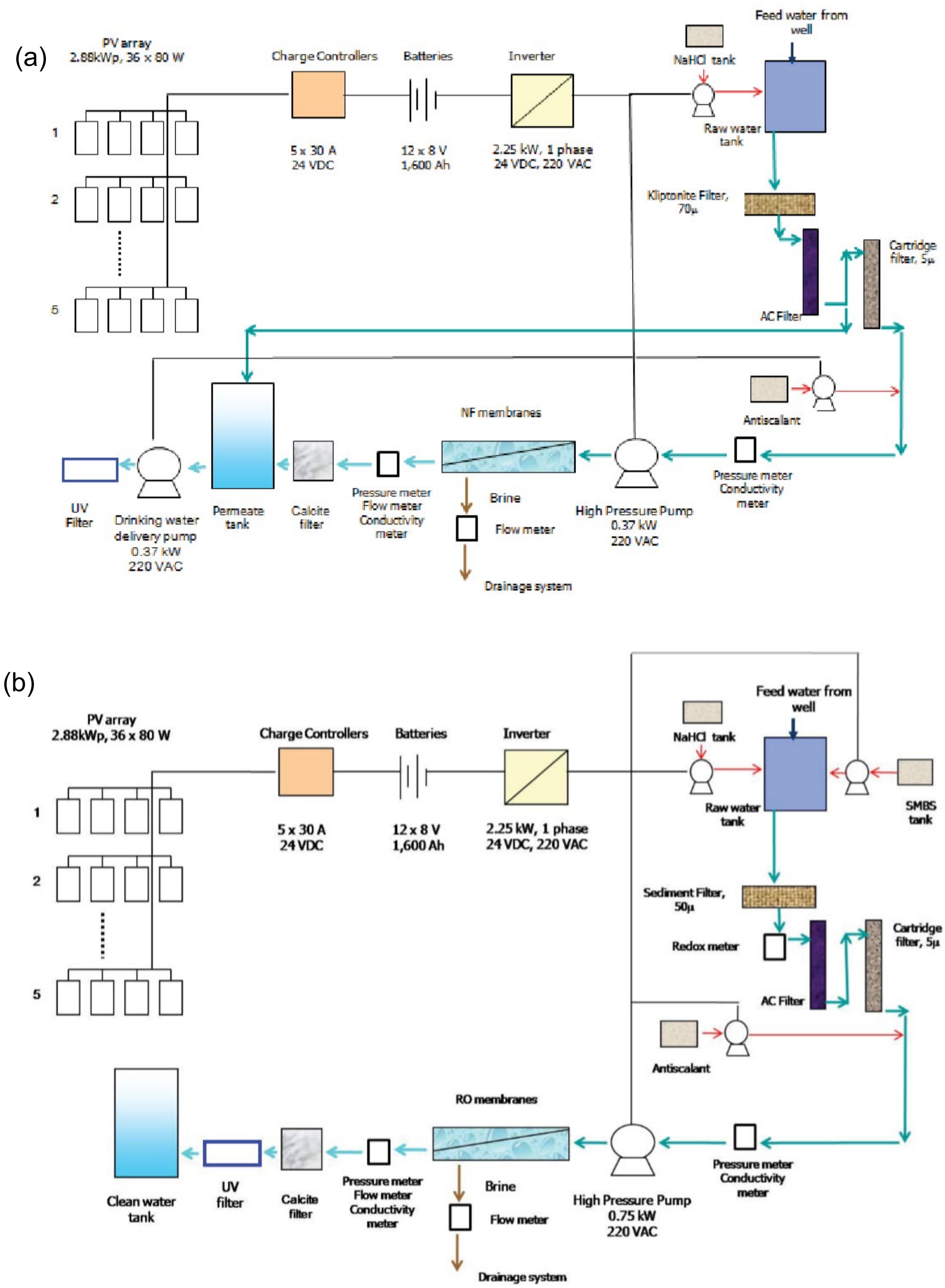

Fig. 2. Process flow diagrams for ADS implemented in Turkey (a) PV–RO plant in tourism complex and (b) PV-NF plant in elementary school [19].

Therefore, there is a safe limit in terms of capacity (up to 10% of the total installed capacity) for diversifying a grid mix with renewables. In case of an ADS, that is, a stand-alone unit having no connection to the grid does not create any problem since all electricity generated will be directed to producing freshwater. ADS systems will be producing water during daylight practically when there is demand for fresh water and any excess water produced can be stored in a water tank.

