AMERICAN UNIVERSITY OF BEIRUT

WATER DESALINATION USING SOLAR ENERGY: VALUE ENGINEERING AND COST BENEFIT ANALYSIS

by
DANIEL NASRI ABDELNOUR

A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Department of Civil and Environmental Engineering
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
October 2012

AMERICAN UNIVERSITY OF BEIRUT

WATER DESALINATION USING SOLAR ENERGY: VALUE ENGINEERING AND COST BENEFIT ANALYSIS

by

DANIEL NASRI ABDELNOUR

Approved by:

Dr. Mutasem El-Fadel, Professor Civil and Environmental Engineering	Advisor
Dr. Mahmoud Al-Hindi, Assistant Professor Mechanical Engineering	Co-Advisor
Dr. Ibrahim Jamali, Assistant Professor Suliman S. Olayan School of Business	Co-Advisor

Date of thesis Defense: October 30, 2012

AMERICAN UNIVERSITY OF BEIRUT

THESIS RELEASE FORM

I, Daniel Nasri Abdelnour

☐ authorize the American University of Beirut to supply copies of my thesis to libraries or individuals upon request.

☐ do not authorize the American University of Beirut to supply copies of my thesis to libraries or individuals for a period of two years starting with the date of the thesis defense.

____
Signature

____
Date

ACKNOWLEDGEMENTS

This thesis brings the end of my long journey in obtaining my Master's degree in Environmental and Water Resources Engineering at the American University of Beirut. This work is the fruit of the support and assistance of several persons.

The first person I would like to thank is my advisor, Dr. Mutasem El-Fadel who was patient enough over the long years and his unconditional guidance and advice were instrumental to the successful completion of the work in the smoothest possible way. His overly enthusiasm and integral view on research and his mission for providing 'only high-quality work and not less, helped me moving away from the Consultancy report writing habits.

I would like also to thank Dr. Mahmoud Al Hindi and Dr. Ibrahim Jamali for serving on my committee keeping an eye on my work and sparing no effort to improve the quality of this work.

Special thanks are equally extended to my father who was supportive over the years and was a real pillar to say the least.

AN ABSTRACT OF THE THESIS OF

Daniel Nasri Abdelnour for Master of Engineering
Major: Civil and Environmental Engineering

Title: Water Desalination Using Solar Energy: Value Engineering and Cost Benefit Analysis.

This study examines several technical and financial aspects of solar driven desalination plants and focuses on the feasibility of replacing gas turbine and fuel oil fired plants by concentrated solar power plants to develop sustainable green energy projects. For this purpose, a comprehensive literature review of the evolution and state of the art desalination and solar energy technologies was coupled with a value engineering (VE) methodology to identify two optimal solar driven desalination plant configurations from a set of five possible scenarios based on technical and financial considerations. A cost benefit analysis (CBA) was then performed on the "two most positively assessed" configurations to evaluate the return on investment. A sensitivity analysis was then conducted on Total Water Cost (TWC) values for plant capacities ranging between 25,000 and 75,000 m^3/day based on 2020 market values. Finally, special economic enhancement schemes were proposed by introducing a progressive periodic subsidy reduction on water and/or electricity end user unit rates under private public partnership (PPP). The deficit between income from public subsidy and capital costs was capped by reducing water unit rates subsidy.

The results of the VE showed that for public sector funding, the Reverse Osmosis (RO) desalination powered by photovoltaics supplemented by a smart grid will yield the lowest TWC of \$1.22/m^3 (GCC) and \$1.24/m^3 (Mediterranean countries) for a plant capacity of 50,000 m^3/day. Multi Effect Distillation (MED) powered by parabolic troughs supplemented by fuel fired power plant will yield a TWC of \$1.62/m^3 (GCC) and \$1.69/m^3 (Mediterranean countries).

The CBA results showed that investing in solar powered desalination plants is most attractive for the public sector.

One special economic enhancement resulted in a deficit of \$149M. The revised water tariff rates were reduced by 3% compared to the TWC of scenario D calculated during the VE assessment. The other economic enhancement resulted in a deficit of \$378M and 28% increased water tariff rates compared to scenario A TWC. The two economic enhancements highlighted the positive externalities associated with the offset of GHG emissions and the benefits of co-generation in solar powered desalination.

CONTENTS

Page

ACKNOWLEDGEMENTS v

ABSTRACT vi

LIST OF ILLUSTRATIONS ix

LIST OF TABLES xi

LIST OF ABBREVIATIONS xiii

Chapter

1. INTRODUCTION 1

2. METHODOLOGY 6

    2.1. Value Engineering Assessment 6

    2.2. Cost Benefit Analysis (CBA) 14

    2.3. Sensitivity Analysis 16

    2.4. Economic Enhancement 17

    2.5. Comparison of Proposed and Actual Water and Electricity Tariff Rates 22

3. RESULTS AND DISCUSSIONS 23

    3.1. Value Engineering 23

    3.2. Cost/Benefit Analysis 31

    3.3. Sensitivity Analysis Results 35

    3.4. Economic Enhancement 42

        3.4.1. First Proposed Enhancement Scheme 43

3.4.2. Second Proposed Enhancement Scheme 44
3.4.3. Comparison of Proposed and Actual Water and Electricity Tariff Rates 46

4. CONCLUSION 48

4.1. Recommendations 51

Appendix

1. REVIEW OF DESALINATION AND SOLAR PLANTS 53

2. COMBINED HEAT AND POWER PROPOSED ENHANCEMENT SCHEME 56

REFERENCES 58

ILLUSTRATIONS

Figure Page

1. Methodology roadmap 7

2. Water Costs ($/m3) for 25,000 m3/day plant for Scenarios A to E for a Brent Oil price of 100$ / Barrel 25

3. Water Costs ($/m3) for 50,000 m3/day plant for Scenarios A to E for a Brent Oil price of 100$ / Barrel 26

4. Water Costs ($/m3) for 75,000 m3/day plant for Scenarios A to E for a Brent Oil price of 100$/Barrel 27

5. Net present value of oil/gas savings or selling “saved” oil / gas – Scenario A (2010) 32

6. Net present value of oil/gas savings or selling “saved” oil/gas–Scenario D (2010) 33

7. Difference between double benefits and costs for MED desalination powered by parabolic troughs and fossil fuels (Scenario A) based on 2010 market values 34

8. Difference between double benefits and costs for RO desalination powered by PV and smart grid (Scenario D) based on 2010 market values 35

9. Capital costs drop – Scenario A (2020 Vs. 2010) Scenario A: MED powered by Parabolic Troughs and fossil fuel 37

10. Capital costs drop – Scenario D (2020 Vs. 2010) Scenario D: RO powered by Photovoltaics and smart grid 37

11. Annual benefits drop in savings or selling oil / gas – Scenario A (2020 Vs. 2010)... 38

12. Annual benefits drop in savings or selling oil / gas – Scenario D (2020 Vs. 2010)... 39

13. Net present value of oil / gas savings or selling “saved” oil/gas–Scenario A(2020) 39

14. Net present value of oil / gas savings or selling “saved” oil/gas–Scenario D (2020) 40

15. Double benefits – Costs Variation: Scenario A (2020 Vs. 2010) 41

16. Double benefits – Costs Variation: Scenario D (2020 Vs. 2010) 41

A.1. Combined heat and power proposed enhancement scheme 57

TABLES

Table Page

1. Overview of contemporary desalination methods 2

2. Scenarios of seawater desalination powered by solar energy 9

3. Key Figures for Financial Evaluation 10

4. Constant Multiplier (DRM) 16

5. Reduction plan of public subsidy (water and electricity costs) 19

6. Discount Rate Multiplier 20

7. Annuity Financing Factors 23

8. Gasoil Cost Requirements 23

9. Target costs and energy consumptions for plant capacity of 25,000, 50,000 and 75,000 m3/day 24 24

11. TWC: RO desalination plants powered by PV 30

12. Solar Field Land Area Requirements 31

13. Target Solar Capital Costs: 2010 and 2020 36

14. Energy consumption reduction: 2010 and 2020 36

15. Target lifecycle GHG emission for the different electricity generation methods 42

16. Annual Income, NPV and revised water costs 43

17. Annual Income, NPV and revised water costs 45

18. Actual water and electricity costs in the GCC 46

A.1. Review of desalination plants... 53

A.2. Review of solar power plants 54

A.3. Review of desalination plants incorporating thermal solar energy 54

A.4. Review of desalination plants incorporating photovoltaics 55

ABBREVIATIONS

AC	Alternate current
A_{CF}	Annual cash flow
Y	Annual demand of desalinated water (m^3/year)
$A_{INC(electricity)}$	Annual Income from electricity end users
$A_{INC(water\&GHG)}$	Annual Income from water end users and mitigated GHG ($/year)
AM_{CO2}	Annual mass of CO_2 to be mitigated (g CO_2/year)
Y_s	Annual savings in avoiding burning fossil fuels
S_{OMCY}	Annual solar operation and maintenance costs ($/year)
Y_{SE}	Annual surplus energy (kwh/year)
A	Annuity (equal cash flows)
AGE	Avoided GHG emissions market value ($17.5/tonne CO_2)
$ B	Billion American Dollars
$CC_{ScenarioA}$	Capital costs to be paid by PPP (Scenario A) ($)
$CC_{ScenarioD}$	Capital costs to be paid by PPP (Scenario D) ($)
CO_2	Carbon dioxide
CSP	Concentrated Solar Power
CBA	Cost benefit analysis
m^3	Cubic meter
m^3/day	Cubic meter per day
D_{TIC}	Desalination capital costs from transformers and inverters ($/$m^3$)
E_d	Desalination energy requirements (kwh/m^3)
D_{OMC}	Desalination operation and maintenance costs ($/$m^3$)
DPC	Desalination plant capacity (m^3/d)
D_{SPCC}	Desalination spare parts and chemical costs ($/$m^3$)
D	Direct current
D_{SDCC}	Direct solar desalination capital cost ($/$m^3$)
D_{RM}	Discount rate multiplier
$D_{RM(25)}$	Discount rate multiplier for 5 years increments over 25 years
$D_{RM\ (25\ years,\ 5\%)}$	Discount rate multiplier for 25 years and 5%
E_E	Effective energy produced by a 435 MW plant (kwh)

E/D	Equity to Debt ratio (80/20 for 25 years and 75/25 for 20 and 15 years)
F	Financing Factor
FR	Freezing
Gal/day	US Gallons per day
GH	Gas Hydrate Processes
G_{DC}	Gasoil daily cost ($/d)
G_{HC}	Gasoil hourly cost ($/h)
GW	Gigawatt
g CO_2/year	Grams of Carbon dioxide per year
gCO2/kwh	Grams of Carbon dioxide per kwh
GHG	Greenhouse gas emission
GTI	Grid Tie In Inverter assuming 600V and 36 MW
GCC	Gulf Cooperation Council
ha	Hectare
ha/MW	Hectare per megawatt
hr	Hour
E	Initial Investment (equity / debt)
I_F	Initial Investment including financing
IR	Interest Rate
IRR	Internal rate of return (discount rate)
Kw	Kilowatt
kwh	Kilowatt hour
kwh / m^3	Kilowatt hour per cubic meter
kwh/day	Kilowatt hour per day
kwh / m^2	Kilowatt hour per square meter
LR	Land Requirements (ha)
LGE	Lifecycle greenhouse gas emission rate (gCO2/kwh)
MVC	Mechanical Vapor Compression
MW	Megawatt
MD	Membrane Distillation
MENA	Middle East and North Africa
mg/l	Milligram per liter
$ M	Million American dollars

MED	Multi Effect Distillation
MSF	Multi Stage flash
NPV	Net present value
NYCR	Net yearly cash receipt
n	No. of years
%	Percent
PV	Photovoltaics
PV_{CC}	Photovoltaics capital cost ($/kw)
PV_{OMC}	Photovoltaics operation and maintenance costs ($/m^3)
P_{MW}	Power Generated (MW)
P	Power generated (solar energy can be collected in a period t (kw)
PPP	Public private partnership
RO	Reverse Osmosis
SWRO	Sea Water Reverse osmosis
S_{EPUC}	Secondary energy for pumping requirements unit cost (kwh / m^3)
S_{EPC}	Secondary energy pumping costs ($/m^3)
SPT	Single Phase Transformer from 600V to 220V
SD	Solar Desalination
S_{OMC}	Solar operation and maintenance costs ($/m^3)
$S_{OMC(CSP)}$	Solar operation and maintenance costs for CSP based scenarios($/m^3)
S_{OMUC}	Solar operation and maintenance unit costs ($/kwh)
SGC	Steam Generation Cost ($)
K	Summation Term
SE	Surplus of Energy (kwh/day)
t_{dcc}	Target desalination capital cost ($/m^3/d)
t_{scc}	Target solar capital cost ($/kw)
t	Ten hours for parabolic troughs and eight hours for photovoltaics
TVC	Thermal Vapor compression
TCC	Total Capital Costs (solar only) ($)
T_{DE}	Total daily energy needed (kwh/d)
T_{DCC}	Total desalination capital cost ($)
TEC	Total Electricity cost ($/kwh)
T_{FCC}	Total financed capital cost ($)

T_{FD}	Total financed debt ($
T_{FE}	Total financed equity ($)
T_{NCC}	Total net capital cost ($)
T_{NTIC}	Total net transformer and inverter capital cost ($)
T_{SCC}	Total solar capital cost ($)
TTC	Total Transformer Cost ($)
TWC	Total water cost ($/m3)
$TWC_{Scenario\ A}$	Total water cost (Scenario A) ($\$/m^3$)
$TWC_{Scenario\ D}$	Total water cost (Scenario D) ($\$/m^3$)
LR_U	Unit Land Requirements rate (ha/ MW)
S_{OMUC}	Unit solar operation and maintenance costs ($/kwh)
USD	U.S Dollars
$\$/m^3$	U.S Dollars per cubic meter
$\$/m^3/day$	U.S Dollars per cubic meter per day
$/day	U.S Dollars per day
$/hour	U.S Dollars per hour
$ / kw	U.S Dollars per kilowatt
$ / kwh	U.S Dollars per kilowatt hour
$\$/m^2$	U.S Dollars per square meter
$/ tonne CO_2	U.S Dollars per Carbon dioxide tonne
$/year	U.S Dollars per year
U_{GC}	Used gasoil cost to generate 1kwh of energy ($/kwh)
UTC	Unit Transformer Cost ($)
VE	Value Engineering
V	Volt

To
My Beloved Family

CHAPTER 1

INTRODUCTION

Freshwater resources in the Middle East and North Africa (MENA) region, being among the most limited worldwide, are subject to increasing pressures due to continuous population growth and economic development in this region resulting in increased water demand, which is expected to exacerbate under climate change conditions (Trieb and Müller-Steinhagen 2008).

The desalination of seawater and inland saline groundwater aquifers is emerging as the main and at times, the only potential long term sustainable solution to face the challenge of water scarcity. In this context, various desalination treatment processes have been developed and applied with continuous ongoing research to improve the three dimensional structure of its sustainability namely quality, cost, and environment (The Royal Academy of Engineering 2005).

This study reviewed the main technologies currently in-use for both water desalination (Table 1) and for the production of solar energy including cogeneration processes with particular emphasis on the potential of powering of desalination plants by solar energy while considering operational, financial and efficiency figures (refer to Appendix 1 for review details).

Multi Stage Flash distillation (MSF) is the most frequently applied thermal desalination technology in the Middle East, whereas Reverse Osmosis (RO) is the most common mechanical based technology and most widely used around the Mediterranean Sea (Trieb and Müller-Steinhagen 2008). However, MED is reportedly more efficient than MSF in terms of primary energy and electricity consumption and is associated with a lower capital investment cost (Darwish and Alsairafi 2004; Nisan and Benzarti 2008). Moreover, the operating temperature of MED is lower, requiring lower pressure steam if connected in co-generation to a steam cycle power plant (Blanco 2003). Thus, MED is selected as representative of thermal desalination, against RO for mechanically driven desalination.

Table 1. Overview of contemporary desalination methods

Separation	**Energy Use**	**Process**	**Desalination Method**
Water from salts	Thermal	Evaporation	Multi-Stage Flash (MSF) Multi-Effect Distillation (MED) Thermal Vapor Compression (TVC) Solar Distillation (SD)
		Crystallization	Freezing (FR) Gas Hydrate Processes (GH)
		Filtration/Evaporation /Humidification	Membrane Distillation (MD)
	Mechanical	Evaporation	Mechanical Vapor Compression (MVC)
		Filtration	Reverse Osmosis (RO)

Source: F. Trieb. 2007. AQUA-CSP-Concentrating Solar Power for Seawater. Section Systems Analysis and Technology Assessment, Institute of Technical Thermodynamics, German Aerospace Center. Federal Ministry for the Environment, Germany.

Despite technology advancement, desalination remains an energy intensive process currently operated using depleted fossil fuels which is non-sustainable in the long term, thus raising the need for the development of alternative energy sources. In most Oil and Gas producing countries, water costs are currently subsidized hence only governments would feel the direct fluctuation impacts. Using produced oil and gas for electricity power generation is actually consuming 20 to 25% of the GCC countries oil & gas resources and if no alternative sustainable energy sources are used, the national hydrocarbon resources will reach a critical status in these countries by 2025 (Meritet 2010). On the other hand, the regions in most need of additional freshwater are also endowed with the most intense solar radiation rendering solar energy the most promising natural resource amongst renewable energies for desalination. The environmental impacts of using solar power which is based on abundant recyclable materials, like steel, concrete and glass for concentrating solar thermal collectors' technology are also likely to be more acceptable in terms of gas emissions compared to other renewable energy sources (Trieb 2007).

