ECONOMIC FEASIBILITY ASSESSMENT OF SOLAR POWERED SEAWATER DESALINATION PLANTS: UNCONVENTIONAL FRESHWATER SUPPLY FOR GUZELYURT, NORTHERN CYPRUS

HUSEYIN ONER

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Approval of the Board of Graduate Programs

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ABSTRACT

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Water is essential for living beings. Without the existence of water, we would not have existed or progressed. Therefore, throughout the history of mankind fresh water supplies have been considered as a strategic resource for prosperity. Nowadays, many researches indicate that due to climate change, fresh water supplies around the globe are expected to become scarcer and more unpredictable which would eventually become a major challenge for our society. One of the earliest energy sources for desalination or distillation said to be solar energy. Recent technological achievements and diminishing costs in both renewable energy and desalination technologies offers an alternative for potential water security problems. In this thesis, by considering possible water shortages in coming decades, economic feasibility assessment for solar powered sea water desalination plant is carried out as an alternate fresh water supply for Guzelyurt, Northern Cyprus. In Northern Cyprus, which is a developing country surrounded by sea, growing population and depleting ground water resources have always been matter of concern since 1980s. The Northern Cyprus Water Supply Project, which was completed in October 2015, aimed to supply 75 Million cubic meter fresh water annually with submerged 80 km long water pipeline from Turkey to Cyprus through the Mediterranean Sea. This project, which has cost almost €380 million Euros, aims to supply drinking and irrigation water to the Turkish Republic of Northern Cyprus for next 30 years. The overall cost of project and true meaning of sustainability is arguable. Would this be enough to combat possible water shortages and droughts that could be caused by climate change? Hence this study intended to investigate and discuss solar powered seawater desalination as an alternate option for the Water Supply Project to provide same amount of water annually to the region using solar energy potential of the island and available desalination technologies. As the Water Supply Project had been completed in the end of 2015, all feasibility assessment assumed to be within the same period of time by using data available for 2016. This allows us to compare alternatives within similar economic environment and ignore problems arise with Lira Crisis in 2018. Equal amount of water, during same time period with identical conditions by using public land and public funds assumed for feasibility study. Results of the study focuses on economic feasibility indicators like LCOW, NPV, IRR, mIRR, Payback Period, DCF and price Sensitivity Analysis. Findings indicate that PV powered SWRO could compete with the Water Supply Project, if supported by the state.

Keywords: Seawater Desalination; Solar Energy; Economic Feasibility; PV; CSP; PTC SWRO; NPV; LCOW; Renewable Energy; Water Scarcity; Northern Cyprus;

ÖZ

GÜZELYURT BÖLGESİ İÇİN GÜNEŞ ENERJİLİ DESALİNASYON TESİSLERİNİN EKONOMİK FİZİBİLİTE DEĞERLENDİRMESİ: ALTERNATİF TATLI SU TEMİNİ, KUZEY KIBRIS

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Su her zaman gezegenimizdeki tüm yaşam için gerekli bir bileşen olarak tanımlanmıştır. Su olmasaydı, insanoğlu var olmaz ya da gelişemezdi. Bu nedenle, tatlı su kaynakları tarih boyunca gelişim ve refah için stratejik bir kaynak olarak görülmüştür.Son yıllarda yapılan bir çok araştırma iklim değişikliği nedeniyle dünyanın dört bir yanındaki tatlı su kaynaklarının azalmasının ve kaynak miktarının tahmin edilemez hale gelmesinin beklendiğini belirtmekte olup, bunun uygarlığımız için büyük bir tehdit haline geleceğinden bahsetmektedir. Yakın zamanda yenilenebilir enerji ve desalinasyon teknolojilerindeki ilerlemeler ve bu teknolojilerin azalan maliyetleri, potansiyel su güvenliği sorunları için bir alternatif sunmaktadır. Güneş enerjisinin, tuzdan arındırma veya damıtma için kullanılan en eski tekniklerden biri olduğu da söylenmektedir. Bu tezde, önümüzdeki yıllarda yaşanması muhtemel su kıtlıkları göz önüne alınarak, Kuzey Kıbrıs’ın Güzelyurt bölgesi için alternatif bir tatlı su kaynağı olarak güneş enerjisi ile deniz suyu arıtma tesisleri için ekonomik fizibilite değerlendirmesi yapılmaktadır. Orta Doğu'daki bazı ülkeler halihazırda desalinasyon teknolojisini kullanarak su kıtlığı için önleyici adımlar atmaktadırlar. 1980'li yıllardan başlayarak, gelişmekte olan bir ada ülkesi olan Kuzey Kıbrıs'ta, artan nüfus ve yer altı su kaynaklarının giderek tükenmesi her zaman endişe verici bir konu olmuştur. Ekim 2015'te tamamlanan ve Türkiye'den Kıbrıs'a su taşımak amacı ile gerçekleştirilen Kuzey Kıbrıs Su Temini Projesi, Akdeniz'den altından geçen 80 km uzunluğundaki boru hattı ile, yılda 75 Milyon metreküp tatlı suyu adaya ulaştırmayı amaçlamaktadır. Yaklaşık 380 milyon Euro’ya mal olan bu proje, önümüzdeki 30 yıl boyunca Kuzey Kıbrıs Türk Cumhuriyeti'ne içme ve sulama suyu sağlamayı hedefliyor. Nehir veya göl gibi bir kaynaktan gelen tatlı su kalitesinin, denizden arıtılmış suya oranla çok yüksek olmasına rağmen, bu projenin toplam maliyeti ve uzun vade de sürdürülebilirliği tartışmalı bir konudur. Bu tür projeler iklim değişikliğinin neden olabileceği olası su kıtlığı ve kuraklıklarla mücadele etmek için yeterli midir? Bu araştırma, adanın güneş enerjisi potansiyelini ve mevcut desalinasyon teknolojilerini kullanarak aynı miktarda suyun bölgeye temini sağlamanın maliyetini ve güneş enerjili desalinasyon teknolojilerinin alternatif bir seçenek olup olmadığını araştırmayı ve tartışmayı amaçlamaktadır. Su Temini Projesinin 2015 yılı sonunda tamamlanması nedeniyle, tüm fizibilite ve ekonomik göstergeler için 2016 yılında mevcut olan veriler kullanılmış ve aynı zaman aralığında olduğu varsayılmıştır. Aynı miktarda suyu, aynı zaman dilimi içerisinde, kamu arazisi ve kamu fonlarının kullanılmasıyla benzer şartlarda gerçekleştirildiği varsayılmıştır. Çalışma sonuçları, LCOW (Suyun uzun vadeli maliyeti), NPV, IRR, mIRR, Geri Ödeme Süresi, DCF ve fiyat duyarlılığı analizi gibi ekonomik fizibilite göstergelerine odaklanmaktadır. Değerlendirme sonucunda; devlet tarafından desteklenmesi durumunda, Fotovoltaik paneller ile çalışan bir desalinasyon tesisinin, Su Temin Projesiyle rekabet edebileceği sonucuna varılmıştır.

Anahtar Kelimeler: Deniz Suyu Arıtma; Güneş enerjisi; Ekonomik Fizibilite; PV; CSP; PTC; NPV; LCOW; SWRO; Yenilenebilir enerji; Kuzey Kıbrıs;

DEDICATION

To my beloved parents and sister. For their unconditional support and encouragement.

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ABBREVIATIONS

TRNC	Turkish Republic of North Cyprus
METU NCC	Middle East Technical University Northern Cyprus Campus
DSW	Desalinated seawater
DSP	Desalination plant
SWRO – (RO)	Saline (Seawater) Water Reverse Osmosis
RE	Renewable Energy
NGO	Non-Governmental Organization
EIA	U.S. Energy Information Administration
IRENA	International Renewable Energy Agency
NREL	National Renewable Energy Laboratory
EU	European Union
UN	United Nations
USGS	United States Geological Survey
DSI	Devlet Su İşleri (Turkish State Hydraulic Works)
IPCC	Intergovernmental Panel on Climate Change
WHO	World Health Organization
WEF	World Economic Form
NCWSP	Northern Cyprus Water Supply Project
MENA	Middle East and North Africa
OECD	Organization for Economic Co-operation and Development
RER	Renewable Energy Resources
RES	Renewable Energy Systems
KIBTEK	Kıbrıs Türk Elektrik Kurumu / Cyprus Turkish Electricity
CIU	Cyprus International University
EMU	Eastern Mediterranean University
O&M	Operation and Maintenance
PV	Photovoltaic(s)
CSP	Concentrated solar power
PTC	Parabolic Trough Collector
USD ($)	United States Dollar
EUR (€)	Euro (European Union Currency)
TRY	Turkish Lira
DNI	Beam (Direct) Normal Insolation
GHI	Global Horizontal Insolation
DHI	Diffuse Horizontal Insolation
LPG	Liquefied petroleum gas
GHG	Green House Gases
IEC	International Electrotechnical Commission
CAPEX	Capital Expenditure
UAE	United Arab Emirates

KSA	Kingdom of Saudi Arabia
BOT	Build Operate (Own) Transfer / BOOT
NER300	New entrants reserve 300 (EU Funding)
ERD	Energy Recovery Device
PTC	Parabolic Trough Collector
RO	Reverse Osmosis
MED	Multi Effect Distillation
MSF	Multi Stage Flash
TVC	Thermal Vapor Compression
SD	Solar Desalination
MEH	Humidification / Dehumidification
MD	Membrane Distillation
NF	Nanofiltration
UF	Ultrafiltration
MVC	Mechanical Vapor Compression
EDR	Electrodialysis
IX	Ionic Exchange
INFOREURO	EU Commission’s monthly exchange rates of the euro
REDAR	Renewable Energy Design and Applications Research
PVGIS	Photovoltaic geographical information system
NREL SAM	NREL System Advisory Model
ASRA	Actual (Terrestrial) Solar Resource Assessment - A(T)SRA
RETScreen	Renewable Energy and Energy-Efficient Technology Screen
EPW	Energy Plus weather data format
TMY	Typical Meteorological Year
GEN.	Diesel Generator
DCF	Discounted Cash Flows
NPV	Net Present Value (USD)
LCOE	Levelized cost of energy
LCOW	Levelized cost of water
IRR	Internal rate of return
mIRR	Modified internal rate of return

NOMENCLATURE

m^3	Meter cube
m^{-3} or $/m^3$	Per meter cube
m^3/d	Meter cube per day
m^3/y	Meter cube per year
$¢/m^3$	Cents per meter cube
$\$\ m^{-3}/d$	Dollars per meter cube per day
$kW/\ m^3$	Kilowatt per meter cube
$Wh\ m^{-2}$	Watt per square meter
TDS	total dissolved solids of a solution
ppm	parts per million
psi	Pounds per square inch
GW	Gigawatts
MW	Megawatts
kW	Kilowatts
W	Watts
kWp	Kilowatt peak
MWe	Megawatt (electric)
TWh	Terawatt-hour
GWh	Gigawatt-hour
GWh/y	Gigawatt-hour per year
MWh	Megawatt -hour
kWh	Kilowatt-hour
¢/kWh	Cents per kilowatt-hour
€/kWh	Euro per kilowatt-hour
kJ	Kilojoule
I	Global Horizontal Insolation (Irradiance)
$I_{b,n}$	Beam (Direct) Normal Insolation (Irradiance)
I_d	Diffuse Horizontal Insolation (Irradiance)
T_{db}	Dry bulb temperature
RH	Relative Humidity
Mil.	Millions
km	Kilometers
km^2	Square kilometer
^{o} or ^oC	Degrees and Degrees Celsius
CO^2	Carbon Dioxide
mm	Cubic millimeter per square millimeter
tCO2/y	Ton of Carbon Dioxide per year

CHAPTER I
INTRODUCTION

“We forget that the water cycle and the life cycle are one.” — J. Y. Cousteau [1]

One could not deny that water is one of the essential ingredients of all life on our planet. Additionally, civilization of the mankind also coexists with the water, from our daily life to our production and economy, water is a vital resource for us. Throughout the history of our civilization, it is a well-known fact that the major ancient cities and empires flourished around freshwater resources whether the civilization was in the dunes of Egypt or in the plains of Europe. Archaeological findings indicate that unless water resources management existed, ancient cities like Rome would have never developed into vast empires [2]. The first agricultural revolution had started with the domestication of water in the Neolithic period and, the industrial revolution started with the steam power generated from water [2]. Thus, water has been the key driving force behind our progression and prosperity, which means that water will always be an important part of our lives and civilization.

Many researchers and respected NGOs (like IPCC, IRENA, Greenpeace etc.) point out that freshwater resources are expected to become scarcer due to climate change which would become a major challenge for our society and future generations [3]. On the other hand, water is one of the most abundant resources; it is literally everywhere but we are unable to utilize it as our species have not been evolved or adapted to consume salty water. Luckily, our technological advancement allows us to generate drinkable freshwater using desalination technology. Moreover, seawater desalination (DSW) has become a major source of freshwater supply in many developing countries as access to the technology gets cheaper, especially in the Middle East and North Africa (MENA) regions where freshwater supplies historically scarce (see Figure 1-1). As population increases and technology becomes more affordable, desalination market grows with a tremendous pace. Figure 1-1 shows billions worth market growth in the last decade whereas just sum of the top three market approaches to 35 billion USD.

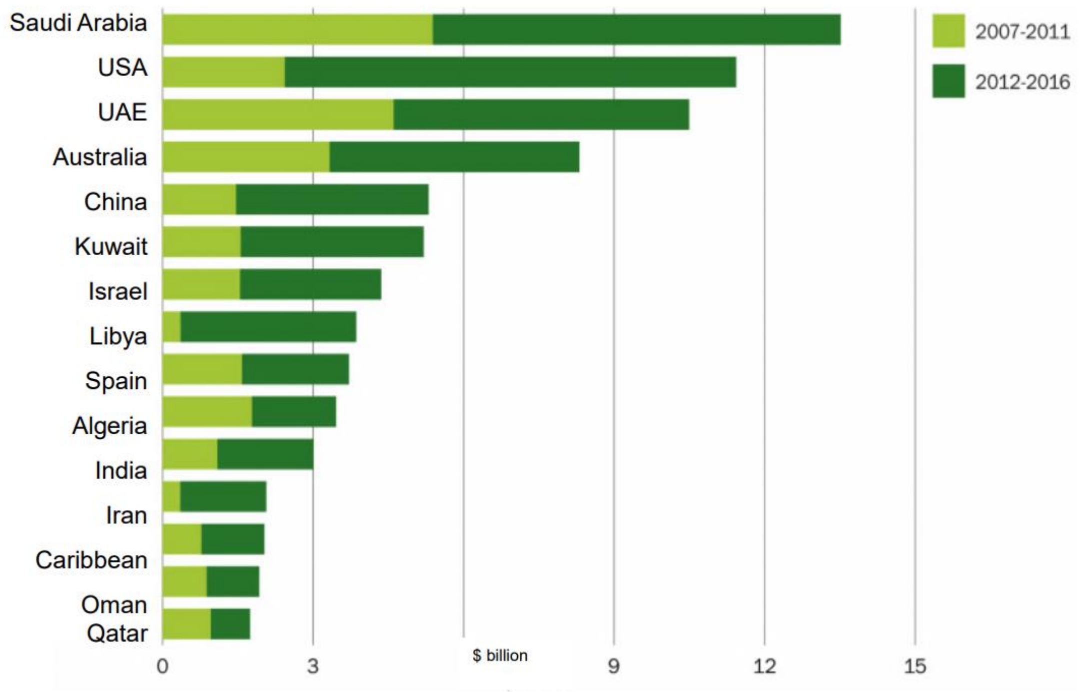


Figure 1-1 Market growth and primary markets of desalination technologies around the world as of 2016 (USD) [4], [5].

Nowadays we know that most of the ancient cities and towns were either sited around sustainable water supplies such as rivers and lakes or carried freshwater to the cities in order to sustain life and growth. On the other hand, desalination provides on-site and on-demand water supply for coastal cities without the need for transporting it. Despite most developing countries having difficulties to access freshwater easily, the UN factsheet stated that, today 10% of the world population lives nearby the sea and 40% of the world population lives in less than 100 km to the coast [6]. Until now, modern cities prefer to carry water from far away land like ancient or historic cities, which were mostly established nearby. While it is convenient to say that every developing society needs sustainable freshwater resources in order to progress, this proposition can be elaborated with that using seawater as an alternative freshwater supply for coastal cities would be the part of mankind’s sustainable future and prosperity.

Consequently, freshwater is also a critical natural resource for the development of Northern Cyprus as well which is an island state with limited resources. The indication of this is that, like many other developing countries; as the wealth and population of the nation increases, the demand for freshwater resources increases as well. However, today it is stated that Cyprus's water resources are poor compared to historical reserves of the island [7]. Ekiran and Ergil [7] discusses that while annual ground water extraction was around 120 million cubic meters in 2005, Northern Cyprus had an average annual water deficit around 29 million cubic meters in the first half of 2000s [7], [8]. Some future projections made by Turkman and Ekiran [9] in 2008 indicate that in the worst case projections the water deficit would reach to 90 million cubic meters by 2020 and it would become even more severe by 2035 reaching to125 million cubic meters [9]. Water scarcity problem is not considered as a new issue in Cyprus, the problem has emerged due to overuse of groundwater resources and increasing population of the island starting from 1960s, which is also stated to cause complete depletion of some of the island's important aquifers [7]. Hence, this led to semi-arid texture of the island we have today [7]. Cyprus is also positioned in Eastern Mediterranean between Turkey, Syria, Lebanon and Egypt, in other words the island is neighboring with the Middle-East, the region known with deserts, poor water resources and semi-arid climate [10]. Some researchers point out that according to UN, the island of Cyprus is on the list of countries which will face severe water stresses starting from 2020s [9]. Cakal [11] discusses effects of climate change and droughts caused by increasing evapotranspiration rates, the analysis made by using Palmer Drought Severity Index method in Figure 1-2 shows increasing intensity of droughts during past decade [11]. It is found that the real danger is not the amount of annual rainfall but the increasing rate of evapotranspiration due to climate change [11].

Nowadays, population of Northern Cyprus has reached nearly to 375,000; up from 290,000 in 2011 [12]. Therefore, as the population of the country increases and progresses, the need for fresh water supply increases and threatens the future generations as the island becomes unfertile year by year with the current consumption rates. On the other hand, despite it is stated that the island has a very productive land and warm climate for farming, it lacks the capacity to sustain minimum required amounts of freshwater for prosperity and sustainability [10].

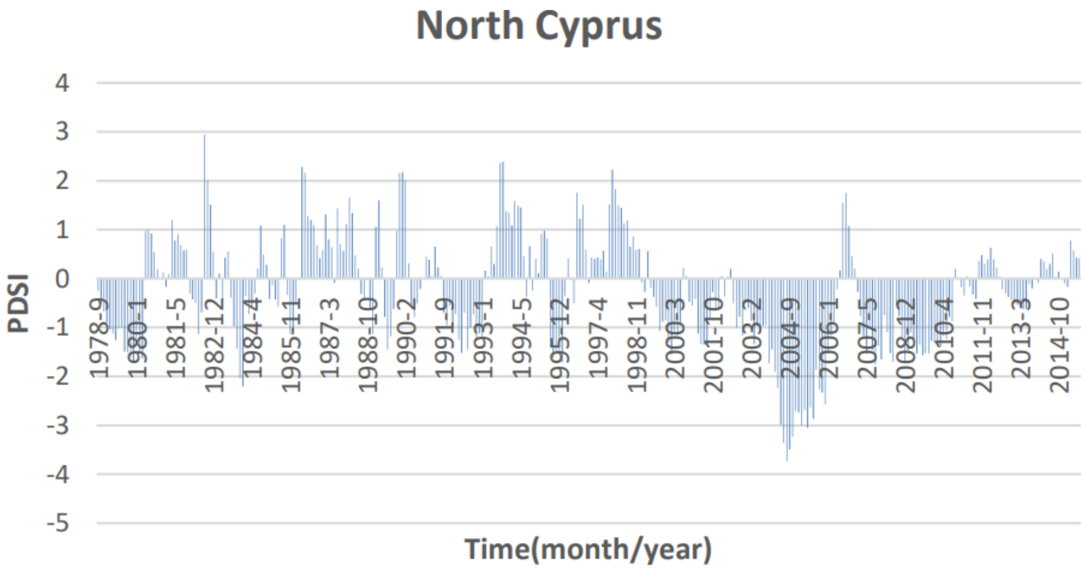


Figure 1-2 Monthly averaged Palmer Drought Severity Index for North Cyprus showing increasing drought intensity [11].

Additionally experts from DSI of Turkey [10] also stated that with proper water resources, crop yields in Northern Cyprus could be as more as 2.3 times per year then current yields [10]. Consequently, the major problem appears to be lack of proper freshwater supply that prevents prosperity of the island even though it is surrounded by water. Recent technological achievements and diminishing costs in both renewable energy and desalination technologies offer an alternative solution for water security problems. On the other hand, despite desalination is spreading across the world, majority of those plants are using conventional energy sources which cause GHG emissions as well.

Being a resource poor country, Cyprus has very prominent solar energy resources. In this thesis, by considering potential water shortages in coming decades that could be caused by climate change and increasing population, the economic feasibility assessment for solar powered sea water desalination plants is carried out as an alternate fresh water supply for Guzelyurt region in Northern Cyprus. This study focuses on total required initial investment, NPV of a such project, simple payback period, IRR, mIRR and LCOW projections with different combinations of solar desalination as well as combination with diesel. Combining PV farm with SWRO plants found to be feasible and promising for future needs.

1.1. Motivation

According to NGOs like UN, IPCC and WEF, the direct effects of climate change could be observed through examining changes in natural cycle of water [3], [13]. Due to climate change, fresh water supplies around the globe is expected to become scarcer and more unpredictable due to sudden extreme weather events [13]. It is stated that more and more countries have exposed to water scarcity problems than ever in recent decades due to change in climate patterns and increasing population [14]. Incidents like increasing threat of sudden flooding caused by intense short-term rainfalls and prolonged droughts could destroy water infrastructure and contaminate fresh water supplies [13]. Subsequently, causing random water scarcity problems around the globe which would eventually harm our economy, productivity, health and society. Extreme weather conditions like higher temperatures than usual are expected to disrupt water cycle and affect distribution of rainfall, snowmelt, river flow regime and groundwater supplies [13].

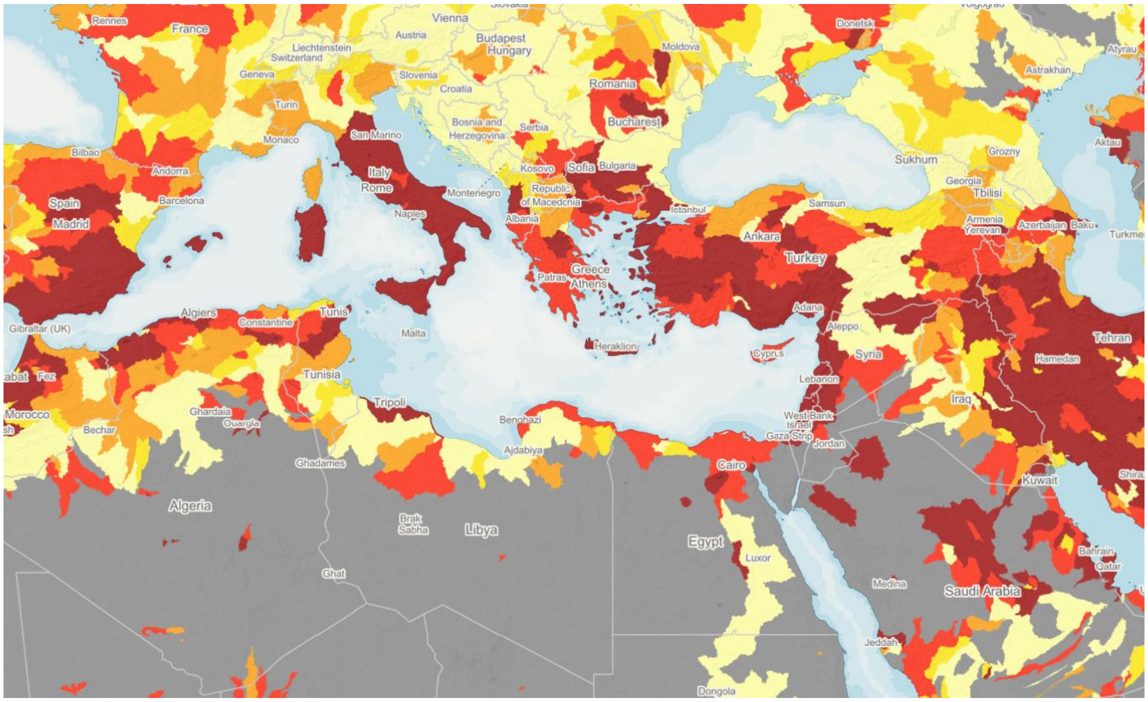


Figure 1-3 Severity of water stress levels around the Mediterranean Basin [15]

Higher evaporation rates discussed by Cakal [11] will cause unpredicted scarcity problems that would not be solved by carrying water from another basin. Figure 1-3 shows water stress levels in and around the Mediterranean Basin, which considered as alarming for future of the region (Red areas considered as higher usage than actual capacity to sustain). Figure 1-3 also indicates that Cyprus is experiencing water scarcity problems and carrying water from Anamur, Turkey does not change the fact that Turkey is also under threat due to increasing population and climate change.

According to UN Water, this will become a major challenge for every nation seeking sustainable future. On the other side of the story, (Table 1) water is an abundant resource as the oceans account for 71 percent of the Earth's surface and contain 97 percent of the Earth's water reserves [14], [6]. Table 1 clearly shows that, although freshwater supplies are very limited, water is an abundant resource and salinity level is the major barrier for utilization.

Table 1 Earth's Water Resources Distribution [16].

Water source	Water volume, in cubic kilometers	Percent of freshwater	Percent of total water
Oceans, Seas, & Bays	1,338,000,000	--	96.54%
Ice caps, Glaciers, & Permanent Snow	24,064,000	68.70%	1.74%
Groundwater	23,400,000	--	1.69%
Fresh	10,530,000	30.10%	0.76%
Saline	12,870,000	--	0.93%
Soil Moisture	16,500	0.05%	0.001%
Ground Ice & Permafrost	300,000	0.86%	0.022%
Lakes	176,400	--	0.013%
Fresh	91,000	0.26%	0.007%
Saline	85,400	--	0.006%
Atmosphere	12,900	0.04%	0.001%
Swamp Water	11,470	0.03%	0.0008%
Rivers	2,120	0.006%	0.0002%
Biological Water	1,120	0.003%	0.0001%

Unsurprisingly, the intensity and availability of solar resources tends to be usually higher in the regions with water scarcity (compare Figure 1-3 and Figure 2-1 from Chapter II).

Therefore, the abundance and sustainability of two resources come into prominence which are namely solar energy and sea water.

Availability of freshwater supplies considered to be a major concern in developing countries. This particularly applies to those who are susceptible to extreme climate events; where, their freshwater supplies subject to salinization because of seawater intrusion to ground water and contamination [17]. Countries stated to be not able to solve these problems with conventional methods and seawater desalination has become a proven to be reliable source of water starting from late 20th century [14]. Therefore, one of the emerging solutions for these countries appear to be desalination technologies, yet it requires a lot energy and contributes to climate change dilemma with more GHG emissions whereas creating a deadlock for us [3]. Increasing use of desalination is a major problem itself, finding truly sustainable way of salt extraction is one of the popular topics in sustainability studies. Considering the amount of money spend on water supply project and possible alternatives that has emerged with recent technological advancements, discussing more sustainable and long-term solution to water scarcity problem in Northern Cyprus appeared to be main idea behind this study.

1.2. Problem Statement

In North Cyprus, possible droughts and increasing population becomes challenging and unsustainable situation that threatens future of the country. On the other hand, neighboring countries like Israel or Southern part of the island investing on desalination to tackle water related problems since 90s. Northern Cyprus could take advantage of having access to sea as well in order to convert sea water to useable resource, however as widely known water desalination requires energy, and energy produced in Northern Cyprus is based on fossil fuels which is the main reason of climate change [18], [19]. It is also stated in various papers that energy cost for operating such plants could take up to 50% of the total production cost of per cubic meter of water [20]. Being a resource-poor island country, power generation in Northern Cyprus also completely relies on imported fossil fuels [19]. As the population increases, more power is generated in existing traditional power plants in order to cover the growth in the demand. This is unsustainable for both power generation and consequently for the water desalination. In order to state water desalination as a sustainable solution for water scarcity issue, it should not be produced in a way that causes more carbon emissions. Likewise, pumping station and treatment plant in the Northern Cyprus Water Supply Project (NCWSP) could not be count as an environmentally friendly solution to water problem, while it is stated that pumping station and treatment plant requires electricity between 15 MW to 25 MW to operate [21]. According to authors in [22], rapid increase in the construction of mass scale water desalination plants has happened in the last decade, which is alarming [22]. Although desalination facilities mostly powered with fossil fuels and contributed climate change, this rapid increase has led to reduction in the cost of technology and increase the learning curve [22]. However, the demand is increasing incrementally as freshwater resources over-exploited all over the world. Therefore, fossil-fuel depletion and climate change forces us to rethink the way we power these plants, thus desalination powered by renewable energy will eventually expected to emerge as sole solution for those arid and solar resource rich regions [23].

Unsurprisingly, overall consumption of the water increases around the world, which forces every country to revisit how they use and plan their resources, and many countries like those arid regions cover this need without considering cost of water, in terms of GHG. Therefore, the role of renewables in this problem would eventually become inevitable alternative for every country's future. Moreover, as you do not need to produce water at night, you can do it in the daylight with the sun. Inevitably, every solution and every project come with a price tag. Therefore, in order to replace existing infrastructure and methods, solar desalination should become economically feasible option.

1.3. Aims and Objectives

In this thesis, economic feasibility assessment for solar powered sea water desalination plant is carried out as an alternate fresh water supply for Guzelyurt, Northern Cyprus. Comparison of different technology combinations used to find best alternative. The Northern Cyprus Water Supply Project, which was completed in October 2015, aimed to annually supply 75 Million cubic meter freshwater with, two reservoirs, pumping stations, treatment plants and submerged 80 km long water pipeline from Turkey to Cyprus through the Mediterranean Sea. This project, which has cost almost €380 million Euros, aims to supply both drinking and irrigation water to the Turkish Republic of Northern Cyprus for next 30 years. Cost of water and total cost of the investment bring up the questions about alternatives. Environmental cost of this project and energy consumption of pumping stations also remains as a question. Reliability of the source of this carried water should also be take into account. Would this be enough to combat possible water shortages and droughts that could be caused by climate change?

We know evaporation rates are becoming another concern due to climate change. Hence this study intended to investigate and discuss solar powered seawater desalination as an alternate option to provide same amount of annual water supply to the region using solar energy potential of the island and available desalination technologies. Actual water deficit or future projections are not part of the study, aim of the analysis is to find direct alternative with same output. Total economic cost of providing same amount of water resources is the main objective, in this manner NPV for desalination plant, NPV and LCOE of solar power plants to run desalination, LCOW from the plant, required capital for the investment, IRR, Cost-Benefit Ratio and SPP analysis are included in this study. The questions that will be answered by this study includes;

How much does it cost to reach same amount of annual water supply capacity?
How much will be the levelized cost of produced water?
Is large scale desalination with solar energy practical and feasible?
If it is feasible, which technologies are feasible?

1.4. Opportunities

Renewable energy potential of the island is apparent, Cyprus is located in Eastern Mediterranean. As the island is positioned in a solar rich belt of the planet, it is stated that the yearly total average solar radiation has potential to peak up to 2000 kWh m^{-2}, and Guzelyurt has the highest DNI on the North [24]. Cost of desalination and cost of solar energy are diminishing very fast. Thus, considering these as an alternative way of supplying water is expected to be increase as well. For solar energy potential of the island, see Chapter II. The main objective of this study is to compare North Cyprus Water Supply project with desalination powered by solar energy as there is an undeniable potential in this technology.

1.5. The Organization of the Thesis

This thesis is further organized to begin with Chapter II which consists of background information about Cyprus and general environment of the region. Then followed by literature review and its subchapters including both review of academic studies, examples around the world and information regarding renewable and desalination technologies. The literature review is designed to introduce the reader to the main topic by using the information from existing literature and to support findings of this study. Literature review is followed by Chapter IV which is the section that explains methodology of the study and tools used to complete the analysis. Chapter V which includes requirements, parameters and data utilized, design of plants and assumptions that are used to analyze the subject. Followed by this section, Chapter VI explains results and discuses main findings in accordance with the analysis. Finally, the thesis concludes with a conclusion and final thoughts in Chapter VII as well as recommendation for further research.

The organization of thesis;

- Chapter I. Introduction
- Chapter II. Background
- Chapter III. Literature Review
- Chapter IV. Methodology
- Chapter V. System Design and Assumptions
- Chapter VI. Analysis and Results
- Chapter VII. Discussion and Conclusion

CHAPTER II

BACKGROUND

In order to identify potential risks, forecasting profitability or feasibility of such investments and deciding rate of return to the investor, it is essential to look current environment in that region and past projects in terms of technology, economic feasibility and legal implications. Furthermore, background information allows us to determine or forecast possible barriers that we could face, make decisions, optimize plant scale and predict outcomes of long-term renewable energy investment opportunities. Technological and economic environment also tends to be dynamic, different scenarios should be evaluated in order to achieve realistic results predictions. Such scenarios possibly include technological advancements, market fluctuations and political changes.

2.1 Information About Cyprus

The island is in Eastern Mediterranean, 35^{o} North of the equatorial plane between Turkey, Syria, Lebanon and Egypt as mentioned previously [25], [26]. The total surface area of the island is consisted of 9,251 km^2 and the Northern Cyprus controls 3,355 km^2 of it [27]. Turkish Republic of Northern Cyprus is one of the two states sharing the beautiful land of the third biggest island in the Mediterranean Sea after the Sicily and Sardinia and biggest island in the Eastern Mediterranean. Due to its strategic location in the Mediterranean and the Middle East, the island has been the area of interest by many great civilizations throughout the history, such as the Mycenaeans, the Phoenicians, Ancient Egyptians, Hittites, Assyrians, Persians, Romans, Byzantines, Lusignan, Venetians, Ottomans and finally Great Britain [27]. This led the island to having been heavily populated and occupied throughout the history and have stressed the natural resources of the island. Starting from 1925 with the treaty of Lausanne until 1960, Cyprus was a British Crown Colony [28], then the island became an independent country in 1960 with the Zürich and London Agreements between ethnic Turks and ethnic Greeks living in the island [26]. Due to ethnic tensions prior and after the independence, intercommunal violence commenced in 1963, Turkish Cypriots were forced to leave their properties in the southern Cyprus and move to the northern regions of the island whereas the violence and clashes eventually led to intervention in 1974, consequently the country and its resources were divided into North and South [26], [27]. After the division, sides exchanged population, however no peace agreement were signed which have left property ownership, resource sharing and ownership of the natural resources at a suspended state. Although the island is also close proximity to the MENA region which is known for being so rich in energy resources, Northern Cyprus still has not got any large scale extraction of natural resources or energy resources, additionally Northern part of the island does not even have any proven potential in contrast to Southern Cyprus's off shore potential [25].

