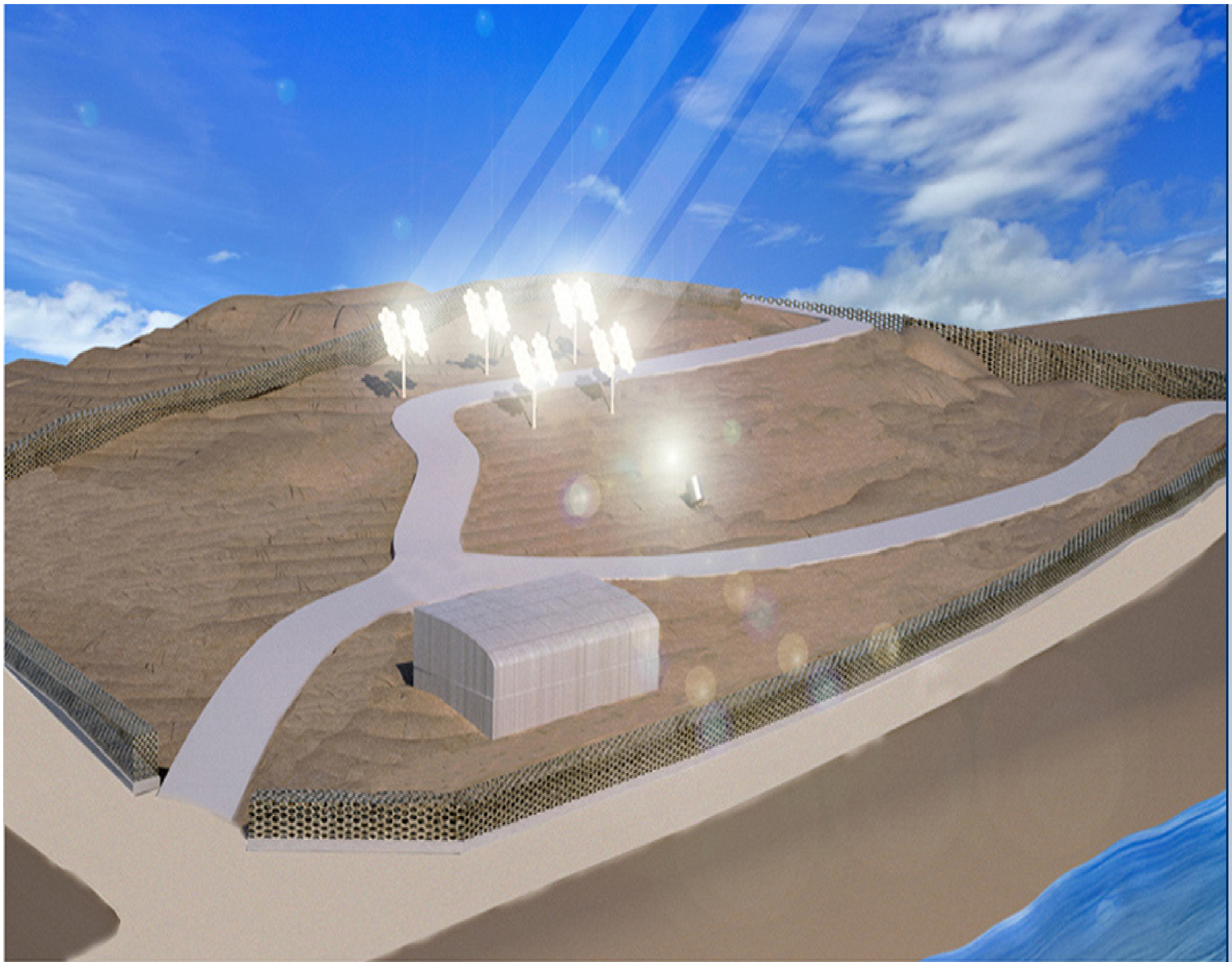

The CSP-DSW Project
An Overview

Techno-economic study of the feasibility of cogeneration of Electricity and Desalinated Sea Water using Concentrated Solar Power

July 2010

The Cyprus Institute

www.cyi.ac.cy

Contents

Acknowledgements

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A. The CSP-DSW Study

Background

Cyprus is facing the severe consequences of climate change; robust model predictions forecast a worsening situation in terms of water precipitation and extreme weather conditions. Precipitation has dropped noticeably in the past few years and continues to decrease at a rate of 1mm of rain per year on average. Temperatures which have been increasing at a rate of 0.01°C on average during the last part of the 20th century, will increase demand and make less efficient the storage of water. A number of projects have been carried out to maximize storage capacity, nevertheless the overall long-term situation is deteriorating in the face of increasing demand for water. It is generally accepted that the only viable, long-term, solution for covering Cyprus' needs for water, in addition to improved management of its storage and use, lies with desalination of sea water which however requires a lot of energy and poses environmental risks.

Cyprus is dependent on oil (mostly heavy oil), for energy production at a rate of 98%. Natural gas which is anticipated to arrive to Cyprus in the next five years is also an imported commodity and its price subjected to outside factors. Isolated from continental power grids, all energy production is taking place on the island. Electricity demand has continued to at a steady rate and although steps have been taken to ensure meeting Cyprus' needs, they also depend on fossil fuel (oil), which will exacerbate the environmental stress.

Cyprus is required to meet the EU environmental standards which demand that by 2020, 13% of Cyprus' energy consumption must come from renewable sources and greenhouse gases emissions (CO_2 especially) must be reduced by 20%.

The co-generation of electricity and useful heat has been recognised by the European Parliament and the EU Council as a major contributor towards energy savings and reducing carbon emissions. A special Directive (2004/8/EC) has been adopted to promote the use of co-generation. The Directive was adopted in Cyprus in December 2006.

The **CSP-DSW study** examines the techno-economic feasibility of cogeneration of Desalinated Sea Water (DSW) and electricity using Concentrated Solar Power (CSP). This cogeneration scheme offers a most promising solution for Cyprus: production of desalinated water to cover the rising demand and simultaneous production of economically competitive, green energy from Concentrated Solar Power (CSP). This co-generation scheme is a novel approach which employs both new and tested technologies, bespoken to Cyprus' needs and conditions.