As to the evolution of solar energy techniques, generating electricity from solar energy is a process whereby direct solar radiation can be concentrated and collected by a range of concentrating solar power technologies (CSP), including parabolic trough, central receiver or solar tower and parabolic dish, where the heat collected runs in a traditional thermodynamic cycle to generate electricity. Alternatively, solar cells or photovoltaic cells (PV) could be used to convert solar energy directly into electricity.

The major advantage of CSP in comparison to PV is the stability and uniformity of power capacity due to its thermal energy storage ability and to the possibility of hybrid operations with fossil fuel, which allows a continuous smooth desalination operation (Cameron and Crompton 2008). Whereas for PVs and for continuous operation of desalination processes, pairing to the electricity grid or to batteries is mandatory, thus requiring large areas and making the system less environmentally friendly and, prohibitively more expensive (Burgess 2005).

Moreover, the life expectancy of a battery is limited, compared to the longer life period of thermal storage. CSP uses a generator to produce electricity resulting in an alternate current (AC) of the right voltage whereas in PV applications, the direct current (DC) provided by the panels must be converted to AC and transformed to the right voltage. The latter is accomplished by using high maintenance inverters and 10-20% of the energy passing through the device in order to operate (Cameron and Crompton

2008). One of the advantages of a PV system over a solar thermal one, includes the minimization of water consumption (only for washing the solar panels) and the direct conversion of sunlight to electricity (REN 21 2011).

Thermal solar power is a proven technique, with installations generating power since the nineties, while total global PV installations amount to nearly six times what they were in 2004. In 2010, Germany more than tripled the runners-up for top PV capacity, accounting for 47% of existing global solar PV capacity. Spain came in at second with 16%, Japan in third with 13%, and the US in fourth with 6%. The Renewable Energy Policy Network for the 21st Century (REN21) 2010 Global Status Report recorded more than 3,200 large-scale photovoltaic power plants (also known as "utility scale") 200 kW and larger installed worldwide, with a combined capacity of 5.8 GW. This was around a quarter of the global PV capacity (REN 21 2011).

It appears from the technical performance comparison, that emphasis in this study should be made on CSP plants as an ideal energy source for thermal desalination while PVs remain suited for membrane desalination systems. However, this statement will be confirmed by the VE and CBA.

VE, also known as value engineering analysis, is a systematic and functionality based approach that can reduce costs while maintaining or improving performance and quality requirements. Functionality is what something can do. Value is the ratio of function to cost and improving the value can be either by improving the functionality or by reducing the cost. In a VE exercise, there are basic and secondary functionalities. The basic functionality considered in this study is the production of potable water by desalination of seawater while the secondary functionality is the power generation for solar desalination.

A CBA determines how well or bad, a planned action will turn out. It finds, quantifies and adds all the positive factors called benefits and subtracts all the negative factors called costs. The difference between the two indicates whether the planned action is advisable.

This study examines several technical and financial aspects of solar driven desalination plants and focuses on the feasibility of replacing gas turbine and fuel oil fired plants by CSP or photovoltaics plants to develop sustainable green energy projects. For this purpose, a comprehensive literature review of the evolution and state of the art desalination and solar energy technologies coupled with a VE methodology, to identify two optimal solar driven desalination plant configurations from a set of five possible scenarios based on technical and financial considerations. A CBA was then performed on the two most positively assessed configurations to evaluate the return on investment and its viability at a country level. Finally, two special economic enhancement schemes were proposed by introducing a progressive periodic subsidy reduction on water and/or electricity end user unit rates under private public partnership (PPP) contractual forms of association.

CHAPTER 2

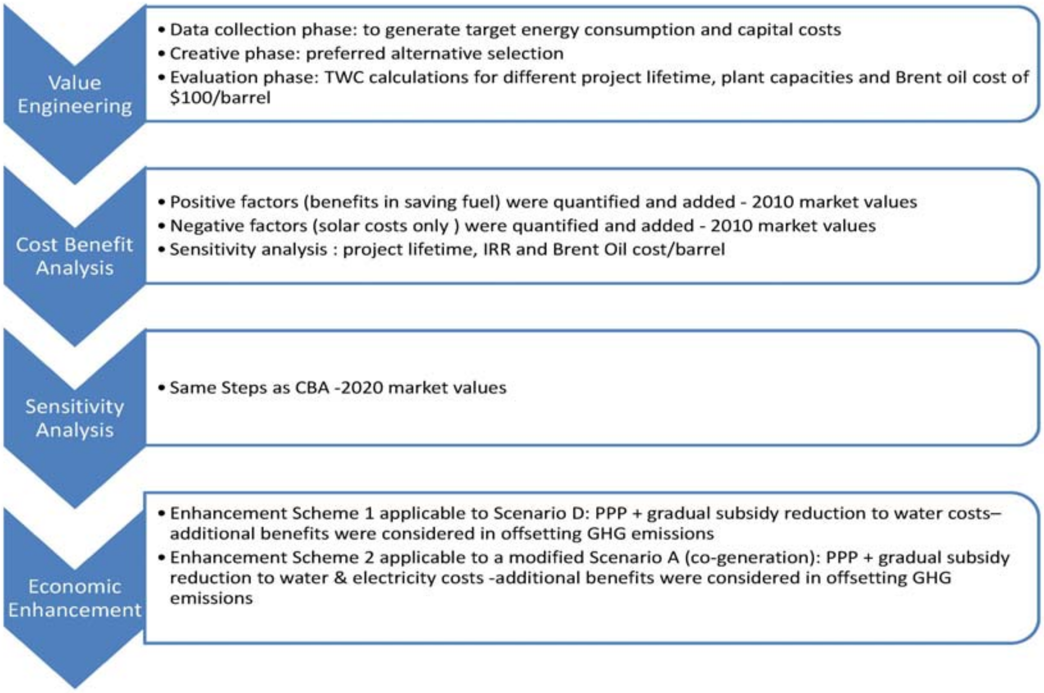
METHODOLOGY

The methodology followed in this study is illustrated in Figure 1. It starts with the value engineering assessment, followed by a cost benefit analysis. A sensitivity analysis based on 2020 market values was then conducted followed by economic enhancements.

2.1. Value Engineering Assessment

A structured approach was adopted in conducting the VE assessment consisting of data collection related to desalination and solar powered plants (Appendix 1), assuming no technical hindrance for operating desalination plants by solar energy instead of conventional fossil fuel based methods, and finally evaluation of alternative solutions for solar energy dependence of proposed scheme while considering different geographic locations affecting solar radiation input and water quality as well as distance separating water source inlet and potential solar field.

A comprehensive data collection phase was conducted (Appendix 1) whereby specialist literature was targeted (Water Desalination Reports, review papers) in order to collect technical, commercial and financial information on desalination and solar power generation technologies. The collected data was evaluated in three folds: data related to desalination plants, data related to solar powered plants and data related to desalination plants powered by solar energy in order to generate target costs and energy consumptions for plant capacities of 25,000, 50,000 and 75,000 m^3/day. A 50,000 m^3/day desalination plant will supply water to 250,000 persons assuming daily water consumption per capita of 200 L which was considered as a sizable community which is between a megacity and a small community in a remote location. The 25,000 and 75,000 m3/day plants were considered to reflect economies of scale impact on total water cost.



Value Engineering

- Data collection phase: to generate target energy consumption and capital costs
- Creative phase: preferred alternative selection
- Evaluation phase: TWC calculations for different project lifetime, plant capacities and Brent oil cost of $100/barrel

Cost Benefit Analysis

- Positive factors (benefits in saving fuel) were quantified and added - 2010 market values
- Negative factors (solar costs only) were quantified and added - 2010 market values
- Sensitivity analysis : project lifetime, IRR and Brent Oil cost/barrel

Sensitivity Analysis

- Same Steps as CBA -2020 market values

Economic Enhancement

- Enhancement Scheme 1 applicable to Scenario D: PPP + gradual subsidy reduction to water costs– additional benefits were considered in offsetting GHG emissions
- Enhancement Scheme 2 applicable to a modified Scenario A (co-generation): PPP + gradual subsidy reduction to water & electricity costs -additional benefits were considered in offsetting GHG emissions

Fig. 1. Methodology roadmap

The creative phase was predominantly concerned with determining whether seawater desalination plants may be powered by solar energy. Despite the steady increase in the number of operational solar energy power plants, there are a limited number of solar powered desalination plants in operation today or even under design or construction phase (Appendix 1).

Technological limitations such as the impact of solar energy diurnal and seasonal variations have been overcome by the progress in thermal storage technology and control technologies, to provide efficient hybrid solar-fossil fuel industrial scale power generation processes (Trieb 2007). MED technology was selected as the "preferred option" of thermal desalination plants as its energy (power and heat) requirements are lower than MSF's (Trieb 2007) while RO technology was chosen as the "preferred option" from the available mechanical desalination plants based on its market dominance worldwide. On the other hand, parabolic trough collectors (line concentrated) was considered as the "preferred option" of the concentrated solar techniques as troughs are more mature than other line concentrated or point concentrated techniques (Trieb 2007) while photovoltaics were selected as direct converters of solar energy into electricity by default.

The evaluation phase was principally concerned with geographically varying solar irradiation in kwh/m^2 and total dissolved solids concentration in mg/l. Since these two factors affect the harvested solar power, land and desalination plant energy requirements for various combinations of technologies, the analysis was applied separately to Gulf Cooperation Council (GCC) and oil and gas generating Mediterranean countries such as Libya, Algeria and Egypt (further referred to as Mediterranean countries in this study). Different energy consumption between the GCC and the Mediterranean based desalination plants is due to the higher salinities in the GCC as compared to the Mediterranean sea despite the fact that higher seawater temperature in the GCC will result in lower energy needs compared to the Mediterranean's.

Note, that for each combination involving thermal desalination, there is a main source of energy to power the desalination process and a secondary source of electricity to power auxiliary processes, such as pumps. The secondary power source can be generated via a fossil fuel fired cycle, or through parabolic troughs or photovoltaics. The combinations or scenarios considered in this study are presented with corresponding justification in Table 2.

Table 2. Scenarios of seawater desalination powered by solar energy

Scenario	Parameters	Justification
A	MED powered by parabolic troughs and secondary power through a fossil fuel fired cycle	Daily energy requirements to be collected in 10 hours, therefore heat storage is required
B	RO with 67% / 33%, ratio of needed energy collected by parabolic troughs to photovoltaics	Energy collected by photovoltaics will be used during the day; therefore electricity storage is not required, only heat storage is required.
C	MED primary and secondary power by parabolic troughs	Daily energy requirements to be collected in 10 hours, hence heat storage is required
D	RO with 100% of required energy by photovoltaics	Smart grid availability was assumed where the extra electricity generated during the day is passed onto the grid and the deficit electricity requirements during night time operation or cloudy days is received from the grid.
E	MED powered by parabolic troughs and secondary power through photovoltaics	Same as Scenario D

The economic evaluation of desalination plants powered with solar energy, assumed a combination of equity and debt capital costs funding. For a 25 year project lifetime, the public sector was assumed to finance both equity and debt in addition to offering the land needed for the solar field and desalination plant. For 15 and 20 years project lifetime, it was assumed that the public and private sector (developers and plant operators) will share financing of equity and debt, while the public sector will offer the land needed for the solar field and desalination plant. The financial evaluation was based on discounted cash flow to calculate a desalinated water cost. By using a Net Present Value (NPV) analysis, to assist in the selection of the preferred option(s) among Scenarios A through E, all cash flows are expressed in value at year (0) and inflation is ignored. The real return on investment is the nominal return or internal rate of return (IRR). Financial parameters are summarized in Table 3.

Table 3. Key Figures for Financial Evaluation

Parameter	Value	Notes
Currency	**USD**	
Construction period and Capital Cost (Equity & Debt) drawdown	1 year	The shortest estimated period
Equity/Debt	80%/20%	Capital Cost financing reimbursement in 25 years
	75%/25%	Capital Cost financing reimbursement in 20/15 years
IR for Equity Loans	3%	Equity part of capital cost financing reimbursement in 25, 20 and 15 years
IR for Debt Loans	5%	Debt part of capital cost financing reimbursement in 25,20 and 15 years
Investment IRR	5%	Investment financing by the public sector in 25 years
Investment IRR	10%	Investment financing by the public & private sectors in 20/15 years
Investment IRR	15%	Investment financing by the public & private sectors in 20/15 years

The key financial figures (discount rate and internal rate of return) are based on assumptions respecting the guide to cost benefit analysis of investment projects (Florio *et.al*. 2008). Interest rates and project life duration have been benchmarked with data collected during the literature review (Olwig *et.al*. 2012; Cameron and Crompton 2008; Fritzmann *et al*. 2007; Sargent and Lundy 2004; Nisan and Benzarti 2008, Reddy and Ghaffour 2007). Project lifetime, discount rates and internal rates of return proposed in this study are within the range stipulated in the literature review. In this study, it was assumed that the same discount factor will be used to GCC and Southern Mediterranean countries which were considered as equity provider based on their natural gas and crude oil resources.

Also in this study, it was assumed that for any project lifetime, payment of equity and debt interest costs for both public and private sectors is achieved by amortization of the equity and debt loans and related interests through annuity payments starting on the first year of the plant operation, rather than reimbursing the loan at the end of the project life which will result in higher water costs for all scenarios. Annuity financing factor was calculated using *equations 1 and 2* (Levy and Sarnat 1990).

$$A = E \times K = E \times \frac{IR \times (1 + IR)^{n}}{(1 + IR)^{n} - 1} \tag{1}$$

$$I_{F} = A \times n = E \times K \times n = E \times F \tag{2}$$

Where IR= Compound interest, n= Years, A= Annuity (equal cash flows), E= Initial Investment (equity or debt), K= Summation term, $I_{F=}$ Initial investment including financing, F= Financing Factor.

Gasoil used to generate 1 kwh worth of energy is needed to calculate the secondary power cost required to operate auxiliary processes (*Equations 3 and 4*).

$$G_{HC} = G_{DC} \div 24 = X \times a \div 24 \tag{3}$$

$$U_{GC} = G_{HC} \div E_{E} = G_{HC} \div (435 \times 1000 \times 1hr) \tag{4}$$

Where G_{DC} = Gasoil daily cost ($/d), X= 1,792 (Ton/d) (EDL 2003), a= $236 / Ton (26$ Brent Oil barrel) (EDL 2003), G_{HC} = Gasoil hourly cost ($/h), E_{E} = Effective energy produced by a 435 MW plant (kwh), U_{GC} = Used gasoil cost to produce 1kwh of energy for a certain Brent oil price

To enable the comparison of the water cost resulting from the five scenarios, three desalination plant capacities were considered 25,000, 50,000 and 75,000 m^{3}/day. The total water cost (TWC) was then calculated as outlined in *Equation 5* (Younos 2005).

$$TWC = D_{SDCC} + D_{SPCC} + D_{OMC} + S_{OMC(CSP)} + S_{EPC} + I_{c} + PV_{OMC} \tag{5}$$

Where TWC= Total Water Cost (\$/m^3), D_{SDCC}= Direct solar desalination capital cost (\$/m^3), D_{SPCC}= Desalination spare parts and chemical costs (\$/m^3, Table 9), D_{OMC}= Desalination operation and maintenance costs (\$/m^3, Table 9), $S_{OMC(CSP)}$= Solar operation and maintenance costs for CSP based scenarios (\$/m^3), S_{EPC} = Secondary energy pumping costs (\$/m^3), I_C= Indirect costs of solar powered desalination plant (\$/m^3, 25% of T_{NCC}), PV_{OMC} = Photovoltaics operation and maintenance cost (\$/m^3)

The total financed capital cost T_{FCC}, a prerequisite to calculate the various components in *Equation 5* was calculated as outlined in *Equation 6*:

$$T_{FCC} = T_{FE} + T_{FD} = (T_{NCC} \times E/D \times F) + (T_{NCC} \times (1 - E/D) \times F) \tag{6}$$

Where T_{FCC}= Total financed capital cost (\$), T_{FE}= Total financed equity (\$), T_{FD}= Total financed debt (\$), E/D= Equity to debt ratio (80/20 for 25 years and 75/25 for 20 and 15 years).