2.2 Renewable Energy in Northern Cyprus

Throughout the world, sustainability is becoming the hot topic and installation of renewables rapidly rising due to the increase in concerns and consciousness about depleting resources, environmental threats and climate change. In Northern Cyprus, besides growing awareness about clean energy and climate change related environmental vulnerability, the economic benefits of clean energy projects started to become attractive for both government and the public. Being a resource-poor island country, power generation in Northern Cyprus completely relies on unsustainable imported fossil-based energy resources, thus becoming self-reliant in energy, which is only achievable through increasing use of in-house alternative energy resources, could be beneficial for the future of the country.

2.2.1 Solar Resources of Northern Cyprus

It is rumored that Cyprus had been called as the island of sun by the ancient Cypriots. Although they did not have the essential scientific measurements, they know most of the days on the island are sunny, and even though it is not the sunniest place on the planet, the amount of sunshine received throughout the year is enough for the people to think that it is very sunny and feasible for solar energy investments. Even in wintertime, days could be very sunny and hot, in other words weather conditions never become so tough like most of other European countries. So, this means even in winter you can get adequate amount of sunlight, therefore the solar radiation could be expected to be abundant as well [25].

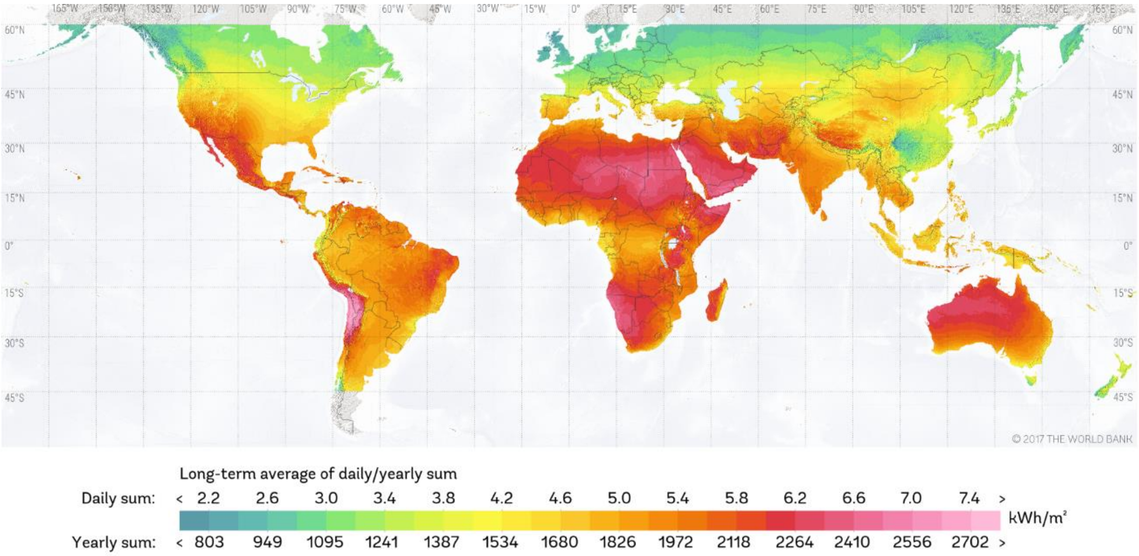
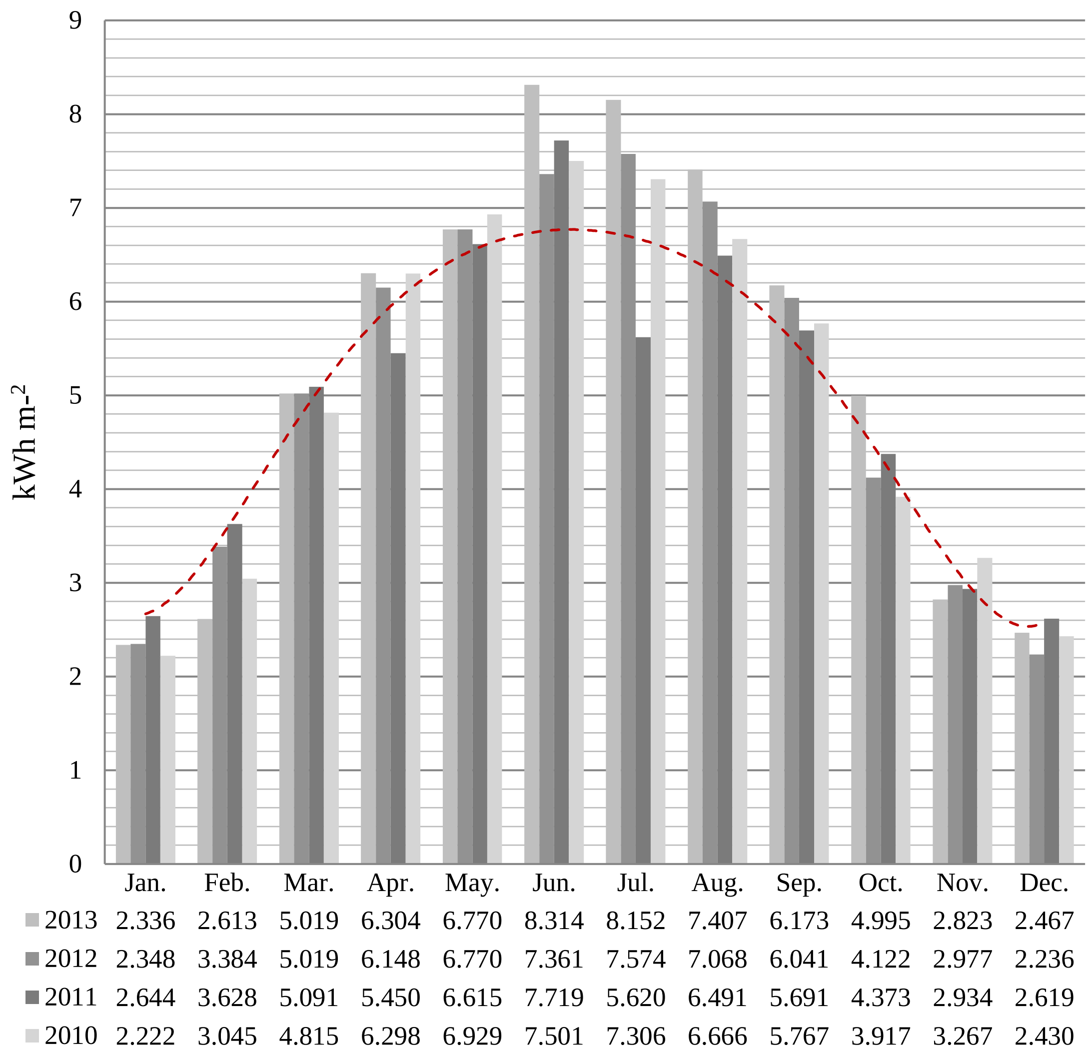


Figure 2-1 Average daily and annual sum of Global Horizontal Irradiance (GHI) map of the world [29].

The island is positioned in a solar rich belt of earth (see Figure 2-1), the yearly total solar radiation has potential to peak up to 2,000 kWh m^{-2} ,and the most efficient period is between March and September [24]. Figure 2-1 shows GHI potential of countries around the world, where the ones with water problems also has high solar resources like Cyprus. On-site five-year measurements of solar energy in METU NCC indicates average daily global horizontal insolation values of nearly 5,000Wh m^{-2} (See Figure 2-2). Guzelyurt considered to be one of the best locations for renewable energy investments due to solar irradiance and open plains in the region (See Figure 2-3). The surface area of the island is 9,250 km^2 consisting plains and mountains, Northern Cyprus has the 3,355 km^2 of the surface area while majority of it consists of plains in contrast to Southern Cyprus where majority of the land is mountainous [26]. The de facto population of the North has declared as around 375,000 as of 2019 [12]. While population density and country itself does not seem to be big, it could be concluded that there should be enough space to sustain and fulfill energy needs thorough solar power plants.



	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
■ 2013	2.336	2.613	5.019	6.304	6.770	8.314	8.152	7.407	6.173	4.995	2.823	2.467
■ 2012	2.348	3.384	5.019	6.148	6.770	7.361	7.574	7.068	6.041	4.122	2.977	2.236
■ 2011	2.644	3.628	5.091	5.450	6.615	7.719	5.620	6.491	5.691	4.373	2.934	2.619
■ 2010	2.222	3.045	4.815	6.298	6.929	7.501	7.306	6.666	5.767	3.917	3.267	2.430

Figure 2-2 Actual measured daily averages of GHI resources between 2010-2013 in Guzelyurt, METU Northern Cyprus.

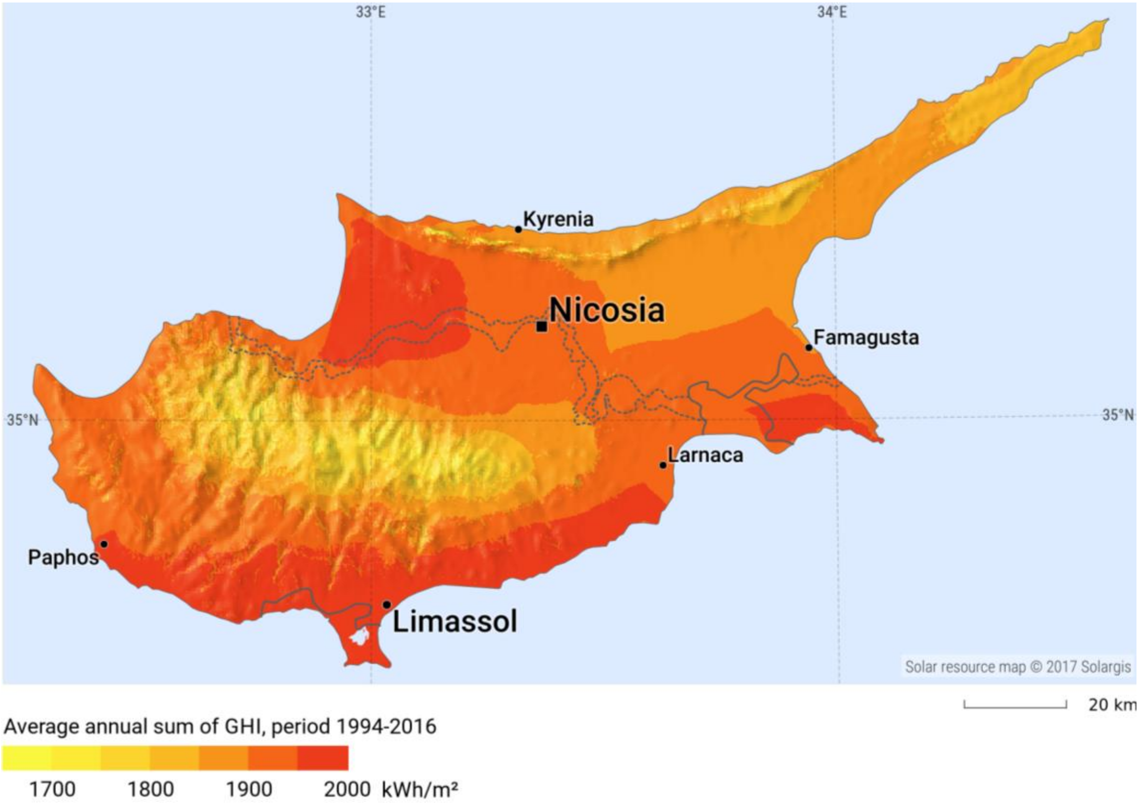


Figure 2-3 Average annual sum of GHI resources of Cyprus between 1994-2016 [29].

2.3 Regulations and Infrastructure

2.3.1 Laws and Regulations in Cyprus

Throughout the last two decades, many states have initiated implementation and approval necessary policies to utilize renewable resources namely water, solar, wind, geothermal and biomass to generate electricity, provide energy, heat and fuel to their population. As the world prioritize renewable energy as the primary source of capacity expansion, the role of governments in encouraging, legislating and subsidizing energy production from renewable sources become undoubtedly vital. Until 2011, there were no regulations in existence defining production of energy from renewable sources in Northern Cyprus. The government's initiative to promote policies in accordance with EU regulations has started when the entire island was accepted into EU as a whole in 2004, since then efforts for integration with EU legislation has boosted.

2.3.2 Act (47/2011) and Introduction of Renewables

Renewable Energy Act (47/2011) passed in 2011 for consistency with European laws and regulations [30]. However, the actual preparations for the renewable energy act dates to 2009, when the government of the southern part of the Cyprus was forced by European authorities to take more action regarding percentage of renewables in total electricity consumption. Despite Southern Cyprus's expansion of related regulations, including the framework and incentives, have happened around 2008-2009; the related act was already accepted in 2003, before the full EU membership. Thus the recent regulation was for encouraging small non-commercial or residential renewable energy systems up to 30 kW and subsidizes them up to 55% (Act 33(I)/2003) [31], [32]. In addition to the law in the South, the law in Northern Cyprus also regulates standards of equipment used in solar PV instalments, where especially Chinese products are not allowed and all the equipment is required to have an equivalent certificate to IEC standards, compatible with European regulations and have to be produced in either North America or Europe [33]. Despite the first drafts of the regulation, Northern Cyprus's renewable energy act does not include direct incentives or allowing excess energy to be sold like in Southern Cyprus, Table 2 shows difference tiers of RER licenses. Act only regulates the market and boosts the sector with tax reductions. Regulating organizations are stated to be Board of Renewable Energy Resources and KIBTEK [33]. There are also restrictions on the scale and capacity of RE investments which are imposed by KIBTEK in order to ensure healthy grid [34]. According to Table 2 and KIBTEK, starting from 2019, larger RE investments will require storage as the grid cannot tolerate more renewables than already licensed, unless new capacity of conventional base load plants added into the mix [34]. Therefore, grid connected solar desalination could not be implemented as it will require very large solar power plant and drain energy when the sun is not shinning. However, it is possible to utilize sun and store water instead of electricity.

Table 2 Solar energy regulations, Act 47/2011 [33], [35]

Certificate Level	RER Certificate	Limitations	Guaranteed Purchase Price (First Draft)	Revisioned Act	
Tier I	Low Voltage	0-15 kWp	0.25 €/kWh	Purchase Removed	
		15+ kWp	0.22 €/kWh	Purchase Removed	
Tier II	Medium Voltage	∞	0.20 €/kWh	Purchase Removed	Storage Required (2019)
	High Voltage		0.20 €/kWh	Purchase Removed	Storage Required (2019)
Tier III	Commercial Production (Plant Size)	∞	0.18 €/kWh	Purchase Removed	Storage Required (2019)

2.3.3 Infrastructure and Energy Consumption

Energy is a vital resource for the economy of Northern Cyprus, and like many other developing countries energy demand increases gradually. In TRNC, much of the energy consumption occurs in the form of either electricity or petroleum-based fuels. Unfortunately, no reliable statistics exists about total energy consumption of the Northern Cyprus. The article [19] stated that there is no need for using energy in the form of heating during a period of 7 months of a typical year due to warm climate in Northern Cyprus [19]. Furthermore, most of the heating demand fulfilled by electricity and water heating mostly done with solar water heaters [19]. While mostly electricity is used for heating purposes; LPG, kerosene and wood are the remaining sources with unknown amounts [19]. According to [35], nearly 70% of the electricity produced has been consumed by residential and commercial users (see figure 2-6) excluding the power losses during 2008, and energy consumption peaks in summer time [35].

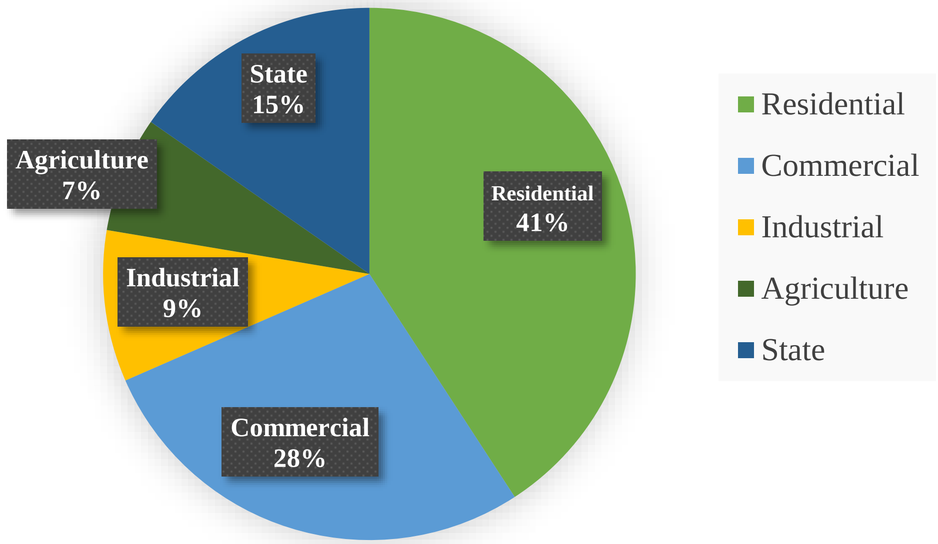


Figure 2-4 Electricity Consumption of Different sectors by 2008 [35].

The duty related to transmission of produced electricity, distribution and regulating production of electricity belongs to state owned KIBTEK (Cyprus Turkish Electricity Authority) and the total established nameplate capacity is around 409 MW in the country as of 2019 [34]. National grid of the Country has been fed by two fossil fuel powered power plants complexes that produce more than 99% of total electricity, see table 3 for further details. These power plants and generators are generating electricity by burning fuel oil No:6 which considered to be harmful for the environment due to high sulfur content (3.5% sulfur content) [19], [34]. Power generation capacity of Northern Cyprus has increased gradually starting from the year 1995 with 60 MW, 120 MW in 1996 with steam turbines and reached capacity of 327.5 MW by 2008. Table 3 shows that the demand fulfilled with additional diesel generators since 2008 which are considered expensive to operate [28].

Table 3. Total installed nameplate capacity of power plants in Northern Cyprus by 2019 [34].

Plant Location	**Units**	Capacity
Teknecik	2x60 MW Steam Turbine	120 MW
Teknecik	8x17,5 MW Diesel Generator	140 MW
Kalecik	8x17,5 MW Diesel Generator	140 MW
Kalecik	8 MW Waste Heat Steam Turbine	140 MW
Serhatkoy	1.3 MWp Photovoltaic Plant	1.27 MW
	Total Installed Capacity	**409.3 MW**

KIBTEK also owns a solar PV plant in Serhatkoy which have been constructed with EU grant in 2011, but renewable energy generation expected to be increased gradually [35]. KIBTEK recently started a tender process for 35-50 MWp solar energy power plant with storage [34]. Minister of energy and economy (at the time), Sunat Atun stated in 2011 that the governmental target is to reach hybrid production of both solar and wind power in Northern Cyprus [30]. The expected capacity will be around 20-30 MW for wind energy with the target of reaching 20% renewable by 2020. Moreover, a five-year energy plan included reaching 60 MW capacity in renewable energy by 2017 [34], [30], [36]. As of 2019, approved unlicensed solar PV projects reached to 87 MW whereas only less than half of it put into practice [37]. Target of 20% renewables also hinges upon the northern part of the island having an underwater transmission line connection to Turkey in order to compensate fluctuation caused by solar energy [38].

The distribution system in Northern Cyprus dates back to the old republic times and most probably to colonial rule, with excluding transmission lines and new extensions of distribution, the core of distribution is still old and has many power losses that have never been calculated realistically by KIBTEK, and there isn’t any research about measuring losses dynamically to find the exact sources of losses [35]. Transmission lines reached a total of 554 km at the end of 2008 [34]. The network losses generally are around 5% to 10% in developed countries. In Northern Cyprus, it was stated as 19% for 2018, which is considerably high, but the grid has been improved since with the target of 5% [34]. Due to high dependence on fossil fuels, insufficient distribution network and lack of extra capacity; possible desalination infrastructure would require additional power plants and cause CO^2 emissions.

2.4 Climate and Water Resources

In some old resources, even ten years ago, sustainable water levels for the countries in the Eastern Mediterranean indicated as alarming, Table 4 shows that Cyprus has second lowest renewable water resources in the region after Palestinian Gaza Strip in Eastern Mediterranean and fifth lowest per capita with 947 cubic meters [10]. Among European countries, Cyprus is one of the most vulnerable regions to water scarcity problems and droughts that will occur due to climate change in coming decades. As previously mentioned in Figure 1-3, water resources have been used way more than it could replenish and this stress on water supplies is not expected to slow down. Severe water scarcity is one of the direct outcomes during droughts, one or more mechanisms like insufficient precipitation, high evaporation and excessive use of water resources together can cause droughts, consequently triggering risks like decline in agricultural yields and fisheries resources, and loss of biological resources [17].

Table 4 Water Resources by 2005, in Eastern Mediterranean [10].

	Total Annual Renewable Water Resources	Population	Per capita water amount	Transboundary Water Resources
Country	**(km^3)**	**million**	**(m^3/per capita anually)**	**%**
Turkey	110.0	71.4	1540.0	5.0
Egypt	69.1	74.0	933.0	96.0
Israel	2,15	6,1	352.0	30.0
Lebanon	5,17	4,5	1148.0	0.0
Syria	19.8	18.0	1100.0	50.0
Jordan	1,7	5.8	293.0	31.0
Gaza	0.1	1.3	46.0	0.0
Cyprus (South)	0,9	0,950	947.0	0.0

According to Elkiran and Ergil the entire island have an average annual precipitation of 500 mm, which is considered to be low for restoring reserves, and as a Mediterranean climate country, the summers are hot, dry and winters are mild in the island [7]. More specifically, study by Zaifoglu, Akintug and Yanmaz [39], found that annual the mean precipitation varies greatly from region to region where in the western Mesaoria it is approximately as low as 260 mm and in the Kyrenia Mountains range, which is known to be highest, annual the mean precipitation reaches to 550 mm. Thus, it cannot be assumed to be 500 in every city [39]. Kyrenia known to be most fertile and Famagusta could be considered the least fertile in this respect. Cyprus is neighboring with Middle East, the region known with arid and semi-arid climate, while island is placed in Mediterranean Climate range. As it is mentioned in Chapter I, Northern Cyprus faced severe and more frequent droughts in the last decade and as it is mentioned by Cakal [11] evapotranspiration is the real danger that stresses already stressed water resources. Various studies have been conducted to predict future water stress levels and forecast consumption.

Table 5 Water consumption and aquifer deficit projections made in 2008.
(numbers as million cubic meters) [9].

		Consumption			Aquifer Deficit		
Scenario	**Season**	**2010**	**2020**	**2035**	**2010**	**2020**	**2035**
Optimistic	Dry	91.95	119.35	149.98	-39.40	-62.80	-88.20
Optimistic	Wet	115.41	149.92	187.71	-5.40	-35.10	-67.50
Pessimistic	Dry	85.93	110.97	138.60	-43.60	-63.50	-87.70
Pessimistic	Wet	142.33	184.99	232.94	-53.20	-87.10	-125.60

Table 5 shows forecast done by [9] in 2008, authors discuss that aquifers were already overstressed through last two to three decades and consumption is expected to increase as well. Even in best case scenario, dry season expected to become a major problem for the country in next decade. Without additional 75 million cubic meters that is supplied by the NCWSP, Northern Cyprus would have faced severe water scarcity and eventually invested in water desalination to meet domestic water supply demand. According to table 5 and by considering possible climate change scenarios, we could still conclude that the NCWSP would not be enough to prevent water scarcity or would not be enough for agricultural use. Meeting the domestic water demand with high quality DSW would also lower the consumption of the NCWSP water which could be used for agriculture without treatment (without additional energy consumption). IPCC warns that annual average temperature increase between 1-1.5ºC will cause droughts and shortages in coming decades [17]. Moreover, according to forecasts that have done by IPCC, Cyprus is among those under serious threat of water scarcity in coming decades [17]. Figure 2-4 shows different scenarios of climate change and the forecasted impact for 2070s.

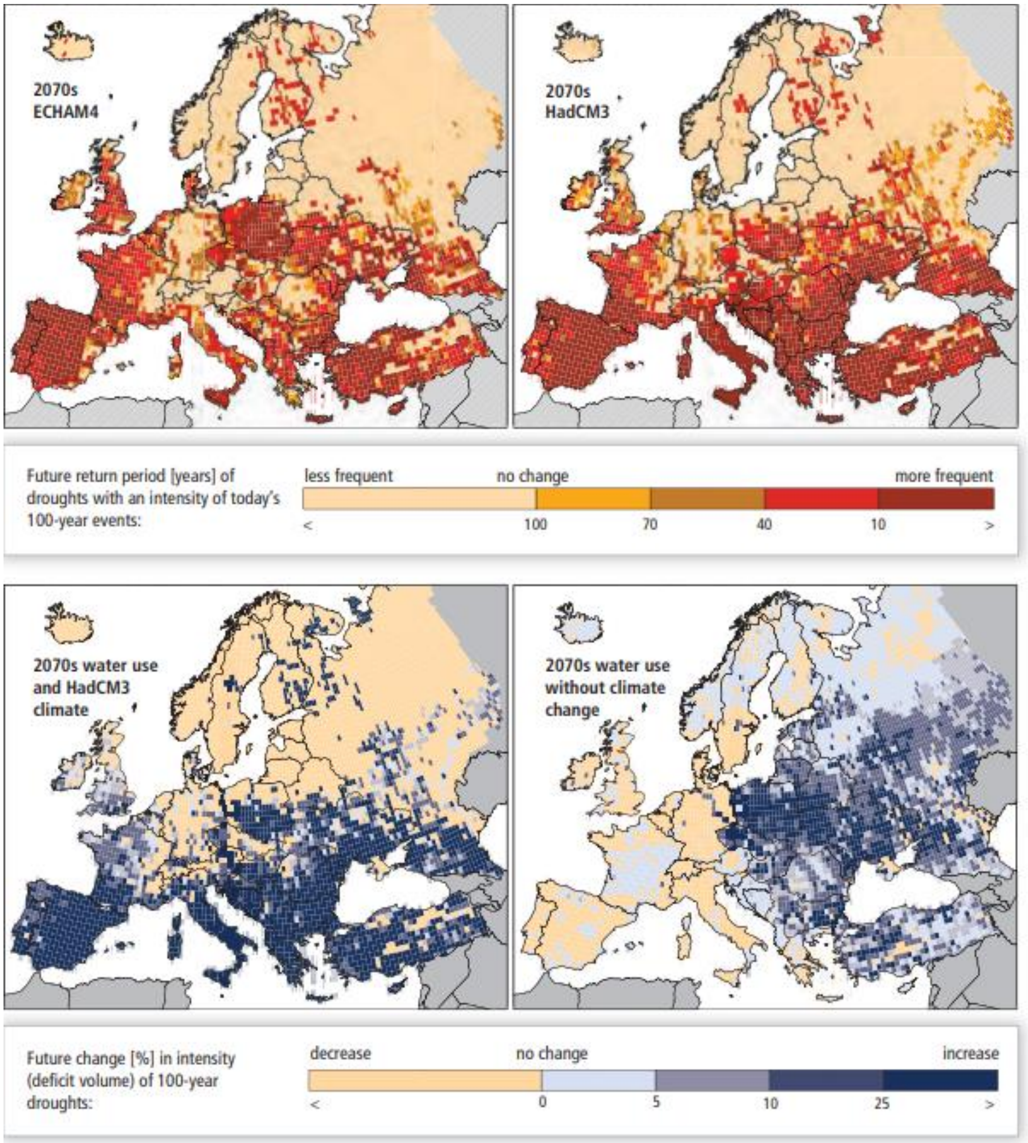


Figure 2-5 Future Projections of Water Stress and Droughts across Europe with climate change impact [17].

2.4.1 Submerged Water Supply Project

In order to deal with water scarcity problems in the island, starting from 1980s, several projects have been offered, including the solutions like transporting water from Turkey via flexible barges, undersea water pipeline from Turkey and of course desalination from seawater, in order to solve the need for daily consumption and boost economy of the island [10]. Finally, the Northern Cyprus Water Supply Project (NCWSP), a unique pipeline project financed by Turkish Republic implemented. The project aims to meet the industrial and drinking water supply needs for a time period that extends to the year 2045. The construction started in the town of Anamur in 2011, and was completed in October 2015 [40]. The project has a long history way back to 1990s, The Alakopru dam, which is the reservoir that supplies water to the pipeline, is fed by the Tasucu containment basin [40]. The Alakopru dam, which also is used to generate hydroelectric power diverts water to the pipeline where 80 km of it is submerged and it transports water from Turkey to Cyprus through the Mediterranean Sea (See Figure 1-7). Then water reaches to the bay of Guzelyalı in TRNC. Through pumping station constructed there the water is pumped into the Gecitkoy Dagdere dam [40].

In addition to the dams and pipeline the project also includes a water treatment plant and a distribution network consisting of pipelines between cities of Northern Cyprus. Consequently, the project to have costed around the amount of almost €380 ($420) million euros for the total investment of infrastructure. Operating expenditures of the project remained mainly unknown. Annual planned water supply expected to be 75 Million cubic meters. It is also stated that both pumping and treatment plant will require 20-25 MW of power to operate, as part of operating cost [41], [21]. The cost of water was €0.70 (TRY 2.30) per cubic meter for the municipalities back in 2016, this amount is lower than what end users pay for [42], [43]. For example, in the capital city of Nicosia, lowest tier of water was costing €1.50 (TRY 5.00) per cubic meter [42], [43]. Before the project implemented, municipalities could have water as cheap as €0.03 but water is not a cheap commodity anymore.

Figure 2-6 Northern Cyprus Water Supply project route, distances and planned pipeline infrastructure [44].

2.5 Water Desalination in Cyprus

2.5.1 Southern Cyprus

Although Southern Cyprus has higher amount of fresh water reserves, where the previously mentioned resources in Table 4 belongs to south, Southern Cyprus has desalination capacity of 33 Million cubic meters per year [45], which accounts nearly the half of the capacity of water transported from Turkey to Cyprus. Due to political reasons, like Northern part of the island, Southern Cyprus could not buy water from Turkey, therefore the only option remains to meet the demand is to use water desalination, there are several projects in order to increase desalination capacity and current desalination plants, which are RO plants, produce fresh water at a price range between €0.78 m^{-3} to €1.32 m^{-3} [46]. However, new desalination means more GHG emissions as well.

Biggest plant in Southern Cyprus is located in Larnaca with the capacity of 18 million cubic metres a year. The plant, which is a SWRO with conventional power input of 4.5

kWh m^{-3}, constructed in 2001 and expanded in 2008. It has been stated that project had an investment cost \$47 million and sells water \$0.79 m^{-3}. Another plant operates in Dhekelia with daily capacity of 40,000 cubic metres per day. Table 6 shows operational desalination plants in Cyprus and relative price of water by 2019.

Table 6 Operational Conventional RO Desalination plants in Southern Cyprus [47].

Desalination Plant	**Capacity per Day**	**Price of Water(€/m^3)**
Dhekelia Desalination Plant	60 000 m³ /d	€0,42
Larnaca Desalination Plant	64 000 m³ /d	€0,594
Limassol (Episkopi) Desalination Plant	60 000 m³ /d	€0,8725
EAC Vassilikos Desalination Plant	60 000 m³ /d	€0,813
Paphos Desalination Plant	15 000 m³ /d	(expected 2019)

Back in 2009, there has been a project for cogeneration of electricity and desalinated sea water using a CSP plant. The project was funded by European Commission and Government of Cyprus and done by the Cyprus Institute [48]. Dozens of researchers have made calculations on a possible 4 MWe CSP plant coupled with either MED or RO [48]. It has concluded that it could cost about €25 million and produce 5,000 m^3 water per day. Author of [49] also made a techno economic analysis on same concept with same capacity and found that it is not commercially viable with current grid prices, using grid fed RO is cheaper unless there are incentives. Table 7 shows comparison of water consumption data including real data in 2010 and forecasted data for 2020.

Table 7 Water Consumption 2010, and Forecast of 2020, Cyprus [45].

Water Usage Stats 2010 (Million m^3)						
		2010			**2020**	
Usage	**Northern Cy**	**Southern Cy**	**Total**	**Northern Cy**	**Southern Cy**	**Total**
Drinking Water	31.4	86.1	117.5	36.1	104.3	140.4
Agricultural	139.0	182.4	321.4	161.6	182.4	344.0
Industrial	2.0	6.0	8.0	2.3	7.0	9.2
Total	172.4	274.5	446.9	200.0	293.7	493.6

2.5.2 Northern Cyprus

The article [7] points the severity of the water scarcity problem in Guzelyurt coastal region, where the main aquifer that supplies city in the region have alarming problem with up to 5,000 ppm total dissolved solids in groundwater making the water supply in the region brackish. According to Table 8 from USGS, it is not usable as fresh water, neither for domestic nor agricultural use before desalination process [50].

Table 8 Water Quality ppm m^{-3} [50].

Water Quality
Fresh water - Less than 1,000 ppm
Slightly saline water - From 1,000 ppm to 3,000 ppm
Moderately saline water - From 3,000 ppm to 10,000 ppm
Highly saline water - From 10,000 ppm to 35,000 ppm

Therefore, even the main aquifers of the Northern Cyprus would require desalination process before using for tap water because of high salinity. One of the first desalination facility in TRNC was constructed for East Mediterranean University with the capacity of 1,000 cubic meters per day in 2001 [51]. in In Northern Cyprus, according to [7] there are 128 wells and boreholes supplying water to country, as an additional supply to those wells there are several private desalination plants owned by hotel chains in Bafra region with the capacity of 4,500 cubic meters per year with cost per cubic meter of $1.5 [45]. Largest desalination facilities are located in Famagusta district. Municipality of Famagusta also contracted a private company to build operate transfer (BOT) a desalination facility back in 2008, the SWRO facility has 4,000 cubic meters per day capacity [51]. Contract period ends in 2023. In compare to Southern Cyprus the capacity of the North is very small. Moreover not only the Southern Cyprus but in compare to MENA region and neighbors like Israel as well [18]. Northern Cyprus has a very poor investment on water desalination plants, that is the reason for high price for desalination. As an example, Israel meets 50% of water demand from large scale desalination plants with cost per cubic meter ranging from $0.68 to $0.95 [52]. Where the size of the plant definitely affects the cost because of economies of scale. It is also stated that consumer price for fresh water in Northern Cyprus is one of the lowest in the region with less than

$1 per cubic meter [53]. Water management and pricing apparently unsustainable and poor.

2.6 Background of the Study

Author started writing first review of solar desalination for Northern Cyprus in 2016, just after completion of the NCWSP. As information of starting point belongs to 2016, most of the inputs in this study also obtained during 2016 in the initial study, thus analysis have been made with old data in order to sustain consistence with previous work and comparison purposes. The Water Supply Project had been completed in end of 2015; therefore, all assessment should be assumed to be within same period of time by using data available at the time. This is important as it allows us to compare alternatives within similar economic environment and ignore problems arise with Lira Crisis in 2018. Same amount of water, during same time period with same conditions by using public land and public funds assumed for analysis. Future work of this study will include comparison of 2019 and 2016

CHAPTER III

LITERATURE REVIEW

’’Water, water everywhere.... Nor any drop to drink’’ Samuel Taylor Coleridge [14].