The comprehensive techno-economic feasibility study comprises the first phase of the overall project for the development and construction of cogeneration units in Cyprus. The second phase of the project consists of the actual installation of a pilot plant that will be used to further advance the concept, engineering and optimize the use of this technology. The third and final phase will see the deployment of the refined technology plants for heavy-load commercial operation.

The CSP technology is most suitable for the Mediterranean region but its usefulness is not limited to it. In the comprehensive study *Concentrating Solar Power for the Mediterranean Region* (2005) carried out by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR), the CSP technology is recognised as the main option for the region for renewable energy. The solar potential is excellent with small cloud coverage and a high factor of irradiation throughout the year. Especially for Cyprus the average time per day of sunshine is 11.5 hours in the summer and 5.5 hours in the winter. CSP provides a clear advantage over other renewable energy generation technologies (such as Photovoltaics – PV, or Aeolic), as it can be combined with energy (thermal) storage in an efficient and economically viable way. The storage option is crucial for solar energy schemes as it can lead to a potential 24-hour, 7 days-a-week operation. All viable CSP technologies such as heliostats, troughs, parabolic dishes and Fresnel lenses, have been examined and evaluated in the framework of this study, technologies that have seen tremendous growth during the last 20 years.

Desalination technologies have also evolved significantly over the years. Ongoing research mainly focuses on refining well-established techniques and on developing new materials to be used as membranes. The two main methods currently employed worldwide, Reverse Osmosis (RO) and Multi-effect Distillation (MED) present both advantages and disadvantages and are selected according to specific needs. Both methods were explored for the co-generation scheme.

The Study principally focused on the investigation of the following main points:

1. The current state of technological developments concerning the production of electricity using CSP, and the available desalination technologies. Detailed examination of alternative technologies and an assessment of their maturity level and advantages and disadvantages vis-à-vis their employment for a CSP-DSW commercial (industrial) plant.
2. An innovative design for a Pilot plant, that is suited to the needs and conditions of Cyprus, with concrete options for its various subsystems: Solar harvesting, Energy Storage, and Power and Water production units, the main operational parameters,

capacity of electricity and water production, and an operational plan of the proposed pilot plant.

3. Characteristics of suitable locations and land requirements for the construction of a pilot plant in Cyprus.
4. An Economic Assessment of the proposed technology through a Discounted Cash Flow (DCF) business model.
5. Recommendations for an action plan based on the findings of the CSP-DSW study.

In this document the main findings, conclusions and recommendations of the Study are presented.

An International Workshop was organised on June 23rd 2010, in Nicosia Cyprus in which the findings of the study were presented. Prominent scientists, stakeholders and policy makers from Cyprus and the region participated. The aim of the Workshop was to present and debate the conclusions of the study, engage local and regional participants to a critical discussion of the findings and the proposed technological solution, and to establish a discussion platform on technological, economic and policy issues for renewables. The comments and recommendations by the participants of the Workshop have been incorporated in the Final Report of the CSP-DSW Study whose findings are summarized in this overview[1].

Organisation of the CSP-DSW Study

The techno-economic Study for the Concentrated Solar Power- Desalinization of Sea Water (**CSP-DSW Study**) was pursued and led by the Cyprus Institute for the benefit of the Cyprus Government through the Department of Control. Principally collaborating institutes and organisations included the Massachusetts Institute of Technology (MIT), the University of Illinois at Urbana Champaign (UIUC) and the Electricity Authority of Cyprus (EAC). In addition a number of Cypriot authorities have contributed to the project: the Water Development Depart (WDD), the Cyprus Energy Regulatory Authority (CERA) and the Cyprus Meteorological Service (CMS). Special acknowledgments are also due to the Department of Control, the Cyprus Land Survey, the Ministry of Commerce, Industry and Tourism, the Ministry of Communication and Works, the Ministry of Interior, the Ministry of Education, and the Cyprus Planning Bureau. The project was co-funded by the EU Cohesion Fund. The study was conducted between January 2009 and May 2010, while preparatory work begun in September 2009. A large part of the study included innovative research in a number of different fields, which helped illuminate a number of technical issues.

[1] The CSP-DSW Final Report is available upon request.

In order to better examine and investigate the various aspects of the project, the latter was divided into seven themes(referred to as work-packages - WP):

General Project Leader and Management (Prof. Papanicolas, CyI)

a. WP1: Policy & Techno economic Assessment (Leader: Prof. Papanicolas, CyI)
b. WP2: Light Harvesting (Leader: Prof. Slocum, MIT)
c. WP3: Thermal storage (Leader: Prof. Slocum, MIT)
d. WP4: Electricity Generation (Leader: Dr. Poullikkas, EAC)
e. WP5: Desalination (Leader: Prof. Georgiadis, CyI and UIUC)
f. WP6: Optimization and Integration (Leader: Prof. Mitsos, MIT)
g. WP7: Siting (Leader: Dr. Anastasiou, CyI)

These seven themes represent critical parts of the techno-economic and for the subsequent anticipated creation of a pilot plant. The overall coordination and management of the project was assumed by the Cyprus Institute. The Principal Investigator of the study was Prof. C.N. Papanicolas. Dr. G. Tzamtzis was the Project Coordinator and Project Manager. The participants of the study are noted below. In bold the Theme leaders of each group are noted.

CSP-DSW Study Collaborators

Study Leader and Coordinator: The Cyprus Institute

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Mr. Alex Pak

B. State of Affairs: National and International Context

Cyprus Conditions

Electricity Production and Demand in Cyprus

Cyprus has no indigenous hydrocarbon energy sources and energy-wise is almost completely dependent on imported fossil fuels. The Electricity Authority of Cyprus (EAC) is currently the sole producer of electricity on the island and operates three thermal power stations with a total maximum capacity of 1438 MW.