The total net capital cost T_{NCC}, a prerequisite to calculate T_{FCC} in *Equation 6*, was calculated as shown in *Equations 7 to 9*:

$$\begin{aligned} T_{NCC} &= T_{DCC} + T_{SCC} + T_{NTIC} + SGC = (DPC \times t_{dcc}) + \\ &(t_{scc} \times P) + T_{NTIC} + SGC + \{AGE \times AM_{CO2}/10^6 \times D_{RM}\} = \\ &(DPC \times t_{dcc}) + (t_{scc} \times P) + T_{NTIC} + SGC + \{AGE \times LGE \times T_{DE} \times 365/10^6 \times D_{RM}\} \end{aligned} \tag{7}$$

$$P = T_{DE} \div t = DPC \times E_d \div t \tag{8}$$

$$\begin{aligned} T_{NTIC} &= GTI + TTC = GTI + (SPT \times UTC) = GTI + \\ &(\frac{P}{10} \times UTC) \end{aligned} \tag{9}$$

(1) Equation 9 is only applicable for Scenarios based on RO desalination

(2) Terms between brackets { } in Equation 7 are only applicable to the economic enhancement section

Where T_{NCC}= Total net capital cost (\$), T_{DCC}= Total desalination capital cost (\$), T_{SCC}= Total solar capital cost (\$), T_{NTIC}= Total net transformer and inverter cost (\$), SGC= Steam Generation Cost (\$) (only applicable when the secondary energy source for Scenario A is a steam turbine - \$ 1M per MW, Griffiths 2011), T_{DCC}= Total desalination capital cost (\$), DPC= Desalination plant capacity (m^3/day), t_{dcc}= Target desalination capital cost (\$/m^3/d) (Table 9), t_{scc} = Target solar capital cost (\$/kw) (Table 9), P= Power generated (solar energy can be collected in a period t (kw), t=10 hours for parabolic troughs and 8 hours for photovoltaics, T_{DE}= Total daily energy needed (kwh/d), E_d=Desalination energy requirements (kwh/m^3), GTI= Grid tie in inverter cost(\$ 26,000, Sunelec 2011), TTC= Total transformer cost (\$), SPT= single phase transformer No. from 600V to 220V, UTC= Unit transformer cost (\$ 1,388, Kurokawa *et al*. 2007), AGE= Avoided GHG Emissions market value (\$17.5/tonne CO_2), AM_{CO2}=Annual mass of CO_2 to be mitigated (gCO_2 /year), LGE=lifecycle greenhouse gas emission rate (gCO2/kwh) (Table 15, 13 gCO2/kwh for economic enhancement scheme 2 and 85 gCO_2/kwh for economic enhancement scheme 1)

The direct solar desalination capital cost (D_{SDCC}) was calculated as outlined in *Equation 10*.

$$D_{SDCC} = NYCR \div Y = (T_{FCC} \div D_{RM}) \div (DPC \times 365) \tag{10}$$

Where NYCR= Net yearly cash receipt, D_{RM}= Discount rate multiplier (Table 4), Y= Annual demand of desalinated water (m^3/year).

The last four components of *Equation 5* are calculated as shown in *Equations 11 to 14*:

$$S_{OMC(CSP)} = S_{OMUC} \times E_d \tag{11}$$

$$S_{EPC} = S_{EPUC} \times U_{GC} \tag{12}$$

$$I_c = \frac{25\% \times T_{NCC}}{Y \times D_{RM}} \tag{13}$$

$$PV_{OMC} = 0.445\% \times PV_{CC} \times P \big/ Y \tag{14}$$

[1] Equation 14 is only applicable for Scenarios based on RO desalination

Where S_{OMUC}= Solar operation and maintenance unit costs ($/kwh) (Table 9), S_{EPUC}= Secondary energy for pumping requirements unit cost (kwh / m^3), U_{GC}= Used gasoil cost to generate 1kwh of energy ($/kwh) (Table 8), PV_{CC}= Photovoltaics capital cost ($/kw) (Table 9)

The land area needed by the solar desalination plant was calculated for all scenarios in GCC and Mediterranean countries knowing the unit surface requirements for power generation (ha/MW) using PV panels or parabolic troughs (Sargent and Lundy 2004, Cameron and Crompton 2008) as expressed in *Equation 15*. Note that the land cost is not included in this analysis as it is assumed that the land will always be made available by the government or the funding agency. Also, it was assumed that land cost in the GCC countries and Southern Mediterranean countries are comparable.

$$LR = P_{MW} \times LR_U \qquad (15)$$

Where LR = Land Requirements (ha), LR_U = Unit Land Requirements rate (ha/ MW), P_{MW} = P x 1000 (MW)

Initial thoughts can lead to conclude that locating a plant in countries where labour and land costs are low often produces a total water cost significantly cheaper than in a country where these costs are high. However, a study by Park *et al.* 1997 concluded that plant location had very little observable effect on the cost of water. Total water costs identified during the literature review were lump sum costs i.e. individual land cost components were not available.

2.2. Cost Benefit Analysis (CBA)

The CBA was applied to the two most “positive” potential combinations of seawater desalination with solar energy for a plant with an average daily water demand of 50,000 m^3/day, namely scenarios A and D. In the CBA, positive factors or benefits and negative factors or costs were quantified. The difference between benefits and costs is used to determine whether to proceed with the planned actions. Since the desalination process is the same irrespective of the powering process, no direct or indirect costs will be incurred from the desalination plant. Only construction costs of the solar power plant and costs of transmission lines (if required) will be of relevance.

The base scenario encompassed a 25 year planning horizon and 5% IRR which was considered as the net minimum acceptable rate of return on a new investment. Wider forecast scenarios were then examined by using a planning horizon of 20 and 15 years with 15% and 10% IRR and Brent Oil prices of $60, $80, $100 and $120 per barrel (current Brent oil price is fluctuating between $100 and $110 per barrel).

The annual savings resulting from the investment in solar energy powered desalination plants were evaluated (*Equation 16*) based on 2010 market values for a 50,000 m^3/day plant with similar trends expected for 25,000 and 75,000 m^3/day.

$$Y_S = T_{DE} \times U_{GC} \times 365 = DPC \times E_d \times 365 \tag{16}$$

Where Y_s = Annual savings in avoiding burning fossil fuels

The NPV of the annual energy saved by shifting to solar powered desalination plants was then calculated (*Equation 17*) using interest rates of 5, 10 and 15% over a project lifetime of 25, 20 and 15 years.

$$NPV = \sum_{i=1}^{n} \frac{A_{CF}}{(1+IRR)^i} = A_{CF} \times \sum_{i=1}^{n} \frac{1}{(1+IRR)^i} = A_{CF} \times D_{RM} \tag{17}$$

Where NPV= Net present value, A_{CF}= Annual cash flow, IRR= Internal rate of return

The summation term in *Equation (17)* was extrapolated for all rates of return and projects lifetime as outlined in Table 4.

Table 4. Constant Multiplier (D_{RM})

Years / IRR	**5%**	**10%**	**15%**
25 years	14.096		
20 years		8.511	6.259
15 years		7.606	5.847

Source: A. Keown, D. Scott, J. Martin, and J. Petty. 1994 *Foundation Finance.* New Jersey, USA: Prentice Hall International Edition.

Capital costs for solar power were evaluated as shown in *Equation 18*:

$$TCC = T_{SCC} + I_c + S_{OMC} + T_{NTIC} \qquad (18)$$

Where all components are as calculated in *Equation 5* and its dependent equations. S_{OMC} will vary according to the solar technology in use i.e. parabolic troughs or photovoltaics.

The solar power capital costs (TCC) are subtracted from twice the annual savings for Scenarios A and D yielding the overall benefits at an oil and gas generating country level as not only fuel oil currently used for desalination will be saved but also sold for other purposes. For non-oil and gas producing countries, the costs are subtracted from the annual savings. This study only considers oil and gas generating GCC and Mediterranean countries.

2.3. Sensitivity Analysis

Over the last decade significant technologic advancements resulted in cost reduction i.e. capital, energy consumption and operation and maintenance. The same trend is expected to occur in the future. In order to determine the attractiveness of shifting to solar powered desalination plants in the longer term capital costs, annual benefits, NPV and overall benefits at a country level (capital costs subtracted from double benefits) previously calculated for the year 2010 were compared to year 2020's using the same financial parameters discussed above. The Brent Oil cost was still limited to maximum 120$ per barrel. In light of the current economic and political climate in the MENA region, the Brent Oil cost is always expected to be on the rise.

2.4. Economic Enhancement

In the Gulf countries, the actual trend is to have the government subsidize the TWC to be paid by the customer, in addition to special fossil fuel prices and contract facilities offered to private firms or consortiums involved in the electrical power generation feeding desalination plants. This has a major influence on the slow shifting from fossil fuels to solar powered desalination plants as solar energy prices cannot realistically compete with subsidized fuel generated energy (Trieb 2007).

Solar electricity generation technologies often are deemed ‘‘carbon-free’’ because their operation does not generate any carbon dioxide. However, this is not so true when considering the entire lifecycle of energy production; carbon dioxide and other gases are emitted during the extraction, processing, and disposal of associated materials (Fthenakis and Kim 2006). The emission of greenhouse gases (GHGs) and their implications to climate change have sparked global interest in understanding the relative contribution of the electrical generation industry (McIntyre *et al.* 2011). There are many different electrical generation methods, each having advantages and disadvantages with respect to operational cost, environmental impact, and other factors. In relation to GHG emissions, each generation method produces GHGs in varying quantities through construction, operation (including fuel supply activities), and decommissioning. Accounting for emissions from all phases of the project (construction, operation, and decommissioning) is called a lifecycle approach (McIntyre *et al*. 2011).

The CBA considered benefits and costs associated with each of Scenarios A and D excluding benefits coupled with offsetting GHG emissions while burning fossil fuels and costs incurred by the solar power plant (CSP or PV) GHG emissions. These additional benefits and costs will be evaluated in the proposed economic enhancement schemes proposed below after identifying target lifecycle GHG emission (LGE) for the different electricity generation methods i.e. PV, CSP and fossil fuels. The benefits are associated with the offset of GHG emissions through regulated and voluntary global carbon markets that allow trading, selling, buying and offsetting of carbon credits. The latter was initiated as part of the Clean Development Mechanism and Joint Implementation mechanisms but has become a global as well as an individual incentive to reduce carbon footprint. Accordingly, based on carbon market price, the avoided GHG emissions (AGE) market value under renewable energy deployment is equal to \$17.5/tCO2 (El- Fadel *et al*. 2012).

Despite the conclusion obtained in the study by Park *et al.* 1997 that plant location had very little observable effect on the cost of water, land cost will be taken into consideration in the economic enhancement schemes to evaluate land opportunity cost impact on TWC in the GCC. Assessed land requirements were only associated with the land needed for the solar farm as land required by the desalination plant would be the same irrespective of the powering mode. Solar power plant requirements were calculated as per *Equation 15.* Following personal investigation with property experts in the GCC, the average land cost for potential solar farms sites was assumed to be \$40/m^2. Impact of land cost escalation on TWC was reflected by also considering land cost of \$80/m^2.

An enhancement scheme that can be applied to scenario D (50,000 m^3/day) was proposed by having the GCC countries governments, participate with the private sector under private public partnership (PPP) contractual forms of association, in parallel with a new policy for a progressive form of limitation of the subsidy offered by the public sector to the end users of the water desalinated product and / or electricity end users as summarized in Table 5 with 5% discount factor and a 25 year project lifetime.

Table 5. Reduction plan of public subsidy (water and electricity costs)

Years	**Total Water Cost ($ / m^3)**	**Total Electricity Cost ($ / kwh)**
1-5	0.6	0.09
6-10	0.7	0.1
11-15	0.8	0.11
16-20	0.9	0.12
21-25	1.0	0.13

The income from the reduction plan to water subsidy (including GHG mitigation cost) is calculated as outlined in *Equation 19*:

$$A_{INC(W\&GHG)} = Y \times TWC = (DPC \times 365) \times TWC + AGE \times {AM_{CO2}}/{10^6} = (DPC \times 365) \times TWC + AGE \times {LGE \times T_{DE} \times 365}/{10^6} \tag{19}$$

Where A_{INC}= Annual Income from water end users ($ / year), TWC= Total water cost (Table 5), LGE= 616 gCO_2 / kwh and AGE=$17.5/ tonne CO_2

The NPV of the income collected from end users was calculated for the project lifetime of 25 years as follows:

$$NPV = \sum_{i=1}^{n} \frac{A_{INC}}{(1+IRR)^i} = A_{INC} \times \sum_{i=1}^{n} \frac{1}{(1+IRR)^i} = A_{INC} \times D_{RM\,(5/25)} \tag{20}$$

Where $D_{RM(5/25)}$= Discount rate multiplier for 5 years increments over 25 years (Table 6).

As shown in *Equations 19 and 20*, the annual income is constant over a 5 year interval and will increase every 5 years as per the reduction plan shown in Table 5. The NPV will be calculated in five stages. Each stage will have its specific discount rate multiplier discounting the income collected over the 5 years as highlighted in Table 6.

Table 6. Discount Rate Multiplier

Years	**$D_{RM(25)}$**
1-5	4.33
6-10	3.393
11-15	2.658
16-20	2.083
21-25	1.632

Source: J. Williams, S. Haka, M. Bettner, and J. Carcello. (2010). *Financial and Managerial Accounting. The Basis for Business Decisions*. Fifteenth Edition. USA: McGraw Hill.

The capital costs of the RO plant, photovoltaics installation, transformers, inverters and other variable costs to be paid by the PPP were calculated as outlined in *Equation 21* based on previously calculated TWCs in *Equation 5*:

$$CC_{ScenarioD} = TWC_{ScenarioD} \times Y \times D_{RM\,(25\,years,5\%)} \qquad (21)$$

Where $CC_{ScenarioD}$= Capital costs to be paid by PPP (Scenario D) (\$), $TWC_{ScenarioD}$= Total water cost (Scenario D) (\$/m^3), $D_{RM(25years,\ 5\%)}$= Discount rate multiplier for 25 years and 5%

The calculated deficit between the capital costs and income NPV will either be subsidized or the proposed tariff charges are to be increased to compensate for the deficit. The revised water tariff rates option is proposed in this study.

Another proposed enhancement scheme that can be applied to a “modified” scenario A (50,000 m^3/day) where an MED plant coupled and powered by a CSP plant shared the collected solar heat, with a power plant in co-generation mode (Appendix 2) in parallel with public subsidy to both water and electricity tariffs as proposed in Table 5. The secondary energy, which was originally generated from fossil fuels will now be generated from the steam turbine. The daily energy requirements for desalination are 312,500 kwh/d which can be generated by a 13.02 MW co-generation power plant which will operate over 24 hours. Assuming that the co-generation power plant will supply 12MW worth of electricity to end users (288,000 kwh/day surplus energy), its overall capacity would be approximately 25 MW (operating over 24 hours) or 600,000 kwh/day. The CSP field will have to collect the power plant heat requirements over 10 hours, hence its capacity will be 60,000 kw.

The same methodology followed for the first enhancement scheme was applied to scenario A. The capital costs of the MED and CSP plants to be paid by the PPP were calculated based on previously calculated TWCs as shown in *Equation 22*:

$$CC_{ScenarioA} = TWC_{ScenarioA} \times Y \times D_{RM\,(25\,years\,,5\%)} \tag{22}$$

Where $CC_{ScenarioA}$= Capital costs to be paid by PPP (Scenario A) ($), $TWC_{ScenarioA}$= Total water cost (Scenario A) ($/m^3), $D_{RM(25years,\,5\%)}$= Discount rate multiplier for 25 years and 5%.

This cost would include the capital cost of a 25MW power plant as well as the cost generated by GHG emissions resulting from the CSP plant. The income to the PPP consortium would be from both water and electricity end users and from mitigated GHG emissions sold as carbon credit. Income from water end users was calculated previously in the first proposed enhancement scheme. Income from electricity end users was calculated similarly as follows (*Equation 23*):

$$A_{INC(electricity)} = Y_{SE} \times TEC = (SE \times 365) \times TEC \tag{23}$$

Where Y_{SE}= Annual surplus energy (kwh/year) and TEC = Total electricity cost ($/kwh)

The NPV of the incomes collected from water and electricity end users were calculated using the same methodology applied in the first proposed enhancement scheme (*Equation 20*).

The total electricity cost generated by a 28.8MW power plant was calculated by using *equation 5* and its dependents by replacing the 50,000 m^3/day desalination plant by a 28,800 kw power plant and by neglecting all cost components related to the desalination process.

The calculated deficit between the capital costs and income NPV will either be subsidized or the proposed tariff charges (electricity and /or water) are to be increased to compensate for the deficit. In order to maintain consistency between the two enhancement schemes and to avoid tremendous increases to electricity tariff rates which are highly subsidized in the GCC, it was assumed that the electricity costs subsidy reduction plan remains as per Table 5 and water tariff rates will be increased to cover for the deficit between capital costs and income collected by the PPP consortium.

The aim of the economic enhancement is to reduce the current oil and gas subsidies smoothly without creating financial pressure on GCC nationals and residents. On the long term, this enhancement scheme is aligned with the new trend of PPP providing means of fund raising to finance national projects.

2.5. Comparison of Proposed and Actual Water and Electricity Tariff Rates

The proposed water and electricity tariff rates were benchmarked and compared to the current rates in various countries of the GCC i.e. Dubai, Abu Dhabi, Kuwait, Kingdom Saudi Arabia, Sultanate of Oman, Qatar and the Kingdom of Bahrain.

CHAPTER 3

RESULTS AND DISCUSSIONS

3.1. Value Engineering

After processing and analyzing the data collected for the VE study, target costs and energy consumption figures were set for the three plant capacities of 25,000, 50,000 and 75,000 m^3/day as outlined in Table 9. The Annuity financing factors were calculated for various scenarios as outlined in Table 7.

Table 7. Annuity Financing Factors

Years / Interest Rate	**Equity at 3%**	**Debt at 5%**
25years	1.435558	1.773890
20years	1.344416	1.60496
15years	1.256451	1.445088

(1) See Equations 1 and 2

The gasoil cost per kwh needed to power secondary auxiliary processes such as pumps in Scenario A was calculated as shown in Table 8.