Seawater desalination is both a booming market sector and focus of many academic studies. There are thousands of papers written about technologies, economics of the technologies and sustainability. Technological Researches are more common, RO is leading the way. According to authors of [54], there is a global trend and since 1980s approximately 16,500 have been made about desalination as of 2018. Figure 3-1 from [54] illustrates different subject categories of desalination publications, major categories of academic research are technology, environment, economic & energy and socio-political effects. Major focus of research and development seems to be technological advancement followed by economics and energy consumption aspects.

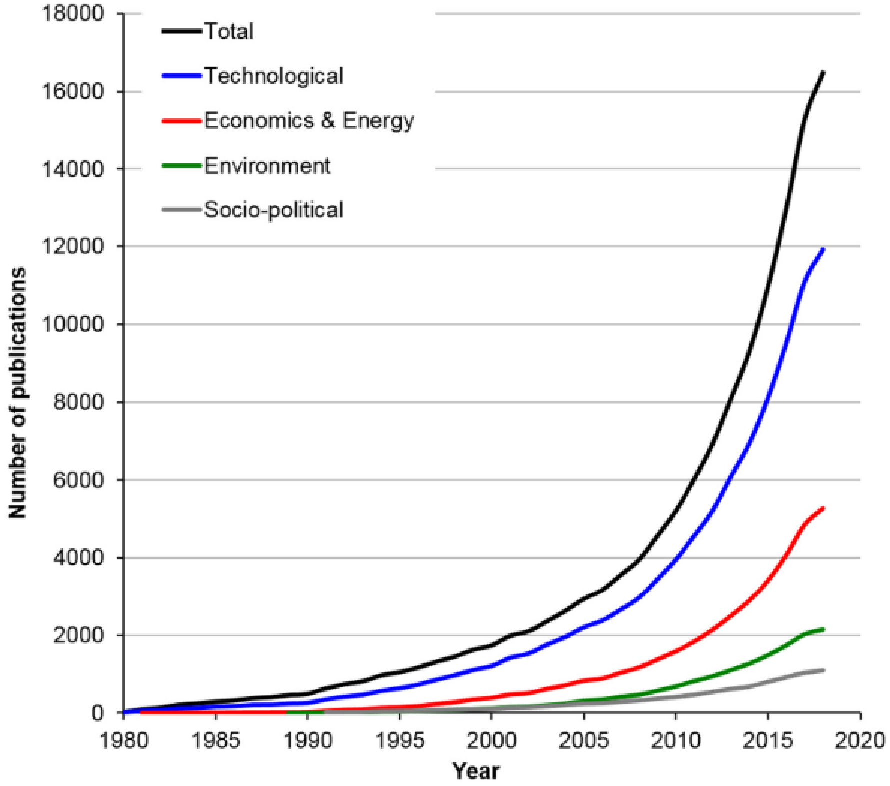


Figure 3-1 Number of desalination related publications by subject as of 2018 (lines showing: total, technical, social, environment, energy & economic) [54].

Researches on improving or optimizing technologies related DSW plants are increasing, technology category of Figure 3-1 also have sub categories illustrated by [54]. Figure 3-2 demonstrated shift in trends of research focus, while RO take over both the industry and academics, emerging technologies are the second most popular trend in academic publications after RO recently. According to authors of [53], full potential of solar desalination remains as a challenge because of the economic barriers of the technology and environmental concerns [54]. One of the most important factors is economic feasibility followed by environmental concerns, however costs related desalination often kept secret by engineering companies. Information regarding economic aspects and costs available in commercial databases for engineering companies which limits public access and prevents for more clear and accurate assessments about the technology.

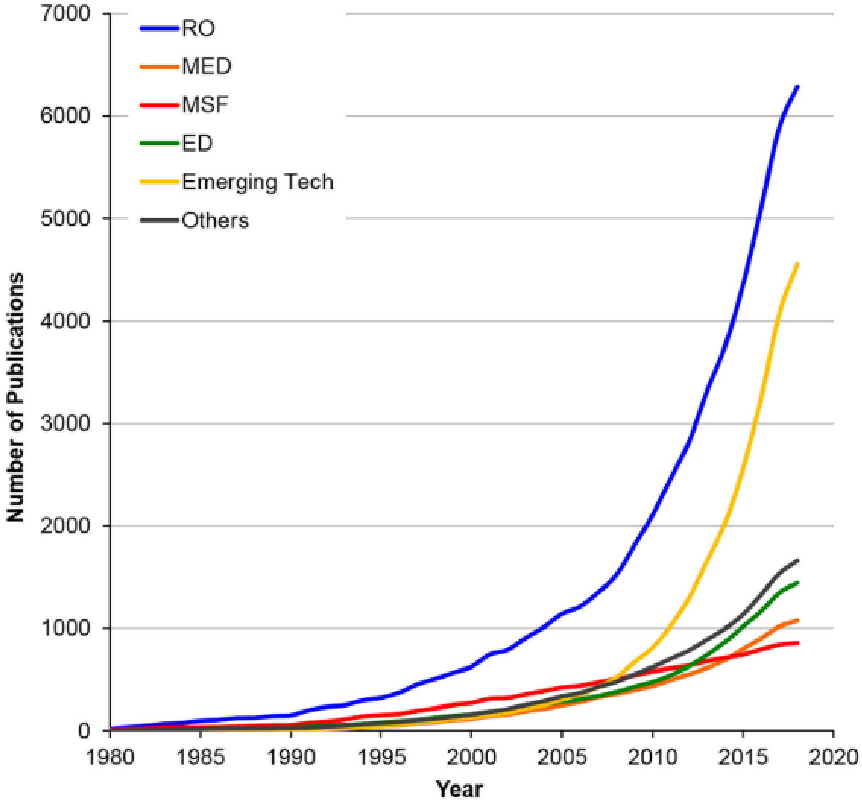


Figure 3-2 Publication amounts by the type of desalination technology focused on, as of 2018 [54].

Although costs like membrane prices, figures like capital requirement and operating costs involved are generally predictable, each DSP project has its own unique price tag due to environmental factors. Global Water Intelligence (GWI) (desaldata.com) has one of the largest paid databases about up to date economic figures surrounding desalination plant investments, it is said that the database contains information about approximately 20,000 DSPs around the world as of 2018. GWI provides information about the plant status, operational year, plant capacity, customer type and information, technology, produced water cost, geographic location and feedwater specifications for every DSP in the database and provides tools for feasibility with up to date information [5], [53].

3.1 Desalination Publications in Cyprus

Similar to the information mentioned back in Chapter II, Southern Cyprus had a long history with desalination and high amount of publication about DSW research in compare to TRNC. Environmental conditions for both sides are mostly relevant, however socio-economic and political climate is different. Under NER300 funding program by European Commission for Renewable Energy Systems (RES) investments and with support of Government of Cyprus several research groups existed and worked in Cyprus Institute of Technology. Many publications can be found about solar desalination which are mostly focusing of technical aspects. NER300 Funded CSP-DSP project lead and gave opportunities to more study to be conducted in the field of both DSW and solar DSW. One of the most prominent papers found in literature about economics of solar desalination published by Fylaktos, Mitra, Tzamtzis and Papanicolas [55]. The paper focuses on economic feasibility and risk analysis of CSP-DSW (4 MW), water export price mIRR, CAPEX, sensitivity analysis and NPV are some focus points of assessment. Table 9 shows most prominent academic studies and publications done for both North and South Cyprus about desalination and solar desalination. For TRNC, there is only one thesis found online for SWRO feasibility written by EMU student, Alaleh Abbasighadi. The thesis titled as “A cost benefit analysis of a reverse osmosis desalination plant with and without advanced energy recovery devices” which focuses on Energy Recovery

Devices and its effect on feasibility and costs [56]. Thesis had findings based on LCOW, NPV and sensitivity analysis.

Table 9 Most prominent academic studies and publications about desalination done for Cyprus.

Author	Localization	Publication	Methods Used	Focuses on
Alaleh Abbasighadi	Northern Cyprus	A cost benefit analysis of a reverse osmosis desalination plant with and without advanced energy recovery devices	Thesis - LCOW, NPV, Energy Recovery Device	SWRO
Fylaktos, N. Mitra, I. Tzamtzis, G. Papanicolas, C. N.	Southern, Cyprus	Economic analysis of an electricity and desalinated water cogeneration plant in Cyprus	Economic, Monte Carlo, NPV, mIRR, IRR, CAPEX, LCOE	CSP Desalination
O. Phillips Agboola ; F. Egelioglu	Northern Cyprus	Water scarcity in North Cyprus and solar desalination research: a review	Technical Review	Solar Stills, General Review
Hikmet Ş.Aybar; FuatEgelioğlu; U. Atikol	Northern Cyprus	An experimental study on an inclined solar water distillation system	Technical Review	Inclined solar distillation
Mehmet Ekin	Northern Cyprus	Experimental Investigation of an Inclined Combined Solar Hot Water and Desalination System	Thesis - Technical Review	Inclined solar hot water
Soteris A.Kalogirou	Southern, Cyprus	Economic analysis of a solar assisted desalination system	System Cost, Lifecycle Cost, Economic review	CSP Desalination
Soteris A.Kalogirou	Southern, Cyprus	Use of parabolic trough solar energy collectors for sea-water desalination	System Design, System Cost	PTC CSP Desalination
Soteris A.Kalogirou	Southern, Cyprus	Effect of fuel cost on the price of desalination water: a case for renewables	Economic Review, Cost of Water	RE Desalination
Soteris A.Kalogirou	Southern, Cyprus	The application of solar desalination for water purification in Cyprus	Review, Evaluation, Sensitivity Analysis, System Design	CSP Desalination
Andreas Poullikkas	Southern, Cyprus	An optimization model for the production of desalinated water using photovoltaic systems	Capital Cost, Capacity FactorScale Optimization	PV RO

3.2 Desalination Technologies

Breaking the word desalination to de-salt, which means “removing salt from” defines the process .As [57] explains it as “process of removing dissolved solids, such as salts and minerals from water”, in other words [57] describes it as desalting process of any product or resource in order to create useful outcomes whereas the process first noted to be used by sailors back in the sixteenth and seventeenth centuries in order to produce freshwater onboard using distillation during long voyages [57]. Desalination using heat is also a natural process driven by evaporation of seawater. Being one of the oldest techniques, distillation evolved throughout the history and dominated desalination process until membrane technology invented. Figure 3-3 shows increasing capacity over the years and change with the implementation of membrane technology.

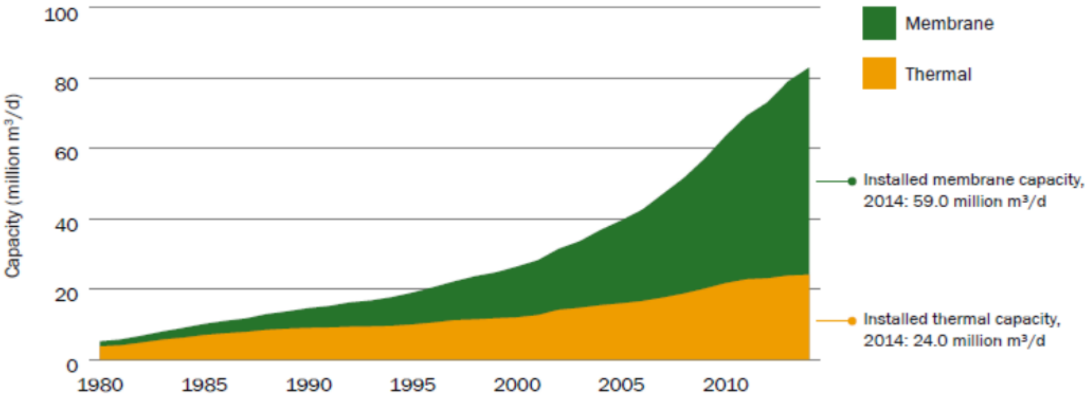


Figure 3-3 Change in plant scale desalination capacity for 45 year and implementation of membrane technology in 1980 [5]

Through the last two-decade desalination is also booming like renewable energy. Figure 3-4 shows incremental increase in desalination projects between 1965 and 2011 which has accelerated even more ins 2010s [5]. As of 2019, there are 20516 operational desalination plants running with cumulative capacity of 122 million meter cube water per day [58]. Perhaps this incremental increase started with cost reductions made with advancement in Reverse Osmosis technology. Figure 3-5 shows desalination plants operational worldwide by type of technology, which points out how fast RO is taking over the industry. Long term leadership of thermal technologies already gone.

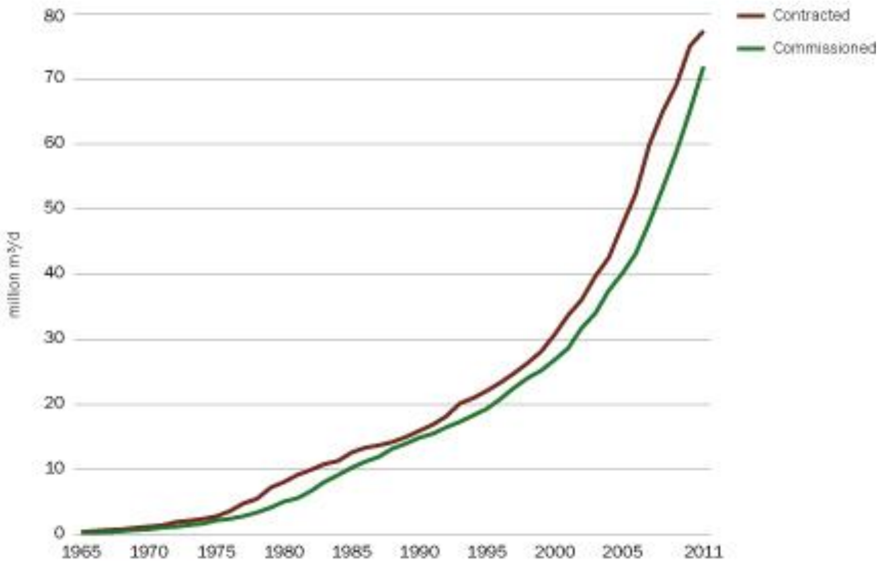


Figure 3-4 Incremental increase in desalination facility projects between 1965 and 2011[5]

In the literature, there many reviews of current technologies in order to produce fresh water from seawater by powering the process with the sun, however a few of them able to reveal economic difficulties for achieving sustainable solution. The article [23] and [24] states that the most common three types of desalination plants are multi-stage flash (MSF), multi-effect distillation (MED), or MED with vapor compression (VC) and reverse osmosis (RO) as the most used one [59]. Figure 3-5 shows percentage of the type of plants currently in operation as of 2015 and in 2013.

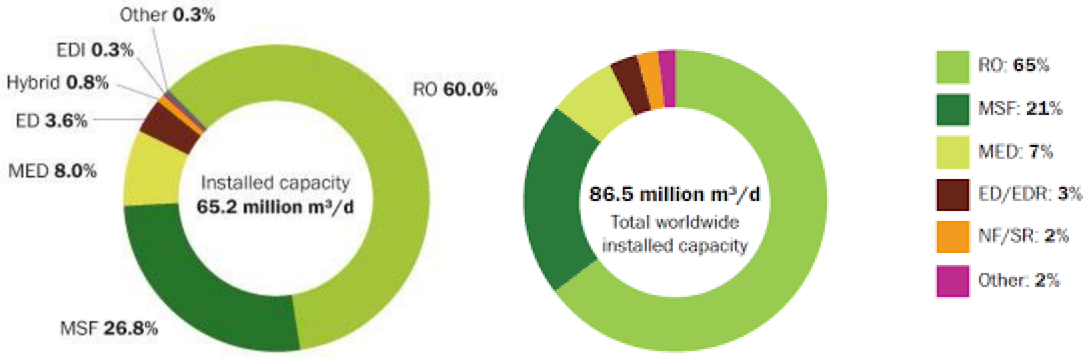


Figure 3-5 Worldwide desalination plants by type, 2013 and 2015 [5], [60].

Table 10 Available Desalination technologies by the type of process and required energy input type[14].

Separation Method	**Energy Type**	**Process**	**Technologies**
Water Extraction	Thermal and Electrical	Evaporation	Multi Effect Distillation (MED) Multi Stage Flash (MSF) Thermal Vapor Compression (TVC) Solar Desalination (SD) (Solar Stills) Humid/ Dehumidify (MEH)
		Evaporation & Filtration	Membrane Distillation (MD)
		Crystallization	Freezing Formation of hydrates
	Electrical	Ionic filtration	Reverse Osmosis (RO) Nanofiltration (NF) Ultrafiltration (UF) & Microfiltration
		Evaporation	Mechanical Vapor Compression (MVC)
Salt Extraction	Electrical	Ionic migration	Electrodialysis (EDR)
	Chemical	Extraction	Ionic Exchange (IX)

Desalination done by either extracting salt or water. There are several emerging technologies like cryo-desalination which is done by freezing water and old processes including solar stills. Table 10 displays most widely available desalination technologies by the type of processing and required energy input type for the process. Multi Effect Distillation (MED) and Multi-Stage Flash (MSF) are the most matured and notable technologies for extracting water using evaporation. Thermal Vapor Compression (TVC) and Membrane Distillation (MD) also done by evaporating water. For solar desalination, up to now, mostly preferred technology was solar stills which is a passive process without energy input. Solar stills have been used for a long time as they are relatively cheap and easy to construct, it is working based on greenhouse effect [20]. The device contains a shallow basin covered by a transparent roof which acts as a condenser and solar energy causes to evaporation and natural desalination [20]. One of the major drawbacks of this technology is the problem of scaling it. The Other methods for solar desalination include

PV reverse osmosis, PV Electrodialysis (EDR), CSP reverse osmosis, CSP thermal MED and MSF. Electrodialysis (EDR) or electrodialysis reversal has become highly promising technology as with renewable addition, it has been commercially used since 1952, one of the oldest [14].Using an electrodialysis membrane, with one anode side and one cathode side at the each end like a batter, it extracts impurities and salt from brackish water [14]. However, there has no large scale EDR application for seawater desalination. The other technologies include crystallization by freezing or forming of hydrates, Mechanical Vapor Compression (MVC), Ionic Exchange (IX) and Nanofiltration (NF). As it is mentioned most widely used and cheapest technology is Reverse Osmosis (RO). Desalination mostly used for converting seawater into freshwater, however removing salts from less salty brackish water is also widely used. Figure 3-6 shows some of the largest DSPs operational, trend shows increasing capacity of the plants.

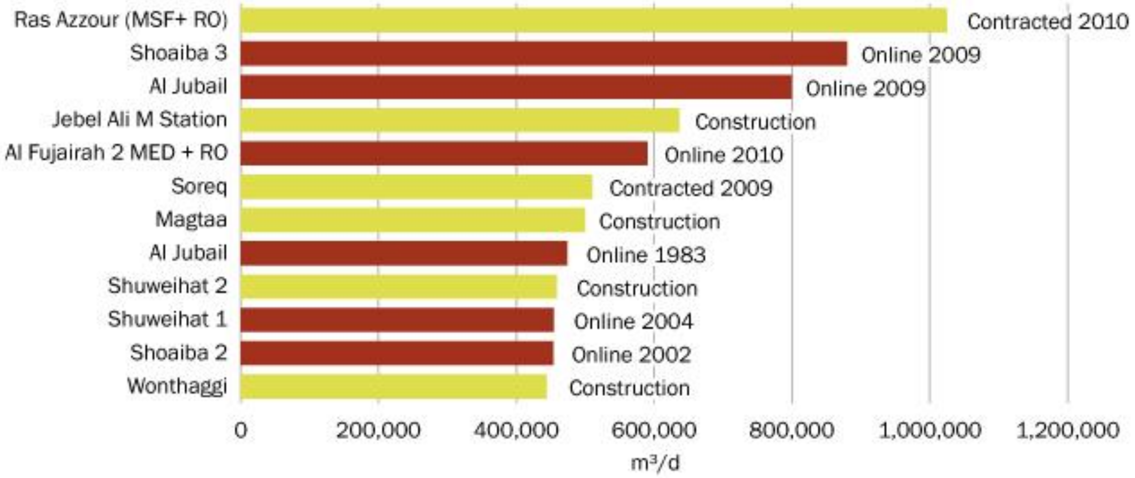


Figure 3-6 Largest Desalination facilities around the world [5].

3.2.1 The Multiple Effect Distillation

The Multiple Effect Distillation (MED) technology uses evaporation, the evaporation occurs over a tube bundle, the tube is heated by the condensing steam, then purifies water with very high energy efficiency in order to produce fresh water [20], [23]. The Figure 3-7 shows how MED process produces fresh water.

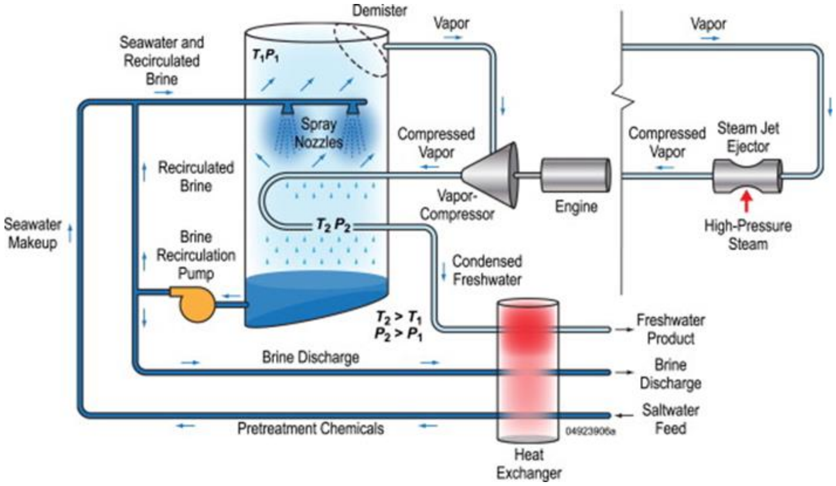


Figure 3-7 The Multiple Effect Distillation (MED) [20].

3.2.2 Multi Stage Flash

Multi Stage Flash (MSF), is the second most used technology for desalination the seawater evaporator with low pressure flashing chambers heated with thermal energy, flash of seawater causes separation of salt and water [20], [23].The series of flashing stages, with low pressure, leads to high amount of steam to be produced and the steam then re condensed at the end of chamber to produce fresh water like in the schematic diagram in the Figure 3-8.

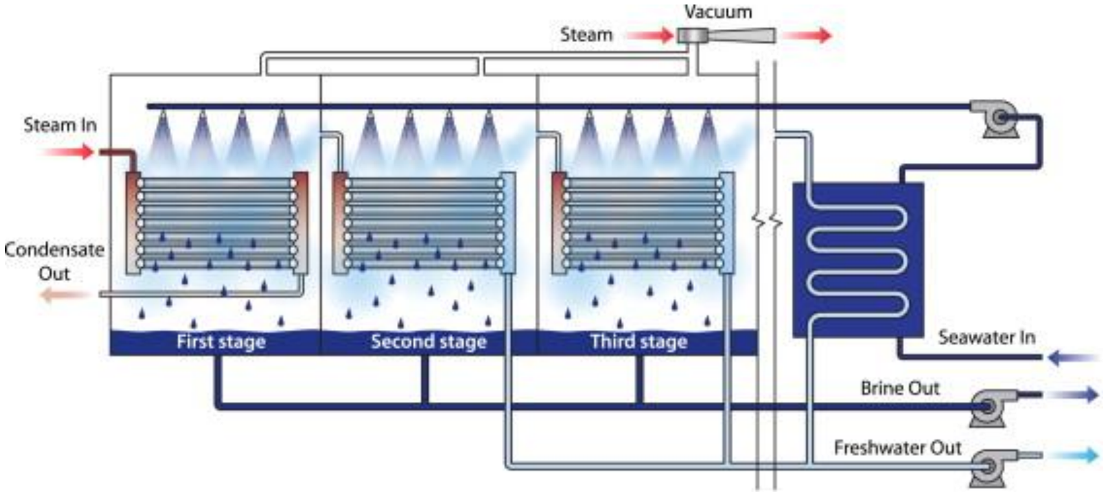


Figure 3-8The Multi Stage Flash(MSF)[20]

Table 11 Worldwide examples of operational MSF Plants [14].

Plant	Year	Number of units	Capacity (m^3/d)	No of stages	(◦C) Brine temperature	PR
Al Taweelah "B" (UAE)	1995	6	57,600	20	112	8
Al Hidd (Bahrain)	1999	4	37,000	21	107–112	9
Ruwais (UAE)	2001	2	15,000	15	105–112	6
Jebel Ali "K" (UAE)	2001	2	45,480	21	105	9
Jebel Ali "K" 2 (UAE)	2003	3	60,530	19	105	8
Mirfa (Abu Dhabi-UAE)	2002	3	34,000	21	110	8.9
Umm Al Nar Station "B" (UAE)	2002	5	56,825	22	110	9
Fujairah (UAE)	2003	5	56,750	22	110	9
Az Zour South (Kuwait)	1999	12	32,731	24	110	8.8
Shuweihat (UAE)	2004	6	75,670	21	111	9
Subyia (Kuwait)	2007	12	56,825	23	110	9.5
Ras Laffan (Qatar)	2007	4	68,190	22	110	9.5
Sohar (Oman)	2008	4	37,504	24	110	9.5
Shoaiba (Saudi Arabia)	2009	12	73,645	22	110	9.5

3.2.3 Reverse Osmosis

Reverse Osmosis is far more the most commonly used process among these processes for desalination, as it can be seen from Figure 3-9. The separation of freshwater done by the use of a semi-permeable membranes specifically produced to let the passage of water whilst and block salts and other particles [23], [20], [61].

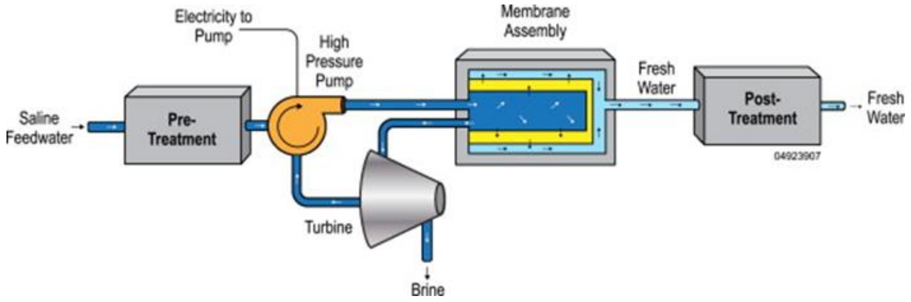


Figure 3-9 The Reverse Osmosis (RO) [15].

Those conventional desalination plants require electricity to run which provided by fossil fuels, and in exchange of fresh water they also contributed to greenhouse gas (GHG) emissions. In recent years, especially including MENA region, renewable powered desalination plants started to be constructed and solar energy is accounted nearly 57% of those new renewable energy based desalination plants [62]. According to [60] most of the cost is due to the energy requirement while maintenance costs are typically between 15–30% per cubic meter produced. Cost breakup can be seen from Figure 3-10.

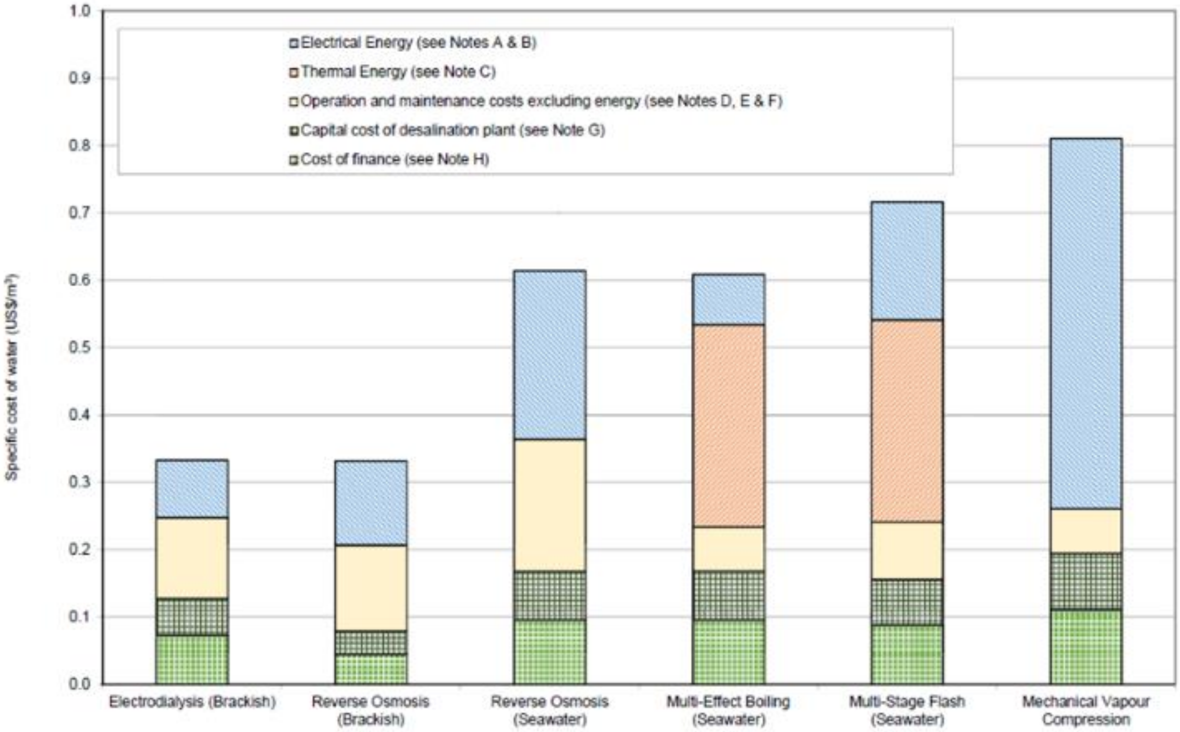


Figure 3-10 The Cost breakup of different types of desalination plants [60].

The arid regions of the MENA without the availability of easy access to water and high transportation cost because of the remoteness of communities in the desert, make water a valuable resource, and low cost, simple and sustainable solution is to convert brackish water to fresh by using heat from the sun. Some small cogeneration facilities constructed in Arabian Peninsula, as a rapid increase in large scale sea water desalination facilities occurred recently, either PV powered or CSP powered reverse osmosis is the choice of technology. However, heat only systems may also be used, Figure 3-11 shows possible combinations.

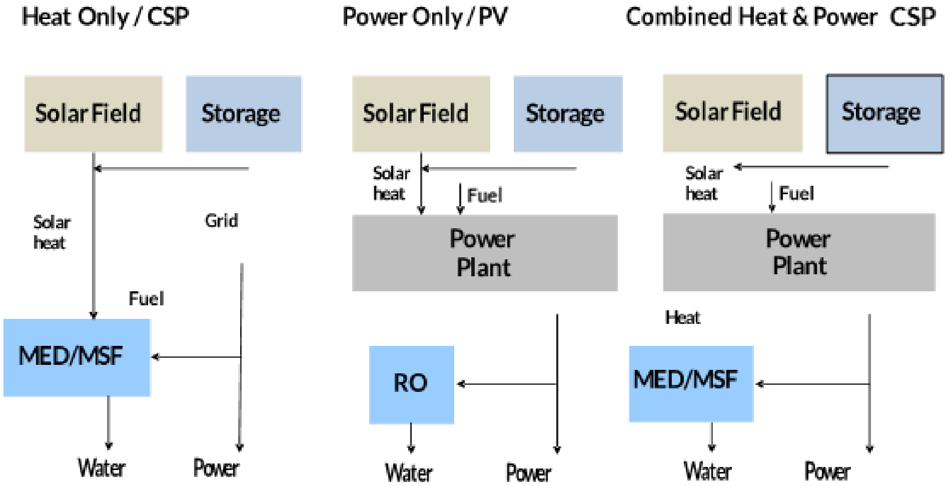


Figure 3-11 Solar-powered desalination options [63].

The combination of desalination with concentrated solar power (CSP) plants could provide cheapest and most effective option for the development of large-scale desalination with vaporization via solar energy [61]. Figure 3-12 shows, how thermal energy from sun could be used for cogeneration of water and electricity [61].

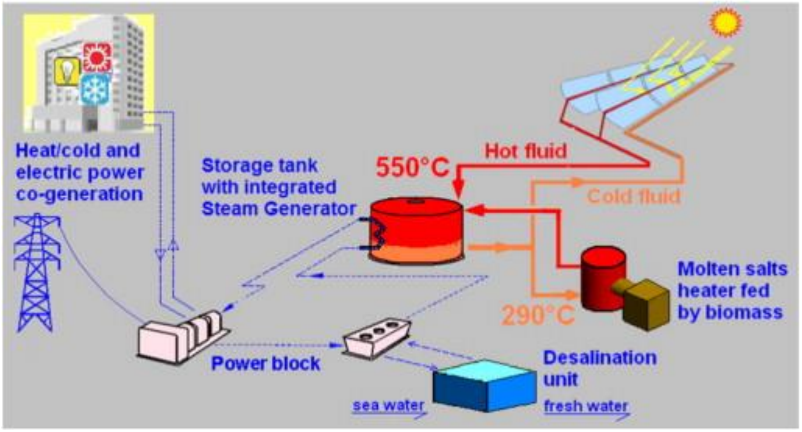


Figure 3-12 Solar Thermal powered desalination cogeneration [61].

3.3 Solar Desalination Around the World

Solar desalination has a long history, with regular distillation it existed even before all the other techniques. Solar stills, implemented by Swedish engineer Charles Wilson, has been used since as far as 1872 [14]. First recorded use was Las Salinas in Northern Chile, for desalination of brackish water for miners. Throughout the history, different designs emerged to optimize technology and it is still improving [14].

3.3.1 Al Khafji Solar Saline Water Reverse Osmosis

Al Khafji solar saline water reverse osmosis plant in KSA is one of the most recent examples of feasibility of solar desalination. Construction of the plant began in 2015, the plant is the first industrial large-scale solar-powered desalination has ever built. Advanced Water Technology (AWT) of KSA and Abengoa made a partnership to build the plant in Al Khafji City [64]. The project had cost of $130 million with the daily capacity of 60,000 m³ freshwater. The technology used for desalination is reverse osmosis and seawater pre-treated using ultra-filtration (UF) [64]. The 15 MWp solar PV power plant with polycrystalline PV panels built next to the plant. In addition to that ultra-high concentrator photovoltaic (PV) also supply power to the desalination plant. In the absence of sunlight, plant would be fed by grid [64]. And excess solar would be sold to the grid as well for reducing operational costs and GHG emissions by utilizing renewables [64]. Figure 3-13 shows working principles of the plant, it has an intake pipe taking water from Persian Gulf, then SWRO produces DSW using PV energy during the daylight to supply Khafji City while selling excess energy to grid. Plant uses Grid during nighttime to supply water.