According to the land distribution of NC, the country has a huge potential for PV-run ADS. Total land area is 3,354 km^2 of which 57% is agricultural land, followed by 20% forest

Table 1
Estimated PV module areas required to run desalination plants to produce freshwater for typical residential units

	Residential unit			
	School	University	Tourism plant	Summer-house
Electricity production from PV units (kWh/m^2) [22]	166.5 (Sept.-May)		99.8 (June-Sept.)	140.8 (June-Sept.)
Daily water demand (L/ca.day or L/bed.day)	30	150	500	250
Students/inhabitants/beds (#)	220	600	60	100
Time span (d)	270	270	120	120
Annual water demand (m^3/year)	1,800	24,300	3,240*	3,000
Fresh water production per m^2 PV area				
Brackish water (m^3/m^2)	111	111	67	94
Seawater (m^3/m^2)	40	40	25	35
Total PV area required				
From brackish water (m^2)	20	220	50	35
From seawater (m^2)	45	600	130	90

*Occupancy rate assumed as 90%.

land, 11% urban land and 5% grassland. Area non-used is about 268 km^2 [3].

The evaluation of the merit of PV systems for operating autonomous desalination units may be carried out, based on the following related data: (i) In NC, PV systems can potentially produce 244 GWh/km^2/year; (ii) On the average, desalination (RO) units require 1.5 kWh/m^3 to generate fresh water from brackish water and 4.0 kWh/m^3 when they operate with seawater. In this context, from a theoretical standpoint, recently calculated 40.3 million m^3/year of municipal water demand [3] can be met with a total of 0.25 km^2 of PV panel, placed in multiple fragments at different suitable locations in North Cyprus, when using a brackish water source; for seawater, the required PV area needs to be increased to 0.70 km^2. The area requirement to produce 1 million m^3 of water per year is much more smaller than the one calculated as 15 km^2 in a similar study [21].

It should be noted that the study only explored the potential and the merit of autonomous desalination and obviously did not intend to provide solutions to specific cases. It only includes the fundamental energy balance calculations, which basically indicate the available solar energy level that would be diverted to solve the water shortage problems at any feasible/desirable ranges. In this context, however, the basis of possible applications was evaluated as presented in Table 1, for four different facilities, namely primary school, university, a tourism resort and a summerhouse complex that would be operative during different periods of the year. Table 1 also indicates different energy production rates (kWh/m^2) corresponding to each related period, derived from monthly solar energy data presented by Yenen [22]. The annual average electricity production from PV panels was determined as 244 kWh/m^2. The primary school was assumed to house 220 students with a unit water consumption of 30 L/ca d, yielding a total water demand of 1,800 m^3 for the school period between September and May, where the magnitude of energy production from PV panels was computed as 166.5 kWh/m^2. Table 1 gives the corresponding PV panel area as 20 m^2 for brackish water and 45 m^2 for seawater. For all facilities, the PV panel area requirement ranges between 20 and 220 m^2 when using brackish water and between 45 and 600 m^2 for the seawater alternative. It should be noted that the data in the table does not stipulate individual desalination units for each facility, but a suitable joint supply, which would prove to be sustainable both from technical and economical standpoints.

This study is quite relevant: As in the case of North Cyprus, in many similar places/ islands in the Mediterranean the water problem could be solved at macro scale, but water shortage would still persist in remote areas with bad or no connection [25]. The study accounts for a sustainable solution that would solve the water problem in these areas based on available solar energy, which would otherwise be wasted.

4. Conclusion

Islands in the Mediterranean generally suffer from water scarcity problems together with quality deterioration of groundwater resources. At the same time, however, they are all blessed with sunshine and abundant solar energy. This study estimated the solar energy potential for North Cyprus as 244 GWh/year per km^2 of solar (PV) panel. This potential is huge and theoretically capable of being coupled with desalination units, which would provide the entire water demand of the island with around 0.25 km^2 of PV panel from brackish water and with 0.70 km^2 from seawater.

The study is quite significant for North Cyprus and all similar locations around the world, where available solar energy is diverted to a different significant application to convert unusable water bodies to new water resources for solving critical water scarcity problems where applicable. This presents a sustainable alternative to conventional electricity generation and local water heating.

The striking feature of autonomous desalination is that it can be operated with the required fragment of solar energy without being connected to the grid, since the produced electric power will be directly used for freshwater generation for the selected facilities in remote rural areas and tourism facilities. The capacity of the selected desalinization units needs to be tailored to ensure sustainable operation both from technical and economical standpoints.

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