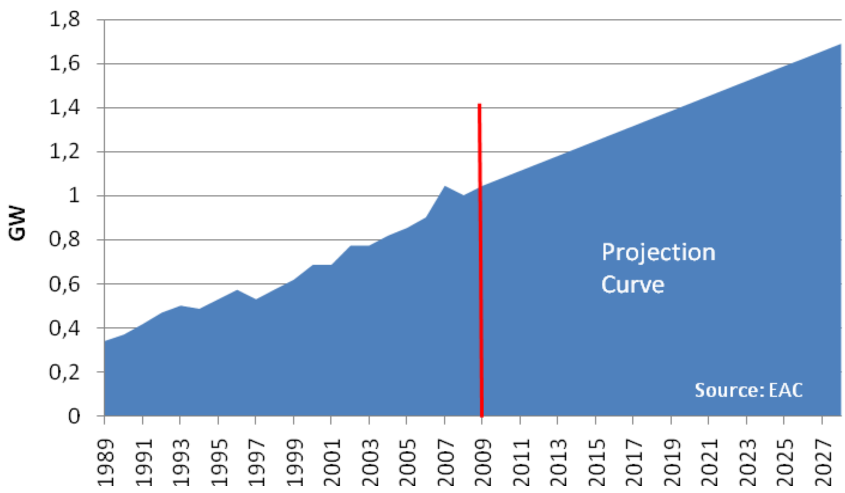
Plant (MW)	2010	2014	2018	2022
Moni	330	150	150	150
Dhekelia	460	340	220	100
Vassilikos	648	1088	1088	1088
Total	**1438**	**1578**	**1458**	**1338**

Current and future electricity production capacity

Concerning the penetration of renewable energy sources for power generation, it is currently small in Cyprus. It amounts to a few cases of small PV systems installed in homes and public buildings, and to a smaller degree, biomass gasification. The first wind farm in Cyprus with a capacity of 82 MW is expected to become operational by the end of 2010, while another with a capacity of 31.5 MW will become operational by the end of 2011. Plans for a third farm with a 20 MW capacity are currently under evaluation.

Due to the increasingly dry and warm weather conditions of recent years and the rising standard of living and tourism, there has been a considerable increase in the demand for electricity, especially during the summer months.

As expected according to scenarios and projections of the EAC the demand for energy is expected to rise over the next years.



Forecast of peak electricity demand until 2020

It is worth pointing out that if Cyprus is going to be successful in meeting the EU Renewable Energy Sources (RES) directive and produce 13% of its electricity demand by RES, then by 2020, 234 MWe will have to be produced by RES.

Water Production and Demand in Cyprus

Cyprus has a semi-arid climate and limited water resources. The Government of Cyprus has since 1960 placed great importance on water management in order to secure an adequate supply of good quality water. Due to this policy, the capacity of dams increased from 6 million m^3 in 1960 to 327.5 million m^3 today. However this path is now exhausted with practically all major works that could be implemented to avoid loss of fresh water to the sea completed.

In recent years, due to the gradual decrease of rainfall, the groundwater resources of the island have been heavily over-pumped, especially during periods of drought. It is estimated that groundwater resources are overexploited by about 40% of the sustainable extraction level. The existing conditions have resulted in, limited thus far, saline water intrusion and consequent quality deterioration in coastal aquifers and depletion of inland aquifers. Seawater intrusion in aquifers has also resulted in spoiling valuable underground water storage room. As a result, the contribution by groundwater to the island's water resources has diminished during recent years.

Over the last 30 years though, rainfall has gradually and significantly decreased, contributing to the exacerbation of the problem. It is worth pointing out that the average rainfall of the 1990-2000 decade decreased by 15% compared to the decades of 1960-1990. In addition, the frequency of draughts (<80% of average rainfall) has significantly increased with the decade of 1990-2000 experiencing 7 years of draughts.

The conditions made it imperative for the Cyprus Government to turn to sea water desalination. The first desalination plant in Cyprus was built in Dhekelia and started contributing fresh water to the system in 1997. Since then desalination, has played and will continue to play a major role in the supply of fresh, potable water for domestic use.

***Production** (m^3/day)*	***2007***	***2008***	***2009***	***2010***	***2011***	***2012***
Dhekelia	*40,000*	*50,000*	*60,000*	*60,000*	*60,000*	*60,000*
Larnaca	*52,000*	*62,000*	*62,000*	*62,000*	*62,000*	*62,000*
Moni (ship based)			*20,000*	*20,000*	*20,000*	*20,000*
Garillis Aquifier			*10,000*	*10,000*	*10,000*	*10,000*
Paphos (ship based)				*30,000*	*30,000*	*30,000*
*Limassol***						*40,000*
*EAC***					*20,000*	*50,000*
TOTAL Maximum Capacity	*92,000*	*112,000*	*152,000*	*182,000*	*202,000*	*272,000*
TOTAL (k m^3/year)*	***30,222***	***36,792***	***49,932***	***59,787***	***66,357***	***89,352***

** The total desalination capacity calculation of m^3/year assumes 365 day operation and on average 90% production of maximum capacity throughout the year.*
***The Limassol and EAC desalination plants are just in the preliminary planning phase – no official agreements have been signed yet*

Desalination Capacity 2007-2012

Forecasts for water demand until 2020 (with scenarios for 1.13% and 2.26% population increase) indicate that the demand will vary between 72-82 million m^3 of fresh water in 2020 – Alternatively, if we apply the same scenarios to the 2007 demand (i.e. where no severe water cuts were imposed, we can expect a demand of 85-98 million m^3 in 2020.

If the Cyprus Government wants to decouple the supply of fresh water from rainfall and cover all its needs for potable water from reliable, non weather dependent resources, more desalination plants will have to be constructed in the island. Since desalination is a very energy intensive process, special consideration must also be given to making sure that any new desalination plant additions are as “green” or energy efficient as possible.

Recent Developments

Since the launching of the CSP-DSW study, the interest in renewable technologies in general and for energy production in particular has grown impressively. A number of reasons, political, economic and technological have contributed significantly to this growth, principally among them the following:

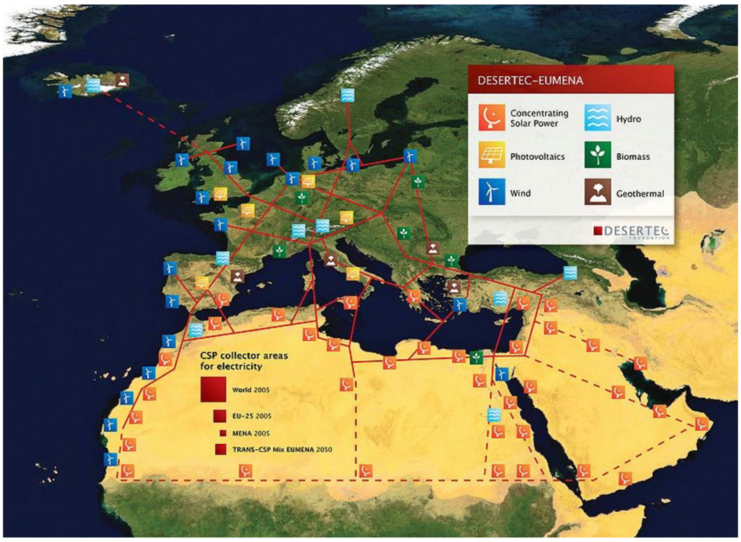
- The growing realization that climate change is occurring at a faster pace than originally anticipated and carbon emissions need to be reduced.
- The administration of B. Obama in the US has reversed the policies of the previous (G. W. Bush) administration, placing central importance to reducing dependence

on fossil fuels. Substantial funds are being allocated in the US for research in renewable technologies and demonstration projects.