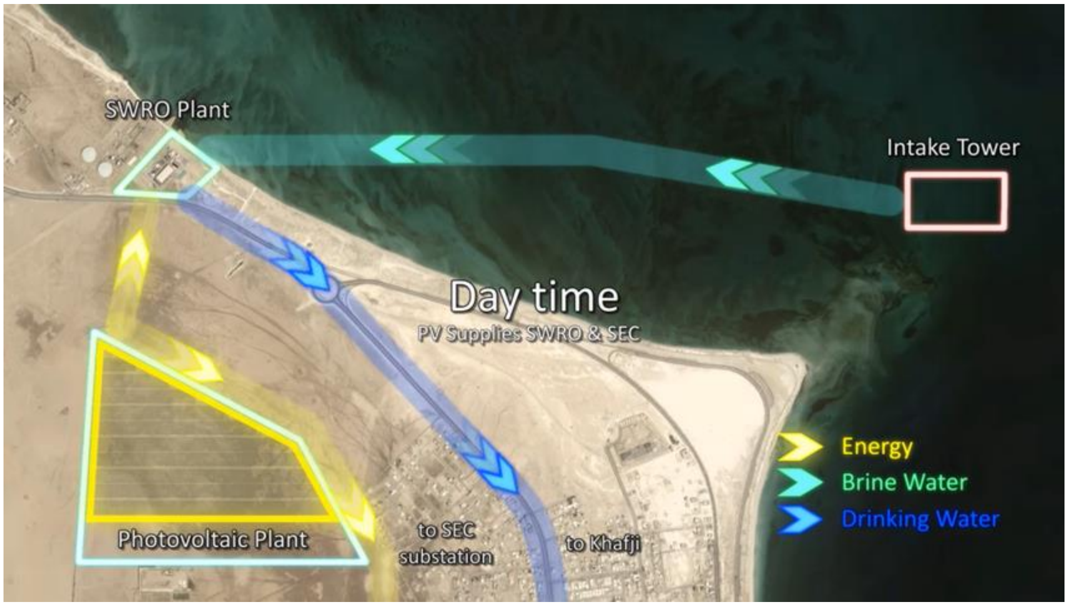


Figure 3-13 Al Khafji Solar Saline Water Reverse Osmosis day time working scheme [65].

3.3.2 EAD Solar PV RO Network

In 2012, Environment Agency of Abu Dhabi, has built a series of small solar PV desalination plants around Abu Dhabi, the UAE [64]. The total of 22 small solar desalination units with capacity of 1,100 gallons of freshwater per hour completed in 2012 and further 8 commenced [64]. The project has been implemented with research purposes. Brackish water from the ground pumped and treated using reverse osmosis in order to later be used in agricultural irrigation system. 35 kWp system using 300m^2 area powers each system and operates when the sun is shining without storage or grid [64]. The cleaned water, stored in ponds and produced not in demand, is not for drinking and used for agriculture. Wastewater from the process, brine also transferred another pond for evaporation. System is a unique zero-carbon process (except GHG cost of equipment) for brackish groundwater desalination which also could be used where seawater intrusion is a problem [64].

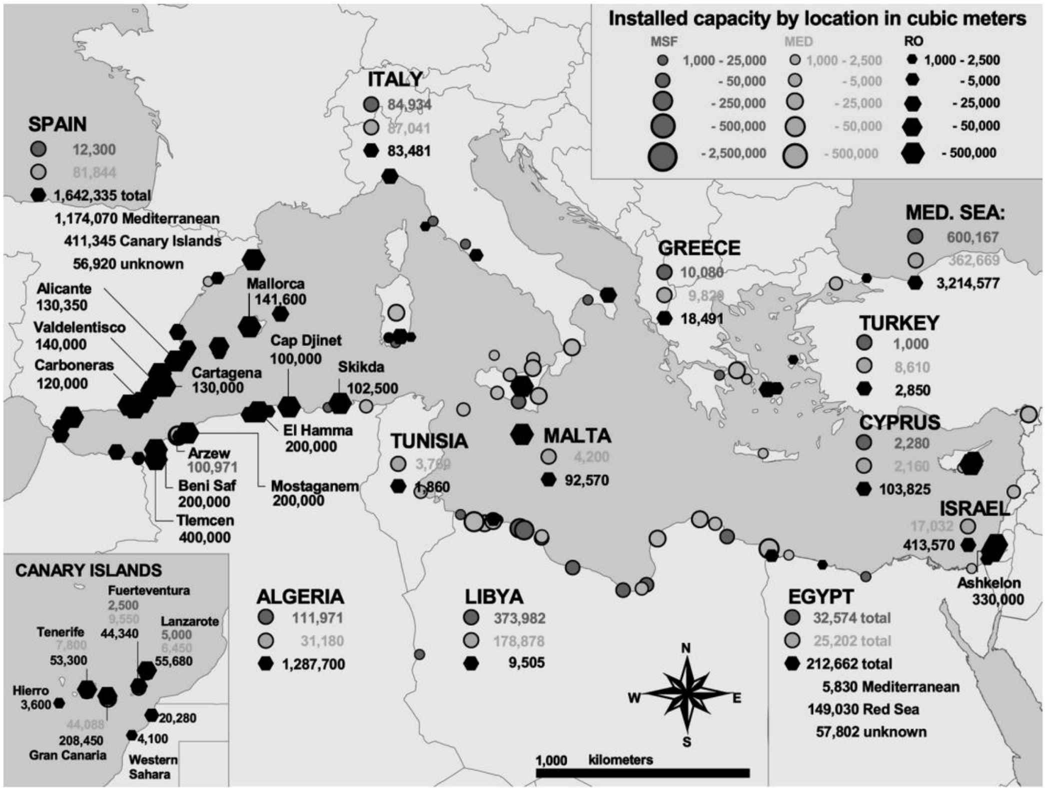


Figure 3-14 Operational Conventional Desalination plants around Mediterranean Sea [87].

3.3.3 PV RO in Turkey

As a part of ADIRA project, a small RO unit of 2 m^3 powered by PV(6 kWp), installed a Hotel in Fethiye Turkey in 2007 [14]. Back then this academic pilot system had estimated cost of water of €18 per m^3 [14]. Figure 3-14 shows DSP plants and capacities of countries around the Mediterranean Sea.

3.3.4 CSP PTC Desalination Plant in California

Like Guzelyurt, many locations in California have salty water problems due to selenium and other natural agricultural salts in soil caused by extensive agricultural irrigation. The agricultural water use accounts for 80 percent of the total consumption in California, therefore it is a very effective way to regain agricultural drainage water by using solar thermal powered desalination [66]. WaterFX, an innovative firm specialized in desalination and water-treatment technologies, established a 24-MW trough-type solar thermal plant that creates direct steam from the sun to run multi-effect distillation for brackish groundwater in agricultural region, the plant expected to produce 7500 cubic meter water per day, and 2.5 million cubic meter per year [66]. This plant is one of the recent and successful examples of its kind.

3.4 CSP

Concentrating Solar Power (CSP) is another form of solar power technology which allows us to produce electricity with thermal power of sun. CSP concentrates DNI from sun to heat a fluid to a temperature between 400-1,000 ^{o}C, using heat it turns water into steam for turning turbine and generating electricity [67]. The book [67] states that typical CSP has efficiency of 16%, so most of the energy is lost during thermal conversion which would be different if desalination is done with thermal energy [67]. Although cost of constructing CSP plants has much higher initial investment cost in compare to PV and other renewables in general, the technology allows prolonged production after sun sets and have higher capacity factor. Unlike PV price per watt, CSP cost seem to be more stable (See Figure 3-15). However, energy storage options of CSP increased in the last decade with longer periods of thermal energy storage available. Desalination with PV only could be done with electricity, on the other hand CSP could do desalination with both electricity and thermal energy, that is one of the reasons that CSP highly considered to be promising technology for desalination. There are 4 types of commercialized CSP technologies. Four most widely used ones are Parabolic Trough Collectors (PTC), Central Receiver (solar power tower) Solar (CRS) or central tower receiver solar thermal power plant (CTRSTPP), Linear Fresnel Reflectors (LFR) and Dish Stirling generators [67]. PTC dominates the market with 85% as it is cheaper, matured and less complicated [67]. As Spain leads the way through technology, South Africa and Morocco are the most promising markets for CSP [67].

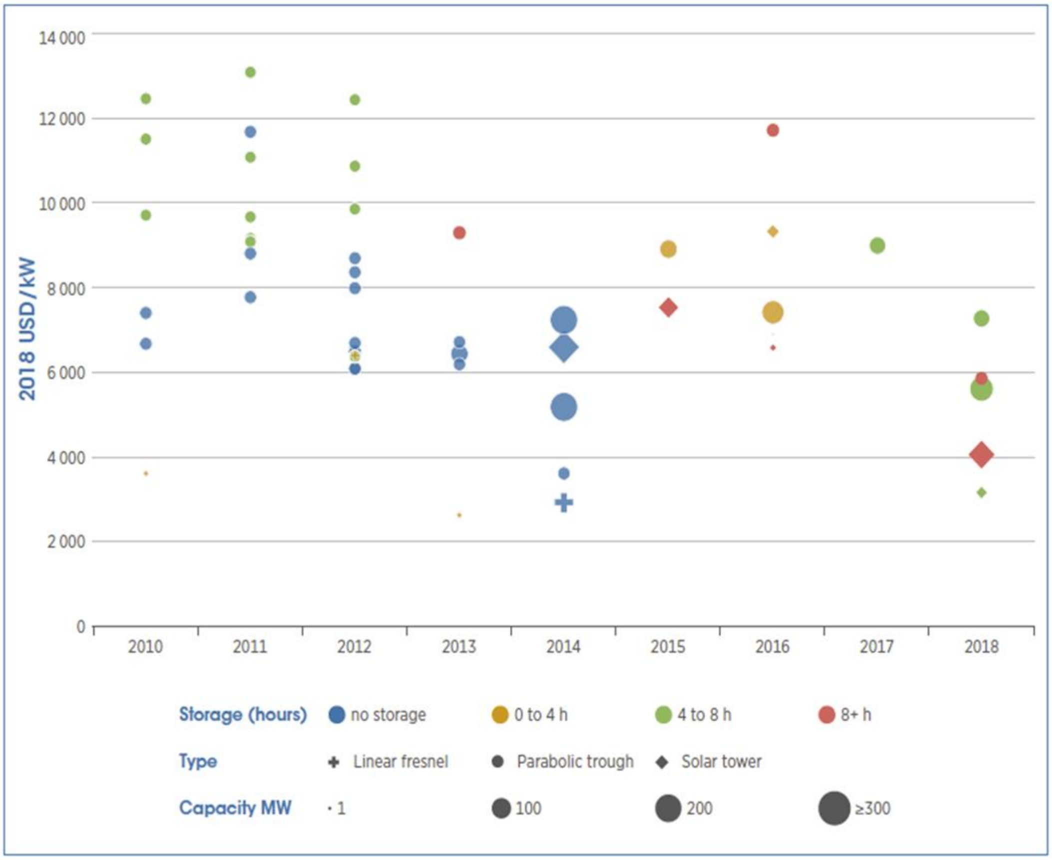


Figure 3-15 Total per kW installation costs of CSP plants by technology and storage duration by IRENA, 2010-2018 [79].

In Cyprus, there aren't any large-scale application of CSP. In 2014, European Commission SETIS awarded Helios Power €46.6 million to build 16920 Stirling Dish solar thermal power units under NER300 funding program with total project capacity of 50.76 MW (3 kW each) over 200 ha area in Larnaca, Cyprus [68]. Unfortunately, there is no further data available about this project. Throughout the article [24], the author has focused on feasibility of Concentrating Solar Power (CSP) technologies or the power production in Mediterranean region, more specifically Southern Cyprus. According to [24]'s work, CSP projects could be implemented in MENA feasibly and cost-effectively by considering the size of the plant, degree of storage, initial cost and the required land [24]. For CSP projects, economies of scale is important.

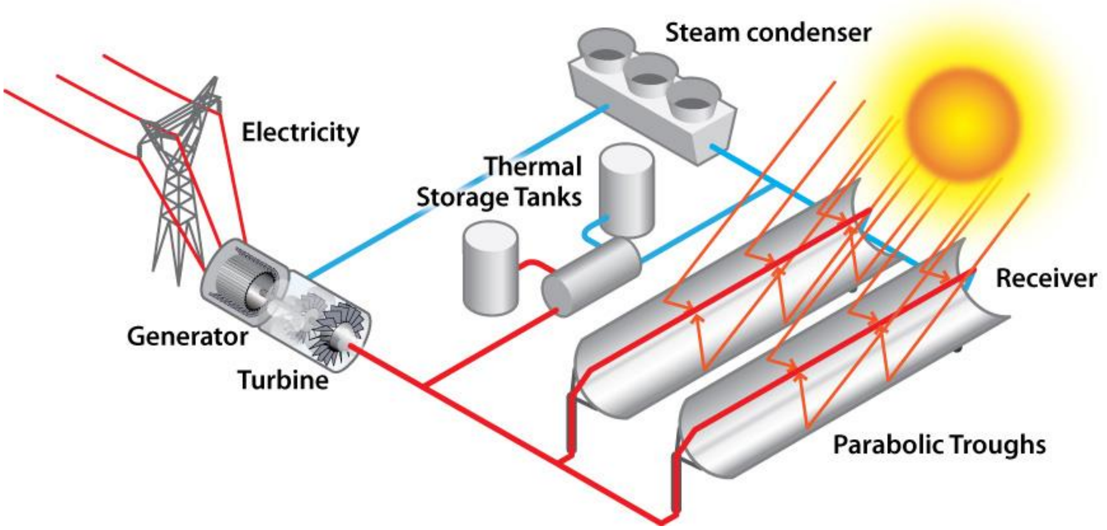


Figure 3-16 Parabolic Trough Collectors solar thermal power diagram [69].

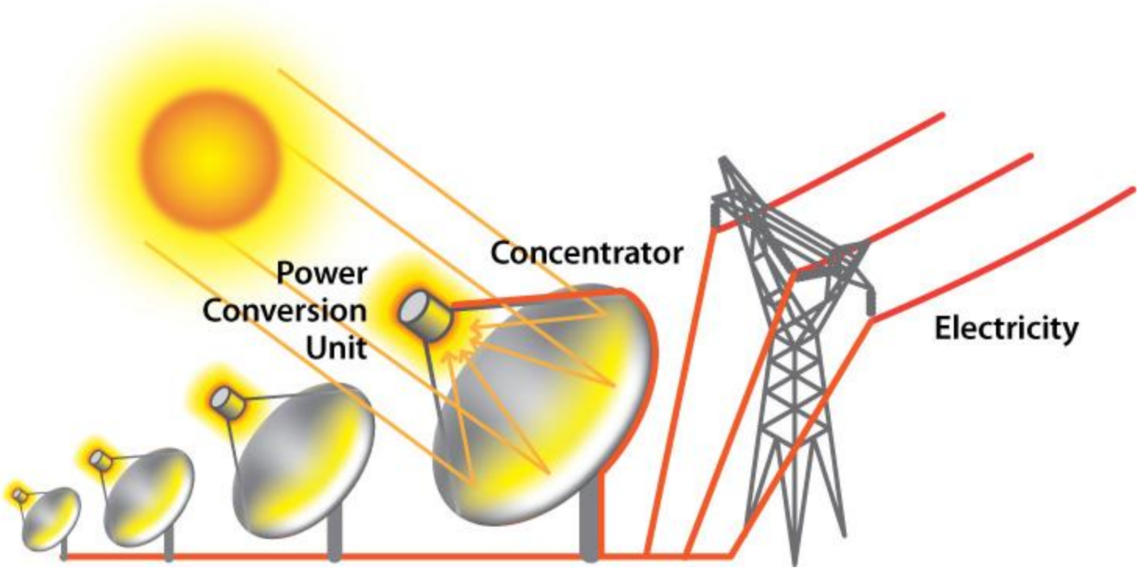


Figure 3-17 Dish Stirling solar thermal power diagram [69].

Moreover it is stated in [24] that mid-size PTC plants with thermal storage option could deliver lower system electricity unit costs in compare to plants of larger capacity or without any thermal storage capability [24]. One article has examined adaptation of CSP technologies for Turkey, which has regional similarities with our case and promising findings for the region [70]. Another article mentions monetary potential of assorted hybrid and solar-only configurations for molten-salt power towers. In general, hybrid power towers were shown to be economically superior to solar-only plants with the same field size [71]. Cyprus is very close proximity to Turkey and Israel but countries that implemented such investments are Spain and Morocco if we consider latitude. In this thesis assumptions based on PS10 in Spain, which has only one hour of thermal storage. In the article [72], authors discuss economic feasibility of solar power generation in India and four different type CSP technologies with working principles and examples around the world used as reference cases. Like in [24], in [72] authors have examined regional economic feasibility for India, using ANDASOL-1 and PS-10 CSP projects. Assessment focuses on capacity factor, annual electricity output and unit cost of electricity at 50 different locations in India. Annual electrical output at the north-western part of India is higher than Seville (for PS-10) and Granada (for ANDASOL-1) because of the higher solar radiation availability, where Northern Cyprus has also higher irradiation, same trend is expected. In [73], authors have examined low, medium and high temperature technologies of solar thermal power plants. Sustainability and technical feasibility of the parabolic trough concentrating solar thermal power plant (PTCSTPP), the parabolic dish concentrator-Stirling engine solar thermal power plant (PDCSSPP) and the central tower receiver solar thermal power plant (CTRSTPP) technologies is proved for low, medium and high temperatures by researches cited in the article. Planta Solar 10 (PS10) in Spain is the first central-receiver solar power plant that producing grid-connected electricity under a purely commercial approach, which has 1-hour thermal storage capacity. Planta Solar 20 (PS20) is a continuation of PS10 built next to it, working with higher efficiency. Gemasolar Thermosolar Plant in Spain is the first high-temperature solar receiver with thermal storage technology using molten salt. It has an annual capacity factor about 75% and it could operate 15 hours with thermal storage.

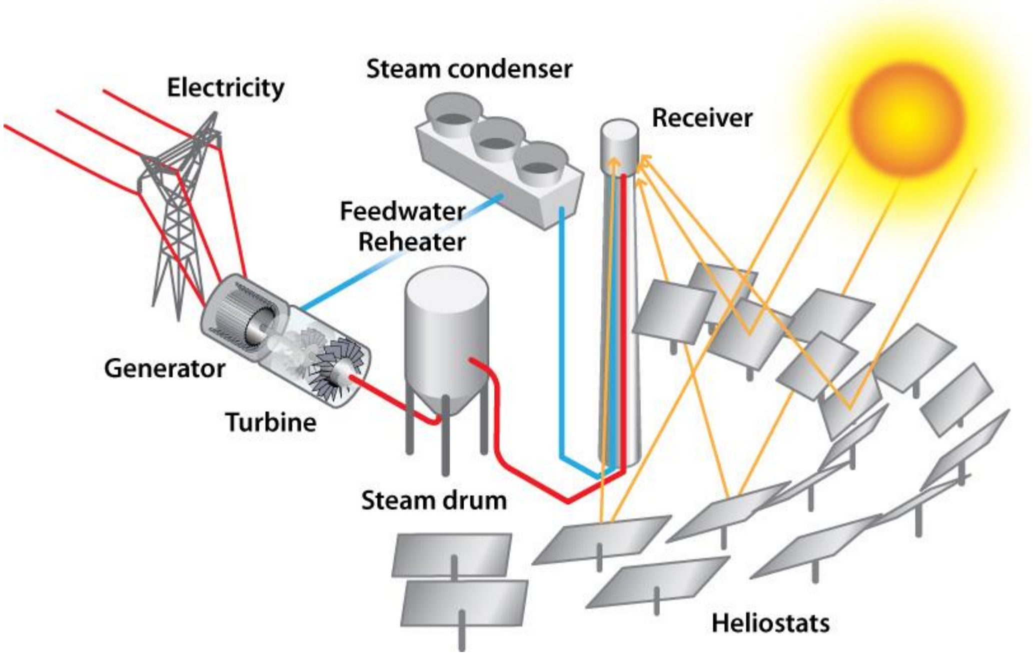


Figure 3-18 Central Receiver solar thermal power diagram [69].

One another recently completed project is Ivanpah Solar Electric Generating System (ISEGS) which has been built in California, US in 2013. The system separated into three units as Ivanpah 1, 2 and 3, where total capacity is around 377MW. One regional CRS system exist which is Greenway CSP Mersin Tower Plant in Turkey, it is the closest power tower system to Northern Cyprus.

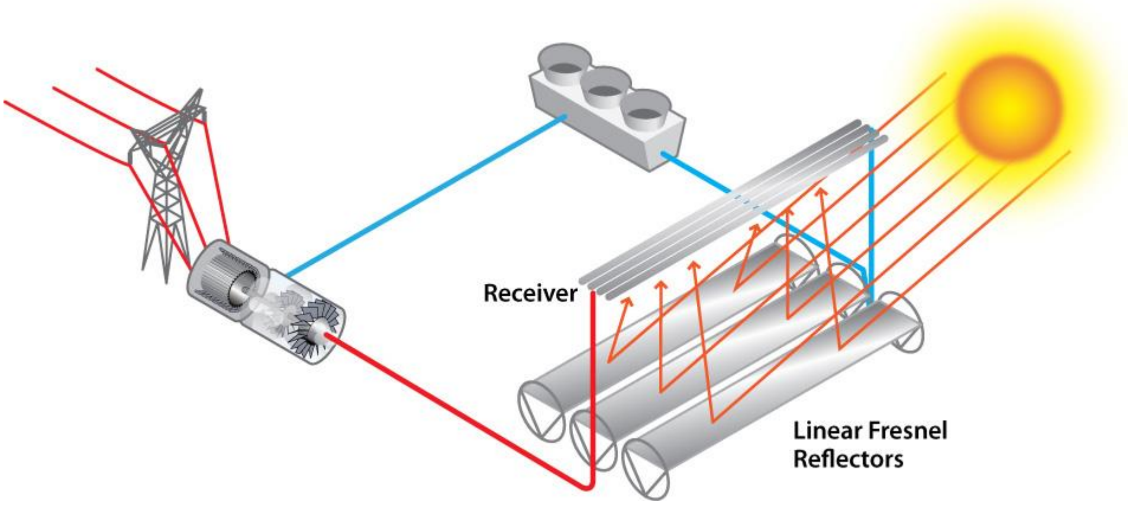
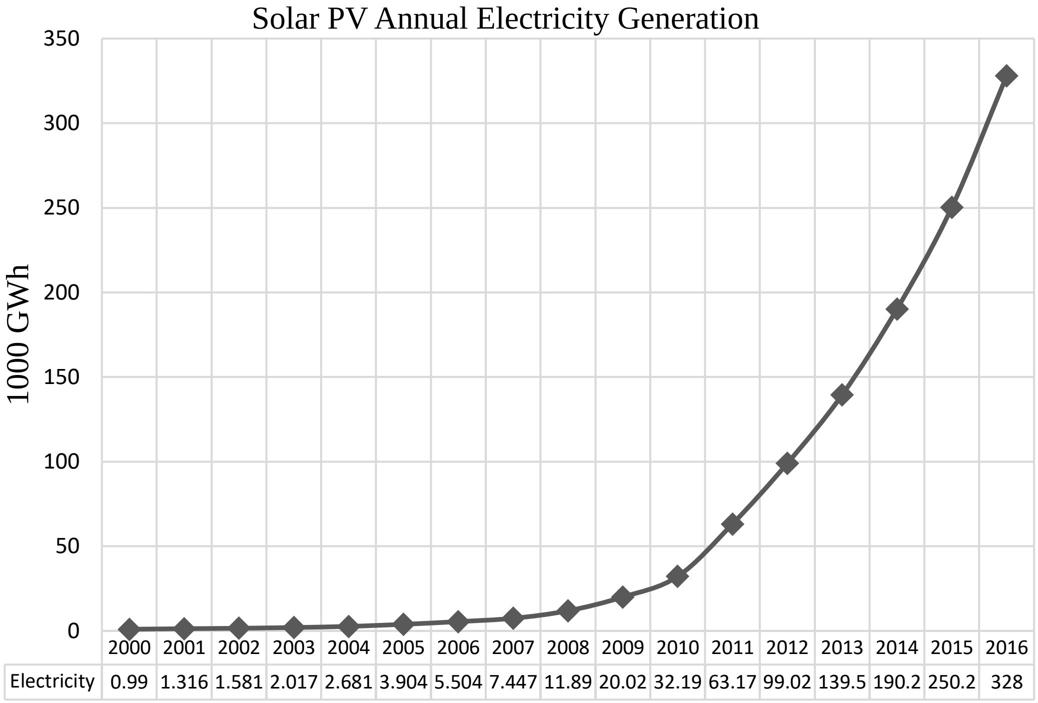


Figure 3-19 Linear Fresnel Reflector solar thermal power diagram [69].

3.4.1 METU NCC CSP

In Northern Cyprus, only CSP plant exists in METU Northern Cyprus Campus. SOLITEM GmbH (Germany) built a concentrating solar thermal power plant using parabolic trough collectors (PTC's) on a 216 m^2 [74], [75]. The project costed total of €830,000 which is around €46,000 per kW capacity [74], [75]. The project uses SOLITEM's PTC1800 collection panels and ElectraTherm's thermal power generators and have a nameplate power capacity of 18 kW [74] , [75]. As plant is intended to be used for academic research, high capital cost is not surprising. Many studies have been done for the use of solar energy for electricity production, cooling, and water heating. Unfortunately plant never been utilized fully for electricity generation. However, there is also capacity to generate 200-400kW thermal heat [74].



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Electricity	0.99	1.316	1.581	2.017	2.681	3.904	5.504	7.447	11.89	20.02	32.19	63.17	99.02	139.5	190.2	250.2	328

Figure 3-20 Annual electricity generation by Solar PV between 2000-2016. Generation as cumulative thousand-gigawatt hour [76].

3.5 Photovoltaics

Photovoltaic (PV) electricity production has a long history, but the technology has recently become commercially viable in terms of efficiency and levelized cost of energy (LCOE) per watt. As of 2016, PV energy generation has reached to 328,038 GWh (Figure 3-20) [76]. PV is a booming renewable energy sector (See Figure 3-20 for period of 2000-2016). Decreasing costs and technological maturity has boosted the sector in last decade. Currently there are two major technologies of solar cells are available on the commercial market, "Crystalline silicon" and "Thin Film". Crystalline silicon technology, which has two types, dominates the market with single crystalline Si (Mono-Si) and multi crystalline Si (Multi-Si) technologies. Both have different production techniques and efficiencies. Thin film technology has recently been evolved with cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (A-Si) material technologies. Apart from those residential PV technologies, there are also high efficiency "Multijunction cells" available for industrial scale application. According to NREL, Multijunction cell efficiencies could reach up to 47% while single junction (crystalline Si) cells have 20-25% peak efficiencies while these are not still commercialized (Figure 3-21). Multijunction cells are generally used with concentrators while single junction cells are regular PV panels. Besides from Figure 3-21, which shows lab results, most of the commercial PV's have efficiencies between 15% to 20%. The recent PV installations in Northern Cyprus are also mostly consist of multi crystalline Si panels manufactured either by European or the US firms, and the majority of them are located in plant size installations like METU NCC PV plant(1 MWp), CIU PV plant (1.1 MWp), Turkcell PV plant (0.9 MWp) and Serhatkoy (1.27 MWp) [34], [37]. According to NREL, the levelized cost of energy (LCOE) of the residential photovoltaic roof installations diminished from 52 cents per kilowatt-hour (¢/kWh) to 15.1 cents per kilowatt-hour between 2010 and 2017 [77]. Furthermore, the report [77] states that The U.S. Department of Energy has a goal to further lower the costs to 5 ¢/kWh by 2030 [77]. In Northern Cyprus, sudden market growth happened in residential PV installations with the help of Act (47/2011) and cost per watt has diminished in the last decade.

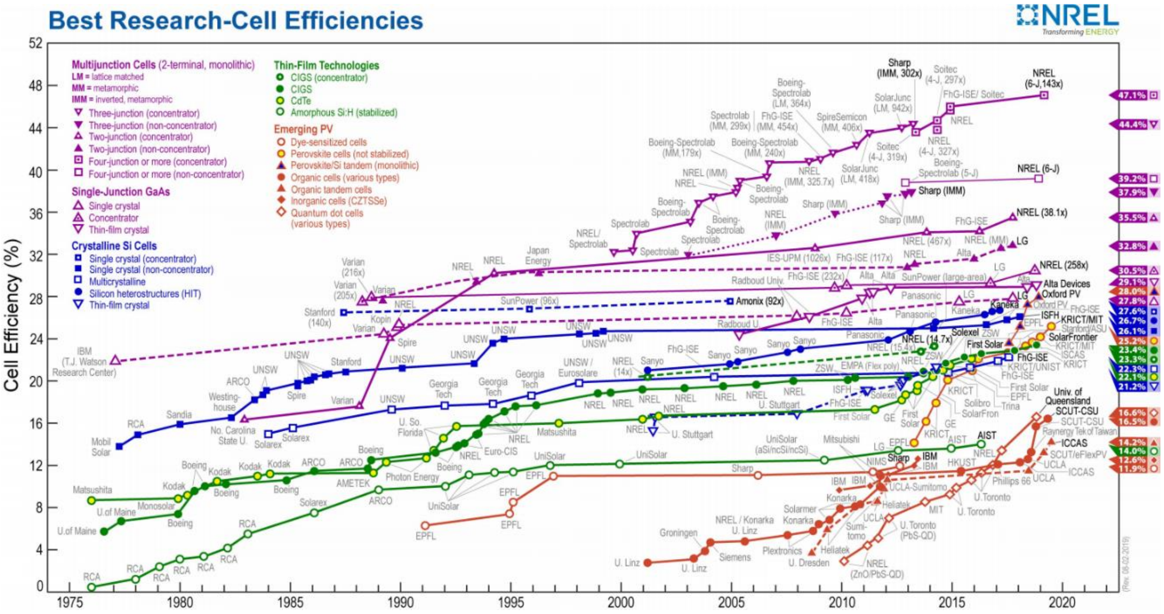


Figure 3-21 Recorded Best PV cell efficiencies by NREL[78].

See Appendix C for larger figure.

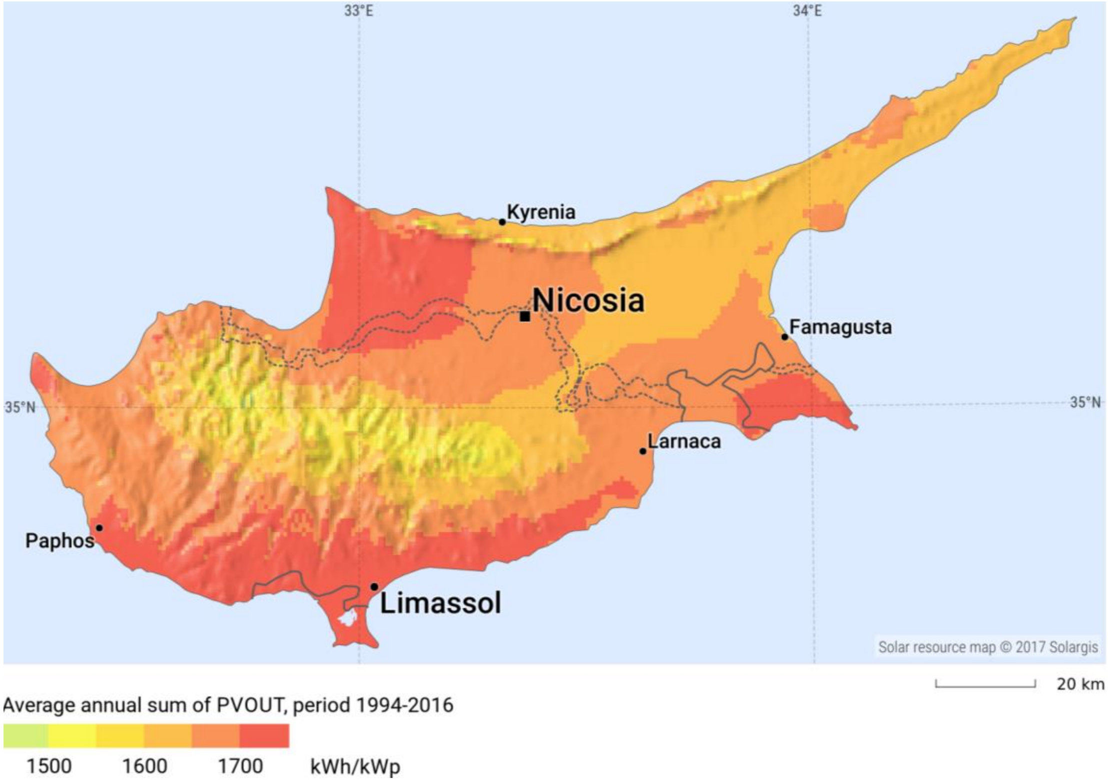


Figure 3-22 Map of average annual sum of potential solar photovoltaic production per meter square in Cyprus [29].

According to IRENA (Figure 3-23), major cost reductions happened at the same era; per watt cost of crystalline silicon panels has diminished from $3.5 per watt to $1 per watt between 2010 – 2014 [79].

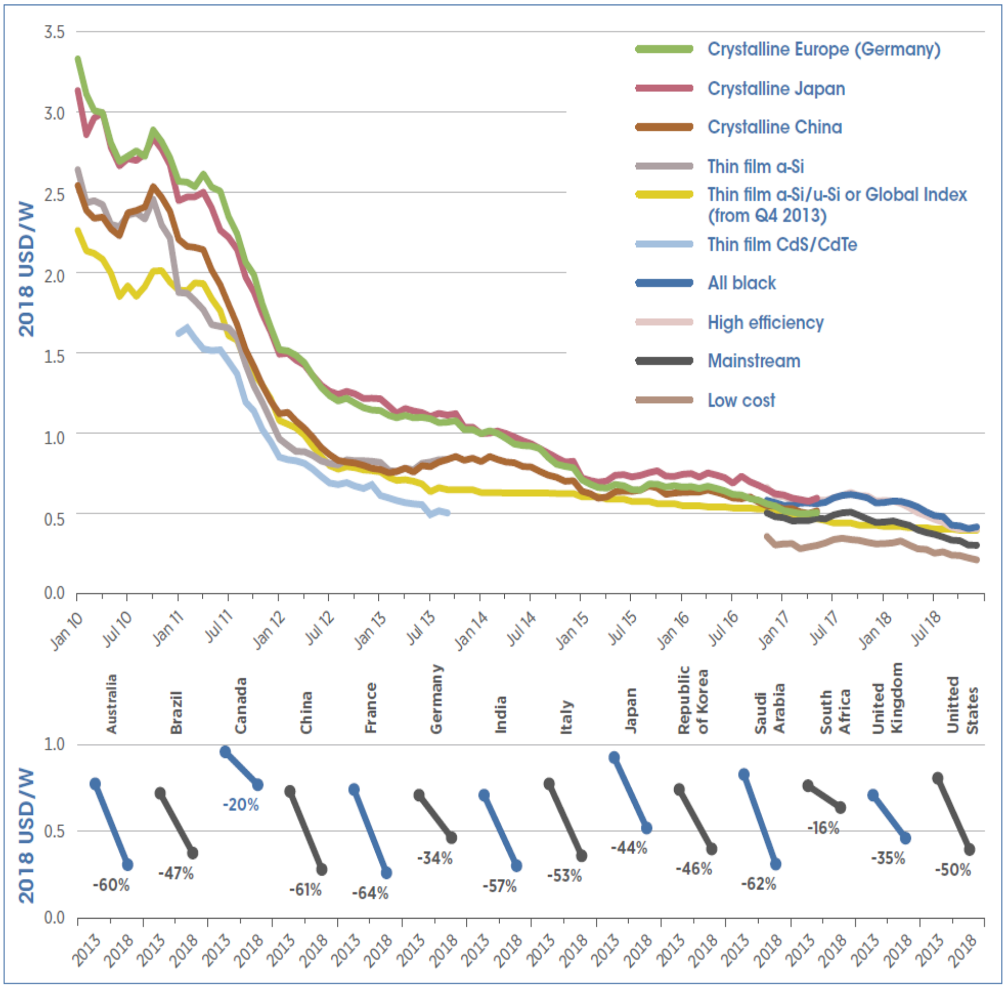


Figure 3-23 Average monthly solar photovoltaic module prices in European markets by different manufacturers and technology. Data between 2010-2018 (USD/W) [79].

