A FUZZY SET METHODOLOGY TO COMPARE BETWEEN DIFFERENT AUTONOMOUS PV-RO DESALINATION PLANTS

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ABSTRACT

The present research provided a strong base for comparing the overall efficiency and viability of different autonomous desalination plants. Reverse osmosis is becoming the technology of chose while the continuous reduction in the cost of photovoltaics, and fresh water shortages, can increase the need for more compact desalination system (hybrid or autonomous) mainly for small or/and isolated communities. The current research utilizes the fuzzy logic (FL) methodology to compare and therefore to make decisions about Autonomous Photovoltaic Reverse Osmosis (APVRO) desalination plants through a Benefit to Cost model in a sense of performance and cost enhancement of both, solar energy utilization by photovoltaics, and fresh water production through reverse osmosis unit, that can achieve as much as accurate results.

Keywords: Fuzzy Sets Methodology, Renewable Energy, Reverse Osmosis, Desalination

1. INTRODUCTION

A widespread intention to couple photovoltaic - among other renewable sources - with desalination technologies is observed over the last decade. Water scarcity problems, increases the need for fresh water supply as well as for a high amount of energy. Although potable water is essential to ensure life in this regions, the energy demands for desalination plants becomes a great socio-economic factor.

A reliable procedure for evaluating the performance of any system at a particular site is an important requirement for encouraging investment. Such a procedure is also useful in comparing the performance of two or more systems, given the conditions at a particular site [1].

Most of the latest studies are investigating different desalination system designs and optimization techniques [2-3]. Tzen et al. [4] presents CRES pilot autonomous hybrid (wind, solar energy) reverse osmosis system (RO) for seawater desalination. Measurements that have been taken as well as lessons learned after many years of operation are presented while proposals for a more economical and effective unit are also presented.

Poullikkas [5] developed an optimization algorithm based on deferential equations for the calculation of water unit cost from various RO candidate schemes. The applicability of this method is demonstrated on an example in which six RO candidate schemes has been compared.

The Jordan water authority has given utmost priority to arid areas water supply in their future development plans whereas Jordan lies in a high solar insulation band and vast solar potential can be exploited to convert saline water to potable water [6]. The major local source of energy in Cyprus is solar radiation and is by nature renewable. Efforts have been made for its commercial exploitation. In contrast, wind energy utilization is practically restricted. With this in mind, Cyprus governments' desire is to utilize them for small water desalination units among other applications [7].

In the present study an APVRO system with batteries is suggested to cover the water needs of a small community in Aqaba (Jordan) and/or Agia Napa (Cyprus). Based on the above a fuzzy set methodology for system sizing and site comparison is presented.

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. Fuzzy logic emerged as a consequence of the 1965 proposal of fuzzy set theory by Zadeh [8].

Over the past few years, the use of fuzzy set theory, or fuzzy logic, in control systems has been gaining widespread popularity, especially in Japan. From mid of seventies, Japanese scientists transformed the theory of fuzzy logic into a technological realization. The success of fuzzy logic controllers is mainly due to their ability to cope with knowledge represented in a linguistic form instead of representation in the conventional mathematical framework. Control engineers have traditionally relied on mathematical models for their designs.

Real-world problems can be also extremely complex and inherently fuzzy. The main advantage of fuzzy logic controllers is their ability to incorporate experience, intuition and heuristics into the system instead of relying on mathematical models. The utilization of fuzzy logic can be clearly helpful at complex and non-linear relationships. This makes them more effective in applications where existing models are ill-defined and not reliable enough.

Fuzzy evaluation is the process of evaluating an objective, through the utilization of the fuzzy set theory. When evaluating an objective, multiple related factors must be considered comprehensively in order to give an appropriate, non-contradicting and logically consistent judgment.

Fuzzy logic methodology has been utilized for wide range of evaluation applications, i.e., evaluation and comparison between different solar systems [9, 10], evaluation of factors affecting solar still production [11], evaluation of parameters that affect leakage in infrastructure systems [12].

In this study a fuzzy set methodology for optimum decision and comparison between several APVRO desalination plants driven by renewable (solar PV) energy has been investigated in order to specify a good benefit to cost solutions.

2. ATTRIBUTES AND DEFINITIONS

The International Electrotechnical Commission (IEC) 61724 "Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis" standard [13], is introduced - among other critical desalination parameters [14] - to characterize the long-term behavior of the suggested APVRO system (Load). This International Standard recommends procedures for the monitoring of energy-related PV system characteristics such as inplane irradiance, array output, storage input and output and power conditioner input and output. The purpose of these procedures is to assess the overall performance of PV systems configured as stand alone (SAS) or utility grid-connected with or without back-up generator.

In this study the APVRO system (load attribute) utilize the photovoltaic (PV) energy as the input source and sea water reverse osmosis (SWRO) technology as the output source, without using any other back-up device. Fig. 1 illustrates the APVRO system design flowchart while Fig. 2 illustrates system design from the energy point of view.