- The most important initiative of the newly founded Union for the Mediterranean (UPM) has been the launching of the Mediterranean Solar Plan (MSP) which aims to increase the already installed capacity based on renewable sources by 20 GW at an estimated budget of 40 to 50 Billion Euro. In particular a subset of this initiative called “DESERTEC” aims to install high capacity CSP plants in the Sahara desert providing electricity through a High Voltage Direct Current (DCHV) supergrid to Europe and North Africa. International Organizations (e.g. World Bank, European Investment Bank etc.) are on record that they will finance big components of the project. The MSP has a small but important provision relevant to this study concerning Mediterranean islands.

- In a number of stimulus packages, particular that of the US, emphasis is placed on using funds to cultivate new “green” technologies, in particular solar. This sector of the economy is projected to grow rapidly and become one of the main industries of the 21st century. Already substantial research funds from the US Government and the European Union are earmarked and are being dispensed towards Research and Development of these initiatives.

- The European Commission, acknowledging the need for small scale co-generation units based on renewable technologies and especially solar, has launched through the 7th Framework programme, a call for the partial funding of a co-generation demonstration unit for deployment in coastal or island environment (Demonstration of innovative multi-purpose solar power plant - ENERGY.2010.2.9-1).



The DESERTEC initiative

These considerations and motivating factors as well as other economic considerations are expected to further enhance in the near future the demand for CSP, leading to more rapid development and reduced cost.

The 2009 United Nations Climate Change Conference which took place in Copenhagen in December, failed to bring the participating nations together in adopting a common policy to mitigate climate change. Part of the failure of the Copenhagen Summit was attributed to the recent global economic crisis from which a number nations, including Cyprus, have yet to recover. Nevertheless as global economic recovery is currently underway, the first signs of increased demand for oil and natural gas have driven market prices high again, and have placed renewables once again in a competitive track. Many countries (including Germany, France and the US) have indeed seen the development of “green technologies”, such as the use of Concentrated Solar Power, as a growth area which could lead to a restructuring of the Economy. Based on the investigations pursued during the course of the CSP-DSW Study it is concluded that this opportunity presents itself strongly in Cyprus and it is recommended that appropriate policies should be implemented to capture it.

Through the duration of the study, the debate on the various forms of renewable energy sources evolved in parallel and it is fair to say that it is now a well accepted fact that in the intermediate (2015-2025) and definitely in the long term (2025 and beyond) solar power will become the dominant component in the basket of the renewable sources. For the southern Europe and the Mediterranean basin solar energy is expected to be the dominant, but not the exclusive, source of energy from renewable sources.

Finally, the choice between the two principal modalities of solar energy, photovoltaic (PV) or Concentrated Solar Power (CSP) has recently tilted towards the CSP. This is due to two primary reasons: a) CSP is considerably less expensive and b) it provides a proven way to remove its intermittency (due to temporary cloud coverage) and to extend its operation into the evening hours of peak demand by thermal storage. The same technology holds the promise to provide continuous operation (24-hour operation). As in the case of the mixture of renewable energy sources, in the long term both CSP and PV will be employed, the exact mixture will depend largely to technological developments.

C. Technology Assessment

State of Technological know-how

The various available CSP and Desalination technologies with particular emphasis on those which are currently at a mature level or on the verge of becoming mature have been thoroughly examined. The main conclusions of the assessment of CSP, Desalination and Power Generation technologies are presented in brief in this section.

Assessment of CSP Technologies

Concentrated Solar Power (CSP) plants utilise Solar Energy by focusing direct beam sunlight at a specific target in order to produce high temperature heat which can then be used for electrical power generation. CSP plants, as with solar energy systems, depend on an intermittent source therefore cannot offer a dependable, autonomous and continuous power generation solution. Nevertheless this problem may be overcome by either using a hybrid solution which uses fossil fuel to compensate for the unavailability of solar energy or by employing various thermal energy storage solutions.

A thorough review of the available Concentrated Solar Power (CSP) technologies has been conducted and an evaluation of the emerging trends has been performed.

The four primary types of CSP technology that were considered are:

1. Parabolic Troughs,
2. Fresnel Systems,
3. Central Receivers (Heliostat arrays), and
4. Parabolic Dishes.

Fresnel Systems and Parabolic Dishes (especially when coupled to Stirling Engines) hold promise for the future but they are not mature enough for commercial implementation. Parabolic Troughs and to a lesser degree Heliostat-Central Receiver systems comprise ***relatively*** safe technologies, ready for pilot plant implementation.

Proponents of the CSP electricity production claim that these technologies are mature enough for industrial mass-scale production, without however claiming base-load operation without the employment of a fossil fuel backup system. None of the above technologies has ever being employed in a co-generation plant.

The four types of CSP Technologies: Parabolic Troughs, Fresnel Systems, Central Receivers, and Parabolic Dishes

The Heliostat-Central Receiver configuration offers great potential in terms of power cycle efficiency (it is the technology that can reach the highest temperature). Future anticipated developments of specialized gas turbines suitable for renewables will need to operate at such very high temperatures (over 600^{o} C). The Central Receiver technology also offers the greatest potential for storage at high temperatures (essential for 24 hour operation, a principal technological goal of our design objectives) and has been receiving increasing research attention both in Europe and the US.

A most important advantage of the Heliostat – Central Receiver system over the Parabolic Trough and Fresnel systems, critical for this application, concerns the flexibility it offers for the placement of the heliostat field on a hilly terrain. The utilization of flat terrain puts heavy restrictions for the implementation of a CSP-DSW plant in an island environment (Troughs and Fresnel could in principle be deployed on gentle slopes with a constant gradient and the correct orientation, a rather infrequent combination of conditions).