This can also be observed in the price difference between Serhatkoy and METU NCC plants. According to Figure 3-23 by IRENA, nearly all types of panels cost less than $0.5 per watt as of 2018 [79]. Paper [35] stated that the cost per watt was as high as €8 per watt of PV panels in 2008 (in TRNC), but with the fast-technological advancement in production and efficiency, the import cost of per watt PV panels lessened from €8 per watt to about €1,25 - €1,8 per watt in 2012. The production data obtained from Serhatkoy and METU NCC is important for us to forecast capacity factor for future considerations.

3.5.1 METU NCC PV Farm and Serhatkoy PV Farm

In 2011, KIBTEK built a 1275 kWp PV Farm in Serhatkoy, Guzelyurt. The Serhatkoy PV Farm have funded by European Union and installed by Anel Enerji of Turkey with the total cost of €4.1 million [35]. Plant is also very close to METU NCC. In the following years PV capacity has increased tremendously. The next large-scale PV plant built by CIU with the capacity of 1,100 kWp in 2014, which has cost almost €1.5 million [80]. Then METU NCC built another one in 2016, it has costed around €1.2 Million with the total capacity of 1,000 kWp [81]. In 2019 Kuzey Kıbrıs Turkcell also opened 900 kWp plant. As mentioned previously, 87 MWp capacity is already licensed. Installation of Serhatkoy costed around €3,200 per kWp while METU NCC plant costed €1,200 per kWp capacity, which is less than half [81]. CIU plant which has been built in 2014, has a cost around €1,360 per kWp installed. For solar capacity factor prediction, we can use Serhatkoy PV farm and METU NCC PV farm data, where annual production is around 2,000 MWh for 2012 for Serhatkoy. The peak production with full capacity factor of 100% expected to be 11,169 MWh, therefore capacity factor on equation (1) told us that we can get 17.5 watt per hour from every 100Wp equivalent quality panel in North Cyprus [35]. Equation 1 and 2 shows the difference between capacity factors of both power plants. Equation 1 total annual generation data obtained from Serhatkoy PV Plant in 2011 and equation 2 total annual generation data obtained from METU NCC PV Plant in 2017. CIU plant also stated to have annual generation around 1,750 MWh which would indicate a capacity factor of 18.15%. Figure 3-24 and 3-25 shows annual monthly electricity generation by Serhatkoy and METU NCC PV plants. PV is a proven and promising technology both in the world and in Cyprus. According to statistics on hand, it can be concluded that it is still better than most countries and feasible enough for more PV farm construction.

$$n_{solar} = \frac{1955319\text{kWh}}{11169000\text{kWh}} \approx 17{,}5\% \qquad (1)$$

$$n_{solar} = \frac{1856000\text{kWh}}{8760000\text{kWh}} \approx 21{,}2\% \qquad (2)$$

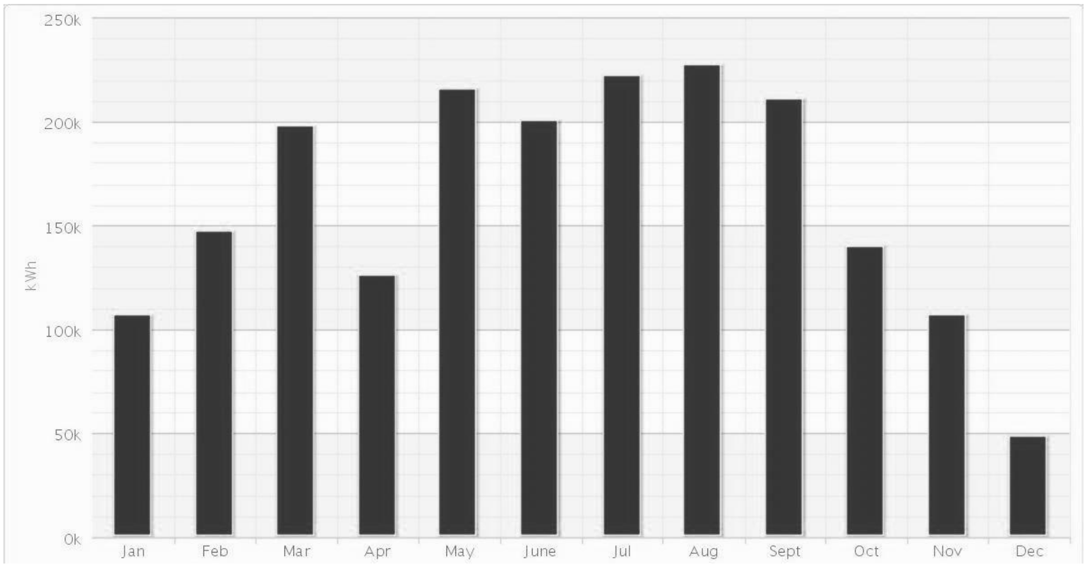


Figure 3-24 Annual monthly power generation (kWh) graph of Serhatkoy PV plant in 2011 [35].

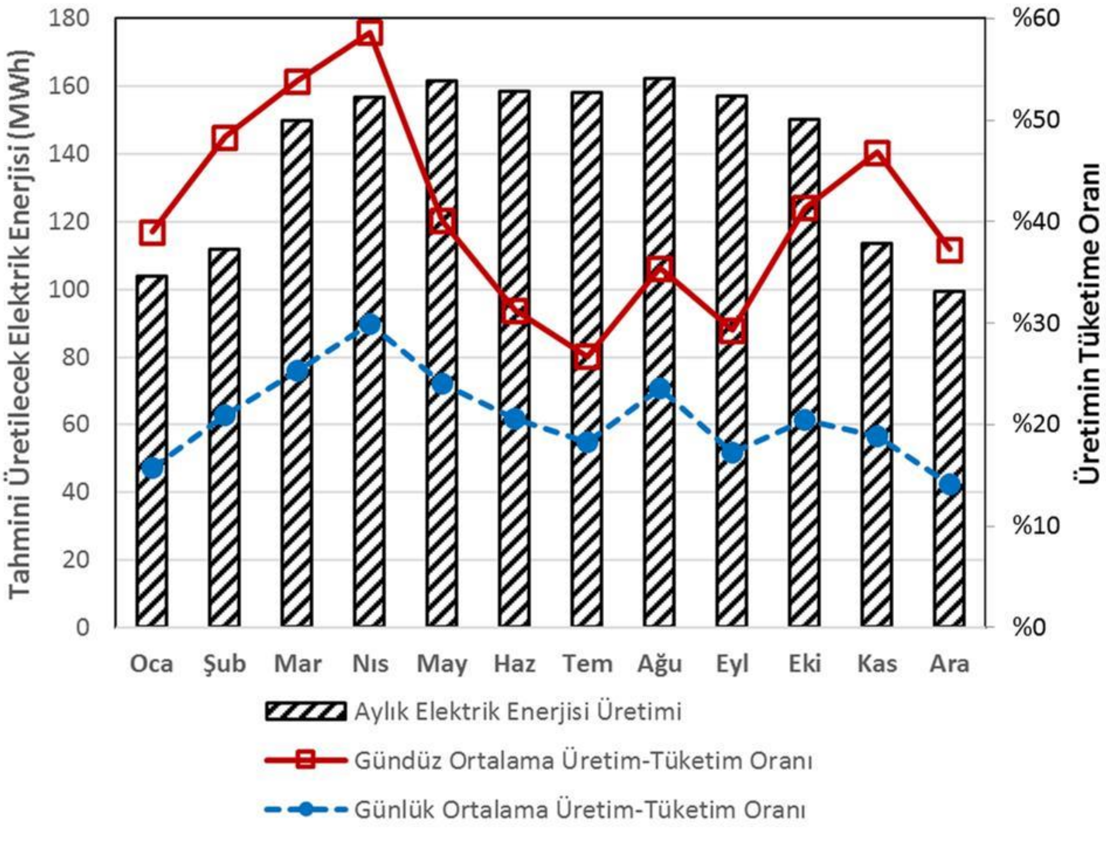


Figure 3-25 Annual monthly power generation (MWh) graph of METU NCC PV plant in 2017.

CHAPTER IV

METHODOLOGY

Through this chapter, data acquisition, modelling, tools used and required inputs be the focus. Before assessing these types of projects, it is crucial to find, measure or store required data. Before estimating the investment related costs, storing and evaluating solar resource data is required in order to design solar power plants. The very first step in this study is to design and establish the data acquisition infrastructure and collection of required on-site measurements of available renewable resources. This includes establishment of sensory equipment, dataloggers, servers, backup configurations, and optionally web based real-time data demonstration and analysis tools. Author has been a member of REDAR research group in METU NCC since 2012 who are responsible from all types of renewable energy resource assessment devices located in the university. Time series of the global horizontal irradiance and the direct normal irradiance measured on campus by REDAR are used for this study (See Chapter II - Figure 2-2).

Additionally, European Commission’s PVGIS provided EPW data and converted TMY2 data used for different locations in order to make assumptions based of correlation (Granada, Spain). Terrestrial solar resource measurement constitutes to the greater portion of the analysis as both Photovoltaic and Concentrated Solar Power output could be forecasted using real-time near surface measurements. TMY2 data provided by NREL or PVGIS could provide an insight but on-ground measurements are necessary for more accurate predictions. It is found that despite the shorter period of records, on-surface real measurements give better results than generated ones. For PV system, there is already existing projects for benchmarking, but for CSP system; analysis should be based on a large scale CSP that is already operational. PVGIS provided weather data used for Aldeire, Granada where Andasol 1 CSP plant operates. Latitude and climate conditions of Cyprus and Granada have similarities. See Table 12 for correlation between average monthly GHI and Latitude tilted insolation data of Granada and Guzelyurt. The latitude of Andasol 1 is 37°13’ North and the latitude of Guzelyurt is 35°15 North. Global

Horizontal radiation found to be 96% correlated. Table 12 compares monthly averages of both sites. Correlation and regression analysis have conducted for both timeseries (TMY2 datasets of Guzelyurt and Granada). Factors like Daylight Saving Time and Time Zone differences adjusted for more consistent results. Analysis shows 89% correlation for hourly average GHI (8760 records) and 64% for DNI. DNI is important for tracking surface CSP technology but correlation for DNI could not provide any insight like GHI as it varies due to many factors. On the other hand, monthly and yearly sum of irradiance is more relevant than correlation (see Table 12). See Figure 4-2 in Analysis and Tools section for DNI comparison. Table 13 shows correlation between TMY2 Timeseries of Granada and Guzelyurt, hourly, daily and monthly average GHI, DNI, DHI, dry bulb temperature and humidity included. Monthly correlation values of temperature and irradiation are promising. For further analysis see Chapter V.

Table 12 Correlation between average monthly GHI and Latitude tilted insolation of Granada and Guzelyurt. (Watt per square meter).

	Average Monthly Insolation (Wh m^{-2})					
	Granada		Guzelyurt		Correlation	
Mon.	**Horiz.**	**Tilted**	**Horiz.**	**Tilted**	**Horiz.**	**Tilted**
Jan	2349	3552	2477	3508	96%	78%
Feb	3125	4160	3225	4115		
Mar	5187	6138	4581	5097		
Apr	5053	5056	5757	5702		
May	6819	6140	6625	5946		
Jun	6896	5947	7259	6258		
Jul	8168	7152	6963	6115		
Aug	6491	6261	7060	6820		
Sep	5030	5509	5347	5769		
Oct	3933	5052	4000	5054		
Nov	3374	5394	2929	4231		
Dec	2828	4879	2400	3608		
Year	4938	5437	4885	5185		

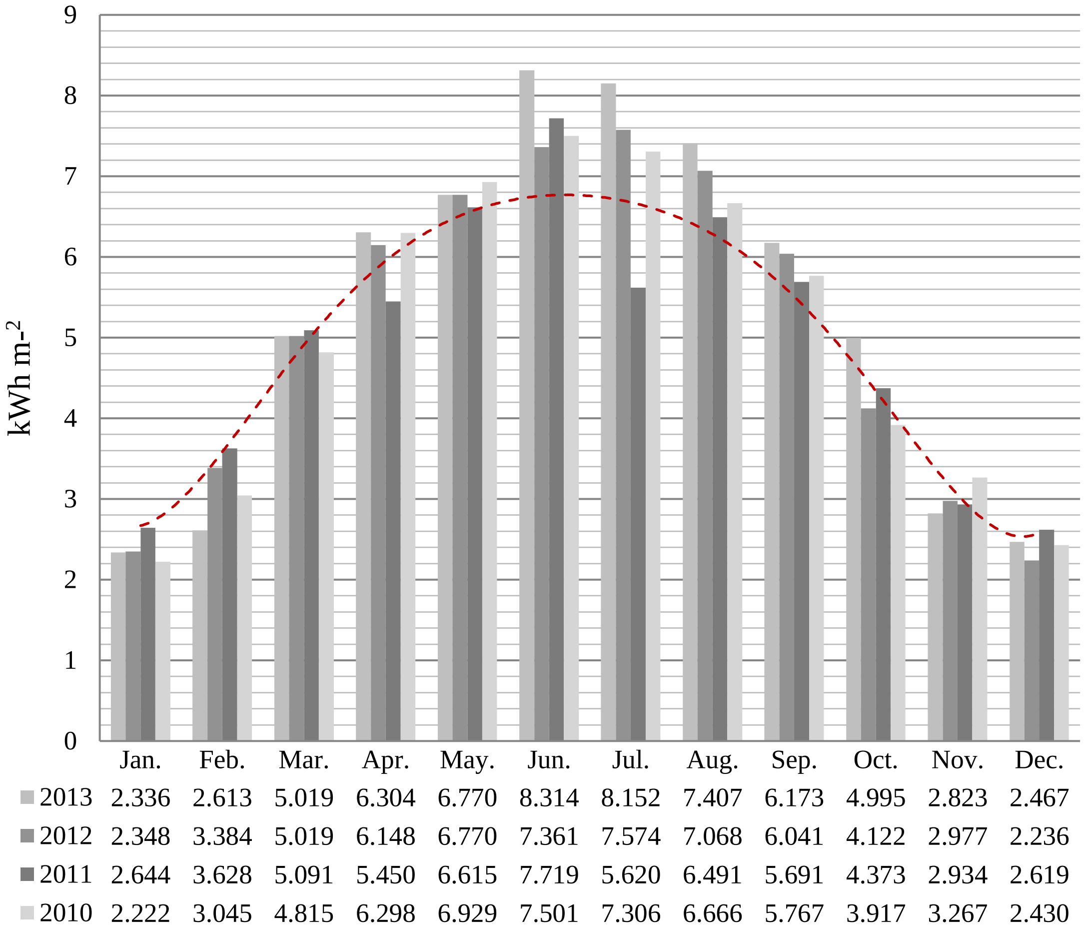
Table 13 Correlation between TMY2 Timeseries of Granada and Guzelyurt. (I = Global Horizontal Insolation; $I_{b,n}$ = Beam (Direct) Normal Insolation; I_d = Diffuse Horizontal Insolation T_{db} = Dry bulb temperature; RH = Relative Humidity)

Correlation of Average Insolation (TMY2 Datasets)					
	I (*Wh m*$^{-2}$)	$I_{b,n}$ *(DNI)* (*Wh m*$^{-2}$)	I_d (*Wh m*$^{-2}$)	T_{db} (*°C*)	*RH* (*%*)
Hourly	89%	64%	78%	84%	58%
Daily	69%	16%	50%	87%	36%
Monthly	96%	72%	95%	97%	75%

4.1 Data Acquisition

There are three different solar resource data that are recorded on-site in METU NCC by radiometers ; these are global horizontal irradiance (GHI) acquired by Pyrgeometer which is the surface infrared irradiance with first data input was starting from 2010; direct (beam) normal irradiance (DNI) recorded by sun tracking pyrheliometer starting from 2013 and diffuse (reflected) horizontal irradiance (DHI). Both Pyrgeometer and tracking Pyrheliometer are positioned on Kipp Zonen Solys 2 sun tracking device which itself was located far from buildings to prevent effects or interruptions caused by human activity like shading. Both devices measures near-surface infrared irradiance with one-minute averages in the form of wavelength then these one-minute intervals converted to 10-minute averages. Data stored by Campbell Scientific CR1000 also includes temperature beside Wm^{-2} radiation. Tilted solar insolation information is required for forecasting angled PV installations or angled and tracking CSP installations. TMY data consisting of global horizontal insolation; direct normal insolation; diffuse horizontal insolation as well as ambient conditions like dry bulb temperature; dew point temperature; relative humidity; atmospheric pressure; on surface wind direction and wind speed used to forecast and analyze different scenarios of solar energy harnessing. NREL SAM software used for running simulations with these datasets. PV simulation based on METU NCC PV plant specifications and PTC simulation based on Andasol CSP in Spain.

In order to forecast the amount of energy that could be produced by typical solar PV system and CSP, hourly solar resources are needed as an input, however solar irradiance is not enough to predict total production without efficiency and specifications of the equipment and capacity factor of the power plant. In this study the actual hourly solar resource data from 2010 to 2013 is used for solar resource model where average irradiance is being archived for every 10 minutes which then converted to hourly/daily/monthly/yearly averages. Data measured after 2015 found to be inconsistent. Additionally, METU NCC constructed 1 MW Solar PV farm in 2016 for scientific purposes and fulfilling in campus energy demand based on assumptions made with these data sets. Figure 4-1 (a call back to Chapter II) shows the data recorded in METU NCC.



	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2013	2.336	2.613	5.019	6.304	6.770	8.314	8.152	7.407	6.173	4.995	2.823	2.467
2012	2.348	3.384	5.019	6.148	6.770	7.361	7.574	7.068	6.041	4.122	2.977	2.236
2011	2.644	3.628	5.091	5.450	6.615	7.719	5.620	6.491	5.691	4.373	2.934	2.619
2010	2.222	3.045	4.815	6.298	6.929	7.501	7.306	6.666	5.767	3.917	3.267	2.430

Figure 4-1 Actual measured daily averages of GHI resources between 2010-2013 in Guzelyurt, METU Northern Cyprus.

4.2 Analysis and Tools

In order to assess cost per cubic meter and find Levelized Cost of Water (LCOW); we should include energy cost in it. In this situation, feasibility of possible CSP Plant and PV plant in Guzelyurt should be included both in the capital requirements and cost per cubic meter. In order to make a better assessment we need to have hourly production capacity of the plant, and hourly energy consumption per cubic meter. Energy production simulated using NREL SAM, Excel A(T)SRA Tool and by using RETScreen energy project modeling software, levelized cost for each plant was then calculated. NREL SAM is a powerful technical modelling, economic modelling and simulation tool used with EPW data. The author has developed an excel module for solar resource assessment, financial forecast and project comparison. Excel VBA assisted module, which had named as Actual (Terrestrial) Solar Resource Assessment Tool (A(T)SRA Tool), able to process TMY2 datasets and produce results showing daily, monthly and yearly averages, predict losses due to orientation, tracking, atmospheric and diffuse, determine tracking path, produce graphs and financial forecast. For further analysis, excel used for economic assessment and RETScreen energy project modeling software used for generator and grid calculations (See Appendix A for screenshots). For designing CSP; the projects in Spain has been taken as reference point. Spain is also located in Mediterranean Basin with similar climate conditions like Cyprus. The latitude of Granada, Spain (where Andasol-1 PTC CSP constructed) is also close to Cyprus as it is mentioned. Assuming the environmental conditions of Spain could be applied to Cyprus too, the technical features of Andasol 1 CSP in Spain used as energy model for the CSP system in NREL SAM (See Chapter V for further information). TMY2 data of Guzelyurt (which is generated using real measurements) and TMY2 data of Aldeire, Granada (by PVGIS) used as both correlated and have similarities. The irradiation values of two locations, which can be seen from Table 12 found to have 96% correlation for monthly values and further analysis between GHI shows 0.56 Standard Error and a regression analysis of TMY2 in Table 14 done with the excel, which defines accuracy of the assumptions. Multiple R value for hourly GHI is 89% with standard error of 130. Figure 4-2 also plots total daily DNI values which is important to compare CSP performances. Figure 4-2 indicates another similarity between both locations, although peak month is different both locations have very similar potential for CSP plants.

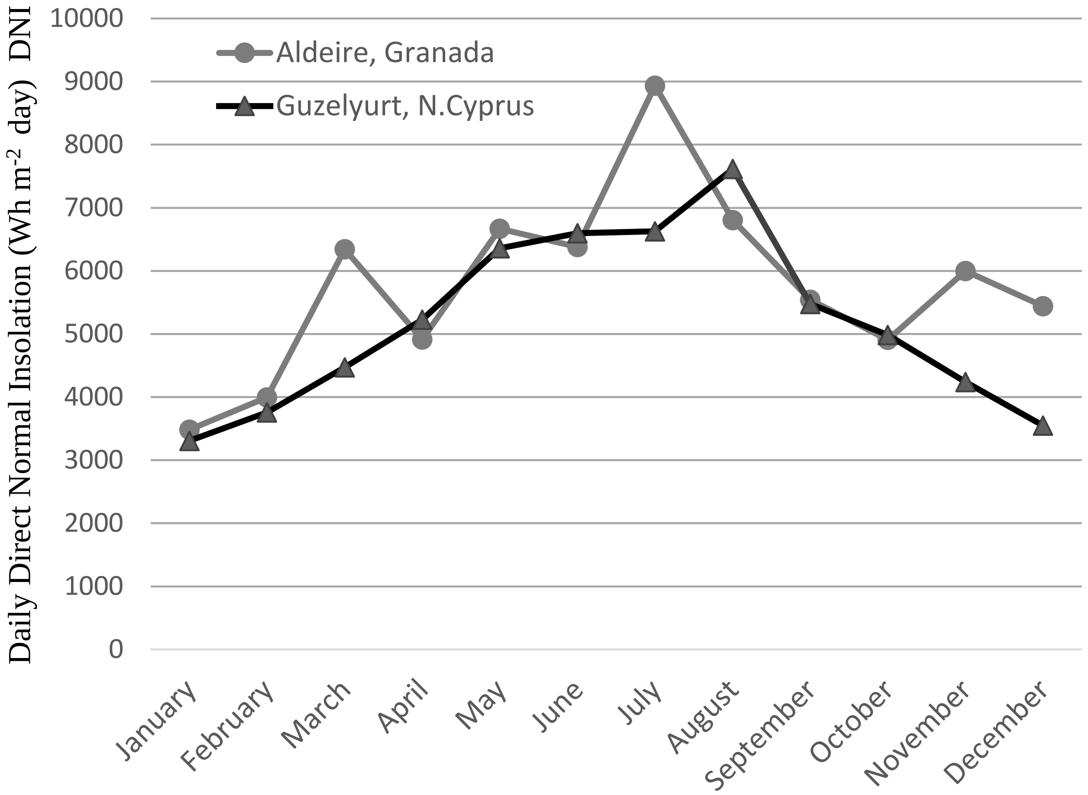


Figure 4-2 Comparison of total daily DNI (Wh m^{-2} day) of Guzelyurt and Granada.

Due to average daily solar radiation of two locations, for latitude oriented sloped surfaces, static surfaces and two axis tracking surfaces, Guzelyurt has slightly lower value than Granada, Spain, which also can be used to define a multiplier between the two.

Table 14 Regression Analysis of Hourly GHI of Granada and Guzelyurt.

Regression Statistics	
Multiple R	89%
R Square	79%
Adjusted R Square	79%
Standard Error	130
Observations	8760

Therefore, NREL SAM simulation run with exact same configuration except thermal storage option. CSP plants without thermal storage has lower capital costs and undeniably storing water considered to be cheaper than storing energy. Furthermore, DNI of Guzelyurt obtained from measurements (TMY2) has been used with capacity factor and technical features of Andasol 1 to estimate annual electricity production (net electricity output) for proofing and cost per kWh. Andasol 1 has been built in 2009 where our plant assumed to be operational in 2016, cost of same components adjusted for 2016 by using NREL and IRENA databases. Same applied to PV by using same components from METU NCC PV Farm. Most important financial measure for energy part of this project is LCOE, which calculates lifetime unit cost of electricity generation by proposed system (*¢/kWh*). Results show very promising values for LCOE. The values could then be added up to cost per cubic meter of proposed DSP.

4.3 Powering with Renewables

In order to make a proper assessment, first we need to identify options available for desalinating seawater via using energy from the sun or other. Table 15 shows available combinations of RE and DSP with respective cost and energy demand. The figures in Table 15 and Table 16 later be used to decide most suitable combinations for solar desalination plant that could be comparable to the NCWSP. Despite the numbers in these tables are not up to date, we could still conclude the most prominent technologies. Recently, with the implementation of energy recovery systems, energy use of DSP lowered, and prices drop as well. The Table 16 shows the technology, capacity and its relevant cost per cubic meter. Economies of scale plays an important role in feasibility. In order to implement a DSP that will supply 75 million cubic meter fresh water annually as an alternative to the Northern Cyprus Water supply project, a water desalination plant with at least 205,500 cubic meter per day capacity is required. However, nameplate capacity does not reflect actual output, moreover the NCWSP also does not provide 75 million m^3 per year without losses due to operation, evaporation and transfer.

Table 15 Energy consumption and water cost of RE powered desalination [20].

RE-desalination process	Typical capacity (m^3/day)	Energy demand (kW he/m^3)	Water production cost (US$/m^3
Solar still	<100	Solar passive	1.3–6.5
Solar MEH	1–100	Thermal: 29.6 Electrical: 1.5	2.6–6.5
Solar MD	0.15–10	45–59	10.5–19.5
Solar pond/MED	20,000–200,000	Thermal: 12.4–24.1 Electrical: 2–3	0.71–0.89
Solar pond/RO	20,000–200,000	Seawater: 4–6 Brackish water: 1.5–4	0.66–0.77
Solar CSP/MED	<5000	Thermal: 12.4–24.1 Electrical: 2–3	2.4–2.8
Solar PV/RO	<100	Seawater: 4–6 Brackish water: 1.5–4	11.7–15.6 6.5–9.1
Solar PV/EDR	<100	1.5–4	10.4–11.7
Wind/RO	50–2,000	Seawater: 4–6 Brackish water:1.5–4	6.6–9.0 small capacity 1.95–5.2 for 1000 m3/d
Wind/MVC	<100	7–12	5.2–7.8
Geothermal/MED	80	Thermal: 12.4–24.1 Electrical: 2–3	2–2.8

4.3.1 Powering with Wind

Wind energy potential of Northern Cyprus found to be poor in compare to solar resources. Even in Southern Cyprus, wind is not a reliable resource for supplying energy for these plants. While solar energy can benefit from heat, wind fed systems can only use electricity. Water use had a peak time during daytime which is overlapping with solar energy availability, however same cannot be assumed for wind.

Table 16 Capacity and Cost per cubic meter, Economies of Scale. [20]

	Type of process	Type of water	Cost of water(US$/m^3)
MSF		Seawater	
	23,000–528,000 m^3/d		0.56 to 1.75
MED		Seawater	
	91,000–320,000 m^3/d		0.52–1.01
	12,000–55,000 m^3/d		0.95–1.5
	Less than 100 m^3/d		2.0–8.0
VC		Seawater	
	30,000 m^3/d		0.87–0.95
	1,000 m^3/d		2.0–2.6
RO		Seawater	
	100,000–320,000 m^3/d		0.45–0.66
	15,000–60,000 m^3/d		0.48–1.62
	1,000–4,800 m^3/d		0.7–1.72
RO		Brackish water	
	Largecapacity:40,000 m^3/d		0.26–0.54
	Medium: 20–1,200 m^3/d		0.78–1.33
	Very small: few m^3/d		0.56–12.99

4.4 Energy requirement for desalination processes

Table 17-18 shows energy requirement for each type of technology in terms of electricity consumed per cubic meter and thermal energy required to vaporize seawater. Although the Table includes higher amounts, most of the sources stated that in room temperature (25^o) seawater (with 3.45% salt) requires 0.86 kWh m^{-3} energy for desalination [62],[20]. Due to economies of scale as the capacity is higher, energy consumption is lower. In [82] it is stated that a mid-size RO plant (250,000 m^3/d) has an energy demand of 5 kWh m^{-3} and also added that multi-stage flash distillation (MSF) could take up to 10 kWh m^{-3} while generally the recent RO plants has a range of energy consumption between 0.8 and 4.2 kWh m^{-3} depending on the salinity level of resource. In our case we consider the levels of Mediterranean sea, which is an salty sea. [20], [62], [82]. ERDs also implemented in the last decade, which helped to further lower energy consumption of RO plants.

Table 17 Typical energy requirements of desalination process by type [20].

Properties	**MSF**	**MED**	**TVC**	**SWRO**	**BWRO**
Typical unit size (m^3/day)	50,000–70,000	5,000–15,000	10,000–30,000	Up to 128,000	Up to 98,000
Electrical energy consumption (kW h/m^3)	2.5–5	2–2.5	1.8–1.6	4–6	1.5–2.5
Thermal energy consumption (MJ/m^3)	190–282	145–230	227	None	None
Equivalent electrical to thermal energy (kW h/m^3)	15.83–23.5	12.2–19.1	14.5	None	None
Total electricity consumption (kW h/m^3)	19.58–27.25	14.45–21.35	16.26	4–6	1.5–2.5
Product water quality(ppm)	≈10	≈10	≈10	400–500	200–500

As mentioned previously, SWRO plants in Southern Cyprus has an energy consumption around 4 – 4.5 kWh m^{-3} as well. Table 18 from [14] confirms same amount of consumption despite plants are not new. Energy recovery devices could be implemented to old and new plants and they are evolving each year.

Table 18 Energy consumption by real world of desalination plants [14].

Plant	**Year**	**Unit capacity (m^3/d)**	**Energy Consumption (kWh m^{-3})**	**Manufacturer**
Ashkelon (Israel)	2005	325,000	< 4	IDE technologies
Tuas (Singapore)	2005	136,000	4.1	Hyflux
Fujairah (UAE)	2003	170,000	3.8	Doosan
Carboneras (Spain)	2005	120,000	4	Hydranautics
Rabigh (KSA)	2008	200,000	4	Mitsubishi
Larnaka (Cyprus)	2001	54,000	4.5	IDE technologies
Florida (USA)	1999	95,000	4	Stone and Webster – Poseidon

4.5 Powering with Non-Renewables

In order to compare desalination with the NCWSP in terms of cost and feasibility, it is crucial to have non renewables for benchmarking purposes. Grid fed desalination could be cheaper although it is against the main idea and it would require adding cost of GHG and environmental harm. Most DSP build with power plants and sometimes fed with waste heat, if it is not directly powered, likewise RE powered systems could also need back up energy supply in close proximity. Besides having grid (as energy input), we should consider insufficient grid capacity as well. Including cost of additional diesel generators would give us better insight. KIBTEK currently operates Wartsila 18V46 diesel generators with name plate capacity of 17.5 MWe. In 2017, KIBTEK requested additional 4 Wartsila 18V46 with reported sale price of €42.5 million. Each generator costs around €10.62 million. As of 2019 average grid price is TRY 0.99 per kWh which is around 17.5 ¢/kWh (TRY/USD 5.63). In 2016, average grid price was TRY0.55 per kWh which is around 18.5 ¢/kWh (See Appendix B). In December 2016, according to EIA price chart, Fuel Oil no:6 (residual) had $1.03 per gallon price tag. An assumption could be made based on Table 19. The diesel generator has an efficiency of 97% and it converts 16290 kW shaft power to 15800 kWe. During this process it loses 4% more internally. The generator with nameplate capacity of 17.5MW expected to annually produce 153 GWh. As diesel generators cannot be utilized 24x365, it could be assumed that the generator runs for 22x365 which would generate 121 GWh annually in reality. That assumptions leads us to 79% – 80% capacity factor for the generator. These inputs used as assumptions in next two chapters. According to EIA, 1 US gallon of residual (No:6) fuel oil contains 158,040kJ energy, which would generate 19 kWh with Wartsila 18V46 according to table 19. Fuel price for every kilowatt produced was 5.5 ¢/kWh without maintenance, salaries etc. according to this assumption based on the prices in the US (which might not extremely different than global market prices).

Table 19 Diesel Generator used by KIBTEK, specifications of Wartsila 18V46 [88]

Name plate Capacity	17 500 kW
Power Plant Type	Diesel
Engine	Wartsila 18V46(500 rpm)
Shaft output ISO	16 290 kWm
Fuel Type	Multi Liquid
Efficiency	97%
Power factor (Capacity)	80%
Fuel consumption gross	8290 - 8330 kJ/kWh (43.4 to 43.2 % efficiency)
Mainstream Fuel	Fuel oil (No:6)
Price Per US Gallon (2016)	$1.03
Lube oil consumption:	0.7 g/kWh
Internal electric consumption	2.5 % at full load up to 4% at low load

Fuel prices could differ from region to region. Grid price also includes many other parameters like distribution, losses, O&M costs and salaries, that is why it would be higher than producing electricity with generators. In desalination plant with diesel case, generator could be next to the plant reducing grid related costs. Using RETScreen and given parameters, diesel coupled DSP also added into the analysis.

4.5.1 Why not Natural Gas?

Considering this as a new investment, either as backup solution or for direct supply, why we could not consider Natural Gas (NG) powered plant? As mentioned previously, whole electricity infrastructure in Northern Cyprus build on fuel oil powered power plants. From fuel storage to maintenance, existing infrastructure is easy to use. This analysis uses non-renewable just for benchmarking purposes. Considering NG as alternative would require whole new infrastructure which will increase costs. Although NG is cleaner, this issue is completely another topic that should be investigated separately.