Table 8. Gasoil Cost Requirements

Brent Barrel Oil Cost ($/ Barrel)	**Gasoil Cost ($ / kwh)**
60	0.094
80	0.125
100	0.156
120	0.188

(1) See Equations 3 and 4

Table 9. Target costs and energy consumptions for plant capacity of 25,000, 50,000 and 75,000 m^3/day

	Unit	**25,000 m^3/day**		**50,000 m^3/day**		**75,000 m^3/day**	
		GCC	**Mediterranean**	**GCC**	**Mediterranean**	**GCC**	**Mediterranean**
Target Capital Cost MED(1)	**(\$/m^3)**	1,387	1,221	1,250	1,100	1,176	1,035
Target Capital Cost RO(2)	**(\$/m^3)**	1,276	1,109	1,150	1,000	1,082	941
Energy Consumption MED(3)	**(kwh /m^3)**	4.5 and 1.75 (electricity)	4 and 1.75 (electricity)	4.5 and 1.75 (electricity)	4 and 1.75 (electricity)	4.5 and 1.75 (electricity)	4 and1.75 (electricity)
Energy Consumption RO(3)	**(kwh /m^3)**	4	3.5	4	3.5	4	3.5
Target Capital Cost Parabolic Trough(4)	**(\$/kw)**	5,327	7,103	4,500	6,000	4,081	5,440
Target Capital Cost Photovoltaics(5)	**(\$/kw)**	3,989	5,129	3,500	4,500	3,335	4,288
Spare Parts and Chemical Costs for MED(6)	**(\$/m^3)**	0.035	0.035	0.035	0.035	0.035	0.035
Spare Parts and Chemical Costs for RO(6)	**(\$/m^3)**	0.050	0.050	0.050	0.050	0.050	0.050
Indirect Costs (contingency, owner cost, overhead) (6)	**(\$/m^3)**	25% of capital costs	25% of capital costs	25% of capital costs	25% of capital costs	25% of capital costs	25% of capital costs
Operation and Maintenance MED(6)	**(\$/m^3)**	0.075	0.075	0.075	0.075	0.075	0.075
Operation and Maintenance RO(6)	**(\$/m^3)**	0.1	0.1	0.1	0.1	0.1	0.1
Operation and Maintenance cost of parabolic trough without thermal storage(7)	**(\$/kwh)**	0.0135	0.0135	0.0135	0.0135	0.0135	0.0135
Operation and Maintenance cost of parabolic trough with thermal storage(7)	**(\$/kwh)**	0.0278	0.0278	0.0278	0.0278	0.0278	0.0278
Annual Operation & Maintenance Cost of PV(8)	**(%of PV capital Costs)**	0.445	0.445	0.445	0.445	0.445	0.445
Fuel fired energy cost for 100\$ Brent barrel(9)	**(\$/kwh)**	0.16	0.16	0.16	0.16	0.16	0.16
Parabolic trough solar field area(7)	**(ha/ MW)**	3.8	4.75	3.8	4.75	3.8	4.75
Photovoltaics PV fixed panels solar field area(10)	**(ha/ MW)**	2.14	2.675	2.14	2.675	2.14	2.675

Source: (1) Burgess 2005, (2) WDR 2008 and Fritzmann 2006, (3) WDR 2008, Blanco 2003, (4) Sargent and Lundy 2004, (5) Arabian Oil and Gas staff 2009 and Cameron and Crompton 2008, (6) Blanco 2003, (7) Sargent and Lundy 2004, (8) Kurokawa et al. 2007 and Cameron and Crompton 2008, (9) EDL 2003, (10) Cameron and Crompton 2008

The total water costs (TWC) for 25,000, 50,000 and 75,000 m^3/day solar powered desalination plants for scenarios A through E located in GCC or Mediterranean countries for different project lifetime and discount factors were calculated as illustrated in Figures 2, 3 and 4 respectively.

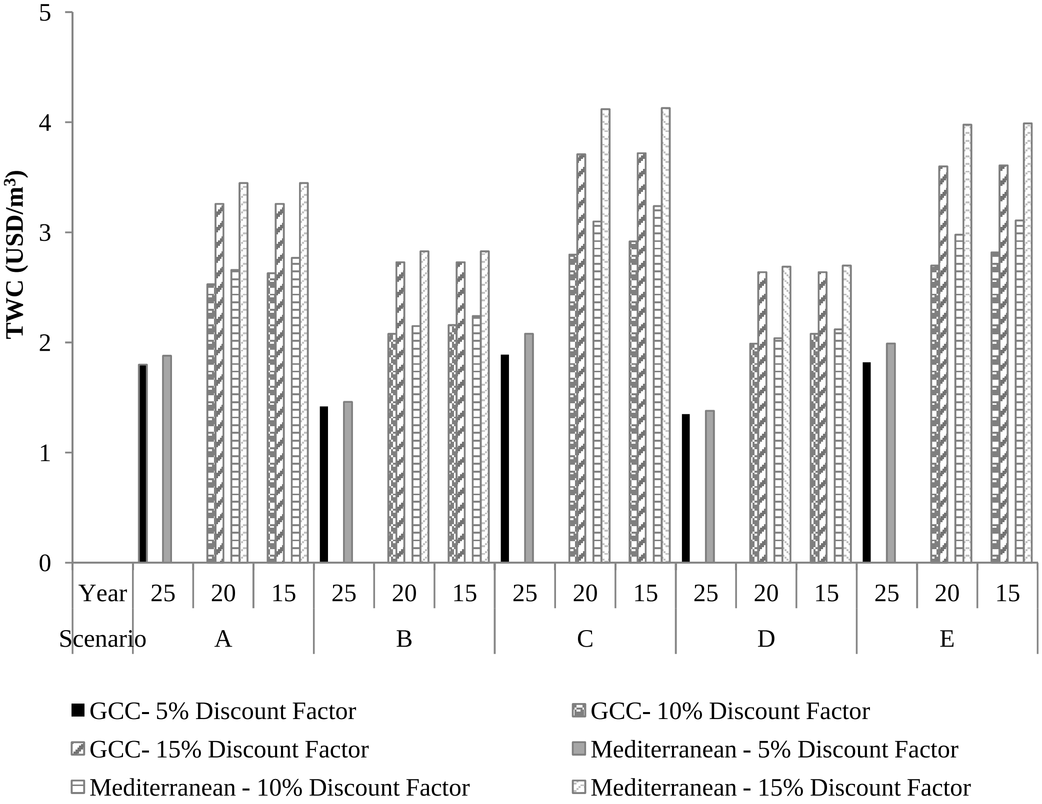


Fig. 2. Water Costs ($\$/m^3$) for 25,000 m^3/day plant for Scenarios A to E for a Brent Oil price of 100$ / Barrel

Scenario A: MED powered by Parabolic Troughs and fossil fuel
Scenario B: RO powered by Parabolic Troughs and Photovoltaics
Scenario C: MED powered by Parabolic Troughs
Scenario D: RO powered by Photovoltaics and smart grid
Scenario E: MED powered by Parabolic Troughs and Photovoltaics and smart grid

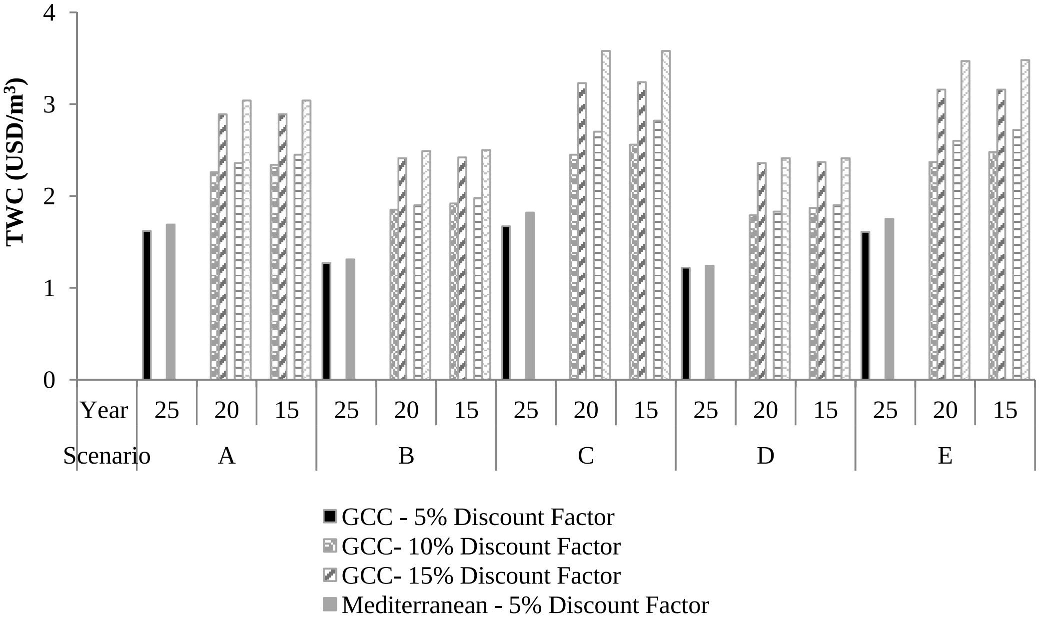


Fig. 3. Water Costs ($\$/m^3$) for 50,000 m^3/day plant for Scenarios A to E for a Brent Oil price of 100$ / Barrel

Scenario A: MED powered by Parabolic Troughs and fossil fuel

Scenario B: RO powered by Parabolic Troughs and Photovoltaics

Scenario C: MED powered by Parabolic Troughs

Scenario D: RO powered by Photovoltaics and smart grid

Scenario E: MED powered by Parabolic Troughs and Photovoltaics and smart grid

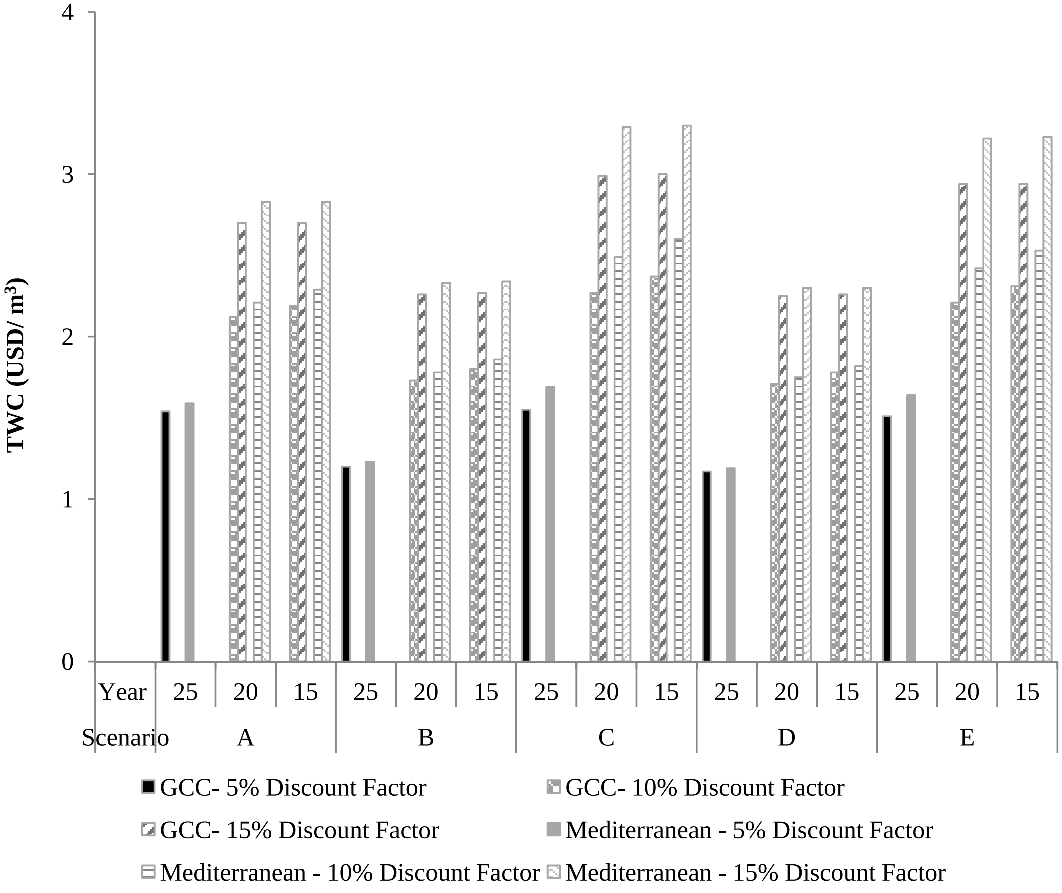


Fig. 4. Water Costs ($\$/m^3$) for 75,000 m^3/day plant for Scenarios A to E for a Brent Oil price of 100$/Barrel
Scenario A: MED powered by Parabolic Troughs and fossil fuel
Scenario B: RO powered by Parabolic Troughs and Photovoltaics
Scenario C: MED powered by Parabolic Troughs
Scenario D: RO powered by Photovoltaics and smart grid
Scenario E: MED powered by Parabolic Troughs and Photovoltaics and smart grid

Overall, RO based solar desalination combinations (scenarios B & D) resulted in a lower TWC when compared to MED based combinations (scenarios A, C & E). All combinations resulted in lower TWCs in the GCC countries when compared to Mediterranean countries irrespective of the project lifetime and / or the IRR. For instance, Scenario A TWC for a 50,000 m^3/day plant (25 years project lifetime and 5% IRR) is $\$1.62/m^3$ for the GCC countries and $\$1.69/m^3$ for the Southern Mediterranean countries. Assuming different IRR is to be used between GCC and Mediterranean countries i.e. 3.5% for the GCC and 7% for the Mediterranean countries, then TWCs would be \$1.46/m^3 and \$1.94/m^3 respectively. This result reflects the impact of the discount factor selection on TWC calculation and leads to an important conclusion: despite the fact that energy consumption is higher in the GCC area, solar technology cost has a higher influence on the total water cost primarily due to the lower solar irradiance in the Mediterranean countries.

Also, combinations that are better ranked for public investment (25 years) are also better ranked for public/private investment (20 or 15 years). This conclusion relies on using the same discount factor to GCC and Mediterranean countries. Should different discount factors be used, a detailed feasibility analysis needs to be conducted.

Scenarios B and D yield similar total water costs for all project durations and discount rates with a slight advantage for Scenario D which is highly plausible for public investors since the use of a smart grid is almost a certainty. However, Scenario B is more favorable for private investors where the power plant is likely to be independent of a grid system.

Scenarios A, C and E result in comparable total water costs for various discount rates and project durations which reinforce a fact that thermal desalination processes, irrespective of solar power technology will offer similar water costs. However, it is important to note that for Scenario A, the actual unit costs for the secondary power were used at market values and did not account for the cost subsidies that are common in GCC and MENA countries. If subsidized electricity is to be considered then Scenario A may be competitive with Scenarios B and D. Another study proposed TWC for conventional desalination based on MED ranging between \$ 0.52 to 1.95/m^3 (Karagiannis and Soldatos 2008) which are lower than the TWC calculated in this study. In the same study, the proposed TWC for RO based desalination is ranging between \$ 0.48 – 0.62/m^{3}which are lower than the TWC calculated in this study. The discrepancies in TWC were expected as water costs presented by Karagiannis and Soldatos 2008 are exclusive of the transition costs to solar powering.

The economic analyses carried out so far have not been able to provide a strong basis for comparing economic viability of each desalination technology. The economic performances expressed in terms of cost of water production have been based on different system capacity, system energy source, system component, and water source. These differences make it difficult, if not impossible, to assess the economic performance of a particular technology and compare it with others. Average TWC from different sources have been compiled in Tables 10 and 11 in an effort to benchmark the TWC calculated in Figures 2, 3 and 4. The various TWC calculated in this study were averaged yielding one TWC for 25,000, 50,000 and 75,000 m^3/day as shown in Tables 10 and 11.

Literature shows that in general, large capacity plants require a high initial capital investment compared to low capacity plants. Also, the increase in cost of product water (per 1000 gallons) is proportional to energy cost (per kwh). However, due to the economies of scale, operation and management costs, the unit production costs for large capacity plants can be lower (Younos 2005).

Table 10. TWC: MED desalination plants powered by CSP

MED Plant Capacity (m^3/day)	**Average Total Water Cost (\$/m^3)**	**Source**
24,000	2.38	Trieb, 2007
25,000	3	This study
50,000	2.63	This study
75,000	2.45	This study

Table 11. TWC: RO desalination plants powered by PV

RO Plant Capacity (m^3/day)	**Average Total Water Cost (\$/m^3)**	**Source**
40	9.5	Al- Karaghouli *et al*., 2009
53	11.6	Al- Karaghouli *et al*., 2009
5,000	2	Fiorenza *et al*., 2003
24,000	2.5	Olwig *et al*., 2012
25,000	2.21	This study
50,000	1.97	This study
75,000	1.87	This study

The resulting TWC of \$3/m^3 (25,000 m^3/day MED plant in this study) is relatively close to \$2.38/m^3, the cost quoted in Trieb (2007) of an equal sized plant. The resulting TWC of \$2.21/m^3 (25,000 m^3/day RO plant in this study) is relatively close to \$2.5/m^3, the cost quoted in Olwig *et al*. (2012) of an equal sized plant.

The land area requirements for scenarios A through E for solar powered desalination plant capacities of 25,000, 50,000 and 75,000 m^3/day located in the GCC or Mediterranean countries were calculated as shown in Table 12. The land needed for the various scenarios show that Scenario A needs least land among the three thermal desalination options (i.e. Scenario A, C and E) and Scenario B needs least land among the two mechanical desalination options (i.e. Scenario B and D). The ranking above was based on the assumption of the availability of the needed vacant land area to install the solar collection field nearby the desalination plant. Non-availability of land will impose restrictions and some of the combinations considered above may become non-feasible. Transmission of heat over long distances is not a common practice; therefore thermal desalination processes will not be technically and practically feasible for projects where the desalination unit is located at a considerable distance away from the solar power generation plant.