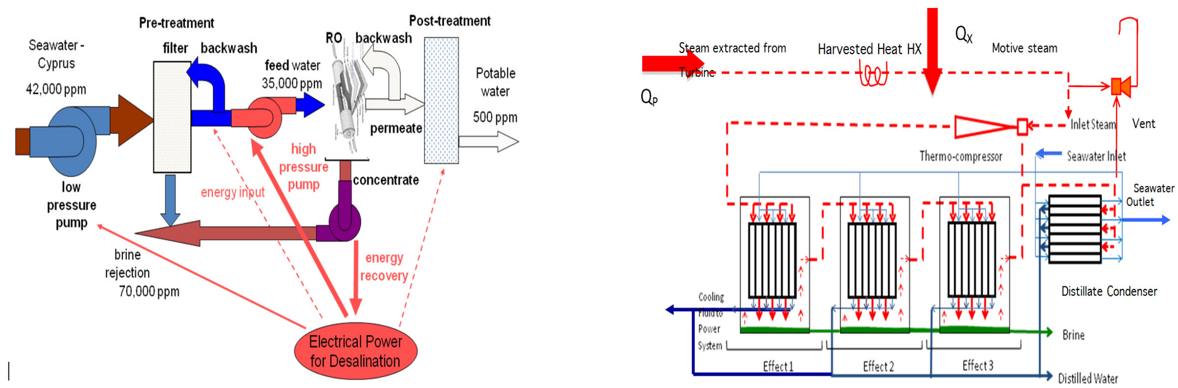
Although a number of Central Receiver systems have been constructed, there is currently, no system which is completely independent, operating in isolation only through its storage device. All systems employ a solar-fossil hybrid cycle which provides power when weather conditions are unfavourable or the heat transfer from storage fails. This emphasises both the importance of storage for continuous operation and the lack of a dependable storage system ready for ***base-load*** and most crucially ***peak-load*** operation at present. In this context, we conducted innovative research and we propose a novel way of storage which minimizes technical complexity. This is based on the CSPonD concept developed at MIT and is presented in the following section.

An important conclusion of this study has been the finding there exists a very big potential for improvement and innovation in the field of Heliostats. Currently only a handful of commercial companies exist which construct heliostats, but they seem to occupy the two ends of the spectrum, i.e. very large (around 100 m^2) or very small (a few m^2) heliostats. There is a significant gap than needs to be covered and unfortunately for a pilot plant in Cyprus, given the choice of a hill deployment and the CSPonD configuration, there exists no ready-made heliostat solution to satisfy these conditions. Moreover, heliostats have so far been developed for deployment away from coastal environments. The corrosive conditions combined with high-wind loads experienced in near-sea areas dictates that a new design approach is needed for Heliostat use in small islands.

Assessment of Desalination Technologies

Facing increasing demand for new sources of fresh water, many coastal communities, especially in the Eastern Mediterranean region are considering building desalination of seawater plants driven by renewable energy sources. A co-generation scheme in which a closed power cycle (driven by CSP) and water desalination are coupled, is both technically feasible and economically viable. A well integrated power plant and desalination system has higher energy utilization than when generating electricity and desalinating water separately.

Although a plethora of methods have been proposed for desalination using renewable resources, two classes of desalination methods appear to be the most promising, in the sense that they are industrially tested and proven to be efficient: membrane-based methods, such as Reverse Osmosis (RO), and thermal desalination methods, such as Multiple Effect Distillation (MED).



The two principle methods for Desalination,
Reverse Osmosis and Multiple Effect Distillation

The state of development, the current state of knowledge and research for these technologies and their comparative advantages and disadvantages have been reviewed. The technological constraints that determine the energetic requirements of each technology separately, with the aim of determining the most favourable option for the development of the co-generation plant on the island were also considered in some detail. Both options offer viable alternatives for single purpose desalination plants. For the case of Cyprus and given a fixed thermal energy source (i.e. CSP) and a Rankine-cycle or any other suitable power cycle (e.g. Brayton Cycle) power plant, MED appears to be the technology of choice for the co-generation plant, while a hybrid solution employing both MED and RO technologies demands further consideration. In the literature, in the considered scale for the pilot plant, only moderate sized MED units are explored with limited production capacity. This is by no means restrictive and an advanced design of a MED-TVC system with enhanced water production performance has been designed for employment in a CSP-DSW pilot plant.

Assessment of Power Generation Technologies

Today, steam turbines with widely varying configurations, sizes and application purposes are used extensively in the electricity generation and process industries. These steam turbines represent a significant part of the capital and operating costs of most plants, and therefore optimizing their selection and sizing is of major economic importance for the viability of the plant. However, the selection of the optimum steam turbine based on type and size for any given new plant is not a simple process, since a number of criteria have to be examined and be satisfied.

Currently, saturated steam cycles are usually employed in this type of plants, while superheated steam cycles are expected to be used in the forthcoming ISCC plants (Integrated Solar Combined-Cycle plants) that employ combined-cycle technology.

A comprehensive review of the available power generation technologies was conducted and an evaluation of the emerging trends has been performed. At the current stage of development only Rankine Cycle (steam turbine) engines should be considered for a pilot plant. These engines are highly efficient and extremely reliable for high power ratings (in excesses of 30 MW), while renewable sources such as CSP, are in need of smaller more efficient engines in the 1 to 10 MW range, and especially in island environments (due to land availability and optical efficiency considerations). Promising new technologies, well adapted to CSP are actively being researched, especially variants of the classical Stirling Engine. It is judged that these concepts are not mature for implementation even at pilot plants and it is inconceivable to consider them for industrial application at the present time. Finally, simulation analysis showed that future large scale deployment of concentrated solar power plants on the island of Cyprus will not disrupt the future stability and reliability of the Cyprus power system and that the reserve margin of the system is maintained above threshold values.

D. Proposal for a pilot CSP-DSW Co-generation Plant

The conceptual design of the co-generation Plant has received considerable attention by the CSP-DSW research team. This design is optimized for Cyprus but also suitable for other islands and isolated coastal regions in the Mediterranean region. It can also be particularly useful in isolated island or coastal communities in need of electricity and high-quality potable water in the developing world. The proposed design of this plant is based on constraints that have influenced the technological choices, performance parameters and operating schemes.

