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

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A B S T R A C T

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\textsuperscript{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\textsuperscript{3}/year and 0.32 million m\textsuperscript{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\textsuperscript{2} for brackish water and 0.70 km\textsuperscript{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\textsuperscript{3}/year; human activities including municipal use, tourism and education amount to more than 50 million m\textsuperscript{3}/year, together with 34 million m\textsuperscript{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,
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 mil-
lion m³/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 gen-
eration 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 mem-
branes 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, respec-
tively; 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 per-
meate, while salts are retained and concentrated on the influ-
ent 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 pro-
duce one cubic meter of freshwater from seawater is between
3 and 10 kWh, with an average value of 5.5 kWh/m³ and
between 0.5 and 2.5 kWh/m³ 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 sys-
tems 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 m³/d for brackish water and 0.5 to 120 m³/d for seawater
[5]. This concept is perfectly applicable for North Cyprus,
which is replete with solar and wind energy at desired pro-
portions, 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 autono-
rous 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
1960s. NC has 13 aquifers, the major aquifers being Güzelyurt,
Lefke, Girne and Famagusta which used to provide 74.1 mil-
lion m³/year whereas surface water resources and reservoirs
used to supply 20 million m³/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 m³/year; however, the withdrawals
amount to 103 million m³/year.

Elkiran and Turkmen [4] summarize the historical water
stress starting with complete salinization of Magosa aqui-
fer 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 m³ 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, Akincilar 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 indi-
cated that the basic water demand for human activities
(including municipal, tourism and education) amounted to
50.6 million m³/year, of which the overall municipal activ-
ities accounted for 40.3 million m³/year, 80% of the total
demand. 72% of the municipal demand was supplied by
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 m³/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 m³/year, mainly greater than the overall water demand. However, available water did not exceed so far 20–25 million m³, 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/cap.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/m²/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/m² followed by August 300 kWh/m², 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 m² (L: 120 m and W: 180 m). The electricity generating area of the park is 8,412 m². 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/m². 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 m³/d) and certain other tourism units (9,400 m³/d). Elkiraz and Turkman [4] reported that cost of desalinated water was between 0.7 and 0.84 USD/m³ for two coastline desalination plants having capacities between 1,000 and 2,000 m³/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 m³. Average unit cost for desalination was reported as 1.08 EUR/m³ whereas the average specific power consumption was 4.0 kWh/m³ [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 progress 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 m³/d; and brackish waters of 3,480 mg/L TDS in Southern Cyprus with 10 kW PV power to produce 50 m³ of freshwater daily. Other PV–RO plants have been successfully operated in Spain (SW-ADS, 1.24 m³/d 4.8 kW PV), Tunisia (BW-ADS, 10.5 m³/d 7 kW PV), Brasil (BW-ADS, 6 m³/d 1.1 kW PV) and Jordan (BW-ADS, 58 m³/d 16.8 kW PV). The unit costs for PV–RO treatment were reported between 35.9 and 2.5 USD/m³ [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 m³/d PV-NF plant was installed at a public school to desalinate brackish water (TDS: 1,500 mg/L) (Fig. 2a) and a 2 m³/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/m³, 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 m³/d) unit in North Cyprus is able to produce 1,500 m³ of freshwater per year [20,21]. The same PV area can produce minimum of 3,140 m³ of freshwater per year in the case of a medium to large-scale ADS (25 m³/d up to >1,000 m³/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/m³ 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 km²) 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.
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 km² of which 57% is agricultural land, followed by 20% forest land.
land, 11% urban land and 5% grassland. Area non-used is about 268 km² [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/km²/year; (ii) On the average, desalination (RO) units require 1.5 kWh/m³ to generate fresh water from brackish water and 4.0 kWh/m³ when they operate with seawater. In this context, from a theoretical standpoint, recently calculated 40.3 million m³/year of municipal water demand [3] can be met with a total of 0.25 km² 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 km².

The area requirement to produce 1 million m³ of water per year is much more smaller than the one calculated as 15 km² 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/m²) 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/m². 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 m³ for the school period between September and May, where the magnitude of energy production from PV panels was computed as 166.5 kWh/m². Table 1 gives the corresponding PV panel area as 20 m² for brackish water and 45 m² for seawater. For all facilities, the PV panel area requirement ranges between 20 and 220 m² when using brackish water and between 45 and 600 m² 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 km² 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 km² of PV panel from brackish water and with 0.70 km² 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 desalination units needs to

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### Table 1

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

<table>
<thead>
<tr>
<th>Residential unit</th>
<th>School</th>
<th>University</th>
<th>Tourism plant</th>
<th>Summer-house</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity production from PV units (kWh/m²) [22]</td>
<td>166.5 (Sept.-May)</td>
<td>99.8 (June-Sept.)</td>
<td>140.8 (June-Sept.)</td>
<td></td>
</tr>
<tr>
<td>Daily water demand (L/ca.day or L/bed.day)</td>
<td>30</td>
<td>150</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>Students/inhabitants/beds (t)</td>
<td>220</td>
<td>600</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>Time span (d)</td>
<td>270</td>
<td>270</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Annual water demand (m³/year)</td>
<td>1,800</td>
<td>24,300</td>
<td>3,240*</td>
<td>3,000</td>
</tr>
<tr>
<td>Fresh water production per m² PV area</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brackish water (m³/m²)</td>
<td>111</td>
<td>111</td>
<td>67</td>
<td>94</td>
</tr>
<tr>
<td>Seawater (m³/m²)</td>
<td>40</td>
<td>40</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Total PV area required</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From brackish water (m²)</td>
<td>20</td>
<td>220</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>From seawater (m²)</td>
<td>45</td>
<td>600</td>
<td>130</td>
<td>90</td>
</tr>
</tbody>
</table>

*Occupancy rate assumed as 90%.
be tailored to ensure sustainable operation both from technical and economical standpoints.

References