Table 12. Solar Field Land Area Requirements

Scenario	Capacity (m^3/day)	Land Area (ha) (GCC)	Land Area (ha) (Mediterranean)
A	25,000	42.75	47.5
	50,000	85.5	95
	75,000	128.25	142.5
B	25,000	34.2	37.45
	50,000	68.4	74.9
	75,000	102.6	112.35
C	25,000	59.38	68.28
	50,000	118.75	136.56
	75,000	178.13	204.84
D	25,000	26.75	28.09
	50,000	53.5	56.18
	75,000	80.25	84.26
E	25,000	54.45	62.12
	50,000	108.9	124.25
	75,000	163.35	186.38

On the other hand, transmission of electricity is not an issue and to minimize losses, the transmission of direct current (DC) is the recommended transmission mode and this would require transformers, inverters and high voltage transmission lines. Transmission limitations favor combinations based on mechanical desalination i.e. Scenarios B and D.

In conclusion to the VE, it is hard to find the best combination alternative in light of the various constraints, however RO desalination powered by photovoltaics and smart grid (Scenario D) will be considered as first ranked since it has the lowest TWC for both private and public investors and MED desalination powered by parabolic troughs for primary and secondary energy through a fuel fired power cycle (Scenario A) as second ranked.

3.2. Cost/Benefit Analysis

After calculating the solar power plants capital costs for various discount factors as well as the annual savings in non-fossil fuels burning for MED & RO desalination plants for Brent Oil cost of 60, 80, 100 and 120$ per barrel, the net present value (NPV) of the said oil/gas savings was calculated for scenarios A & D based on 2010 market figures as illustrated in Figures 5 and 6.

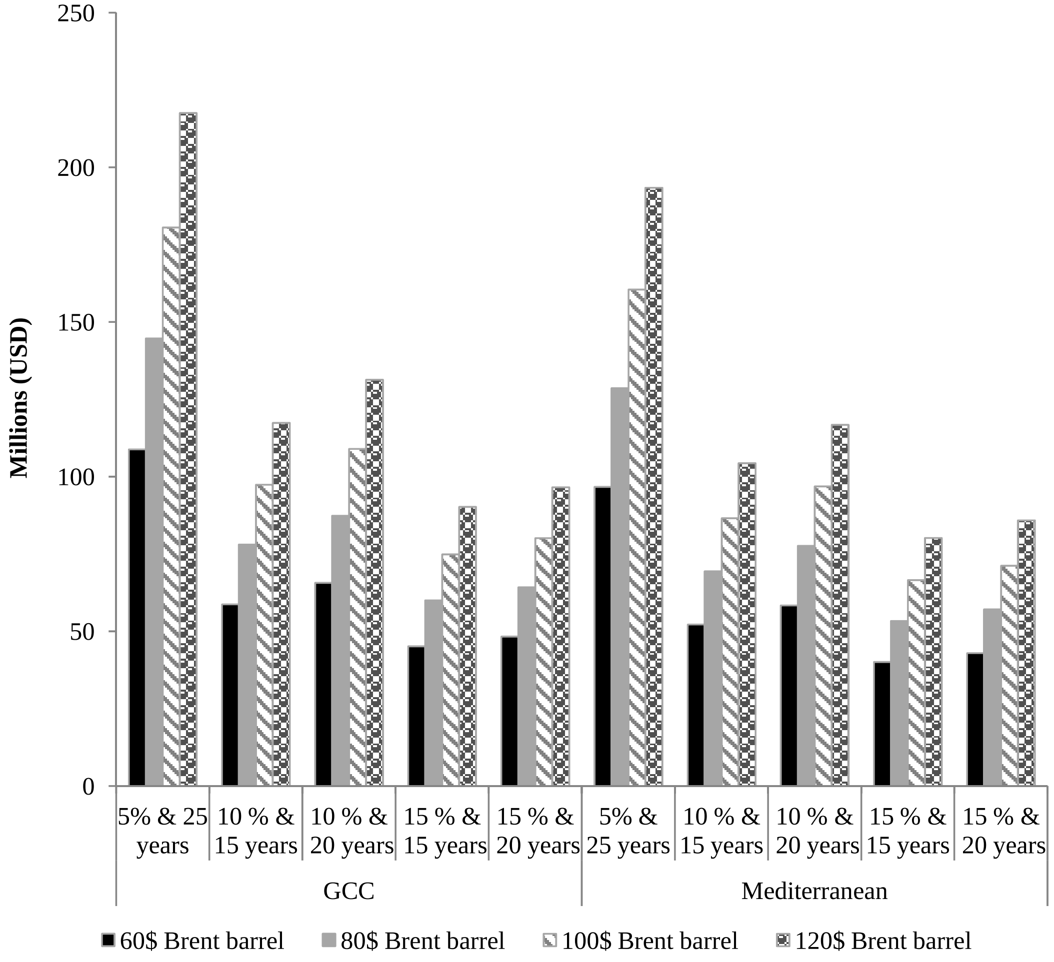


Fig. 5. Net present value of oil/gas savings or selling “saved” oil / gas – Scenario A (2010)
Scenario A: MED powered by Parabolic Troughs and fossil fuel

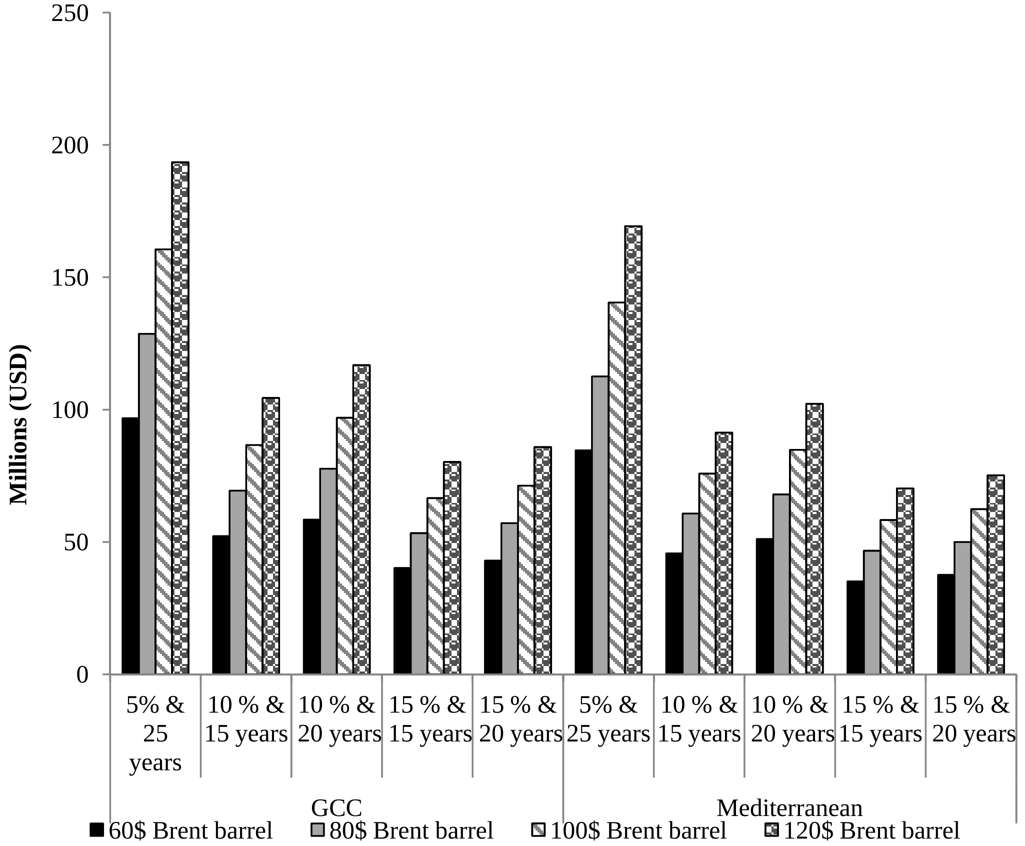


Fig. 6. Net present value of oil/gas savings or selling “saved” oil/gas–Scenario D (2010)
Scenario D: RO powered by Photovoltaics and smart grid

Subtracting the capital costs from double the benefits calculated above, demonstrated that investing in solar powered desalination plants in 2010 for Scenarios A and D was most attractive (positive difference) for public investment (25 years project lifetime and 5% discount factor and all Brent oil costs) as illustrated in Figures 7 and 8.

The investment was also attractive in the GCC countries for Scenarios A and D for Brent Oil cost of 120$ per barrel and 10% and 15% discount factors and partially attractive for Brent Oil cost of 100$ per barrel and 10% discount factor as shown in Figures 7 and 8. The investment was also attractive in the Mediterranean countries for

Scenarios A and D only for Brent Oil cost of 120$ per barrel and 10% discount factor as illustrated in Figures 7 and 8.

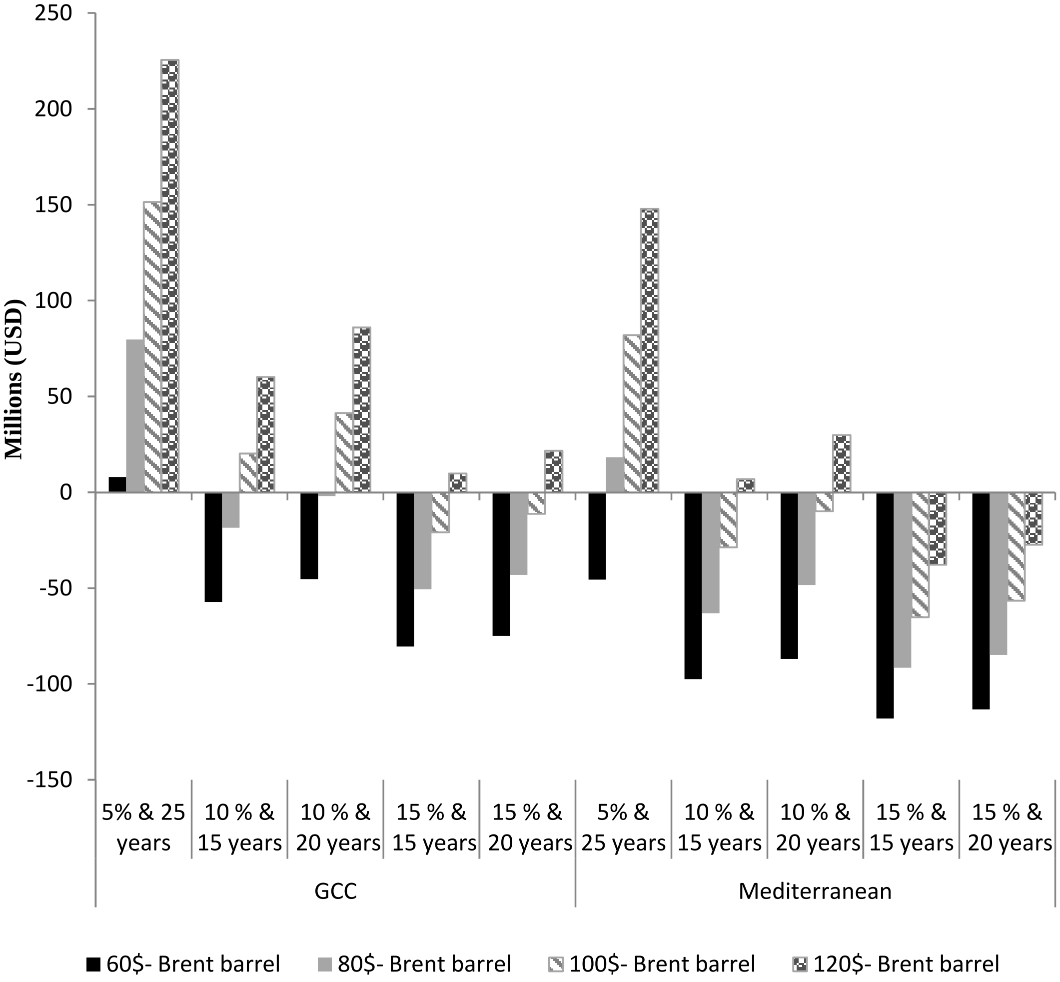


Fig. 7. Difference between double benefits and costs for MED desalination powered by parabolic troughs and fossil fuels (Scenario A) based on 2010 market values

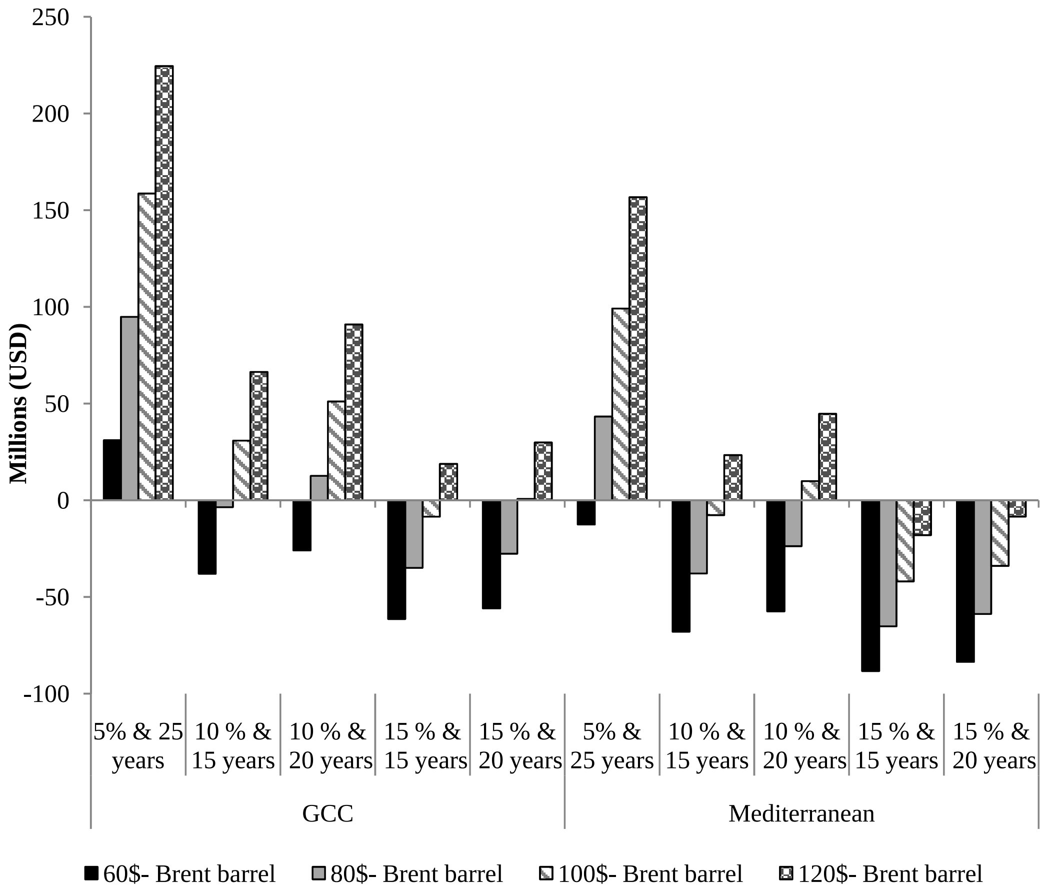


Fig. 8. Difference between double benefits and costs for RO desalination powered by PV and smart grid (Scenario D) based on 2010 market values

3.3. Sensitivity Analysis Results

Target solar capital costs and energy consumption were assumed to vary from 2010 to 2020 as shown in Tables 13 and 14.

Table 13. Target Solar Capital Costs: 2010 and 2020

	Unit	2010		2020	
		GCC	**Mediterranean**	**GCC**	**Mediterranean**
Parabolic Troughs	**($/kw)**	4,500 (1)	6,000 (2)	4,050(3)	5,400 (3)
PV	**($/kw)**	3,500 (5)	4,500 (4)	2,725(6)	3,500 (6)

Source:(1) Salisbury 18 January 2010, (2) Salisbury 2010, (3) Sargent & Lundy 2004, (4) Cameron and Crompton 2008, (5) Kurokawa *et al*. 2007, (6) Von Tschirschky *et al*. 2010

Table 14. Energy consumption reduction: 2010 and 2020

		Unit	2010		2020	
			GCC (1)	**Mediterranean(1)**	**GCC (1)**	**Mediterranean(1)**
MED	Thermal	**(kwh/m^3)**	4.5	4.0	3.375(2)	3.0(2)
	Electrical	**(kwh/m^3)**	1.75	1.75	1.5 (2)	1.5 (2)
RO	Electrical	**(kwh/m^3)**	4.0	3.5	3.4 (3)	3.0(3)

Source: (1) IDA 2008, 2009 and 2010 (2) Blanco 2003, (3) Thomson 2003

The solar capital costs of scenarios A and D were compared for 2010 and 2020 market figures. As illustrated in Figures 9 and 10, scenario A’s solar capital costs showed a drop of approximately 32% in 2020 whereas scenario D capital costs dropped by 33% in 2020 for all project lifetime and IRR.