The basic constraints for the proposed unit were the following:

-The unit must present **a co-generation solution bespoken for Cyprus' needs and conditions**. Cyprus has an isolated grid and is depended completely on fossil fuel.

-The unit must **operate independently**, i.e. powered only by the sun. It should not employ a combined cycle with fossil fuel. This crucially demands the presence of a **storage solution** with the capacity to allow a 24hour base-load operation.

-The unit must be able to **combine both electricity and water production in the most efficient way**. It is desired that all low-grade heat be used to enhance its performance and introduce savings into its operation.

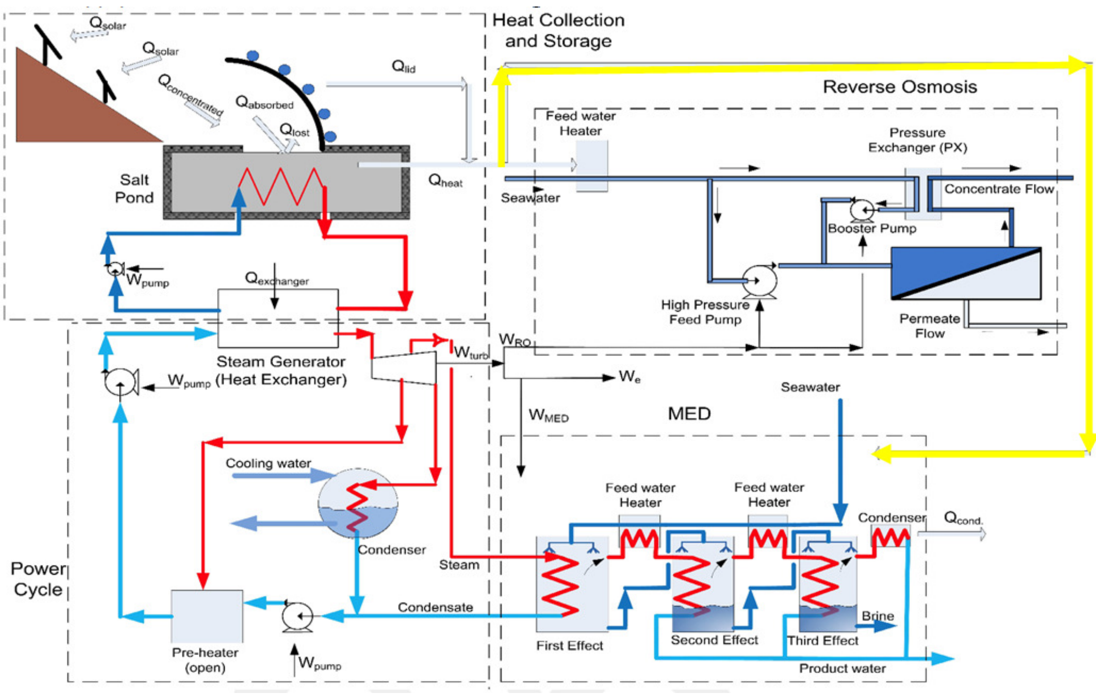
-The **availability of flat land by the coast is very scarce** and when not, extremely expensive to be used for such projects. Hilly terrain is to be preferred.

Satisfying the constraints stated above has led to a number of designs. We present here an illustrative novel design that employs technologies which are both commercially available and some that have not yet reached a level of technological maturity for base-load operation.

A design for a pilot plant is presented below having the following components:

- Solar energy will be harvested by a field of Heliostats on a hilly, south facing, location near the sea.
- The solar energy will be captured by a central receiver and converted to heat and stored in a salt container of novel design at high temperatures.

- Steam will be generated from the heat reservoir of the salt container or from an alternative thermal storage concept.
- Electricity will be produced using commercially available Steam extraction turbine.
- Desalinated water will be produced using an innovative Multiple Effect Distillation (MED) with a Thermal Vapour Compressor, from the heat output of the steam turbine and other heat sources of the system.



CSP-DSW Plant Conceptual Design with added RO modality

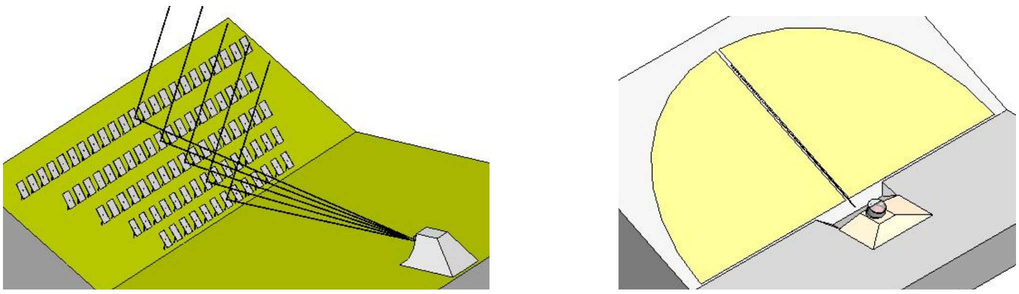
Components of a CSP-DSW pilot plant

Solar Harvesting and Storage

A Heliostat - Central Receiver technology for the Concentrated Solar Power modality is proposed. It should also incorporate thermal storage at high temperatures for 24-hour operation.

Although the Central Receiver system has been demonstrated in various cases, it has not been proven reliable in base-load operation yet, without power generation assisted by fossil fuel (typically natural gas). A research challenge is identified in the energy storage system, which constitutes a critical part of our design goal. The molten-salt storage concept is currently the most successful large-scale solution; however it suffers from technical problems and high capital and O&M costs. In addition, the technical complexity of a Power Tower, and specifically its Receiver module and salt pumping system for capturing and exchanging heat, add costs and technical complexity to a design which has not proven to be economically viable yet, in particular at small scales.

An innovative variation of the conventional Central Receiver System, based on the concept of Concentrated Solar Power on Demand (CSPonD) developed by Prof. Slocum and his colleagues at MIT, was explored. In the proposed design, one of the few considered, the Receiver and the Storage unit are integrated into one entity which is located on the bottom of a hillside, while the heliostats are placed on the hillside thus eliminating the need for flat land or the construction of a Tower. The optical losses associated with the "cosine effect" due to the concentrating point lying on ground level, are weighted against the economic and technical simplicity of the concept, and by the smaller seasonal variation in the received radiation. The latter constitutes a benefit of the specific design as the heliostat field is utilised better between the summer and winter months.