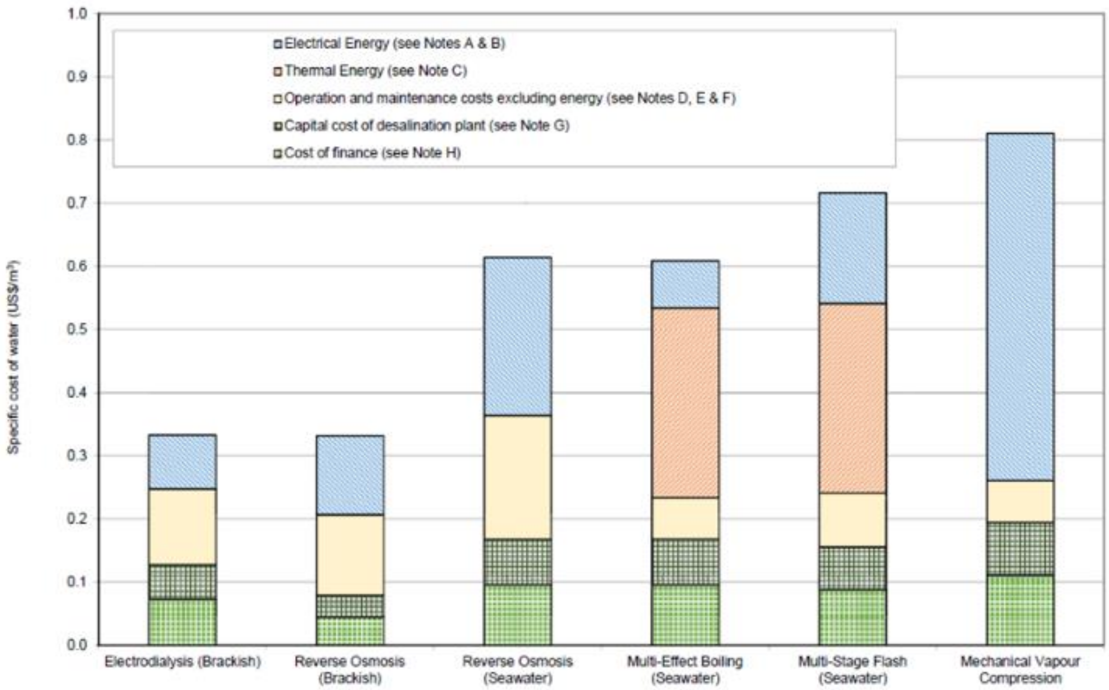


Figure 4-3 The Cost breakup of different types of desalination plants [56]

4.6 Operational Expenditures

Breakdown of costs and comparison between conventional and renewable energy water desalination systems are shown in Table 14. Using renewable energy eliminates the cost of energy input but increases overall required initial investment. It can be regarded as some sort of energy cost if both investments analyzed differently later selling the energy to DSP using LCOE. Back to chapter two, Figure 4-3 also points out different ratios regarding cost of the water produced. Below Figure 4-3, the Table 21 shows general data about cost break up of typical desalination plant. Based on these, projected DSP expected to have 10% to 15% O&M costs.

Table 20 Cost Breakup for Typical DSW Plants [83]

Type of process	Investment costs (%)	Operational costs (%)	Energy costs (%)
Conventional (RO)	22–27	14–15	59–63
Conventional (MSF)	25–30	38–40	33–35
Renewable energy	30–90	10–30	0–10

4.7 Economic Assessment

Economic assessment of the project is carried out using; Microsoft Excel, NREL SAM and RETScreen 4 renewable energy project assessment software which includes CSP, PV and Wind systems. Financial performance indicators like Net Present Value (NPV), DCF (Discounted Cash Flow) Analysis, Internal Rate of Return (IRR) and Payback, LCOE and LCOW used for comparison. As a part of study sensitivity analysis of NPV has done due to different electricity and water export rates, the main determinant of feasibility considered as cost of initial investment which required to be feasible in compare to existing infrastructure in order to be viable and, in order to counter desalination using conventional energy resources. For economic analysis, discount rate assumed as 6% as it is commonly used on renewable energy projects, and average inflation assumed to be 3%. Project has a lifetime of 30 years based on Pipeline project, and most solar power plants also has lifetime between 25 to 30 years. Average grid price of electricity in Northern Cyprus is around $0.185 per kWh. This value is used for benchmarking, grid only option, electricity cost of pumping stations and payback of solar power used for desalination process.

CHAPTER V

SYSTEM DESIGN AND ASSUMPTIONS

5.1. Assumptions of Expenditures and Parameters

Investment cost and water production cost could change due to number of factors. In this thesis, some of these factors eliminated. Theoretical DSP assumed to be operated by government just like the NCWSP. Due to the fact that powering these plants with solar energy requires large open fields and enormous funding. As both DSP and Solar power plant would be next to the shore, it is not practical to forecast land cost or be able to accurate while it could also be provided by government. DSP's that are built by private companies might involve debt ratio or profit which are important for investors unlike government bodies. Governments generally opt for BOT projects which increases total cost. The NCWSP does not include these costs, therefore having similar parameters for each project plays an important role in objectivity.

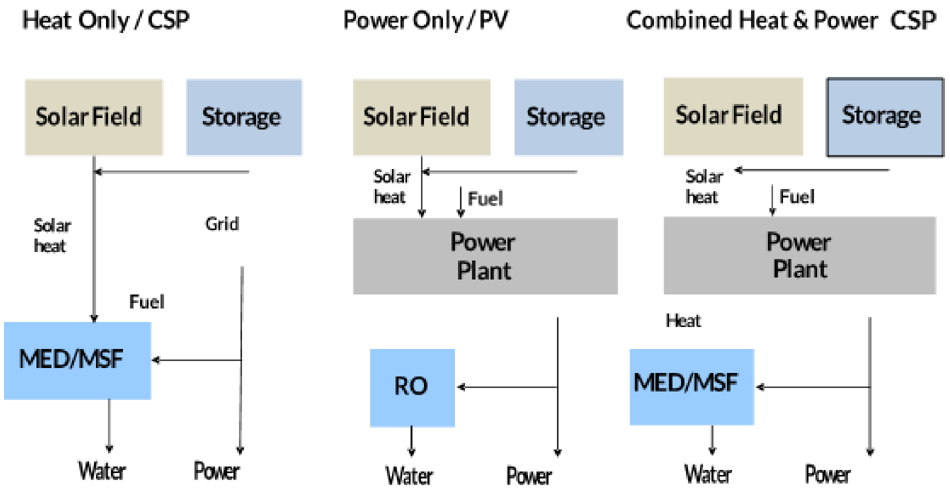


Figure 5-1 Solar-powered desalination options [63].

5.1.1. Choosing Desalination technology

Choosing most suitable method is crucial to determine overall cost. PV powered RO, CSP (PTC) electricity powered RO, PV powered MSF and MED and CSP thermal powered MSF and MED are the options for large scale solar desalination. As RO is highly dominated the market, RO is the priority. For further information about chosen technology, see section 5.2 Decision Matrix. Figure 5-1 shows most common combinations.

5.1.2. Economies of Scale

Size of a DSP regarded as a major determinant of the overall cost of investment and cost of water as well. Methods like MED and MSF are not considered to be commercially viable to build in small scale. On the other hand, membrane technologies could be scaled up and down due to requirement. In general, all kinds of DSPs affected by overall size of the plant. Author [14] created Table 21 using different studies that have been done to show difference of costs affected by the size of DSPs with different technologies. As plant size gets bigger, cost of produced water diminishes. These findings used to give scores for these technologies in decision matrix.

Table 21 Aspects of Economies of Scale in Desalination Plants [14].

Publication	**Process**	**Capacity (m^3/day)**	**Unit product cost (\$/m^3)**
Frioui and Oumeddour	MVC	1,000	1.02
	RO	1,000	1.8
	MSF	1,000	1.2–1.34
	MED	1,000	1.38–1.45
Karagiannis and Soldatos	MVC	1,000–1,200	
	RO	12,000–60,000	0.44–1.62
	MSF	23,000–528,000	0.52–1.75
	MED	12,000–55,000	0.95–1.95
Díaz-Caneja and Farinas	RO	65,000–170,000	0.7
Ophir and Lokiec	MED	100,000	0.54
Borsani and Rebagliati	RO	205,000	0.45
	MSF	205,000	0.52
	MED	205,000	0.52

5.1.3. Electricity price and Energy Recovery

Undeniably, if desalination plant run with conventional power sources or fed by grid, price of electricity is an important determinant. Infrastructure required to integrate DSP to national grid is another expenditure, in this case, it is not included like many other determinants as theoretical plant will be operated by government. Grid prices for industrial facilities was 18.5 ¢/kWh in 2016. This rate used in analysis for comparing chosen configuration with grid. However, in real world conditions; these types of plants use subsidized rates, thus using consumer or industrial level grid rates could not reflect reality. In this study, grid has been used for benchmarking rather than comparison. Recovering used energy or using waste heat from power plant might affect operating cost of DSPs as well. There are many new ERD technologies that reduced energy consumption and lowered overall cost of produced water. Technologies like Pressure exchangers, turbo chargers or waste heat utilization methods are not included in this study. Having ERDs or not including them are a broad subject that should be addressed separately. Therefore, it is assumed that cost of ERD included in capital cost and energy recovery also assumed as part of total energy consumption (for instance: 4 kWh m^{-3} for SWRO)

5.1.4. Water Storage and Energy Storage

While conducting such analysis and building this type of plants, either storing RE or DSW plays important role in both operation and initial capital cost. For PV and CSP, no energy storage assumed as grid could be used as back-up. In order to show how grid problems could be overcome, additional diesel generator assumed. Proposed plant works during day and producing freshwater like AL Khafji SWRO, during nights either it could be fed by grid or it can store excess water produced during daytime. Energy storage options increases costs, while storing water is cheaper. Proposed plant also includes a public owned reservoir to store water before distributing. Storing water in a reservoir has its own negative aspects like evaporation, contamination or need for re-treatment. These are neglected as it could be another subject to research. Further analysis should include land cost of reservoir and losses vs storing energy or using grid as backup.

5.1.5. Feed Water

Saline water source considered to be highly important input in determining to cost of water produced. Likewise, while it is irrelevant in plants using RO method, temperature of feed water affects process and energy consumption in evaporating methods like MSF and MED. Average monthly temperatures of seawater given in the Table 22 for Guzelyurt bay. Annual mean seawater temperature in Guzelyurt Bay is 27.6°C. Temperature of water affect performance of thermal processes powered by CSP.

Table 22 Mean monthly seawater temperatures in the Bay of Guzelyurt [84].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min °C	16.2	15.9	15.9	16.4	18.8	22.4	25.7	27.6	26.3	22.9	18.9	17.2
Max °C	19.5	17.7	18.8	19.7	23.3	27.2	29.9	29.7	29	27.4	24.3	20.9

On the other hand, RO technology more affected by the number of dissolved particles (TDS) in the water while evaporating methods does not. Salinity also causes more erosion, subsequently increasing O&M costs. Eastern Mediterranean Sea has a highly saline water in compare to other Mediterranean regions or oceans. Larnaca has salinity of 40,500 ppm TDS and plants in Israel has a feed water with 40,750 ppm TDS while regular seawater is 30,000- 35,000 ppm TDS. Freshwater for agriculture requires less than 1,000 ppm and tap water stated to require less than 500 ppm to be considered as healthy by WHO, see table 8 from Chapter 2. Table 23 shows how pressure requirements increase for RO plants depending on feedwater quality and TDS amount. The temperature also affects the viscosity of water which influences membrane performance [85]. For this analysis, same input in Southern Cyprus and Israel assumed. Energy requirement could be lower for brackish or ocean water desalination.

Table 23 Pressure Requirements of Reverse Osmosis plants depending on feedwater quality [85].

Source	**Associated Salinity, (mg/L)**	**Typical Pressure Range, psi (bar)**
Surface (Fresh) Water (MF/UF)	<500	15 - 30 (1-2)
Brackish Water (RO)	500 – 3,500	50 - 150 (3.4-10.3)
Brackish to Saline (RO / SWRO)	3,500 – 18,000	150 - 650 (10.3-44.8)
Seawater, typical range		
• USA	18,000 – 36,000	650 – 1,200 (44.8-82.7)
• Middle East	18,000 – 45,000+	

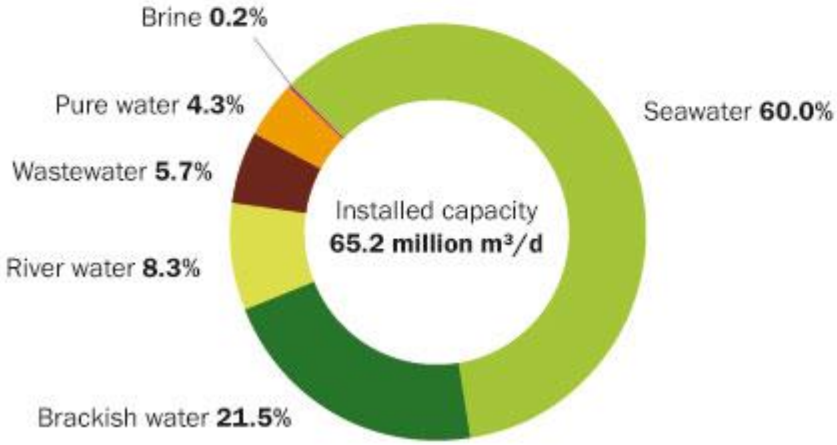


Figure 5-2 Worldwide desalination feed water types as of 2013.

5.1.6. Choosing Location and Land Cost

Choosing where to build a desalination facility is another aspect that determines cost. Cost of land affects cost of investment as such plants require large open fields next to coast which would be valuable. Proximity to saline water and elevation of the plant affects cost of water. Guzelyurt Bay with 10m elevation is the chosen site for this project. Location also important for storing the water or transporting using existing infrastructure. Another factor is seawater intake source, how far is the intake, how deep is the sea and where to discharge brine also regarded as important for construction site. A desalination plant consumes lot of electricity which might require to be positioned next to a powerplant of a reliable power source. In our case it will be powered by solar power plants or generators while grid option regarded as independent of source location. Solar power plants require vast open fields, in our analysis it is assumed and simulated that PV field requires 1,084,009 m² and CSP PTC field requires 877,000 m². Gecitkoy Dagdere Dam which stores the NCWSP water in Cyprus has a surface area around 1,030,000 m². The dam is a public land without any cost of purchase. Desalination requires no storage if there is no need to store excess water. In this analysis, land cost is not taken into account.

5.1.7. Pretreatment of Water and Cost of Pretreatment Plant

Saline water requires pretreatment procedures, before feeding water into the desalination unit large particles, trash, organic matter or other contaminants should be removed before desalination started. Thus, every desalination facility requires pretreatment and cleanness of water affect cost of this procedure. Water quality improved by treatment like wastewater treatment and biological life forms also filtered before water treated. From similar projects [18], it is assumed that pretreatment plant costs around 25 million USD.

5.1.8. Adding Minerals and Post-treatment

The purpose of desalination highly considered to be one of the factors that determine overall cost and cost of water. A facility intended to provide tap water requires more input than agricultural water. This also is a factor for choosing technology. If final market is residential users, then water needs post-treatment and addition of minerals or other ingredients to improve overall quality of produced water. Brackish water and Seawater also have different requirements in terms of post treatment. Requirement and complexity of post treatment procedures affect cost of water. These are included in O&M costs.

5.1.9. Overall Infrastructure costs

Some of the above-mentioned determinants might affect infrastructure requirements. Depending on the location, DSPs could require additional infrastructure, better building materials, longer or shorter intake and discharge points, longer or deeper pipelines, transmission lines, roads and facilities for workers etc. Depending on the other parameters infrastructural investment might vary significantly. See Table 24 for price variations between DSPs around the world. While these plants have been built around same period of time, water cost varies due to different factors. In this analysis, proposed DSP assumed to have piping, intake pipe and pumping cost around 15 million USD by considering similar projects [18]. These expenditures are separate from cost of plant. There are also pre-project expenditures like feasibility study, engineering of the plant, bureaucracy and other.

Table 24 Price variations between DSPs around the world [14].

Plant	**Technology**	**Water Cost ($\$/m^3$)**	**Plant capacity (m^3/d)**	**Date of estimate**
Shuweihat (UAE)	MSF	1.13	454,610	2008
Ras Laffan (UAE)	MSF	0.80	272,520	2008
Hidd (UAE)	MSF	0.69	400,000	2008
Tenes (Algeria)	SWRO	0.59	200,000	2008
Taunton (Massachusets)	SWRO	1.53	18,925	2008
Palmachim (Israel)	SWRO	0.86	83,270	2008
Oued Sebt (Algeria)	SWRO	0.68	100,000	2008
Hadera (Israel)	SWRO	0.86	330,000	2008
Ashkelon (Israel)	SWRO	0.78	326,144	2008
Tianjin (China)	SWRO	0.95	150,000	2007
Dhekelia (Cyprus)	SWRO	0.88	40,000	2007
Carlsbad (California)	SWRO	0.77	189,250	2007
Pert (Australia)	SWRO	0.75	143,700	2006
Marafiq (KSA)	MED	0.83	758,516	2006
Shoaiba 3 (KSA)	MSF	0.57	881,150	2005
Reliance refinery (India)	MED	1.53	14,400	2005

5.1.10. Laws and Environmental regulations

Every country or region subject to different environmental rules and regulations. EU countries have more strict regulations than middle eastern countries. This regulation might affect required infrastructure in order to protect marine life or environment overall. Consequently, region specific regulations affect cost of the investment.

5.1.11. Cost Input and Sources

Aim of this thesis is to find out a sustainable alternative to the NCWSP. As NCWSP completed in 2016, taking the prices for that year gives better results. Since it has completed, the price of water to municipalities have not been changed despite end user prices increased. Another reference point is METU NCC PV plant which was also completed in 2016. Prices and costs are based on 2016 data or closest year available. Cost of components taken from IRENA and NREL databases (2016) for RE plants. Costs related to DSP obtained from publications that mentioned previously. Appendix B includes respective average monthly currency rates obtained from INFOREURO (see Appendix B). In order to have consistent results, all costs and prices converted to USD with USD/TRY 0.3354 and EUR/USD 1.1060 which are the annual average exchange rates for 2016. This also helps to deal with unstable results that would appear due to Lira Crisis in 2018.

5.2. Decision Matrix and Technology Selection

Decision matrix is a tool used in business studies for making a multi-criteria decision analysis. This simple tool allows investors or managers to select and decide projects from multiple alternatives. Table 25 is a decision matrix and there are multiple combinations of desalination and solar energy technologies. In order to reduce the number of alternatives, a preselection has been made based on data available. Most common technologies for desalination are multi-stage flash (MSF), multi-effect distillation (MED), thermal vapor compression (TVC), Electrodialysis and reverse osmosis (RO). Based on publications in literature, previously mentioned information in both literature review and methodology are used for scoring combinations. The criteria that are considered; average water cost of similar DSPs, capital expenditure for both DSP and Solar in other projects, average energy demand of the system, known O&M costs and scalability of the system as projected DSP is a large facility. Based on these criteria, each combination has been given scores between 0-10, while best performer had received 10pts, worst performer had been given 0. Even numbers are used for more clarity. Final Scores are adjusted as percentages, therefore overall performance evaluated over 100. Top two combinations are PV/SWRO and CSP/SWRO systems followed by PV/MSF. For this thesis, PV/SWRO and CSP/SWRO are evaluated.

Table 25 Decision Matrix for DSP technology selection.

	Decision Criteria					Score	
Combination	**Water Cost**	**Capital Cost**	**Energy Demand**	**O&M**	**Scaling**	**Total**	**Adjusted**
Weight (%)	**30**	**20**	**20**	**15**	**15**		**100**
PV/SWRO	10	10	6	10	10	920	**92**
PV/MED	6	6	8	8	6	670	67
PV/MSF	8	8	6	6	8	730	**73**
PV/TVC	6	4	8	2	4	510	51
PV/EDR	2	4	10	8	0	460	46
CSP/SWRO	10	8	6	8	10	850	**85**
CSP/MED(E)	6	4	8	8	6	630	63
CSP/MED(T)	6	4	2	8	6	510	51
CSP/MSF(E)	8	6	6	6	8	690	69
CSP/MSF(T)	8	6	0	6	8	570	57
CSP/TVC(E)	6	2	8	2	4	470	47
CSP/TVC(T)	6	2	4	2	4	390	39
Solar Still	6	6	10	10	0	650	65

5.3. Assumptions

Throughout the analysis, assumptions must be made based on already constructed projects, including desalination plants and solar energy projects. Unfortunately, a large-scale desalination plant powered with only solar power has not available in terms of economic data. Al Khafji solar saline water reverse osmosis plant is the only example of this technology and closest available reference. Despite total cost of Al Khafji SWRO known, actual composition of the capital expenditure is unknown like cost of PV Plant next to it. Moreover, the plant also utilizes grid which makes examination difficult. Furthermore, economic data seems limited except its investment cost per m^3 capacity ($2167). There are several large-scale RO plants powered with electricity, Table 25 shows capacity and investment made to those projects, however those projects sometimes include power plants (like Ras Al Khair) or certain infrastructure along with the plant, which adds up to the overall capital cost. Therefore, it is impossible to determine capital cost of such plants with perfect conditions. Sorek seawater desalination plant in Israel is one of the most advanced plants with its low cost and better efficiency in compare to older ones, yet it is hard to find detailed economic data about these plants as they are commercial projects. The assumptions made by using average capital invested per daily capacity of plants. DSPs with powerplants are not included and desalination methods separated. Average capital cost of $950 per cubic meter daily capacity is found for typical SWRO. This value assumed for RO plant. Cost per cubic meter capacity assumed separately from infrastructure and pre-construction related costs that mentioned previously, which includes pre-treatment, post-treatment, piping and pumping stations.

Table 26 Recently Built Major Desalination Plants around the World
[14], [46], [58], [64].

Desalination Plant	**Location-Year**	**Investment (Million US$)**	**Water Price (US$/$m^3$)**	**Capital In. Per US$/$m^3$**
Ras Al Khair (MSF&RO) 728 000 m^3 /d	KSA - 2014	$ 7,200.00* *(With 2650MW CCGT)*		9890
Magtaa SWRO 500 000 m^3 /d	Algeria- 2014	$ 495		989
Sorek SWRO 624 000 m^3 /d	Israel -2013	$ 500	$ 0.58	801
Hadera DSP 462 000 m^3 /d	Israel -2010	$ 339	$ 0.86 (2008)	734
Ashkelon SWRO Phase 1 - 165 000m^3/day PHASE2 330 000m^3/day	Israel -2005	$ 212	$ 0.53	642
Shoaiba MSF DSP 450 000 m^3 /d	KSA - 2001	$ 1,060	$ 0.57	2356
Victorian DSP 410 000 m^3 /d	Australia-2012	$ 3,950		9634
Ashdod SWRO 384 000 m^3 /d	Israel -2016	$ 163		424
Adelaide DSP 300 000 m^3 /d	Australia-2012	$ 1,260		4200
Al Khobar SWRO 210 000 m^3 /d		$ 220		1048
Carlsbad DSP 190 000 m^3 /d	USA - 2015	$ 992	$ 0.45	5221
Southern SWRO DSP 100 000 m^3 /d	Australia-2013	$ 660		6600
Larnaca SWRO 64 000 m^3 /d	Cyprus - 1999	$ 47	$ 0.79	734
Al Khafji Solar SWRO 60 000 m^3 /d	KSA-2017	$ 130		2167

*CCGT is Combined cycle power plant (Natural Gas), Ras Al Khair Capital Cost includes 2650MW CCGT.

Although there are some other cost figures, this study intends to find average capital cost, and payback of typical desalination plants with solar powered systems. Hence other parameters like operational, financial or maintenance cost, might not reflect real world conditions. Al Khafji Solar SWRO capital investment includes both PV and desalination unit cost. Average \$950 per cubic meter of capacity for SWRO assumed and total capital cost for DSP assumed to be \$1300 with the addition of \$1074 per m^3/d PV capital cost gives us \$2374 which is very close to Al Khafji (\$2167). Table 27 shows general assumptions made for our proposed DSP. Cost of land neglected, and debt is not included in general assumptions. Average inflation rate for USD assumed to be 3% with the insight from Federal Reserve historic timeseries. Discount rate for energy projects varies between 5% to 10%. While USD interest rates also varies between 6% to 8% in Northern Cyprus, discount rate assumed to be 6%. It is unrealistic to have a static price for water, thus 3% price escalation starting with 77 ¢/m^3 (the NCWSP) assumed as price variation in time considering the inflation rate. As plant will be operated by state, there is no corporate or other tax inputs. However even for state, there should be cost of financing which will later be included.

Table 27 General Assumptions about proposed DSP.

	Solar PV SWRO	**Solar CSP SWRO**	**NCWSP**
Funding	Public	Public	Public
Project Lifetime	30 years	30 years	30 years
Land Use	1,084,009 m²	877,000 m²	1,030,000 m²
Land Cost	Free (Public)	Free (Public)	Free (Public)
Debt Ratio	0.00%	0.00%	0.00%
Taxation	No Tax	No Tax	No Tax
Corporate Tax	Public Owned	Public Owned	Public Owned
Water price escalation	3.00%	3.00%	Unknown
Inflation	3.00%	3.00%	Unknown
Discount Rate	6.00%	6.00%	Unknown
Investment Cost DSP only \$950 for only SWRO (m^3/d)	\$1,300	\$1,300	\$2,043
Capital Cost (m^3/d)	\$2,428	\$4,027	\$2,043

5.4. System Design

Both powering systems and desalination plant included in cost analysis. Based on previous assumptions, this section includes system design and finalized costs of these systems. PV/SWRO; reverse osmosis powered with PV, CSP/SWRO; reverse osmosis powered with parabolic through collector; Gen/RO reverse osmosis powered with diesel electricity generator and as a benchmark Grid/RO powered with grid only assumed. Table 28 shows final designs of proposed powering options and respective costs for building desired capacity. Capacity factor for PV plant based on NREL SAM simulation with REDAR TMY2, which is 18.6%. Capacity factor is very similar to other photovoltaic electricity production facilities in that region (Chapter III). For CSP, cost per capacity and capacity factor based on Andasol 1 CSP in Spain with the defined multiplier in the assumptions due to the difference between TMY2 irradiation data. Thus, as it is seen from the Table 9, capacity factor for Concentrated solar power for Guzelyurt assumed to be 28.5%. Both for PV and CSP, irradiation of Guzelyurt used as basis, and for PV modules, cost per kW capacity in the analysis are based on 2016 market prices research in IRENA like CSP.

Table 28 Powering units, Investment and O&M Cost assumptions.

	PV/SWRO	CSP/SWRO	Gen/SWRO
Power Plant Assumptions			
Capacity Factor	18.60%	23.70%	79.00%
Nameplate Capacity	167000 kWp	131400 kWp	52500kW
Annual Generation	271.9 GWh	272.3 GWh	363.3 GWh
Capital Cost Per kW	$1,317	$4,024	$766
Initial Investment			
Inverter ($2500)	$17,352,500		
Power Generator		$124,100,000	$35,254,745
PV Panel ($0.50)	$83,499,216		
Collectors &Solar Field		$235,440,000	
HTF System		$94,176,000	
Engineering	$18,369,826	$35,316,000	$1,300,000
Equipment (other)	$50,099,528	$14,600,000	
Labor	$25,049,764	(Engineering)	
Overhead	$16,699,842	$4,880,864	
Transmission & Subs.			$750,000
Transport			$1,000,000
Contingency	$9,635,042	$25,181,600	$1,915,237
Total Investment	$220,705,718	$533,694,464	$40,219,983
O&M Expenditures			
Maintenance & Other	$1,669,984	$9,636,000	$1,762,737
Fuel ($1.03 per gallon)	-	-	$20,253,444
Indirect revenue			
Excess Electricity	1.83 *GWh*	2.31 *GWh*	93.29 *GWh*
Income (15 ¢/kWh)	$275,209	$346,283	$13,994,100

5.4.1. Designing PV Plant

Table 29 shows and compares projected PV plant for powering DSP to METU NCC PV farm. Both plants exist in same location thus, proposed system designed by using METU NCC Plant as a reference point and using NREL SAM. Total of 667,905 panels used in 1.08 km^2 land to produce required amount of energy.

Table 29 PV Plant Design Parameters for powering SWRO.

	Projected PV Plant	**METU NCC PV**
Total installed cost	$220,705,712	$1,371,440
Cost Per kWe	$1,322	$1,371
Nameplate Capacity	167 DC *MW*	1 DC *MW*
Annual Generation	271 861 *MWh*	1 640 *MWh*
Capacity Factor	%18.6 (mean)	%18.7 -%21.2
Panel Model	AXITEC AC-250P/156-60S	AXITEC AC-250P/156-60S
Cell material	Multi-c-Si	Multi-c-Si
Module area	1.62 *m²*	1.62 *m²*
Module capacity	250.03 DC Watts	250.03 DC Watts
Quantity	667 905	4000
Inverter	SMA 24000TL	SMA 25000TL
Number of Inverters	6,941	40
Cost of Inverters	$2,500	?
Total area	1,084,009 *m²*	16500 *m²*

Capacity Factor calculated by NREL SAM. METU NCC PV farm which also constructed 2016 is much smaller thus using same prices does not create consisted results. Costs related to PV plant obtained from IRENA and NREL databases for 2016 (50 ¢ per Wp), and quite similar results obtained for cost per kWe capacity. Note that as of 2018, IRENA shows 35 ¢ per Wp price for panels where cost of PV/SWRO could go further down [79].

5.4.2. Designing CSP Plant

Table 30 shows parameters and components used in NREL SAM analysis; technical specifications based on Andasol 1 as it is mentioned previously in Chapter IV. Cost of materials used obtained from NREL and IRENA for respective year (2016) [79]. Andasol 1 constructed in 2009 and our proposed plant assumed to be operational in 2016, despite cost of materials used had not been changed dramatically, removing thermal storage from design lowered per kWe installation cost from $7,485 to $4,062. However, removing thermal storage also shrinks the hours that plant is operational resulting capacity factor to diminish from 41.5% to 23.7%. Deciding which option is better lies in LCOE and proposed PTC CSP has lower LCOE than Andasol.

Table 30 Design parameters of PTC CSP Plant for powering SWRO.

	Project CSP Plant	**Andasol-1**
Data Location	Guzelyurt (TMY)	Aldeire, Granada (EPW)
Data Type	Measured (METU NCC)	PVGIS
Construction Date	2016	2009
Nameplate Capacity	131.40 MWe	55 MWe
Total installed cost	\$533,694,464	\$411,690,000
Annual Generation	272 335 MWh	179 103 MWh
Cost Per kWe Capacity	\$4,062	\$7,485
Capacity Factor	23.7%	41.5%
Technology	parabolic trough collector	parabolic trough collector
Collector (SCAs)	EuroTrough ET150	EuroTrough ET150
Irradiation at design	950 W m^{-2}	700 W m^{-2}
Field aperture	877 000 m^2	510 120 m^2
Receivers	Solel UVAC 3	Solel UVAC 3
Thermal Storage *	0	7.5 hr
Per year decline	0.5	0.5

Figure 5-3 plots total daily DNI values from Granada and Guzelyurt. TMY and EPW (converted) of Guzelyurt and EPW of Granada used in NREL SAM simulations and A(T)STRA Tool to test reliability of output obtained. Note (Table 30) that Andasol 1 has 7.5-hour thermal storage while we rely on direct steam generation and storing water instead.

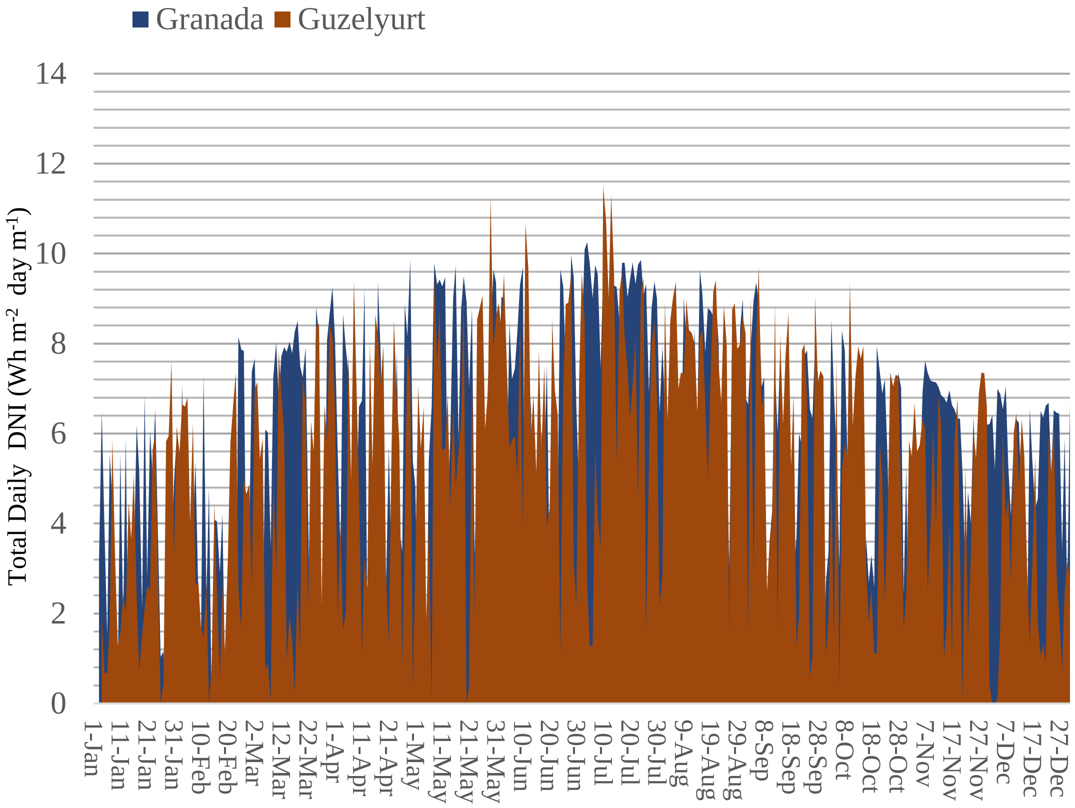


Figure 5-3 Comparison of total daily DNI values of Granada and Guzelyurt.

5.4.2.1. Orientation and Losses

Appendix D includes an extensive table generated using Excel A(T)SRA Tool by author. TMY data of Guzelyurt used to determine orientation of PTC CSP solar collector units as well as PV orientation. Table includes Non-Concentrating and Concentrating surfaces with daily average irradiance (kWh m^{-2}). Figure 5-4 shows performances of tracking surfaces in Guzelyurt (TMY2), 2 axis (2A) tracking, EW (East West Tracking) and NS (North South Tracking) values compared Losses in the system could occur based on orientation of collectors. NS and 2A shows closer relation and performances. In CSPs, EW and NS are the main options. Moreover, Losses could occur during nighttime in solar energy, atmospheric losses (atm) and diffused radiation are also expected. Losses that can be managed include the orientation (orient) and thermal losses. For Orientation see 5-5 and 5-6, East-West orientation has the highest losses thus our system designed as North-South. Appendix D shows annual average daily irradiance of 3.94 kWh m^{-2} for EW and 4.56 kWh m^{-2} for NS. Further, considering parasitic and thermal conversion losses, system designed as 146 MWe with conversion ratio of 90%. The total nameplate peak capacity of 131.40 MWe achieved with these specifications.