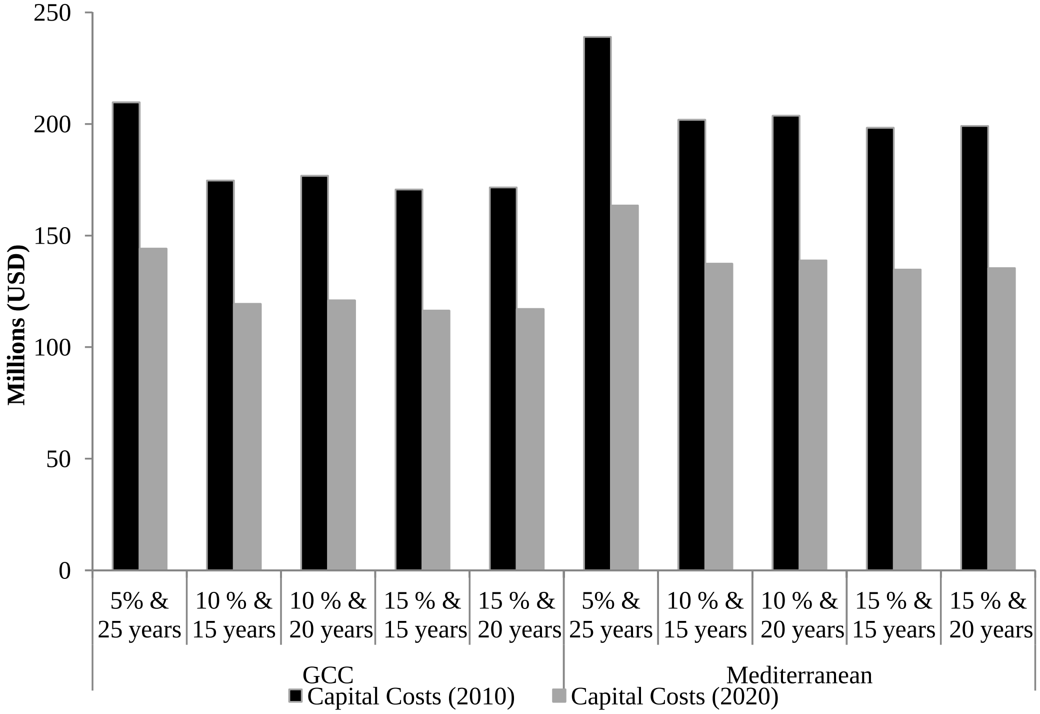


Fig. 9. Capital costs drop – Scenario A (2020 Vs. 2010)
Scenario A: MED powered by Parabolic Troughs and fossil fuel

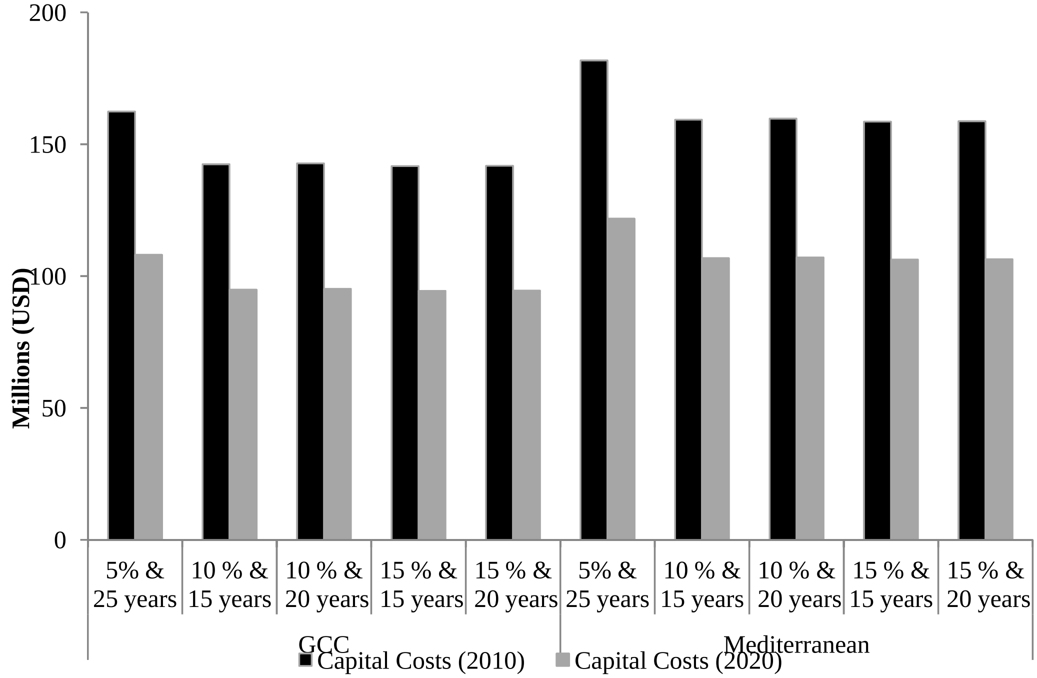


Fig. 10. Capital costs drop – Scenario D (2020 Vs. 2010)
Scenario D: RO powered by Photovoltaics and smart grid

As a result of technologic advancement, annual benefits dropped by 25% and 15% in year 2020 for Scenarios A and D respectively. Scenario A showed a higher drop as it is more energy intensive than Scenario D as illustrated in Figures 11 and 12. However, if the Brent Oil cost per barrel exceeds 120$ the annual benefits will not drop by the same amount.

As expected from the energy consumption reduction in Table 14, the annual benefits from saving fossil fuels for all countries shifting their desalination plants to solar energy will drop with technologic advancements by year 2020. Solar desalination processes based on thermal desalination are more energy intensive and will witness a 25% reduction in annual benefits whereas mechanical desalination will undergo a 15% decrease. Naturally, the overall decrease in annual benefits yielded a 33% NPV decrease for scenario A and 15% decrease for scenario D as illustrated in Figures 13 and 14.

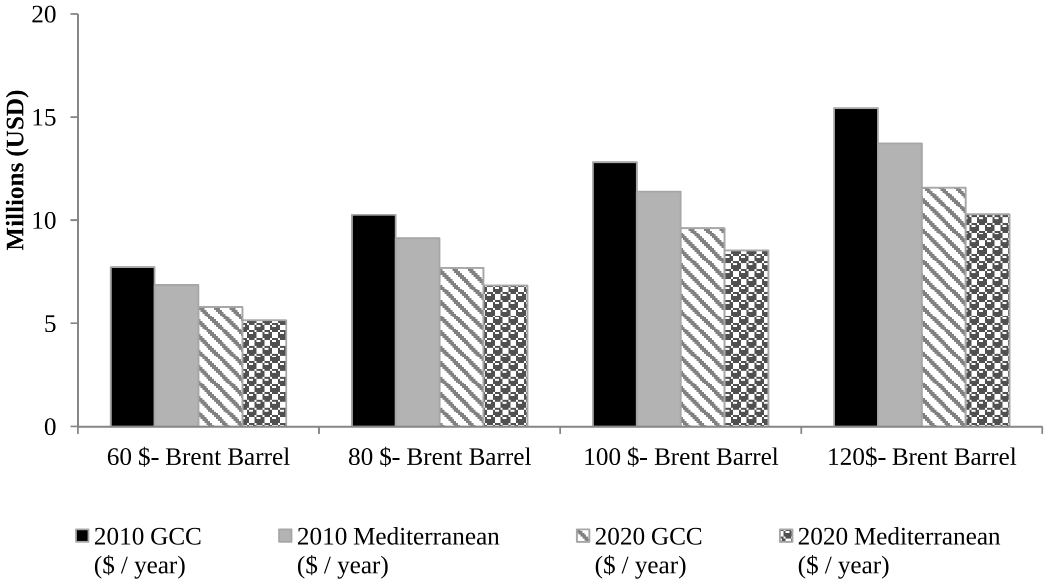


Fig. 11. Annual benefits drop in savings or selling oil / gas – Scenario A (2020 Vs. 2010)
Scenario A: MED powered by Parabolic Troughs and fossil fuel

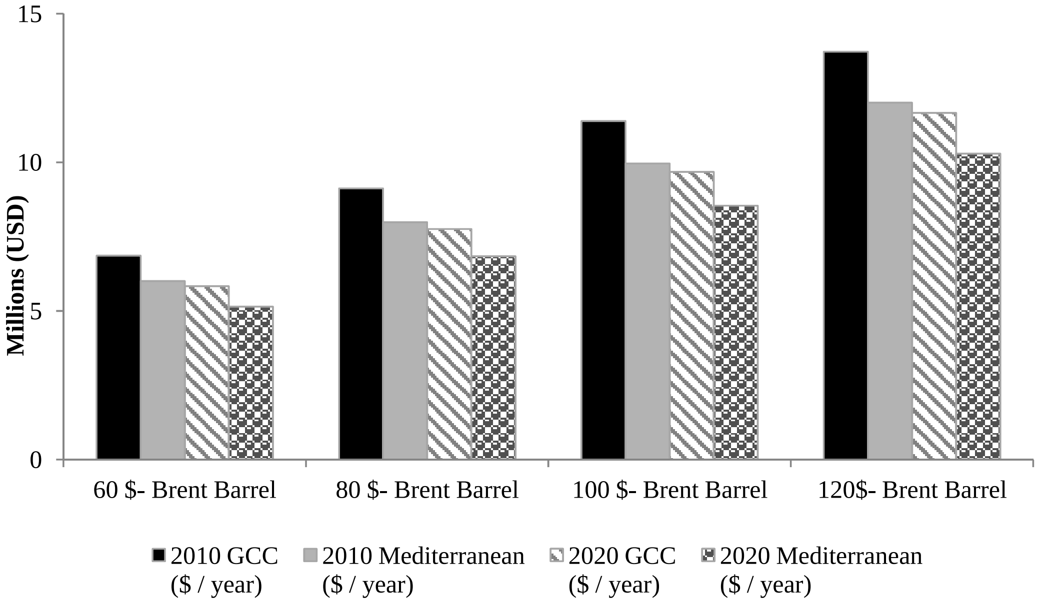


Fig. 12. Annual benefits drop in savings or selling oil / gas – Scenario D (2020 Vs. 2010)
Scenario D: RO powered by Photovoltaics and smart grid

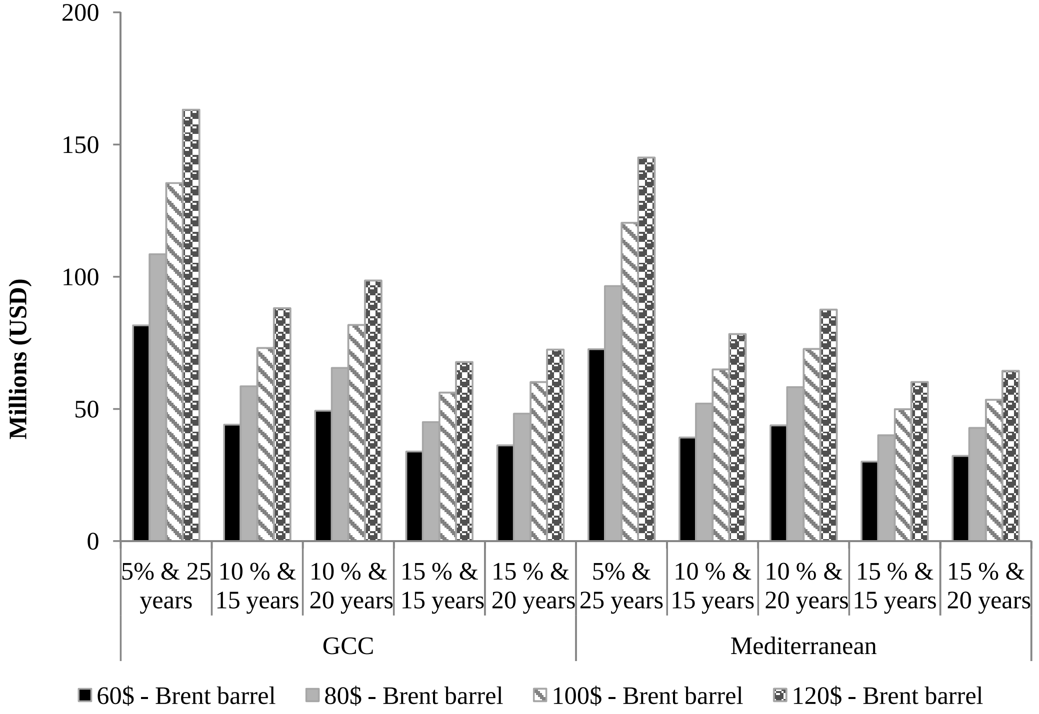


Fig. 13. Net present value of oil / gas savings or selling “saved” oil/gas–Scenario A (2020)
Scenario A: MED powered by Parabolic Troughs and fossil fuel

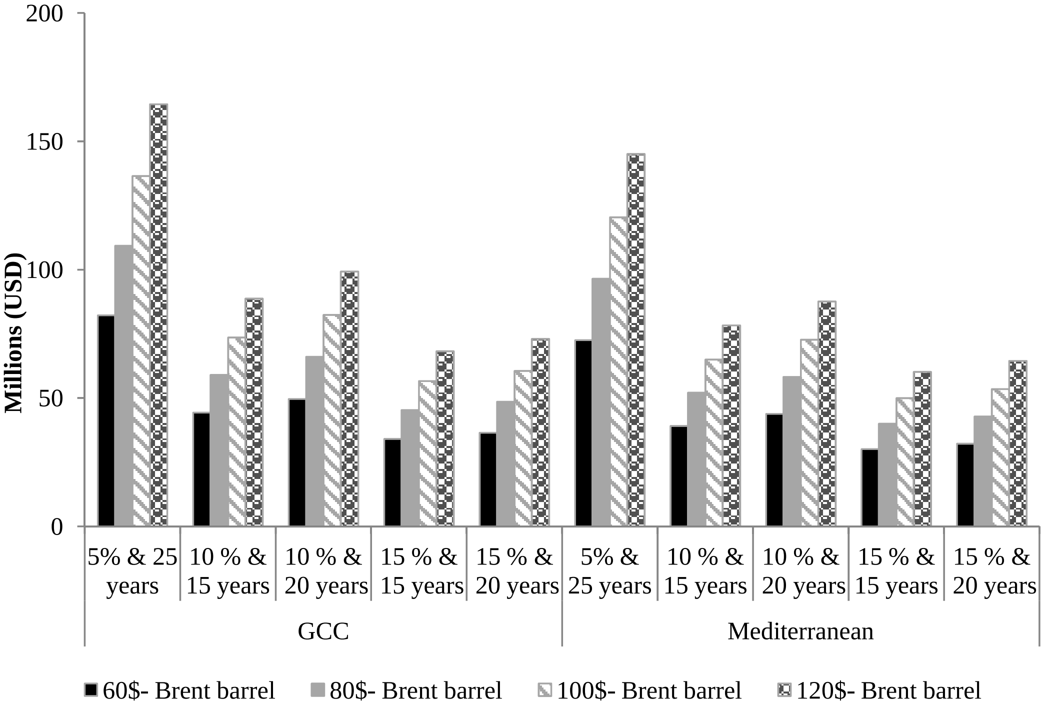


Fig. 14. Net present value of oil / gas savings or selling “saved” oil/gas–Scenario D (2020)
Scenario D: RO powered by Photovoltaics and smart grid

Subtracting the capital costs from double the benefits calculated above, demonstrated that investing in solar powered desalination plants in 2020 for Scenarios A and D was most attractive (positive difference) for public investment (25 years project lifetime and 5% discount factor and all Brent oil costs) as illustrated in Figures 15 and 16. The investment was also attractive in the GCC countries for Brent Oil cost of 120$ and 100$ per barrel and 10% and 15% discount factors as shown in Figures 15 and 16. The investment was also attractive in the Mediterranean countries only for Brent Oil cost of 120$ per barrel and 10% discount factor as illustrated in Figures 15 and 16.

Scenario D showed slight improvements compared to Scenario A in year 2020 because of its less energy intensive nature.