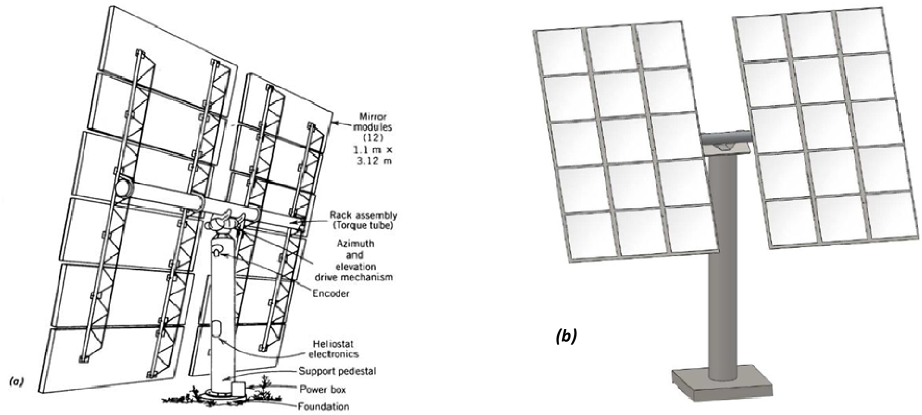
a) *b)*

a) Idealized sketch of first few hillside heliostat rows of a CSPonD system
b) Idealized sketch of two, 90° arc-type side by side hillside heliostat fields aimed at a twin aperture central CSPonD receiver

For the CSP-DSW application investigated, this design is technically simpler and economically more attractive, whilst using in principle the same heat extraction method currently employed by CSP with storage plants. With small changes to its design and storage medium (from nitrate to chloride salts), it has the potential to increase its working temperature up to 1000° C and therefore to be coupled to the more efficient Brayton cycle gas turbines (e.g. supercritical CO_2 power cycle) which are viewed as one of the most promising emerging technologies. The CSPonD concept has only been demonstrated in laboratory-scale experiments and at this stage real-scale testing is required. The Cyprus Institute in collaboration with MIT plans to test and experiment on the viability of this method on a real-scale experiment in its facilities in order to analyse and prove the validity of the concept at real operating conditions.

While the CSPonD storage-receiver is currently the technology of choice for the pilot plant implementation, it is not the only one. Other options, such a variant of the conventional tower-receiver with a two-tank molten salt storage solution are also applicable and they have been considered.

Commercially available Heliostats have not been operated or designed for operation in coastal environments. Special considerations are needed for the deployment of the high-wind and corrosive conditions by the sea. In addition special consideration is needed for their deployment at hillsides.



Schematics of heliostats with:
(a) showing the support structure from (W. Stine 2001) while
(b) shows the faceted construction of the reflective surface.

The currently available designs and commercially available options, limited as they are, can provide the required harvesting light but it is unlikely they will be durable for the given environment, for the required minimum period (15-20) years so as to render the facility economically viable.

Power Generation

As a primary option for power generation the commercially available Rankine (steam turbine) engines, which are proven and widely used in steam generating plants, are recommended.

The power generation scheme to be employed in the considered pilot plant is a standard Rankine Cycle steam turbine with a nominal capacity of 4 MWe. The turbine will be an extraction turbine, which is compatible with the co-generation scheme as it allows steam extraction for desalination at various pressure-temperature conditions. Steam extraction however bears a very hefty penalty: it redirects high quality steam to desalination, thus hampering the electricity production, which in the case of Cyprus is heavily penalised due to the skewed tariff system for water and electricity (see below). This is a crucial observation of

The study: Steam turbines have for the past decades been developed to be most efficient for large scale production, therefore they underperform at the lower limit which stands at 4 MWe. In contrast exploitation of renewable energy demands smaller than larger scales with wider geographical distribution. There is therefore a significant gap in efficient power production methods designed for renewables, something which is widely acknowledged and is the driving force in the development of Stirling engines. This consideration applies *a fortiori* for CSP-DSW co-generation as further geographical constraints come into play. However the renewed interest in RES has induced a vigorous activity in the development of more efficient and smaller engines for electricity production which are expected to reach maturity in the next five years.

Desalination

Multiple Effect Distillation (MED) is the proposed technology for desalination. Given the choice of the thermal energy source (CSP) and a Rankine-cycle power plant, performing seawater desalination via MED is a better option than Reverse Osmosis (RO) within the co-generation scheme. A hybrid solution where both technologies are employed should be further examined.

For the desalination system, the choice between MED and RO simply added in tandem to the power production cycle is complex, as they both offer comparable performance.

Following a detailed analysis, it is concluded that the MED energy requirements are higher than typical RO energy requirements when a typical MED unit (with 8 effects and a low GOR) is considered. An advanced MED system employing a Thermal Vapour Compressor has been designed taking better advantage of the available thermal energy, and is shown to be competitive with RO on energetic basis and more favourable on economics basis within the CSP-DSW scheme. This advanced design incorporates the ability to by-pass the turbine or the MED system for added operational flexibility.

Financial Analysis

A financial assessment of the CSP-DSW technology has been conducted, examining various scenarios based on different economic and engineering choices. From early on it was observed that the application of a Feed-in Tariff (FIT) in Cyprus for electricity production from renewables but not for desalination from renewables, introduces an imbalance for co-generation schemes. The main conclusions of the financial analysis are the following:

- The CSP-DSW co-generation technology is a profitable endeavour with the current feed-in tariff for electricity which stands right now at 0.26 €/kWh. The most profitable scheme is achieved with the lowest production of water and the highest amount of electricity sold to the grid. This is because producing water induces a heavy financial penalty by reducing electricity production, which is in turn sold at a premium tariff.

- Without a Feed-in Tariff, the scheme is not financially viable. This is expected as CSP technologies, especially at such small scale, are not yet competitive with conventional power production methods, a fact well-documented and universally accepted.
- Consideration of Tariffs not withstanding, the best option for desalination is a large capacity MED system. The implication for the CSP-DSW design, is that MED is financially a preferred choice than RO, while on an equal production footing, and if heat is harvested and used for thermal desalination. For co-generation schemes to work, it is imperative that water production from renewable sources must also be subsidised.