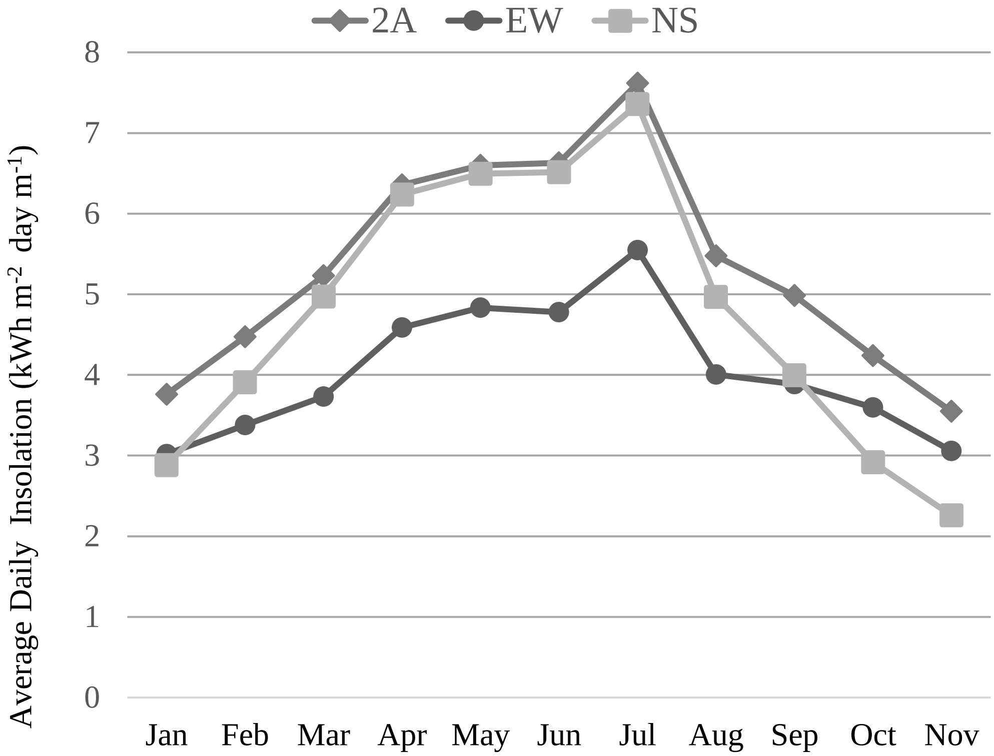


Figure 5-4 Average Daily Insolation for 2 Axis, North-South and East-West Tracking Surfaces (kWh m^{-2} day m^{-1})

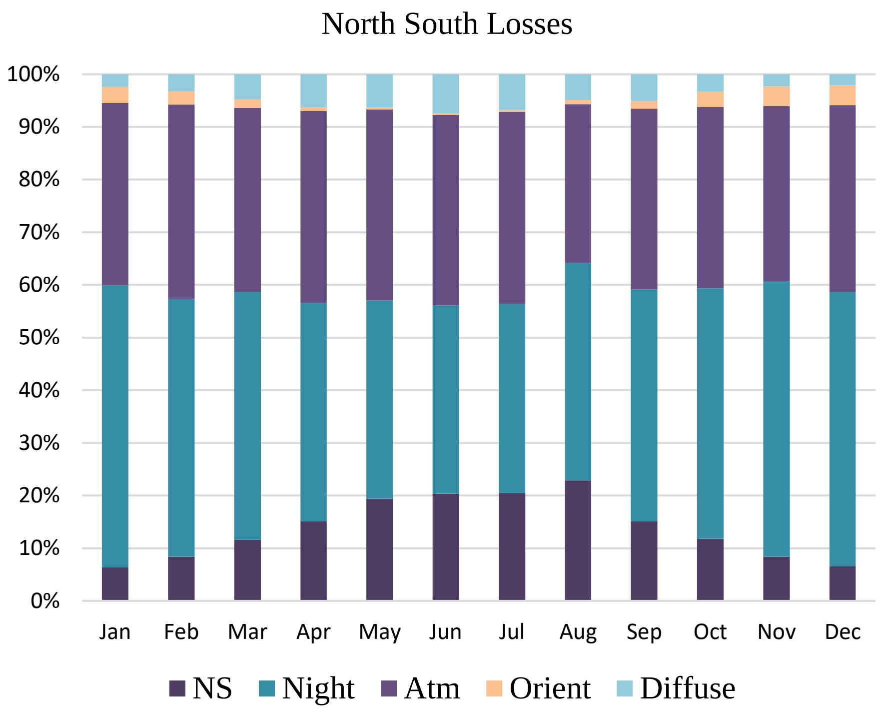


Figure 5-5 North-South Tracking Collector Losses

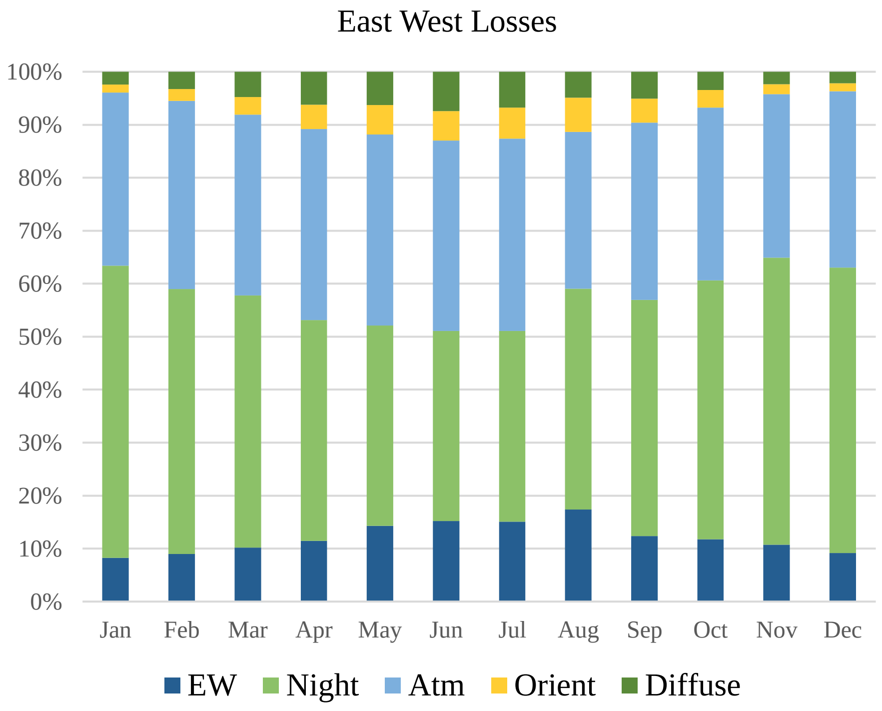


Figure 5-6 East-West Tracking Collector Losses

5.5. Designing SWRO Plant

Table 31 shows general assumptions made for SWRO desalination Unit, including capital investment, pretreatment plant, piping, pumping station, other capital costs and O&M costs. SWRO assumed to have \$950 capital cost per cubic meter daily capacity \$1300 for overall DSP including other costs. Without any energy investment plant would consume \$49,9 million worth electricity with regular grid price (18.5 cents). These types of plants normally use subsidized industrial electricity with lower prices. However, our assumption does not include this.

Table 31 SWRO Plant Assumptions for the Project. Desalination Unit, Investment and O&M Cost assumptions.

SWRO Assumptions		
General		
Daily Capacity	205,500 m^3/d	
Capacity Utilization	90%	
Annual Electricity Required	270.03 *GWh*	
Energy consumption	4 kWh m^{-3}	
Initial Investment		
Feasibility study	\$	1,500,000
Engineering Cost	\$	3,000,000
Site Development	\$	5,000,000
Reverse Osmosis Plant (\$950 per m^3/d)	\$	195,225,000
Spare Equipment (10%)	\$	9,761,250
Pre-treatment Plant	\$	25,000,000
Intake - Pumping - Pipelines	\$	15,000,000
Contingencies (5%)	\$	12,724,313
Total Investment	\$	267,210,563
O&M Expenditures		
Maintenance & Other (10%)	\$	19,522,500
Annual Electricity Cost (Grid)	\$	49,954,995

5.6. Utilization Factor

Like capacity factor in power plants, DSPs have utilization factor. Nameplate capacity does not constitute to exact amount of production. Utilization amount could change due to many variables. Typically, like conventional power units, desalination units could run on demand. Thus, deciding exact amount of water output seems to be hard. Similar to diesel generators, DSPs require maintenance and have an efficiency percentage. Table 32 shows, nameplate capacity of real-world DSPs based on Table 26, data also include annual output and respective utilization percentage calculated by using capacity factor formula. An average of 90% utilization has found and used in all calculations in this thesis.

Table 32 Utilization factor based of real-world DSPs (SWRO).

Capacity m^3 /d	Utilization million m^3 /year	Utilization Percentage
624000	150	66%
450000	150	91%
384000	100	71%
300000	100	91%
300000	100	91%
330000	108	90%

5.7. Utilized Amount and Scenarios

There are couple of options for providing the amount of water mentioned. Designing a plant that could deliver 75 million cubic meters of water annually is the first option. Considering the utilization factor, we would need to have 83.3 million m^3/y capacity or 228,300 m^3/d capacity to reach exact amount. However, it is impossible for the NCWSP to supply nameplate amount of water. There are two reservoirs, and even only Dagdere Dam have surface area of 1.03 km^2. Assuming 1 liter of evaporation (generally specified amount) per square meter could shows how high the losses could be. Considering evaporation from both dams, leakage from pipes and seepage; we can assume that the NCWSP could have at least 10%-15% losses. Further considering that 75 million m^3/y would not be needed in year zero, we could design a system that expands gradually. The option (scenario) this thesis uses is that the projected Solar DSP starts to provide water in year zero with nameplate capacity of 75 million m^3/y or 205,500 m^3/d. Assuming 10% (at least) losses, utilized amount expected to be 67.51 million m^3/y.

CHAPTER VII
ANALYSIS AND RESULTS

6.1. Analysis of Inputs and Findings

Based on the input data and assumptions that have been made in previous chapters, simulations run by using NREL SAM and calculations have been done with excel models including RETScreen Software. Findings of this analysis included in the Table 33. Analysis and feasibility show projected SWRO powered by PV, CSP, Grid and Diesel. Cost of energy consumption taken as 4 kWh m^{-3} based on worldwide averages and Larnaca SWRO as mentioned previously. With 4 kWh m^{-3} energy requirement; RO plant expected to consume annual electrical energy of 270.03 GWh per annum to produce required amount. SWRO found to be most cost-effective option in the decision matrix, in terms of capital requirements and energy requirements. SWRO powered with electricity from CSP, PV, Grid or standalone Diesel expected to require same amount of electricity. It is assumed that nameplate capacity of 205,500 m^3 per day needed to match 75 million m^3 per annum. As mentioned previously, the assumption also includes losses, it is likely that no DSPs can be run 7/24 for whole year as stated. Based on utilization factor of 90%, the projected plant expected to produce 67.5 million m^3 per year (Table 33).

From another perspective, the plant size could have been increased to 228,300 m^3 per day to meet the 75 million per year target. However, as it is said previously the NCWSP also suffers from losses and could not deliver exact amount. This is the main reason for focusing on nameplate capacity. 67.5 million m^3 per year is the actual output in the analysis. Thus, SWRO will require 270.03 GWh electricity annually. In previous chapter, as it is revealed in the system design section, by using data on hand, every option designed to deliver at least 270.03 GWh annual electricity with the exception of Diesel Generator. Two generators would be insufficient, and three generators will produce extra electricity, which could be sold to the grid. Table 33 includes all required output to assess the best option. Price of water is 77 cents from the NCWSP. Although consumer price of water is around $1 in municipalities, desalination plants could not sell water directly to consumer.

Thus, water assumed to be sold to municipalities or state with the same cost. For all assessment, 77 cents used for generating revenue for the plant and evaluating feasibility. As prices could not stay static, a price escalation rate also included as 3% per year in the analysis depending on average USD inflation. Table 33 shows general information like; capacity, energy consumption, capital cost per capacity, project lifetime, inflation, discount and escalation rate. Table 33 also shows results that depends on to grid electricity selling price and capital cost (\$/MWe) for producing required power. Further information includes findings like LCOE of power plants and LCOW of designed systems which are the main findings of this analysis.

Table 33 Reverse Osmosis Analysis with different energy providers.

	NCWSP	**Solar PV SWRO**	**Solar CSP SWRO**	**Grid SWRO**	**Gen. SWRO**	**Units**
Water Supply						
Annual Capacity	75 Mil.	75 Mil.	75 Mil.	75 Mil.	75 Mil.	m^3/y
Daily Capacity	Unknown	205,500	205,500	205,500	205,500	m^3/d
Capacity Utilization	Unknown	90%	90%	90%	90%	%
Water Output	Unknown	67.51 Mil	67.51 Mil	67.51 Mil	67.51 Mil	m^3/y
Electricity Consumption	131-219	270.03	270.03	270.03	270.03	GWh/y
Capital per m^3/d Capacity	2,050	2,428	3,897	1,300	1,496	$\$ \text{m}^{-3}/\text{d}$
Cost of Water (DSP only)	77	48.9	48.9	48.9	48.9	¢/m^3
Energy consumption	-	4	4	4	4	kWh m^{-3}
Energy Supply						
Capacity Factor	80.00%	18.50%	23.70%	100.00%	79.00%	%
Nameplate Capacity	25000	167000	131400	30825	52500	kWp
Annual Generation	0	271.86	272.34	0	363.32	GWh/y
Cost Per MW	0	1,322	4,062	0	766	\$/kW
LCOE (nominal)	0	6.92	20.17	18.50	8.53	¢/kWh
LCOE (real)	0	5.13	14.95	18.50	6.33	¢/kWh
Annual Electricity Cost	32,412	18,686	54,464	49,955	23,047	\$1000
Grid Price (2016)	18.50	18.50	18.50	18.50	18.50	¢/kWh
Export Amount	0.00	1.83	2.31	0.00	93.29	GWh/y
General Parameters						
Lifetime	30	30	30	30	30	years
Discount	6%	6%	6%	6%	6%	
Inflation	3%	3%	3%	3%	3%	
Price Escalation (Inf)	3%	3%	3%	3%	3%	
WACC		9.18%	9.18%		9.18%	
Results						
LCOE + LCOW		55.81	69.06	67.39*	57.42	¢/m^3
LCOW Final (nominal)	77	67.85	103.14	122.89	63.78	¢/m^3
LCOW Final (real)	77	50.30	76.46	91.10	47.28	

*Grid rate plus LCOE of RO only.

6.1.1. Findings and Insight

PV/SWRO found to has lower levelized cost of electricity and lower levelized cost of water than every other option except diesel generator. Analysis for SWRO without energy cost resulted in LCOW of 48.9 which is quite realistic even for real world. LCOW and cost of water could not be used interchangeable, but it is assumed that the NCWSP has cost of 77 ¢/m^3 for water as we do not have the information about real LCOW. Throughout the study it is also assumed that these plants would sell produced water at the same rate 77 ¢/m^3 to generate revenue. LCOE of the proposed systems are also promising. Grid price assumed as LCOE of grid. Grid/SWRO found to be most expensive in terms of LCOE. The reason behind this is that the expensive consumer electricity rate preferred for the analysis. As of 2016, average rate of 18.5 cents per kWh used for residential and commercial users. However, rates expected to be lower for DSPs in real world. Gen/SWRO is the most feasible option, if excess electricity converted to revenue. Excluding electricity revenues increases the O&M cost ratio of the plant for Gen/SWRO. The final LCOW rate is the result of total capital cost of project rather than desalination only. Including capital and operating expenditures of respective power supply options with DSP gives us the final LCOWs (Table 33). For benchmarking purposes, sum of LCOE and SWRO only option included. Although ranking stay same, difference between values diminished dramatically. CSP/SWRO has high nominal LCOW than PV because of the high operating and capital cost. And Grid/SWRO has high nominal LCOW as it has high operating or recurring cost (energy) that would increase gradually with inflation. Nevertheless, the main indicator is nominal LCOW rates which lead us to conclusion that only PV/SWRO could become a competitive alternative for the NCWSP. We could state that 77 ¢/m^3 is a feasible and realistic price to supply Northern Cyprus with solar powered desalination, which is not too expensive in compare to real prices. Water pipeline project from Turkey cost to $420 Million USD, in compare to PV/SWRO configuration ($487,916,275) the initial investment costs are closer. Thus, PV/SWRO is the best solar option to produce 67.5 million cubic meter water from seawater per year with 2016 prices and efficiency.

6.1.2. Negative Sides of PV

The negative aspect PV/SWRO has is that it cannot be operational during night times and production only peaks in the midday. However, it is not required to run a desalination plant during night hours. On the other hand, fluctuation from PV plant would not be a preferred thing while running these types of plants and direct connection would harm the DSP. Thus, there would be some engineering difficulties that is not included in this analysis. Furthermore, water could be stored easily, so cost of storage is neglected. A typical solar desalination facility would definitely require a backup solution which would be either energy storage or grid connection.

6.1.3. Cash Flow Analysis

Appendix E demonstrates both discounted cashflows or DCF analysis, breakeven year, and lifetime value generated by the configurations due their discounted cash flows generated throughout lifetime of project. Non-adjusted cashflows also included for reader to compare. Figure 6-1 and Figure 6-2 shows cashflows from negative to positive both for PV/SWRO and CSP/SWRO analysis.

4.1. Results

NPV is the main determinant of feasibility of a such project. Despite assuming public ownership, NPV should be positive in order to prevent loss of money. NPV for each type of Solar SWRO found in Table 34. Despite both options have different power plant configuration, same SWRO plant used to achieve the results. Whole investment assumed as one project, therefore final analysis includes summation of overall capital cost and overall O&M related costs. Hence, NPVs in Table 34 shows overall net present value of the investments. Results also has shown that at this rate of electricity, required electricity could be fulfilled with PV. The option seems cheaper, it has positive NPV and good cost benefit ratio. Photovoltaic also has early payback in compare to CSP which would then reduce cost of desalination or further reduce the payback of desalination plant. On the other hand, PV in such capacities is not very common without storage as mentioned. Thus, electricity could be generated at nights with CSP and larger capacities are more common in CSP despite its negative NPV. Both configurations discarded the storage option as storing water is cheaper than storing energy. PV configuration presented lower LCOW then the NCWSP. However, LCOW does not reflect feasibility of the project itself. Under these circumstances, PV/SWRO configuration found to be feasible with NPV value of \$122,409,798. PV/SWRO has a simple payback of 13 years, and discounted payback of 16 years, IRR of 7.88%, mIRR (10) of 9.18% and cost benefit ratio of 1.25. On the other side, CSP/SWRO configuration have \$-349,803,145 worth negative NPV due to high initial investment and higher maintenance cost than PV. CSP/SWRO also has a simple payback of 24 years, discounted payback of 35 years which is more than project lifetime, IRR of 2.0%, mIRR (10) of 6.32% and cost benefit ratio of 0.56. Despite the negative NPV, one should not forget that these projects generally get incentives or subsidized and yet this analysis does not include any incentive or funding. From investor perspective PV/SWRO could be regarded as feasible whereas CSP/SWRO is definitely not feasible with current configuration. In this part of study only electric powered plants compared as thermal heat from a CSP has different values for different regions. Moreover, literature review and decision matrix has shown that powering MED or MSF with electricity is not preferable or feasible. Powering these with CSP electricity could not make sense. However, cogeneration is a promising topic. In order to compare direct steam distillation, we need further details and simulations for converting thermal collector provided energy as heat, thermal efficiency of the systems and some more details. On the other hand, diesel generator fed desalination also looks feasible and subsidized grid could be feasible as well but GHG cost should be regarded in this manner. Sum of LCOE and LCOW is another indicator to analyze, selling electricity to DSP without profiting would be an option too. Problem with the Grid and Diesel are unsustainability and carbon cost of water, which should be included more in the analysis as well. Section 4.1.2 gives a brief insight about the issue. Total investment cost of PV/SWRO is \$487,916,275 with positive NPV and \$800,905,027 for CSP/SWRO with negative NPV. Considering the cost of \$420,000,000 of the NCWSP and 25 MW electricity needed to operate the NCWSP; PV/SWRO is the best alternative option to supply water to Northern Cyprus. Also, there would not be any need to build a plant in year 0 with this scale, best side of having PV/SWRO would be its scalability depending on requirement. Last thing to mention is that construction of the

NCWSP started years before than 2015 and we know that PV prices come down just around 2012. For 2019, PV/SWRO could be the most feasible option. Future work of this study aims to find up to date rates for PV/SWRO.

Table 34 Financial Indicators of the Feasibility Study.

	Solar PV SWRO	**Solar CSP SWRO**	**Grid SWRO**	**Gen. SWRO**
Initial Investment	$487,916,275	$800,905,027	$267,210,562	$307,430,546
Total O&M	$21,192,484	$29,224,500	$69,478,050	$41,538,676
Project Lifetime	30 years	30 years	30 years	30 years
Water Price	¢77	¢77	¢77	¢77
LCOW	¢68	¢103	¢123	¢64
NPV (30 yr)	$122,409,798	$ -349,803,145	$ -614,082,556	$ 176,973,634
Discounted Payback	15.8	35.2	never	12.6
Simple Payback	12.8	23.9	never	10.6
IRR	7.88%	1.97%	negative	10.10%
mIRR (10%)	9.18%	6.32%	negative	10.03%
mIRR (5%)	6.25%	3.46%	negative	7.07%
Cost-Benefit Ratio	1.25	0.56	-1.30	1.58

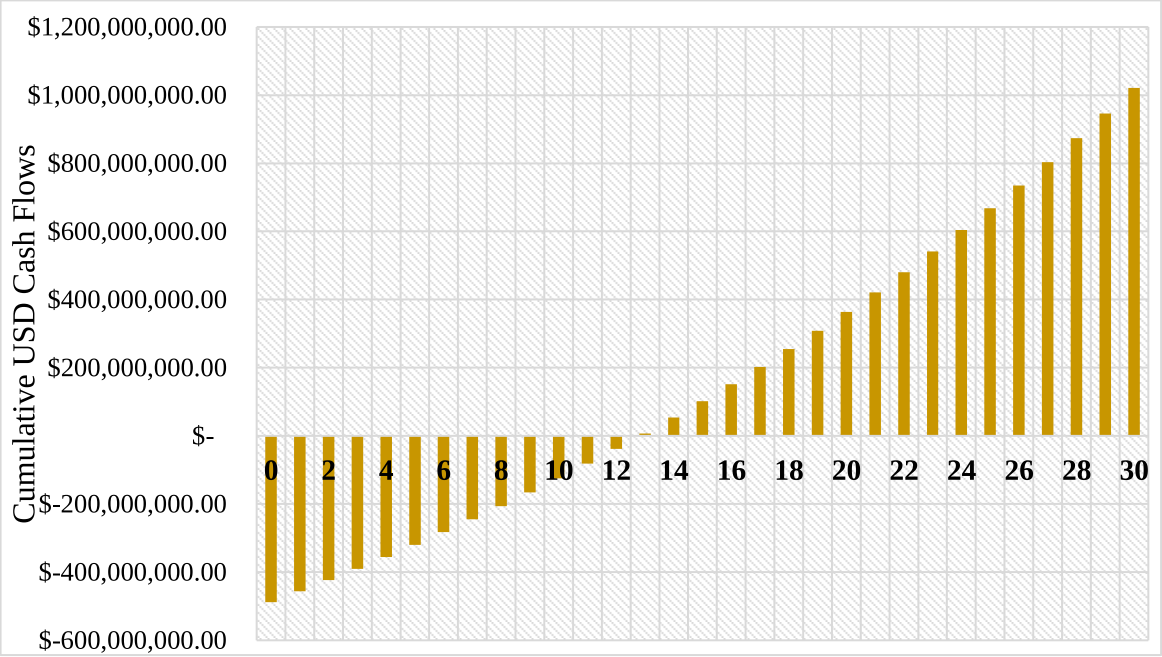


Figure 6-1 Cumulative cash flows from PV/SWRO Plant (USD).

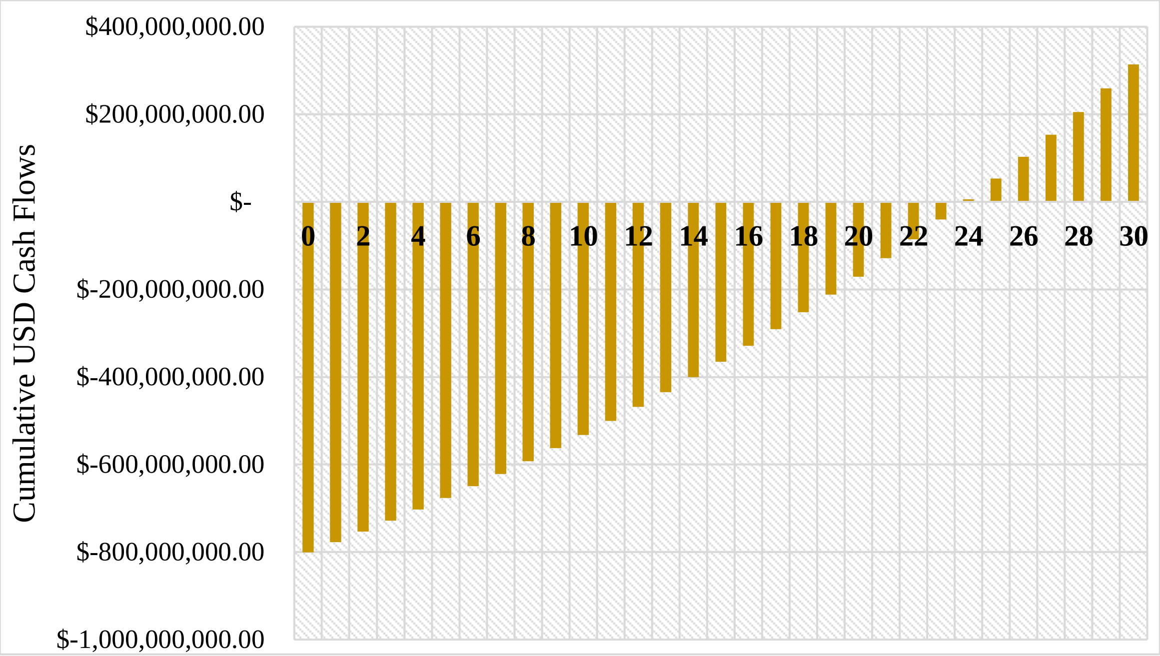


Figure 6-2 Cumulative cash flows from CSP/SWRO Plant (USD).

4.1.1. Sensitivity Analysis

As PV/SWRO combination found to be feasible with positive NPV, further analysis for cost of capital should be done. Even governments use debt as a tool, and money has a cost as well. Thus, considering the financing options of the project, Table 35 shows changes in payback period and NPV variations depending on debt ratios. USD has a 6% to 8% interest rate in commercial banks of Northern Cyprus. Table 35 assumes 10-year loan with 8% interest rate. The analysis shows us that even with 80% debt ratio, PV/SWRO is feasible at this capital cost. However, financing such risky projects with 80% or 100% debt is not possible, either banks would not take the risk, or they would increase the cost of debt. 25% to 50% debt is the realistic option to be considered for commercial organizations. Ignoring the other expenditures like cost of land, private companies could also invest in such projects if it is subsidized by the state.

Table 35 NPV sensitivity analysis for Debt Ratio of PV/SWRO.

Debt Ratio	**NPV**	**Payback Period**
10%	$ 117,683,352.65	13.4
15%	$ 115,320,129.93	13.6
20%	$ 112,956,907.21	13.9
30%	$ 108,230,461.77	14.4
40%	$ 103,504,016.33	14.9
50%	$ 98,777,570.89	15.4
60%	$ 94,051,125.45	15.8
70%	$ 89,324,680.01	16.3
80%	$ 84,598,234.57	16.8

The analysis shows PV/SWRO investment as a feasible option. However, due to many reasons (like debt ratio, crisis, cost of land, etc.), cost of investment would rise which could eliminate benefits. In order to determine the vulnerability of PV/SWRO NPV, sensitivity analysis have been done. Table 36 shows changes in NPV depending on initial investment cost (vertically) and water sale price (horizontally). Sensitivity done by considering 10% 20% and 40% negative and positive changes in capital cost of the project. Additionally, by considering 20% negative or positive changes in sale price. If price of water goes down -20%, then NPV becomes negative with current capital and O&M costs. Moreover, it can stay positive, even if initial investment cost would rise up to 20%.

Table 36 NPV Sensitivity analysis depending on Capital Cost Changes
and Water Sale Price.

		Water Sale Price		
		¢62	¢77	¢92
Capital Cost	**Change**	**-20%**	**0%**	**20%**
$292,749,765	**-40%**	$ 111,488,449.24	$ 317,576,307.90	$ 523,664,166.55
$390,333,020	**-20%**	$ 13,905,194.34	$ 219,993,053.00	$ 426,080,911.65
$439,124,647	**-10%**	$ -34,886,433.11	$ 171,201,425.55	$ 377,289,284.20
$487,916,275	**0%**	$ -83,678,060.56	$ 122,409,798.10	$ 328,497,656.75
$536,707,902	**10%**	$ -132,469,688.01	$ 73,618,170.65	$ 279,706,029.30
$585,499,529	**20%**	$ -181,261,315.46	$ 24,826,543.20	$ 230,914,401.85
$683,082,784	**40%**	$ -278,844,570.36	$ -72,756,711.70	$ 133,331,146.95

Considering CSP/SWRO as a failed option, a sensitivity analysis required to find what is needed to make CSP/SWRO NPV positive. There are two options, either capital cost would go down or price of goods sold (water) increase in order to make the option feasible. Table 37 shows sensitivity of CSP/SWRO NPV to water price. It is found that 40% could make CSP/SWRO more feasible. $1.08 per m^3 is the threshold for CSP/SWRO feasibility. The rate is achievable as municipalities in Northern Cyprus have rates closer to this value.

Table 37 NPV sensitivity analysis for Water Price of CSP/SWRO

Water Price		**NPV**
¢77	0%	$ -349,803,144.82
¢85	10%	$ -246,759,215.49
¢92	20%	$ -143,715,286.17
¢100	30%	$ -40,671,356.84
¢108	40%	$ 62,372,572.49
¢116	50%	$ 165,416,501.82
¢123	60%	$ 268,460,431.15

4.1.2. Carbon Cost

Every action we take has a carbon footprint. Even solar desalination causes emissions. Although it is not included in this study, carbon emission from these options should be compared. Nevertheless, GHG emissions by Grid/SWRO or Gen/SWRO could be found. If assumed that three generators run at full capacity, they would generate 342,235 tons of CO2 per year. Table 37 shows predicted carbon cost of producing electricity to run desalination facility. For desalination facility, whether it is from grid or from generators (which are same generators), projected SWRO would cause at least around 255,593 tons of CO2 per year. Fossil fuel powered desalination could not be a sustainable alternative for the NCWSP with this manner.

Table 38 Predicted GHG emission by Residual Fuel Oil (No:6) powered desalination .

	Fuel consumption	CO2 emission factor	CH4 emission factor	N2O emission factor	GHG emission factor	Total GHG emission
	MWh/y	**kg/GJ**	**kg/GJ**	**kg/GJ**	**kgCO2 /kWh**	**tCO2/y**
Full Load	363,321	259.419	0.010	0.007	0.942	342,235
Desalination	270,300	259.419	0.010	0.007	0.942	255,593

CHAPTER VII

DISCUSSION AND CONCLUSION

5.1 Environmental Cost

Even though desalination technologies are efficient way of obtaining sustainable water, they also harm the environment in the process of extracting drinking water. The biggest environmental concerns of using these technologies are the emission of greenhouse gases, air pollutants and chemicals that are discharged to the sea water that threaten the ecosystem of marine life. There are also other factors that damage the marine life such as using big quantities of seawater for cooling purposes which leads to entrainment and impingement of underwater organisms in addition to construction process affecting nearshore habitats [14]. As it is stated, the emission of greenhouse gases is considered as a side effect of desalination technologies in the literature; although, this can be eliminated or minimized by using solar energy which indicates creating sustainable water source by using renewable energy sources. Nevertheless, it is undeniable that desalination technologies come with a number of side effects that cannot be eliminated. According to [86] the byproduct of SWRO technology consists of high concentration salt and chemicals that is discharged back to coastal regions continuously as well as the water warming during the cooling process. In this case, brine effluent is likely to sink down on the seabed and flow with the current. As a result, warmth and the brine effluent accumulate into the seawater which is the main reason that marine ecosystem and the organisms in it are affected adversely by the process. The natural habitats of these organisms do not consist of such dense brine water. In support of this, [86] state further that high concentrated saltwater creates osmotic stress in the environment meaning it leads to physiologic dysfunction in seawater.

Moreover, there may also be complications with the use of solar energy as it does not provide consistent energy supply which may demand another source of electricity as a backup power plant. Thereafter, in the case of backup energy plant being powered by fossil fuel, it is also potential that there may be a small amount of greenhouse gas emissions. It is potential that the damage done can be minimized in other ways which will not be discussed in this thesis as the main topic focuses on the feasibility of a potential investment in desalination technology powered by solar energy.

5.2 Future Work

This study of economic assessment of solar desalination focused on SWRO coupled with most common solar power plants. Whole assessment based on data available for 2016, but recent data could give better results. Further study will include rates for 2019 to compare with 2016. The study could also further expand to include thermal combinations or cogeneration like CSP/MSF. More sensitivity analysis for different scenarios also provides better understanding. Public owned DSPs are not common in real world as well, thus future work will include and investigate private ownership or BO(O)T options. For investors more and detailed economic indicators should be included like CAPEX and OPEX (Operating Expenditure), cost of land and Monte-Carlo risk analysis. Environmental Effects also requires further expansion with GHG Emissions or savings. Review of emerging technologies like floating desalination and cryo-desalination will be on focus too. More storage options like thermal storage, reservoir and PV coupled Pumped-Hydro Storage which could generate freshwater from brackish water using pressure (Reverse Osmosis) with elevation (Water Tower) also investigated. Future work for this study will be extending the analysis for economic applicability of solar powered saline water treatment including Solar Stills, CSP/MSF and PV/EDR.

5.3 Conclusion

Increasing concerns regarding climate change and growing environmental concerns have created strong public support for the renewable powered systems in Northern Cyprus. Despite having a pipeline from Turkey which intends to solve unsustainable water resource problem, one should not ignore the fact that the climate change may also affect the resource diverted from another region. Thus, it is important to foresee that a resource from other place is not a solution for another place. Furthermore, solutions are sustainable only if it is supplied from a resource that is abundant or renewable. Whereas this could only be seawater produced via abundant solar energy. While it is believed that running seawater desalination plants are costly, it should be considered as a cost that we pay for our unsustainable life and over-stress on natural resources done by humankind. Recent developments are paving the way to solar desalination age. Although Sorek SWRO is fed from grid and Al Khafji Solar SWRO partially uses grid; it shows us the innovation and cost reductions in these technologies are our destiny. PV/SWRO system in our analysis seems to be one of the fastest evolving technology due to feasibility and economies of scale in production of both PV cells and desalination membranes. Findings in this thesis proves that solar desalination is feasible and will be profitable as well in the places with poor water resources. Even now, our projected solar DSP reached to positive NPV with 2016 prices and further cost reductions are expected. Assumptions in this thesis based on that the project will be commenced by Public Bodies or Government without aiming profit. Thus, profit of companies might increase the prices that we found. Moreover, capital cost does not include purchase of Land or financial costs relating to debt.