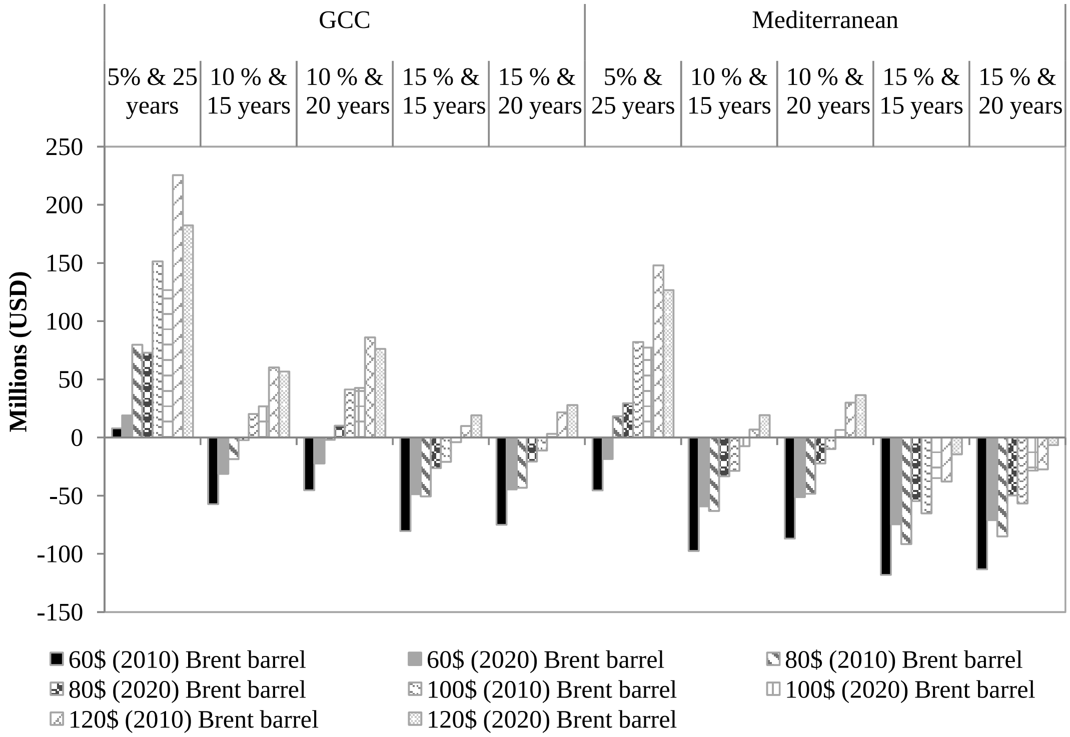


Fig. 15. Double benefits – Costs Variation: Scenario A (2020 Vs. 2010)
Scenario A: MED powered by Parabolic Troughs and fossil fuel

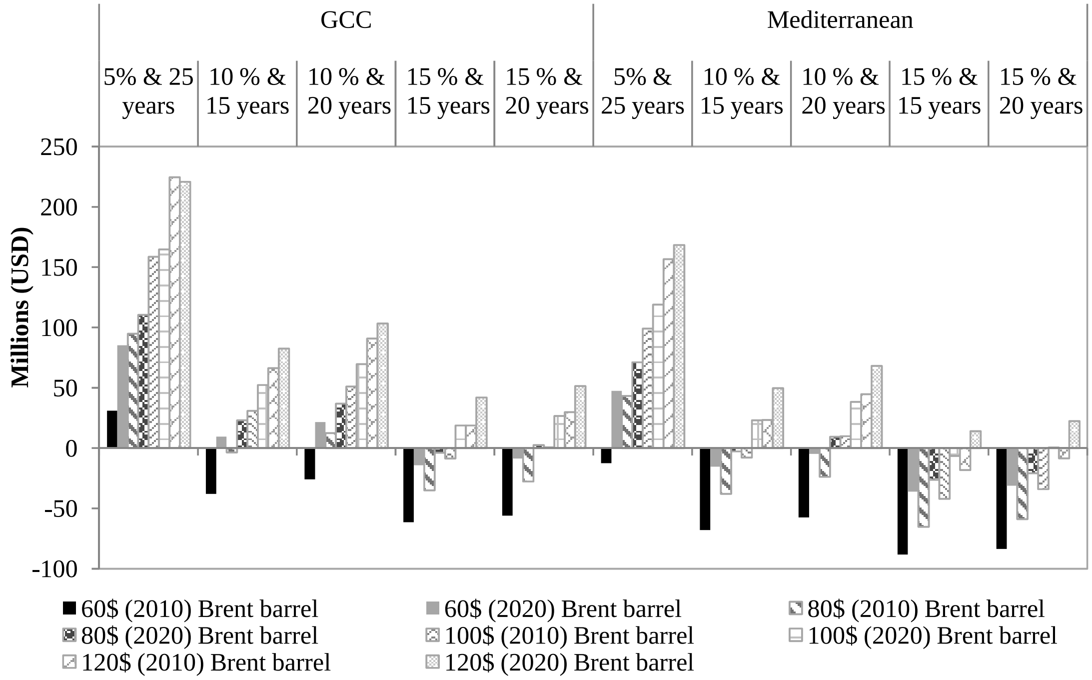


Fig. 16. Double benefits – Costs Variation: Scenario D (2020 Vs. 2010)
Scenario D: RO powered by Photovoltaics and smart grid

Scenarios A and D showed improvements in the CBA results as a consequence of the expected drop in energy consumption and target capital costs by year 2020. Scenario D is more promising than Scenario A for all project lifetime and different discount rates which coincide with the technologic boom of photovoltaics. In the unlikely event, where the Brent Oil cost drops to 60$ or 80$ per barrel in 2020, seawater desalination using solar power as an alternative to conventional oil/gas burning will be less attractive and cannot dominate the desalination market.

3.4. Economic Enhancement

A range of LGE from various sources (Table 15) was compiled and used to identify target LGE to be used in the CBA. As each LGE value is based on different assumptions and reported in different units, the adopted target range for analysis was based on the most recent McIntyre *et al*. (2011) for all renewable energy sources except solar thermal which was based on Sovacool 2008 values. LGE for fossil fuels was assumed as 616 g CO_2/kwh as an average between oil and natural gas LGEs.

Table 15. Target lifecycle GHG emission for the different electricity generation methods

	Lifecycle Gas Emissions g CO2 / kwh					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**Adopted**
Solar Thermal (CSP)	n/a	n/a	n/a	n/a	13	13
PV	85	43-73	24	114.1 (average)	32	85
Oil	733	500-1200	n/a	755.6	778	733
Natural Gas	499	440-780	n/a	420	443	499

Source: (1) McIntyre *et al*. 2011, (2) Weisser 2007, (3) Fthenakis and Kim 2007, (4) Krauter and Rüther 2004, (5) Sovacool 2008

3.4.1. First Proposed Enhancement Scheme

The income from the reduction plan to water subsidy was calculated as $ 73M and the income from selling carbon credit from mitigated GHG as $ 4M. The NPV of the collected income was then calculated for the project lifetime of 25 years as $ 205M split as shown in Table 16. The capital costs of the RO plant, photovoltaics installation, transformers, inverters and other variable costs to be paid by the PPP were calculated as $ 316M excluding land cost and 354M for a land unit cost of $\$40/m^2$ and $ 391M for a land unit cost of $\$80/m^2$. The deficit between the capital costs and income NPV is approximately $111M excluding land cost and $ 149M.and $ 186M for the two proposed land unit costs. In order to breakeven, proposed water tariff charges were modified as shown in Table 16:

Table 16. Annual Income, NPV and revised water costs
(First proposed enhancement scheme)

Years	Annual Income to PPP from Water ($M / year)	Annual Income to PPP from GHG ($M / year)	NPV (Water) ($M)	NPV (GHG) ($M)	**TWC – Excluding Land Cost ($\$/m^3$)**	**TWC – Land Cost $40\$/m^2$ ($\$/m^3$)**	**TWC – Land Cost $80\$/m^2$ ($\$/m^3$)**
1-5	11	0.8	47	3	**1.03**	**1.18**	**1.32**
6-10	13	0.8	43	3	**1.13**	**1.28**	**1.42**
11-15	15	0.8	39	2	**1.23**	**1.38**	**1.52**
16-20	16	0.8	34	2	**1.33**	**1.48**	**1.62**
21-25	18	0.8	30	1	**1.43**	**1.58**	**1.72**

The revised water tariff rates in the proposed enhancement scheme were reduced by 16% while excluding land cost and 3% for a land unit cost of $\$40/m^2$ over the first 5 years compared to scenario D TWC calculated during the value engineering assessment. A similar study resulted in TWC of 0.905 $\$/m^3$ for a RO plant powered by CSP in co-generation mode (Olwig *et al*. 2012) which is 23% cheaper than the TWC obtained in the first economic enhancement while allowing for land cost. This highlights the importance of co-generation in solar desalination processes. Escalation of land unit costs (100% escalation) over the first five years of the project lifetime will result in 12% increase in TWCs.

3.4.2. Second Proposed Enhancement Scheme

The capital costs of the MED and CSP plants to be paid by the PPP were calculated based on calculated TWCs and adding the cost of the 25MW power plant (approximately $1M per MW), and the cost incurred by GHG emissions as $ 701M excluding land cost and $ 761M for a land unit cost of $40/m^2 and $ 821M for a land unit cost of $80/m^2.The income to the PPP consortium would be from water, electricity end users as well as mitigated GHG emissions. Income from water end users was calculated previously in the first proposed enhancement scheme as $ 73M. The income from mitigated GHG emissions was calculated as $ 12M and from electricity end users as $ 58M as shown in (Table 16).

Therefore, the total income to the PPP from electricity and water end users and mitigated GHG emissions is $ 143M.

The total NPV of the income collected was calculated as $ 383M distributed as shown in Table 17.

The TEC generated by a 28.8MW power plant was calculated as $0.18/kwh. Clearly, electricity tariff rates are 50% cheaper than the actual production rates yielding a considerable deficit between capital costs and income NPV. The deficit between the capital costs and income NPV is $318M excluding land cost and $ 378M and $438M for the two proposed land unit costs. In order to breakeven, proposed water tariff charges were kept as originally proposed and electricity tariff charges were modified as shown in Table 17:

The revised water tariff rates in the proposed enhancement scheme were increased by 13% while excluding land cost and 28% for a land unit cost of $\$40/m^2$ over the first 5 years compared to scenario A TWC calculated during the value engineering assessment. An alternative to increased water tariff rates would be a mixed rate increase between electricity and water rates or by government subsidy. Escalation of land unit costs (100% escalation) over the first five years of the project lifetime will result in 11% increase in TWCs.

Table 17. Annual Income, NPV and revised water costs
(Second proposed enhancement scheme)

Years	Annual Income to PPP (electricity) ($M/year)	Annual Income to PPP (water) ($M/year)	Annual Income to PPP (GHG) ($M/year)	NPV (electricity) ($M)	NPV (water) ($M)	NPV (GHG) ($M)	**TWC – Excluding Land Cost ($\$/m^3$)**	**TWC – Land Cost 40$\$/m^2$ ($\$/m^3$)**	**TWC – Land Cost 80$\$/m^2$ ($\$/m^3$)**
1-5	9	11	2	41	47	10	**1.84**	**2.07**	**2.30**
6-10	11	13	2	36	43	8	**1.94**	**2.17**	**2.4**
11-15	12	15	2	31	39	6	**2.04**	**2.27**	**2.50**
16-20	13	16	2	26	34	5	**2.14**	**2.37**	**2.60**
21-25	14	18	2	22	30	4	**2.24**	**2.47**	**2.70**

By comparing the results of the two proposed enhancement schemes, it is clear that subsidy limitation using heat and electric power co-generation is very promising and clearly shows that the initial additional investment in a power plant will be advantageous on the long term and will reduce the social and economic impact of introducing a subsidy reduction plan. This conclusion was not obvious in the GCC because of high water and electricity subsidies. Moreover, selling carbon credit will provide considerable benefits to the PPP consortium.

A similar study resulted in TWC of 0.943 \$/m3 and TEC of \$0.24/kwh for a

MED plant powered by CSP in co-generation mode (Olwig *et al*. 2012). TWC is 120% more expensive in the second proposed economic enhancement but TEC is 62% cheaper which highlights similarities between the two studies and confirms the importance of co-generation in solar desalination processes

3.4.3. Comparison of Proposed and Actual Water and Electricity Tariff Rates

The currently published water and electricity tariff rates of the different utilities in the GCC are summarized in Table 18.

Table 18. Actual water and electricity costs in the GCC

Country/Emirate	Acutal Water Cost ($/m^3)	Actual Electricity Cost ($/kwh)	Source
Dubai	2.38	0.08	http://www.dewa.gov.ae
Abu Dhabi	0.6	0.04	http://www.rsb.gov.ae
Kingdom of Saudi Arabia	1.08	0.04	http://www.se.com.sa www.mowe.gov.sa
Kuwait	0.75	0.007	http://mew.gov.kw
Kingdom of Bahrain	0.07	0.008	http://www.mew.gov.bh
Sultanate of Oman	1.14	0.03	http://www.paew.gov.om
Qatar	1.2	0.03	www.km.com.qa
Average	**1.03**	**0.03**	

As shown in Table 18, water and electricity costs vary significantly between various countries in the GCC. The average actual water cost in the GCC is $1.03/m^3 and electricity cost $0.03/kwh. In the first proposed enhancement scheme, the proposed water cost is equal to the actual water cost in the GCC over the first five years of the project lifetime. In the second proposed enhancement scheme, the proposed water cost is 78% more expensive to cover for the highly subsidized electricity costs in the GCC. The balance to breakeven between water costs and electricity costs can be modified to suit specific utilities and countries requirements.

CHAPTER 4

CONCLUSION

Desalination technology which developed extensively over the past 40 years is now reliably used to produce fresh water from saline sources. There is no ‘‘best’’ method of seawater desalination. Local circumstances may play a significant role in determining the most appropriate process for an area (Al-Karaghouli *et al.* 2009). Proximity of the desalination and the solar field to the sea has a major influence on the feasibility of the project.

The VE and CBA results showed a preference for RO desalination over MED and this conclusion is applicable for all Brent Oil costs and all discount rate multipliers as well as project lifetime, for GCC and Mediterranean countries. Overall, RO based solar desalination combinations (scenarios B & D) resulted in a lower TWC when compared to MED based combinations (scenarios A, C & E). The minimum TWC of \$1.17 /m^3 is associated to Scenario D and the maximum TWC of \$3.3 / m^3 is associated to Scenario C.

All combinations resulted in lower TWCs in the GCC countries when compared to the Mediterranean countries irrespective of the project lifetime and / or the IRR. Also, combinations that are better ranked for public investment (25 years) are also better ranked for public/private investment (20 or 15 years). RO desalination powered by photovoltaics and smart grid (Scenario D) will be considered as first ranked since it has the lowest TWC for both private and public investors and MED desalination powered by parabolic troughs for primary and secondary energy through a fuel fired power cycle (Scenario A) as second ranked.

The CBA revealed that for Brent Oil costs of $60 and $80 per barrel the investment is only attractive for the public sector with a 5% IRR and 25 years project lifetime and unattractive for all other discount rates and project lifetime based on 2010 market figures. The sensitivity analysis conducted based on 2020 market figures led to the same conclusion. Scenarios A and D showed improvements in the CBA results as a consequence of the expected drop in energy consumption and target capital costs by year 2020. Scenario D is more promising than Scenario A for all project lifetime and different discount rates which coincide with the technological boom of the photovoltaics. Moreover, GCC countries and oil and gas Mediterranean producing countries can achieve double benefits by saving and selling the saved oil & gas while non-productive countries are saving the cost of importing oil/gas to power their plants.

The solar capital costs of scenarios A and D were compared for 2010 and 2020 market figures. Scenario A’s solar capital costs showed a drop of approximately 32% in 2020 whereas scenario D capital costs dropped by 33% in 2020 for all project lifetime and IRR. These results might change in case a detailed CBA is to be conducted to take into account the cost of land which can be phenomenal near the sea. A fair assumption was done in the above study, where it was assumed that the public sector will offer the land needed for such a project.

As a result of technologic advancement, annual benefits dropped by 25% and 15% in year 2020 for Scenarios A and D respectively. Scenario A showed a higher drop as it is more energy intensive than Scenario D. However, if the Brent Oil cost per barrel exceeds 120$ the annual benefits will not drop by the same amount.

The land needed for various scenarios show that Scenario A needs least land among the three thermal desalination options (i.e. Scenario A, C and E) and Scenario B needs least land among the two mechanical desalination options (i.e. Scenario B and D).

Considering treatment of brine resulting from RO desalination will definitely affect the cost benefit analysis and might give advantages to thermal desalination processes.

The solar industry needs short-term “green subsidies”, because there are subsidies that apply to conventional power generation, but these do not at present extend to solar which is at a disadvantage. To make solar power commercially attractive, there must be a green subsidy that bridges the gap between the cost of generating solar power and the regulated cost of conventional electricity.

The economic enhancement schemes that were proposed in this study revealed that while applying a reduction plan to subsidized water and electricity costs will encounter a social opposition on the short term as it will be considered a financial burden on individuals relying so far on government subsidies to utilities, on the long term it would be serving the benefits of the country as governments could invest the saved capital investment in other areas. One special economic enhancement resulted in a deficit of $111M between the income from public subsidy and the capital costs paid by the PPP consortium. The revised water tariff rates were reduced by 16% over the first 5 years compared to scenario D TWC calculated during the value engineering assessment i.e. $\$1.03/m^3$ and $\$1.22/m^3$, were enough for breakeven. The other economic enhancement resulted in a deficit of $318M. The revised water tariff rates were increased by 13% over the first 5 years compared to scenario A TWC calculated during the value engineering assessment i.e. $\$1.84/m^3$ and $\$1.62/m^3$. An alternative to increased water tariff rates would be a mixed rate increase between electricity and water rates or by government subsidy. Investing in cogeneration appeared to be a wise investment as the heat collected will power the desalination process over 24 hours and the balance heat will be sold to customers in the form of electricity generated by the power plant.

The two economic enhancements highlighted the positive externalities associated with the offset of GHG emissions through regulated and voluntary global carbon markets that allow trading, selling, buying and offsetting of carbon credits as well as the benefits of co-generation in solar powered desalination.

Note that all the results strongly depend on the technical and economic input parameter sets. Therefore, results presented in this study have to be treated as a rough guideline for assessment of solar desalination plants powering. Water costs of a certain project can only be evaluated based on a detailed feasibility study considering all boundary conditions.

All the results concerning the economics in this study have to be treated with uncertainties. The given numbers result from the chosen set of technological data, site-specific data, economic boundary conditions and assumptions made. The total desalinated water cost comprises capital and operational costs which are specific to location, feedwater characteristics, energy costs and other parameters. The cost figures reported in the literature thus vary considerably. Each cost component used in this study serves the purpose of knowing the range rather than the absolute value.

4.1. Recommendations

Areas of potential enhancement will depend on technology advancements in the following three aspects: (1) enhancing solar-energy collection, (2) technological improvements of desalination techniques, and (3) better matching the solar field and desalination unit. These areas of investigation directly relate to the economic performance improvement of the system.