The Cyprus Institute is further exploring the current dataset and will pursue further analysis of the performance of the CSP-DSW co-generation scheme.

Consideration on the Placement of the CSP-DSW pilot facility

In terms of choice of location, the Study concluded that not only contiguous flat land but also hilly south facing terrain could be gainfully utilized. This is a major finding of the study that has already changed the “conventional wisdom” of the field layout. Particular specific sites or areas that fit these criteria include:

(a) The area south of the Technological Park at Pentakomo

(b) The area surrounding Vassilicos Power Plant

(c) The area surrounding Moni Power Plant

(d) The area surrounding Dhekelia Power Plant

These locations all have the desired characteristics for the placement of a CSP-DSW pilot.

A detailed technical investigation and optimization study should be conducted to finalize the choice using a detailed software tool developed at MIT (by Prof. Mitsos team) which can evaluate the solar potential of various sites and for various CSP configurations given elevation data of sufficient resolution. At the present stage, the Pentakomo site is judged as the most promising choice, that needs to be explored further.

Pilot Plant Capacity

A detailed investigation of the desired pilot plant capacity revealed a number of conflicting considerations and requirements. These considerations dictate that a minimum plant capacity of 4.0 MWe (nominal) should be aimed. This is solely driven by the requirements of reasonable efficiency in electricity production. Most other considerations demand a smaller rather than larger Pilot Plant. A plant of this size should be able to co-generate desalinated water in excess of 1000m^3 per day (conservative estimate) and possibly as much 5000 m^3 per day (if the advanced MED-TVC design is incorporated).

A realistic, cost assessment of such a facility is in excess of 25 Million Euros.

E. Conclusions and Recommendations

The thorough examination of all relevant parameters that pertain to the design of a CSP-DSW co-generation plant, leads to the following findings and recommendations concerning the desirability and feasibility of constructing a pilot plant:

I. The concept of co-generation of electricity and Desalinated Sea Water using Concentrated Solar Power is sound both from an engineering point of view and from an economic and policy point of view.

II. Among the various options examined for the particular application in the physical, economic and technological constraints of the island, the Heliostat – Central Receiver technology is judged to be the most suitable. It will be most beneficial if it is implemented in conjunction with a substantial storage capability so as to render the plant a “base load” facility operating on 24h/7d schedule. Variants of this technology such as a tower receiver or the MIT/CSPonD receiver both complemented with heat storage could provide the desired solution. Desalination employing Multi Effect Distillation possibly in hybrid mode with Reverse Osmosis for added flexibility is recommended.

III. Given the currently available turbine technology a minimum size of 4MWe is required. A capital investment approaching 25 Million Euros (excluding the cost of land) will be needed.

IV. We recommend the utilization of a south facing hilly terrain on the south coast of Cyprus as the preferred location to site such a plant. While the use of hilly terrain is a novelty, we recommend this option with confidence.

V. A detailed and sophisticated business model of the pilot plant whose conceptual design we have studied in detail reveals that such a plant, with the above mentioned parameters will be economically profitable.

VI. An investigation of the commercially available components reveals that key components (such as heliostats) are not optimized for the particular application and for deployment in Cyprus; components that are available have not been designed or tested for conditions of saline humid coastal environment. This will introduce unnecessarily high risk of rapid aging and imparting unacceptable financial risk. Furthermore, not being able to predict their behaviour of these components prevents their integration into an optimized dual purpose plant. In situ testing of components should immediately begin to correct this technological risk.

VII. A number of “custom” solutions that need to be engineered for the particular application, such as the receiver and storage units, which are currently at the experimental stage need to be further tested, preferably in the Cyprus coastal environment, to a sufficient degree to achieve a well-integrated CSP-DSW design and to present acceptable risk for an investment to a pilot plant.

The choices recommended and the detailed information provided in the main body of the report provide a sound basis for the commencement of research and engineering studies for a 4 MWe CSP-DSW demonstration plant, a size we propose as appropriate. As implied in points VI and VII above, a decision to proceed with the construction of such a plant with components not tested and adapted to the Cyprus (or in general island environments) introduces high risk. The technological and financial risk will be substantially reduced if the pilot project is launched with a first phase (approx. three year duration) in which components will be tested, adopted and optimized before they are employed in large numbers in the pilot plant.

The viability of projects in Renewable Energy Sources is strongly related to economic incentives, an argument which is well understood and to which the Government of Cyprus subscribes, as it is manifested by its generous Feed-in Tariff policy for electricity production from Renewable Energy Sources. Based on our economic analysis, it is recommended that a Feed-in Tariff be introduced for water production from renewable energy sources so that the current market distortion is corrected, and more “green desalination” is encouraged.

Study Conclusion

Concentrated Solar Power – Desalinated Sea Water (CSP-DSW) co-generation plants are technologically viable and economically sustainable in the Cyprus business climate and Renewable Energy Sources policy context. It is recommended that the CSP-DSW demonstration pilot plan considered by the Cyprus Government be launched, along the lines of the conceptual design presented in the main body of the CSP-DSW report. The pursuit of testing and demonstration of critical subsystems at an experimental scale in order to assess the robustness and suitability of the technologies chosen in an island environment is strongly recommended. It would be in the national interest that these tests - experiments be launched immediately. These experiments and tests are closer to a development phase and they may offer substantial opportunities for spawning competitive (internationally) high-tech enterprises thus catalyzing an important component in the development of green economy.

Abbreviations

CERA	Cyprus Energy Regulatory Authority
CMS	Cyprus Meteorological Survey
CSP	Concentrated Solar Power
CSP-DSW	Concentrated Solar Power - Desalinization of Sea Water
CSPonD	Concentrated Solar Power on Demand
CyI	The Cyprus Institute
EAC	The Electricity Authority of Cyprus
kWe, MWe	Power units in terms of Electrical Equivalent
MED	Multi-Effect Distillation
MED-TVC	Multi-Effect Distillation with Thermal Vapour Compressor
MIT	The Massachusetts Institute of Technology
PV	Photovoltaic
RO	Reverse Osmosis
UIUC	The University of Illinois at Urbana Champaign
WDD	The Water Development Department

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