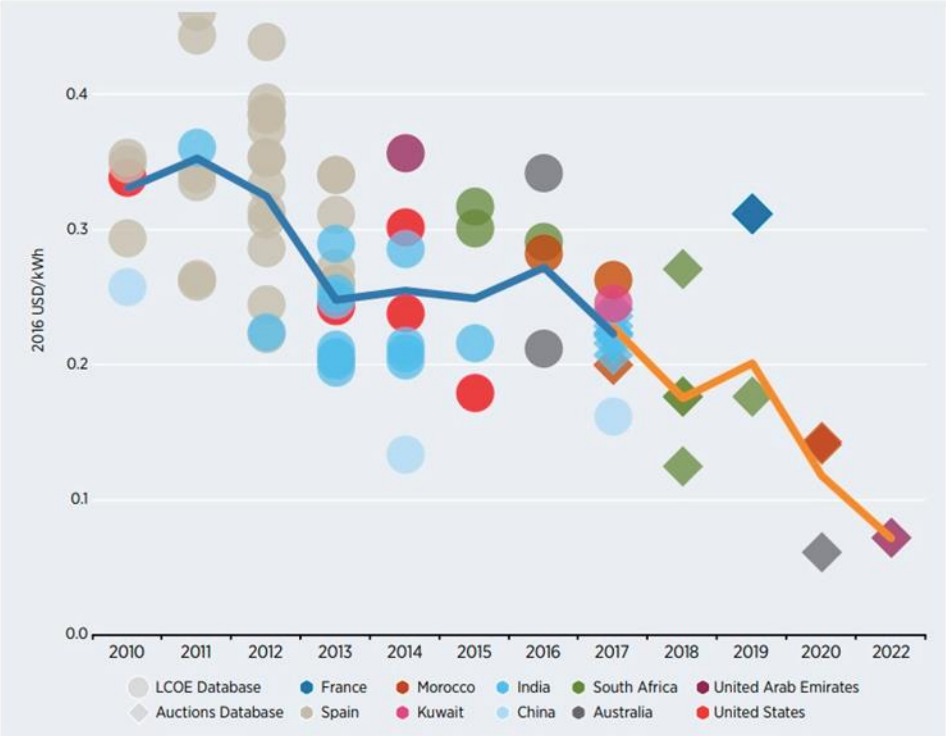


Figure 7-1 Forecasted price per kWh of electricity generated by CSP (IRENA)[79]

On the other hand, the combination of desalination plants with concentrated solar power plants will also expected to emerge as a solution for the water crisis. CSP is one of the genuine options to provide better and large-scale desalination with solar energy is using solar thermal powered desalination through vaporization of saline water. Thermal energy loss during conversion of sunlight into electricity. Then it provides energy to desalination process using electricity, this may indicate us where the exact problem is. If corrosion problems are addressed, direct steam from seawater could become a viable option too. Figure 7-1 from IRENA also shows expectations for CSP produced electricity to become cheaper in near future. The problems that is faced in this thesis are high capital cost and high operating cost for CSP plants. Generating electricity is still expensive for CSP. For better efficiency, thermal energy should be used directly via combined CSP-MED or CSP-MSF technologies or for cogeneration. As stated, investment costs of CSPs also expected to diminish according to IRENA. Despite it is found to be most expensive in this thesis, evolution and optimization of the CSP-MED and CSP-MSF are expected. Due to the increasing awareness about renewable energy and cost reduction in these systems, rise of solar desalination is matter of time. Eventually, small PV/SWRO plants expected to become cheaper than Grid/SWRO plants, thus every nation with seawater and solar energy would use this technology to meet increasing water demand.

In this analysis, the main focus is on the financial performance of these type of plants, and the findings show that despite high start-up costs low LCOW, LCOE and positive NPVs are possible. Hence solar desalination could be a profitable investment with governmental incentives. The technology could be considered as sustainable option for water supply both in terms of water scarcity and in terms of GHG emissions.

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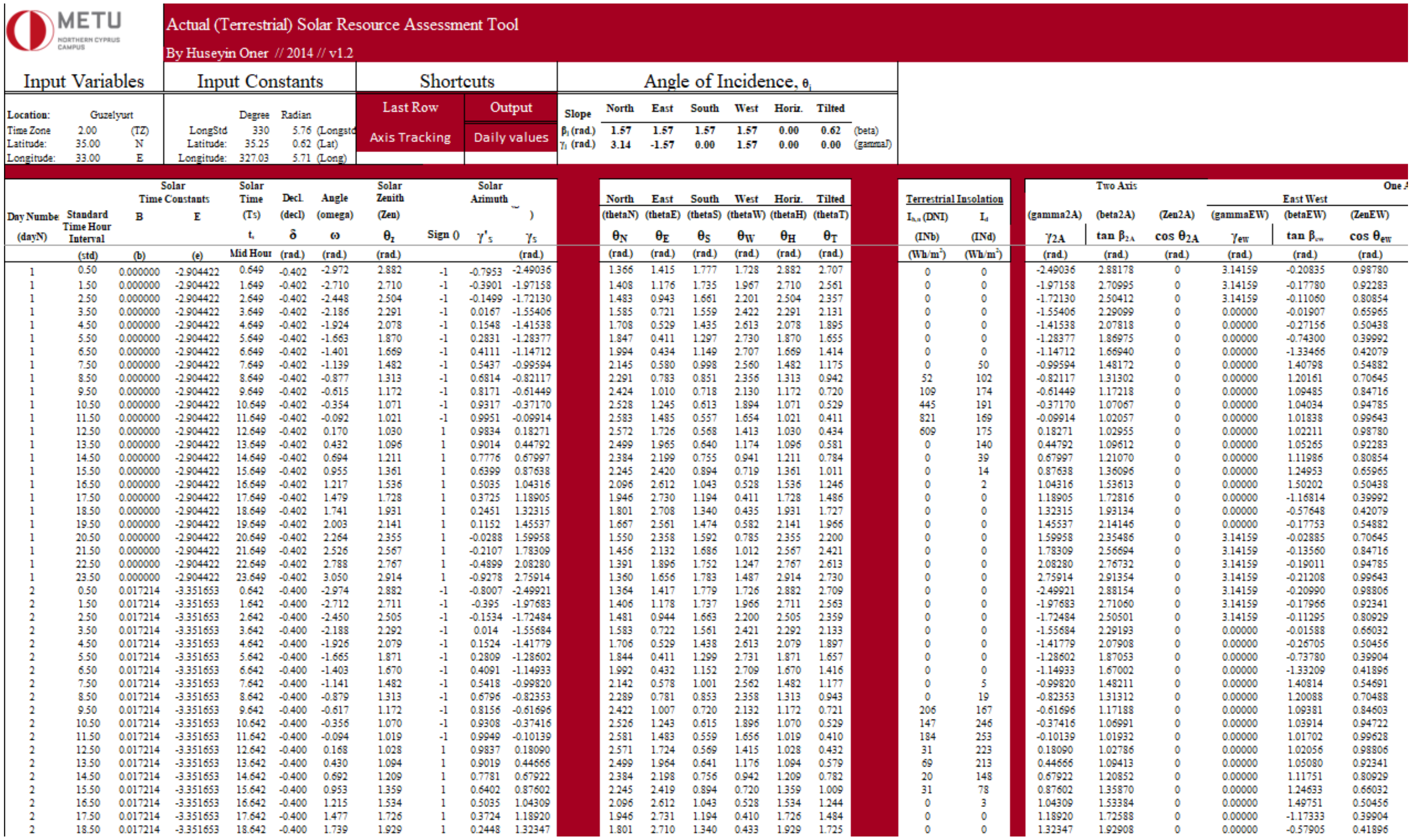
APPENDICIES

APPENDIX A – Excel A(T)SRA Tool Used for Analysis

Screenshot of Excel A(T)SRA Tool by H. Oner



Actual (Terrestrial) Solar Resource Assessment Tool

By Huseyin Oner // 2014 // v1.2

Input Variables

Location:	Guzelyurt	
Time Zone	2.00	(TZ)
Latitude:	35.00	N
Longitude:	33.00	E

Input Constants

	Degree	Radian	
LongStd	330	5.76	(Longstd
Latitude:	35.25	0.62	(Lat)
Longitude:	327.03	5.71	(Long)

Shortcuts

Last Row | Output

Axis Tracking | Daily values

Angle of Incidence, θ_i

Slope	North	East	South	West	Horiz.	Tilted	
β_i (rad.)	1.57	1.57	1.57	1.57	0.00	0.62	(beta)
γ_i (rad.)	3.14	-1.57	0.00	1.57	0.00	0.00	(gamma)

		Solar Time Constants		Solar Time	Decl.	Angle	Solar Zenith		Solar Azimuth		North	East	South	West	Horiz.	Tilted	Terrestrial Insolation		Two Axis			One A East West		
Day Numbe	Standard Time Hour Interval	B	E	(Ts)	(decl)	(omega)	(Zen)			)	(thetaN)	(thetaE)	(thetaS)	(thetaW)	(thetaH)	(thetaT)	$I_{b,n}$ (DNI)	I_d	(gamma2A)	(beta2A)	(Zen2A)	(gammaEW)	(betaEW)	(ZenEW)
(dayN)				t_s	δ	ω	θ_z	Sign ()	γ'_s	γ_s	θ_N	θ_E	θ_S	θ_W	θ_H	θ_T	(INb)	(INd)	γ_{2A}	$\tan \beta_{2A}$	$\cos \theta_{2A}$	γ_{ew}	$\tan \beta_{ew}$	$\cos \theta_{ew}$
	(std)	(b)	(e)	Mid Hour	(rad.)	(rad.)	(rad.)			(rad.)	(rad.)	(rad.)	(rad.)	(rad.)	(rad.)	(rad.)	(Wh/m^2)	(Wh/m^2)	(rad.)	(rad.)	(rad.)	(rad.)	(rad.)	(rad.)
1	0.50	0.000000	-2.904422	0.649	-0.402	-2.972	2.882	-1	-0.7953	-2.49036	1.366	1.415	1.777	1.728	2.882	2.707	0	0	-2.49036	2.88178	0	3.14159	-0.20835	0.98780
1	1.50	0.000000	-2.904422	1.649	-0.402	-2.710	2.710	-1	-0.3901	-1.97158	1.408	1.176	1.735	1.967	2.710	2.561	0	0	-1.97158	2.70995	0	3.14159	-0.17780	0.92283
1	2.50	0.000000	-2.904422	2.649	-0.402	-2.448	2.504	-1	-0.1499	-1.72130	1.483	0.943	1.661	2.201	2.504	2.357	0	0	-1.72130	2.50412	0	3.14159	-0.11060	0.80854
1	3.50	0.000000	-2.904422	3.649	-0.402	-2.186	2.291	-1	0.0167	-1.55406	1.585	0.721	1.559	2.422	2.291	2.131	0	0	-1.55406	2.29099	0	0.00000	-0.01907	0.65965
1	4.50	0.000000	-2.904422	4.649	-0.402	-1.924	2.078	-1	0.1548	-1.41538	1.708	0.529	1.435	2.613	2.078	1.895	0	0	-1.41538	2.07818	0	0.00000	-0.27156	0.50438
1	5.50	0.000000	-2.904422	5.649	-0.402	-1.663	1.870	-1	0.2831	-1.28377	1.847	0.411	1.297	2.730	1.870	1.655	0	0	-1.28377	1.86975	0	0.00000	-0.74300	0.39992
1	6.50	0.000000	-2.904422	6.649	-0.402	-1.401	1.669	-1	0.4111	-1.14712	1.994	0.434	1.149	2.707	1.669	1.414	0	0	-1.14712	1.66940	0	0.00000	-1.33466	0.42079
1	7.50	0.000000	-2.904422	7.649	-0.402	-1.139	1.482	-1	0.5437	-0.99594	2.145	0.580	0.998	2.560	1.482	1.175	0	50	-0.99594	1.48172	0	0.00000	1.40798	0.54882
1	8.50	0.000000	-2.904422	8.649	-0.402	-0.877	1.313	-1	0.6814	-0.82117	2.291	0.783	0.851	2.356	1.313	0.942	52	102	-0.82117	1.31302	0	0.00000	1.20161	0.70645
1	9.50	0.000000	-2.904422	9.649	-0.402	-0.615	1.172	-1	0.8171	-0.61449	2.424	1.010	0.718	2.130	1.172	0.720	109	174	-0.61449	1.17218	0	0.00000	1.09485	0.84716
1	10.50	0.000000	-2.904422	10.649	-0.402	-0.354	1.071	-1	0.9317	-0.37170	2.528	1.245	0.613	1.894	1.071	0.529	445	191	-0.37170	1.07067	0	0.00000	1.04034	0.94785
1	11.50	0.000000	-2.904422	11.649	-0.402	-0.092	1.021	-1	0.9951	-0.09914	2.583	1.485	0.557	1.654	1.021	0.411	821	169	-0.09914	1.02057	0	0.00000	1.01838	0.99643
1	12.50	0.000000	-2.904422	12.649	-0.402	0.170	1.030	1	0.9834	0.18271	2.572	1.726	0.568	1.413	1.030	0.434	609	175	0.18271	1.02955	0	0.00000	1.02211	0.98780
1	13.50	0.000000	-2.904422	13.649	-0.402	0.432	1.096	1	0.9014	0.44792	2.499	1.965	0.640	1.174	1.096	0.581	0	140	0.44792	1.09612	0	0.00000	1.05265	0.92283
1	14.50	0.000000	-2.904422	14.649	-0.402	0.694	1.211	1	0.7776	0.67997	2.384	2.199	0.755	0.941	1.211	0.784	0	39	0.67997	1.21070	0	0.00000	1.11986	0.80854
1	15.50	0.000000	-2.904422	15.649	-0.402	0.955	1.361	1	0.6399	0.87638	2.245	2.420	0.894	0.719	1.361	1.011	0	14	0.87638	1.36096	0	0.00000	1.24953	0.65965
1	16.50	0.000000	-2.904422	16.649	-0.402	1.217	1.536	1	0.5035	1.04316	2.096	2.612	1.043	0.528	1.536	1.246	0	2	1.04316	1.53613	0	0.00000	1.50202	0.50438
1	17.50	0.000000	-2.904422	17.649	-0.402	1.479	1.728	1	0.3725	1.18905	1.946	2.730	1.194	0.411	1.728	1.486	0	0	1.18905	1.72816	0	0.00000	-1.16814	0.39992
1	18.50	0.000000	-2.904422	18.649	-0.402	1.741	1.931	1	0.2451	1.32315	1.801	2.708	1.340	0.435	1.931	1.727	0	0	1.32315	1.93134	0	0.00000	-0.57648	0.42079
1	19.50	0.000000	-2.904422	19.649	-0.402	2.003	2.141	1	0.1152	1.45537	1.667	2.561	1.474	0.582	2.141	1.966	0	0	1.45537	2.14146	0	0.00000	-0.17753	0.54882
1	20.50	0.000000	-2.904422	20.649	-0.402	2.264	2.355	1	-0.0288	1.59958	1.550	2.358	1.592	0.785	2.355	2.200	0	0	1.59958	2.35486	0	3.14159	-0.02885	0.70645
1	21.50	0.000000	-2.904422	21.649	-0.402	2.526	2.567	1	-0.2107	1.78309	1.456	2.132	1.686	1.012	2.567	2.421	0	0	1.78309	2.56694	0	3.14159	-0.13560	0.84716
1	22.50	0.000000	-2.904422	22.649	-0.402	2.788	2.767	1	-0.4899	2.08280	1.391	1.896	1.752	1.247	2.767	2.613	0	0	2.08280	2.76732	0	3.14159	-0.19011	0.94785
1	23.50	0.000000	-2.904422	23.649	-0.402	3.050	2.914	1	-0.9278	2.75914	1.360	1.656	1.783	1.487	2.914	2.730	0	0	2.75914	2.91354	0	3.14159	-0.21208	0.99643
2	0.50	0.017214	-3.351653	0.642	-0.400	-2.974	2.882	-1	-0.8007	-2.49921	1.364	1.417	1.779	1.726	2.882	2.709	0	0	-2.49921	2.88154	0	3.14159	-0.20990	0.98806
2	1.50	0.017214	-3.351653	1.642	-0.400	-2.712	2.711	-1	-0.395	-1.97683	1.406	1.178	1.737	1.966	2.711	2.563	0	0	-1.97683	2.71060	0	3.14159	-0.17966	0.92341
2	2.50	0.017214	-3.351653	2.642	-0.400	-2.450	2.505	-1	-0.1534	-1.72484	1.481	0.944	1.663	2.200	2.505	2.359	0	0	-1.72484	2.50501	0	3.14159	-0.11295	0.80929
2	3.50	0.017214	-3.351653	3.642	-0.400	-2.188	2.292	-1	0.014	-1.55684	1.583	0.722	1.561	2.421	2.292	2.133	0	0	-1.55684	2.29193	0	0.00000	-0.01588	0.66032
2	4.50	0.017214	-3.351653	4.642	-0.400	-1.926	2.079	-1	0.1524	-1.41779	1.706	0.529	1.438	2.613	2.079	1.897	0	0	-1.41779	2.07908	0	0.00000	-0.26705	0.50456
2	5.50	0.017214	-3.351653	5.642	-0.400	-1.665	1.871	-1	0.2809	-1.28602	1.844	0.411	1.299	2.731	1.871	1.657	0	0	-1.28602	1.87053	0	0.00000	-0.73780	0.39904
2	6.50	0.017214	-3.351653	6.642	-0.400	-1.403	1.670	-1	0.4091	-1.14933	1.992	0.432	1.152	2.709	1.670	1.416	0	0	-1.14933	1.67002	0	0.00000	-1.33209	0.41896
2	7.50	0.017214	-3.351653	7.642	-0.400	-1.141	1.482	-1	0.5418	-0.99820	2.142	0.578	1.001	2.562	1.482	1.177	0	5	-0.99820	1.48211	0	0.00000	1.40814	0.54691
2	8.50	0.017214	-3.351653	8.642	-0.400	-0.879	1.313	-1	0.6796	-0.82353	2.289	0.781	0.853	2.358	1.313	0.943	0	19	-0.82353	1.31312	0	0.00000	1.20088	0.70488
2	9.50	0.017214	-3.351653	9.642	-0.400	-0.617	1.172	-1	0.8156	-0.61696	2.422	1.007	0.720	2.132	1.172	0.721	206	167	-0.61696	1.17188	0	0.00000	1.09381	0.84603
2	10.50	0.017214	-3.351653	10.642	-0.400	-0.356	1.070	-1	0.9308	-0.37416	2.526	1.243	0.615	1.896	1.070	0.529	147	246	-0.37416	1.06991	0	0.00000	1.03914	0.94722
2	11.50	0.017214	-3.351653	11.642	-0.400	-0.094	1.019	-1	0.9949	-0.10139	2.581	1.483	0.559	1.656	1.019	0.410	184	253	-0.10139	1.01932	0	0.00000	1.01702	0.99628
2	12.50	0.017214	-3.351653	12.642	-0.400	0.168	1.028	1	0.9837	0.18090	2.571	1.724	0.569	1.415	1.028	0.432	31	223	0.18090	1.02786	0	0.00000	1.02056	0.98806
2	13.50	0.017214	-3.351653	13.642	-0.400	0.430	1.094	1	0.9019	0.44666	2.499	1.964	0.641	1.176	1.094	0.579	69	213	0.44666	1.09413	0	0.00000	1.05080	0.92341
2	14.50	0.017214	-3.351653	14.642	-0.400	0.692	1.209	1	0.7781	0.67922	2.384	2.198	0.756	0.942	1.209	0.782	20	148	0.67922	1.20852	0	0.00000	1.11751	0.80929
2	15.50	0.017214	-3.351653	15.642	-0.400	0.953	1.359	1	0.6402	0.87602	2.245	2.419	0.894	0.720	1.359	1.009	31	78	0.87602	1.35870	0	0.00000	1.24633	0.66032
2	16.50	0.017214	-3.351653	16.642	-0.400	1.215	1.534	1	0.5035	1.04309	2.096	2.612	1.043	0.528	1.534	1.244	0	3	1.04309	1.53384	0	0.00000	1.49751	0.50456
2	17.50	0.017214	-3.351653	17.642	-0.400	1.477	1.726	1	0.3724	1.18920	1.946	2.731	1.194	0.410	1.726	1.484	0	0	1.18920	1.72588	0	0.00000	-1.17333	0.39904
2	18.50	0.017214	-3.351653	18.642	-0.400	1.739	1.929	1	0.2448	1.32347	1.801	2.710	1.340	0.433	1.929	1.725	0	0	1.32347	1.92908	0	0.00000	-0.57905	0.41896

APPENDIX B – Additional Information

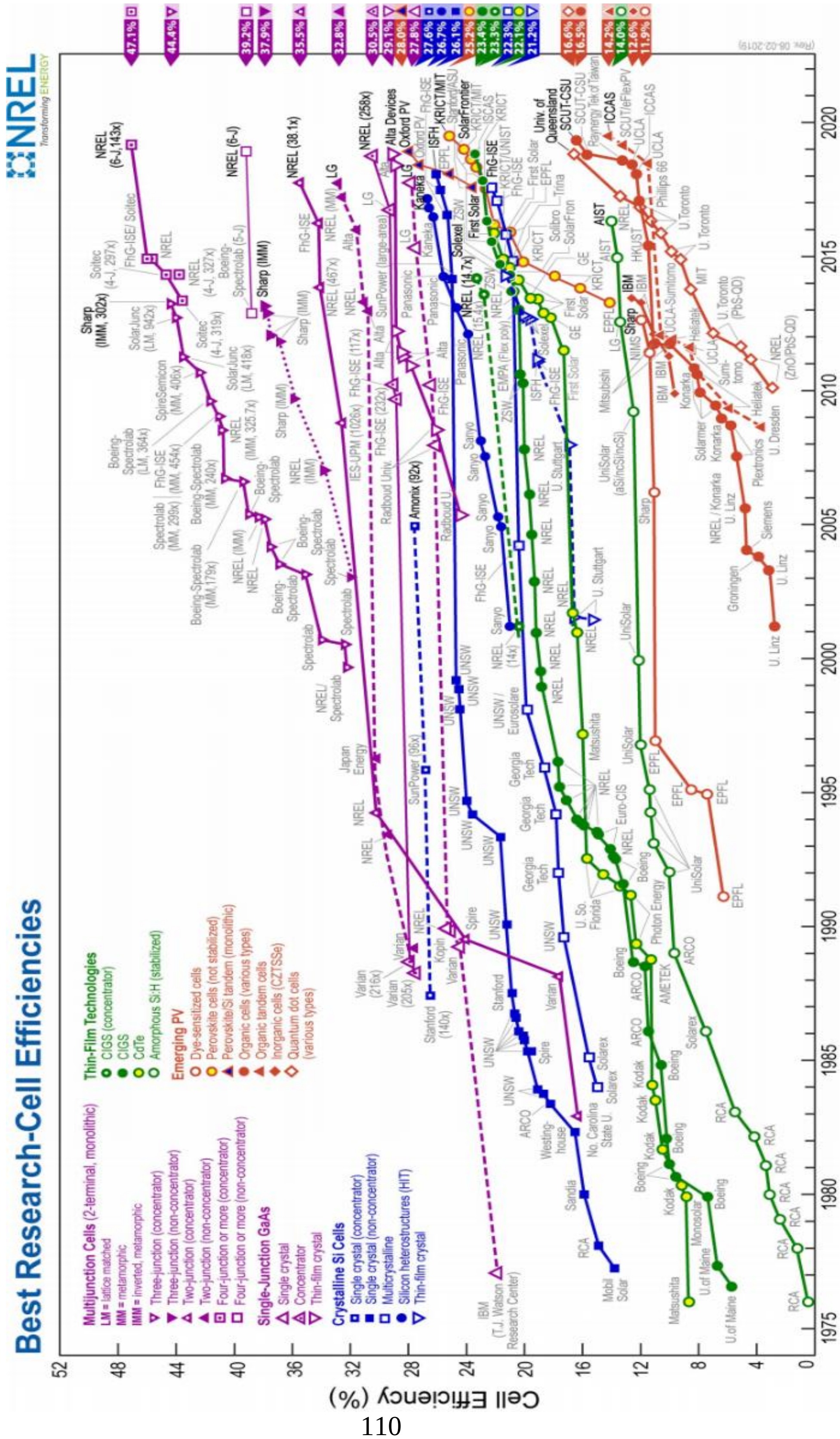
Solar PV Panel Specifications

DC Electrical Characteristics	
STC Power Rating	250W
PTC Power Rating	225.4W 1
STC Power per unit of area	14.3W/ft2 (153.7 W m^{-2})
Peak Efficiency	15.37%
Power Tolerances	0%/+2%
Number of Cells	60
Nominal Voltage	not applicable
Imp	7.98A
Vmp	31.45V
Isc	8.65A
Voc	37.9V
NOCT	45°C
Temp. Coefficient of Isc	0.06% /K
Temp. Coefficient of Power	-0.44% /K
Temp. Coefficient of Voltage	-0.125V/K
Series Fuse Rating	15A
Maximum System Voltage	1000V

INFORURO Monthly Exchange Rates

	EUR/TRY	USD/TRY	EUR/EUR
January 2016	0.3141	0.3432	1.0576
February 2016	0.3078	0.3356	1.0922
March 2016	0.3092	0.3403	1.1221
April 2016	0.3111	0.3523	1.1168
May 2016	0.3129	0.3554	1.1090
June 2016	0.3037	0.3382	1.1090
July 2016	0.3110	0.3449	1.1139
August 2016	0.2986	0.3311	1.1358
September 2016	0.3032	0.3387	1.1324
October 2016	0.2971	0.3334	1.1006
November 2016	0.2936	0.3207	1.0903
December 2016	0.2757	0.2916	1.0926
Annual Average	0.3032	0.3354	1.1060

APPENDIX C – NREL Best PV cell efficiencies



APPENDIX D – Guzelyurt Daily Irradiance assessment for Tracking Surfaces obtained from A(T)SRA Tool.

	Average Daily Solar Radiation (kWh m^{-2})													
	Non-Conc (KWh m^{-2})			Concentrating (KWh m^{-2})			EW Tracking Losses (KWh m^{-2})				NS Tracking Losses (KWh m^{-2})			
Mon.	**2A**	**EW**	**NS**	**2A**	**EW**	**NS**	**Night**	**Atm**	**Orient**	**Diffuse**	**Night**	**Atm**	**Orient**	**Diffuse**
Jan	4.22	3.74	3.13	3.48	2.98	2.24	18.67	11.00	0.51	0.74	18.67	12.08	1.24	0.74
Feb	5.00	4.25	4.14	4.00	3.19	3.00	16.82	11.82	0.80	1.00	16.82	12.68	1.00	1.00
Mar	7.63	6.18	6.84	6.34	4.75	5.45	15.80	9.75	1.59	1.29	15.80	10.54	0.89	1.29
Apr	6.72	5.55	6.49	4.91	3.51	4.63	13.60	12.31	1.40	1.81	13.60	12.53	0.29	1.81
May	8.70	7.12	8.57	6.67	4.83	6.51	12.13	11.28	1.84	2.04	12.13	11.41	0.16	2.04
Jun	8.57	7.19	8.47	6.38	4.74	6.26	11.44	11.78	1.64	2.19	11.44	11.88	0.12	2.19
Jul	10.62	8.45	10.45	8.94	6.55	8.75	11.48	9.64	2.39	1.68	11.48	9.82	0.19	1.68
Aug	8.58	6.85	8.34	6.81	4.83	6.52	13.33	10.07	1.98	1.78	13.33	10.32	0.28	1.78
Sep	7.06	5.67	6.60	5.54	3.97	4.99	14.48	10.92	1.57	1.52	14.48	11.38	0.55	1.52
Oct	6.03	5.11	5.10	4.91	3.90	3.85	16.12	10.87	1.01	1.12	16.12	11.80	1.06	1.12
Nov	6.66	5.69	4.83	6.00	5.00	4.06	18.16	8.70	1.00	0.66	18.16	10.53	1.94	0.66
Dec	6.01	5.27	4.05	5.44	4.68	3.37	17.87	9.41	0.76	0.57	17.87	11.36	2.07	0.57
Year	7.15	5.92	6.42	5.79	4.41	4.97	14.99	10.63	1.37	1.37	14.99	11.36	0.82	1.37

APPENDIX E –Cash Flows form solar DSPs

Discounted 30 Year Cash Flow Comparison of PV/SWRO and CSP/SWRO

	PV SWRO		CSP SWRO	
Year #	**Cashflows (USD)**	**Cumulative (USD)**	**Cashflows (USD)**	**Cumulative (USD)**
0	$ -487,916,273.50	$ -487,916,273.50	$ -800,905,025.50	$ -800,905,025.50
1	$ 31,711,344.91	$ -456,204,928.60	$ 23,438,368.43	$ -777,466,657.08
2	$ 32,662,685.25	$ -423,542,243.34	$ 24,141,519.48	$ -753,325,137.60
3	$ 33,642,565.81	$ -389,899,677.53	$ 24,865,765.06	$ -728,459,372.54
4	$ 34,651,842.78	$ -355,247,834.75	$ 25,611,738.01	$ -702,847,634.52
5	$ 35,691,398.07	$ -319,556,436.68	$ 26,380,090.15	$ -676,467,544.37
6	$ 36,762,140.01	$ -282,794,296.67	$ 27,171,492.86	$ -649,296,051.51
7	$ 37,865,004.21	$ -244,929,292.46	$ 27,986,637.64	$ -621,309,413.86
8	$ 39,000,954.34	$ -205,928,338.13	$ 28,826,236.77	$ -592,483,177.09
9	$ 40,170,982.97	$ -165,757,355.16	$ 29,691,023.88	$ -562,792,153.21
10	$ 41,376,112.46	$ -124,381,242.70	$ 30,581,754.59	$ -532,210,398.62
11	$ 42,617,395.83	$ -81,763,846.88	$ 31,499,207.23	$ -500,711,191.39
12	$ 43,895,917.70	$ -37,867,929.17	$ 32,444,183.45	$ -468,267,007.94
13	$ 45,212,795.23	$ 7,344,866.06	$ 33,417,508.95	$ -434,849,498.99
14	$ 46,569,179.09	$ 53,914,045.15	$ 34,420,034.22	$ -400,429,464.77
15	$ 47,966,254.46	$ 101,880,299.62	$ 35,452,635.25	$ -364,976,829.52
16	$ 49,405,242.10	$ 151,285,541.72	$ 36,516,214.30	$ -328,460,615.21
17	$ 50,887,399.36	$ 202,172,941.08	$ 37,611,700.73	$ -290,848,914.48
18	$ 52,414,021.34	$ 254,586,962.42	$ 38,740,051.76	$ -252,108,862.73
19	$ 53,986,441.98	$ 308,573,404.40	$ 39,902,253.31	$ -212,206,609.42
20	$ 55,606,035.24	$ 364,179,439.65	$ 41,099,320.91	$ -171,107,288.51
21	$ 57,274,216.30	$ 421,453,655.95	$ 42,332,300.53	$ -128,774,987.97
22	$ 58,992,442.79	$ 480,446,098.73	$ 43,602,269.55	$ -85,172,718.42
23	$ 60,762,216.07	$ 541,208,314.81	$ 44,910,337.64	$ -40,262,380.79
24	$ 62,585,082.55	$ 603,793,397.36	$ 46,257,647.77	$ 5,995,266.98
25	$ 64,462,635.03	$ 668,256,032.39	$ 47,645,377.20	$ 53,640,644.18
26	$ 66,396,514.08	$ 734,652,546.47	$ 49,074,738.52	$ 102,715,382.69
27	$ 68,388,409.50	$ 803,040,955.98	$ 50,546,980.67	$ 153,262,363.37
28	$ 70,440,061.79	$ 873,481,017.77	$ 52,063,390.09	$ 205,325,753.46
29	$ 72,553,263.64	$ 946,034,281.41	$ 53,625,291.79	$ 258,951,045.25
30	$ 74,729,861.55	$ 1,020,764,142.96	$ 55,234,050.55	$ 314,185,095.80

30 Year Cash Flow (Non-adjusted) Comparison of PV/SWRO and CSP/SWRO

	PV SWRO		CSP SWRO	
Year #	**Cashflows (USD)**	**Cumulative (USD)**	**Cashflows (USD)**	**Cumulative (USD)**
0	$ -487,916,273.50	$ -487,916,273.50	$ -800,905,025.50	$ -800,905,025.50
1	$ 32,347,119.43	$ -455,569,154.08	$ 24,315,103.43	$ -776,589,922.08
2	$ 33,953,307.53	$ -421,615,846.55	$ 25,921,291.53	$ -750,668,630.55
3	$ 35,607,681.27	$ -386,008,165.27	$ 27,575,665.27	$ -723,092,965.27
4	$ 37,311,686.23	$ -348,696,479.04	$ 29,279,670.23	$ -693,813,295.04
5	$ 39,066,811.34	$ -309,629,667.70	$ 31,034,795.34	$ -662,778,499.70
6	$ 40,874,590.20	$ -268,755,077.50	$ 32,842,574.20	$ -629,935,925.50
7	$ 42,736,602.42	$ -226,018,475.08	$ 34,704,586.42	$ -595,231,339.08
8	$ 44,654,475.02	$ -181,364,000.06	$ 36,622,459.02	$ -558,608,880.06
9	$ 46,629,883.79	$ -134,734,116.27	$ 38,597,867.79	$ -520,011,012.27
10	$ 48,664,554.82	$ -86,069,561.45	$ 40,632,538.82	$ -479,378,473.45
11	$ 50,760,265.99	$ -35,309,295.47	$ 42,728,249.99	$ -436,650,223.47
12	$ 52,918,848.49	$ 17,609,553.02	$ 44,886,832.49	$ -391,763,390.98
13	$ 55,142,188.46	$ 72,751,741.48	$ 47,110,172.46	$ -344,653,218.52
14	$ 57,432,228.63	$ 130,183,970.12	$ 49,400,212.63	$ -295,253,005.88
15	$ 59,790,970.01	$ 189,974,940.13	$ 51,758,954.01	$ -243,494,051.87
16	$ 62,220,473.63	$ 252,195,413.76	$ 54,188,457.63	$ -189,305,594.24
17	$ 64,722,862.36	$ 316,918,276.13	$ 56,690,846.36	$ -132,614,747.87
18	$ 67,300,322.75	$ 384,218,598.88	$ 59,268,306.75	$ -73,346,441.12
19	$ 69,955,106.96	$ 454,173,705.84	$ 61,923,090.96	$ -11,423,350.16
20	$ 72,689,534.69	$ 526,863,240.52	$ 64,657,518.69	$ 53,234,168.52
21	$ 75,505,995.25	$ 602,369,235.77	$ 67,473,979.25	$ 120,708,147.77
22	$ 78,406,949.62	$ 680,776,185.39	$ 70,374,933.62	$ 191,083,081.39
23	$ 81,394,932.63	$ 762,171,118.02	$ 73,362,916.63	$ 264,445,998.02
24	$ 84,472,555.13	$ 846,643,673.15	$ 76,440,539.13	$ 340,886,537.15
25	$ 87,642,506.30	$ 934,286,179.46	$ 79,610,490.30	$ 420,497,027.46
26	$ 90,907,556.01	$ 1,025,193,735.47	$ 82,875,540.01	$ 503,372,567.47
27	$ 94,270,557.21	$ 1,119,464,292.68	$ 86,238,541.21	$ 589,611,108.68
28	$ 97,734,448.45	$ 1,217,198,741.14	$ 89,702,432.45	$ 679,313,541.14
29	$ 101,302,256.42	$ 1,318,500,997.56	$ 93,270,240.42	$ 772,583,781.56
30	$ 104,977,098.64	$ 1,423,478,096.20	$ 96,945,082.64	$ 869,528,864.20