Future work can encompass use of heat and electrical power co-generation and the use of hybrid desalination systems. Combined generation of heat and power by CSP has particularly promising potential as the high value solar energy input is used to the best possible efficiency and the process heat from combined generation is used for seawater desalination.

Recent combinations of membrane and thermal desalination plants so-called hybrid systems have offered further improvements in desalination efficiency. Hybrid desalination concepts make use of different technologies to combine their different advantages and eliminate their drawbacks when possible (Fritzmann 2006 and Younos 2005). Simple hybrid systems combine MSF or MED and RO and can achieve many advantages relative to standalone RO or MSF. Typically, hybrid systems can benefit from a common seawater intake and outfall used for both plants which will reduce overall capital investment. RO permeate and MSF or MED water product can be blended to achieve the contracted or required water standards.

Another area of enhancement would be in validating capital and operating costs as well as energy consumption figures to reflect actual data collected from operational solar desalination plants (Tables 9 and Table A1, A2, A3 and A4). Once this information is validated, the VE and CBA have to undertaken and results obtained in this study might change accordingly.

Also, this study can be enhanced by taking into account inflation over the project lifetime which can vary periodically just like the Brent Oil price. The real return on investment would be IRR less the inflation rate.

APPENDIX 1

REVIEW OF DESALINATION AND SOLAR PLANTS

Table A.1. Review of desalination plants

Capacity m^3/d	**Process**	**Location**	**Installation Date**	**Energy**	**Water Cost (\$/m^3)**	**Project Costs (\$)**
30,000 (1)	SWRO	Jeddah, Saudi Arabia	2007		0.78	
318,000 (2)	SWRO	Ajman, UAE				37.8M
272,520 (1)	MED-TVC	Hidd, Bahrain	2008		0.69	\$1.2B
315,000 (2)	MSF	Abu Dhabi, UAE	2008	60MW		1.213B
272,520 (2)	MSF	Ras Laffan, Qatar	2008		0.80	900M
1,025MW(3)						
22,730 (3)	SWRO	Sharjah, UAE		4.0675 kwh/m^3		13M
800,000 (3)	MED	Jubail, Saudi Arabia	2008			3.4B
2,500MW(3)						
18.925 (1)	SWRO	Massachusetts, USA	2008		1.53	
136,360 (1)	SWRO	Shuwaikh, Kuwait			0.57	
500,000 (1)	SWRO	Oran, Algeria	2008		0.577	
200,000 (3)	SWRO	Algiers, Algeria	2008		0.82	250M
326,144 (1)	SWRO	Sulaibiya, Kuwait	2007		0.52	
120,000 (1)	SWRO	Tipaza, Algeria	2008		0.57	
150,000 (2)	SWRO	Jeddah, Saudi Arabia	2007		0.70	
100,000 (2)	SWRO	Skikda, Algeria	2008		0.73	
120,000 (1)	SWRO	Barka, Oman	2008		0.75	
200,000 (2)	SWRO	Jeddah, Saudi Arabia	2007		0.82	
100,000 (1)	SWRO	Jebel Ali, UAE	2008		0.74	

Source: (1) WDR 2007 2008, (2) WDR 2009 2010, (3) IDA 2008 2009, (4) Sargent and Lundy 2004

Table A.2. Review of solar power plants

Plant Type	**Location**	**Installation Date**	**Capacity (MW)**	**Solar Field Area (ha)**	**Total Plant Cost ($M)**	**Electricity Unit Cost ($/Kw)**
Solar Thermal Trough (1)	Australia	2008-2012	22	120	141 (including Land & Infrastructure)	
PV Cell-based Plant (1)	Spain	2008	57	75	424	
Solar Thermal Trough (1)	USA	2007	44	240		2500
Solar Thermal Trough (1)	Spain	2007	26	120		
Solar Thermal Trough (1)	Spain	2007	22	120	27 (grant funding –20 (equity)	
CPV (1)	Germany	2009	45	56	427	8525
Trough (1)	USA	2007	64			4549
Tower (1)	Spain	2007	11			2500
Trough (1)	Spain	2010	50			9300
Fresnel (1)	Australia	2009	38			800
Tower (1)	Australia	2012	10			3100
Tower (1)	Spain	2012	15			5888
Trough (1)	Abu Dhabi, UAE	2010	100			5000
Photovoltaic (2)	Abu Dhabi, UAE	2009	10	21.2		

Source: (1) National Geographic 2009, (2) Arabian Oil and Gas Staff 2009

Table A.3. Review of desalination plants incorporating thermal solar energy

Location	**Type of Solar Energy**	**Type of Desalination**	**Capacity (gal/day)**
Lapaz Mexico (1)	Flat plate and concentrating collectors	MSF	2,642
Kuwait (1)	Solar electricity generation system	MSF + RO	6,604 & 11,890
Arabian Gulf (1)	Solar Parabolic Troughs	MED	1,585,000
Al Ain, UAE (1)	Solar Parabolic Troughs	MED / MSF	132,100
Area of Hzag, Tunisia (1)	Solar Collector	Distillation	2,692
Safat, Kuwait (1)	Solar Collector	MSF	2,642
Almeria, Spain (2)	Solar Collector		19,000
Sultanate of Oman, MEDRC (2)	Solar Collector		266

Source: (1) Younos and Tulou 2005, (2) Al-Karaghouli *et al* 2009

Table A.4. Review of desalination plants incorporating photovoltaics

Location	**Power Generated (kw)**	**Type of Desalination**	**Capacity (gal/day)**
Perth, Australia (1)	1.2	RO	634- 3170
Jeddah, Saudi Arabia (1)	8	SWRO	845
Doha, Qatar (1)	11.2	SWRO	1,506
Lampedusa Island, Italy (1)	100	SWRO	19,020+12,680

Source: (1) Younos and Tulou 2005

APPENDIX 2

COMBINED HEAT AND POWER PROPOSED ENHANCEMENT SCHEME

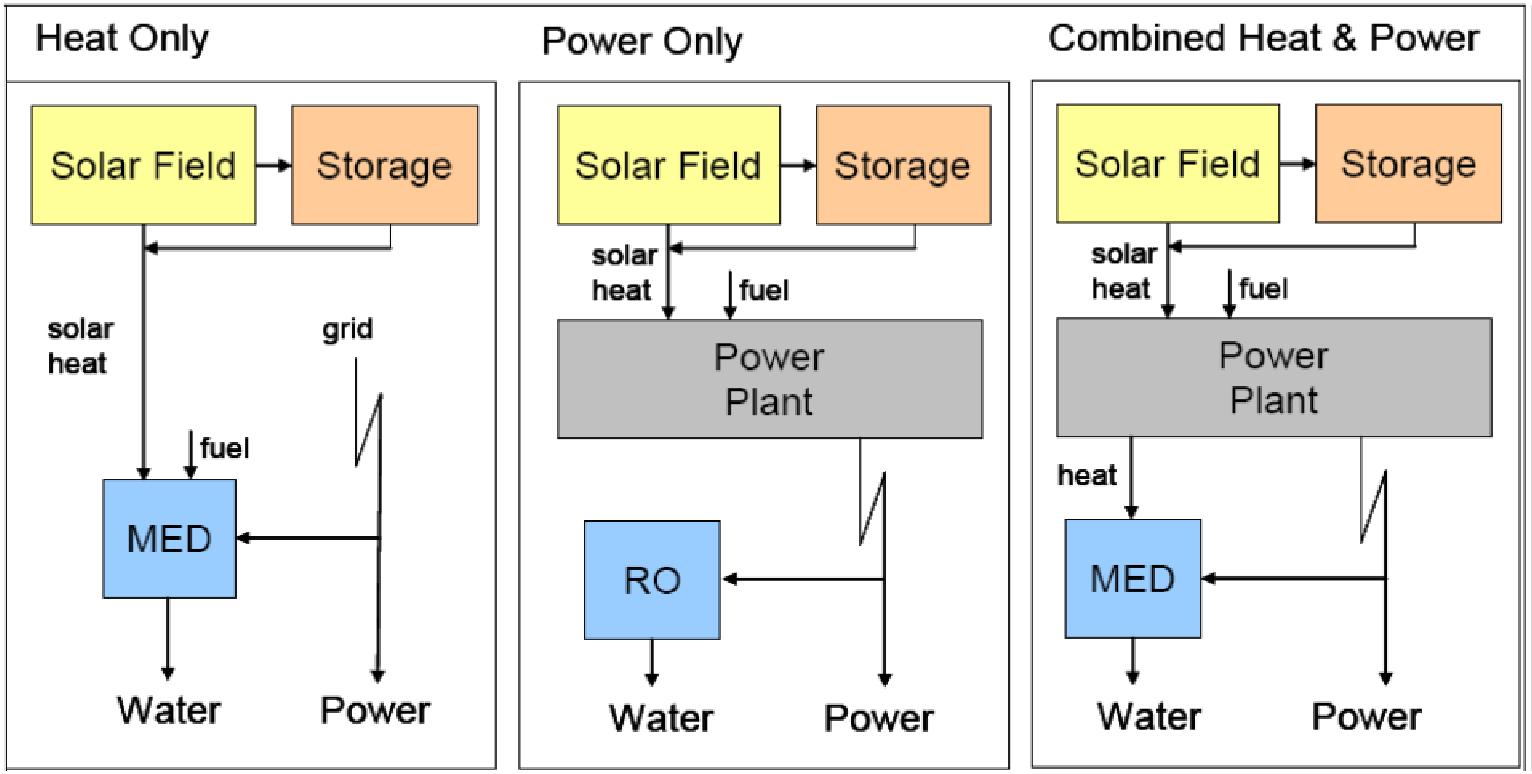


Fig. A.1. Combined heat and power proposed enhancement scheme
Source: F. Trieb. 2007. AQUA-CSP-Concentrating Solar Power for Seawater. Section Systems Analysis and Technology Assessment, Institute of Technical Thermodynamics, German Aerospace Center. Federal Ministry for the Environment,

REFERENCES

Al- Karaghouli, A., Renne, D., and Kazmerski, L. (2009). Solar and Wind Opportunities for Water Desalination in the Arab regions. *Renewable and Sustainable Energy Reviews* 13: 2397–2407.

Appleyard, D. (2009). Solar Trackers facing the sun. Renewable Energy World Magazine; available from http://www.renewableenergyworld.com/rea/news/article/2009/06/solar-trackers-facing-the-sun; Internet; accessed June 2012.

Arabian Oil and Gas Staff. 2009 New Kid on the Grid, Utilities ME; available from http://www.arabianoilandgas.com/article-5132-new_kid_on_the_grid/; Internet; accessed December 2009.

Blanco, J., and Alarcon, D. 2003. Innovative Ideas to reduce current cost of solar seawater desalination based on MED Technology. Centro de Investigaciones Energeticas, Medioambientales y Technologicas (CIEMAT), 1-13.

Brakmann, G., Geyer, M., and Teske, S. 2007. Solar Thermal Power: The basics-Parts one and two. AQUA-CSP Study Report; available from http://www.dlr.de/tt/aqua-csp, 23-39; Internet; accessed June 2012.

Burgess, D. 2005. Solar Thermal Powered Desalination: membrane versus distillation technologies. Center for Sustainable Energy Systems, Department of Engineering Australian National University, Australia.

Cameron, P. and Crompton, G. 2008. Solar Power Plant Pre-feasibility Study. ActewAGL and ACT Government. Parsons Brinckerhoff Australia Pty Limited, Australia; available from http://www.environment.act.gov.au/_data/assets/pdf_file/0019/154054/Solar_Power_plant_Pre-feasibility_study.pdf;, Internet, accessed February 2010.

Darwish, M.A and Alsairafi, A. (2004). Technical comparison between TVC/MEB and MSF. *Desalination* 170: 223-239.

Electricite du Liban. 2003. Gasoil needed to start Zahrani and Deir Ammar power plants. Published by Electricite du Liban Internal Report.

El-Fadel, M., Rachid G., El-Samra R., Bou Boutros G., and Hashisho J. 2012. Emissions Reduction and Economic Implications of Renewable Energy Market Penetration of Power Generation for Residential Consumption in the MENA Region. Faculty of Engineering and Architecture, American University of Beirut.

Fiorenza, G., Sharma, V.K., and Braccio, G. (2003) Techno-economic evaluation of a solar powered water desalination plant. *Energy* 44: 2217-2240.

Florio, M., Finzi, U., Genco, M., Levarlet, F., Maffii, S., and Tracogna, A. 2008. Guide to cost benefit analysis of investment projects. Directorate General Regional Policy, European Commission; available from http://ec.europa.eu/ regional_policy/sources/docgener/guides/cost/guide2008_en.pdf; Internet; accessed April 2011.

Fritzmann, C., Lowenberg, G., Wintgens, T., and Melin, T. (2007). State –of- the- art of reverse osmosis desalination. *Desalination* 216: 1-76.

Fthenakis, V.M., and Kim, H.C. (2007). Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. *Energy Policy* 35: 2549-2557.

Griffths, B. 2011. *Electricity Generation Cost Model. Department of Energy and Climate Change*. London: Parsons Brinckerhoff.

International Desalination Association Yearbooks. (2008-2009-2010); available from http://www.idadesal.org; Internet; accessed November 2010

Karagiannis, I. and Soldatos, P. (2008). Water desalination cost literature: review and assessment. *Desalination* 223: 448-456.

Keown, A., Scott, D., Martin, J., and Petty, J. 1994. *Foundation Finance.* New Jersey, USA: Prentice Hall International Edition.

Krauter, S., and Rüther, R. (2004). Considerations for the calculation of greenhouse gas reduction by photovoltaic solar energy. *Renewable Energy* 29: 345-355.

Kurokawa, K., Komoto, K., Van Der Veuten, P., and Faiman, D. (2007). Energy from The Desert: Practical Proposals for very large scale photovoltaics systems. London, Earthscan

Levy, H. and Sarnat, M. 1994. *Capital Investment and Financial Decisions*. 5th Edition. United Kingdom: Prentice Hall International.

McIntyre, J., Berg, B., Seto, H., and Borchardt, S. (2011). Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources. World Nuclear Association, UK; available from http://www.world-nuclear.org/ uploadedFiles/org/reference/pdf/comparison_of_lifecycle.pdf; Internet; accessed on November 2012

Meritet, S. 2010. L'état énergétique du monde. Revue pour la science No. 69 Dossier pour la science, France.

National Geographic. 2009. Solar Power: Endless Potential; available from http://www.ngm,com; Internet; accessed April 2010.

Nisan, S. and Benzarti, N. (2008). A comprehensive economic evaluation of integrated desalination systems using fossil fuelled and nuclear energies and including their environmental costs. *Desalination* 229: 125-146.

Olwig, R., Hirsch, T., Sattler, C., Glade, H., Schmeken, L., Will, S., Ghermandi, A., and Messalem, R. (2012). Techno–economic analysis of combined concentrating solar power and desalination plant configurations. *Desalination and Water Treatment* 41(1-3): 9-25.

Reddy, K.V. and Ghaffour, N. (2007). Overview of the cost of desalinated water and costing methodologies. *Desalination* 205: 340-353.

REN21. 2011. Renewables Global Status Report; available from http://www.ren21.net; Internet, accessed January 2012.

Salisbury, P. (2010). Masdar to push ahead with alternative power plants by March. *MEED* (18 January); available from http://www.meed.com/3003531; Internet; accessed January 2010.

Salisbury, P. 2010. Masdar plans Abu Dhabi solar power project. MEED.

Sargent & Lundy LLC Consulting Group. 2004. Assessment of Parabolic Trough & Power tower Solar Technology. National Renewable Energy Laboratory, San Diego Regional Renewable Energy Study Goup, Colorado.

Sovacool, B.K. (2008). Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy* 36: 2940-2953.

Sunelec. 2011. PV, Transformers, inverters market prices; available from http://www.sunelec.com; Internet, accessed January 2012.

The Royal Academy of Engineering. 2005. Engineering for Sustainable Development: Guiding principles, London; available from http://www.raeng.org.uk; Internet, accessed March 2009.

Thomson, M. 2003. *Reverse Osmosis Desalination of Seawater Powered by Photovoltaics without batteries*. UK: Loughborough University.

Trieb, F. 2007. AQUA-CSP-Concentrating Solar Power for Seawater. Section Systems Analysis and Technology Assessment, Institute of Technical Thermodynamics, German Aerospace Center. Federal Ministry for the Environment, Germany.

Trieb, F. and Müller-Steinhagen, H. (2008). Concentrating solar power for seawater desalination in the Middle East and North Africa. *Desalination* 220:165-183.

Von Tschirschky, C., Ziegler, R., De Clerq, M., and Ariatti, A. 2010. Tapping the Sun. Capital Business Magazine.

Water Desalination Report. Market Profile-World charts compiled from the IDA inventory and Desalination data. IDA Desalination Yearbooks. (2007-2008-2009-2010). Global water intelligence, United Kingdom; available from http://www.globalwaterintel.com Internet, accessed 2007, 2008, 2009, 2010.

Weisser, D. (2007). A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy* 32(9): 1543-1559.

Williams, J., Haka, S, Bettner, M., and Carcello, J. 2010. *Financial and Managerial Accounting. The Basis for Business Decisions*. Fifteenth Edition. USA: McGraw Hill.

Younos, T. (2005). The Economics of Desalination. *Journal of contemporary Water Research &Education* 132: 39-45.

Younos, T. and Tulou, K. (2005). Energy Needs, Consumption and Sources. *Journal of Contemporary Water Research & Education* 132: 27-38.