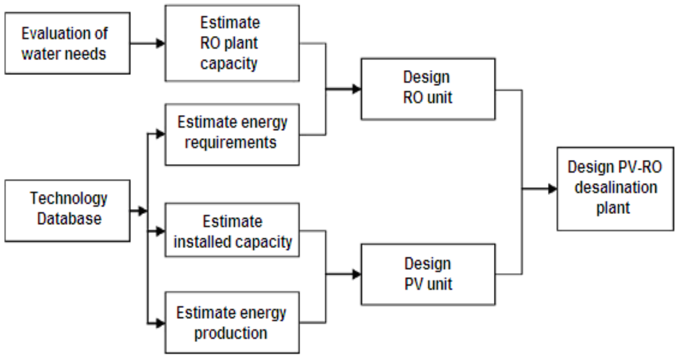


Fig. 1 – APVRO system design flowchart.

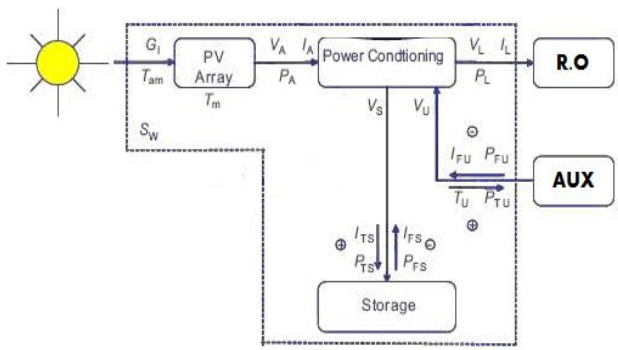


Fig. 2 – APVRO system design from the energy point of view.

The parameters used in the fuzzy model are described as follow:

Reference Yield (RY): The reference yield ($Y_{r,A}$) is based on the inplane irradiation and represents the theoretically available energy per day and kWp in (*hours/day*) and can be used as a site specific parameter (Eq.1).

$$Y_{r,A} = \int_{\tau} G_i dt / G_{STC} \tag{1}$$

Final PV System Yield (FPVSY): The final PV system yield ($Y_{f,A}$) is the energy used by the system (Eq.2), to the total PV power in (*hours/day*), and shows how the load (RO unit), utilize the energy from PVs.

$$Y_{f,A} = E_{A,use} / P_{A,N} \quad (2)$$

System Autonomy (SA): System autonomy it is strictly depending on the follows two factors: The energy autonomy, mostly based on optimal battery sizing, and water autonomy based on tank sizing, both at the Most Demanding Period (MDP), usually ranging between 1 to 5 days.

Performance Ratio (PR): The performance ratio (*PR*) is the ratio of PV energy actually used to the energy theoretically available. It is independent of location and system size and indicates the overall losses on the array's nominal power due to module temperature, incomplete utilization of irradiance and system component inefficiencies or failures. It is given as follow:

$$PR = Y_{f,AD} / Y_{r,AD} \quad (3)$$

Usage Factor (UF): is the ratio of energy supplied by the PV array (E_A) to potential PV production (E_{pot}) and indicates how the system is using the potential energy. It is a measured energy quantity, which differs from for all stand-alone (SAS), presenting PV array disconnection due to a fully charged battery. It is given as follow (Eq.4):

$$UF_D = E_{cons} / E_A \quad (4)$$

Energy Savings (ES): is the percentage (%), which describes the energy savings due to the recovery device system. In a typical RO plant using an energy recovery unit, the main pump provides 41% of the energy, the booster provides 2% and the recovery unit provides the remaining 57%. Since the recovery unit uses no external power, the total power saving is 57% compared to a system with no recovery.

Specific Energy Consumption (SEC): is the energy consumption per m^3 of water produced. Water desalination plants consume a large amount of energy to desalinate water. Efforts for reducing this consumption have been carried out so far with continual improvements. SEC is currently in the range of 1 to 6 kWh/ m^3. It is one of the main parameters for balancing the system (BOS).

RO Hours of Operation (ROHO): the average useful hours of operation per day in which RO system consumes energy and produce water.

Social Benefits (SB): Can be seen as the average total water production (i.e. m^3/day) over a specified period. It is the real plant capacity parameter**.**

Reliability Factor (RF): is a percentage (%) of the yearly average water surplus (m^3/day) to the average water surplus (m^3/day) at the MDP (Eq.5).

$$RF = \frac{W_{Sur}}{W_{Sur,MDP}} \qquad (5)$$

For, $W_{Sur,MDP} > W_{Sur}$

Desalination system cost (DSC): is the capital investment in €/year of the Desalination System which consists of the purchase and installation cost of all the pieces of equipment required for the actual desalination, including pre-treatment items, RO unit itself and possible motor and pump. Sometimes, if the Brine Water Disposal System is not significant, it is assumed and treated as part of the desalination system. Each APVRO system needs some means of fresh water storage because of the irregular nature of the energy resource availability. The bigger the volume of the water tank, the more secure the water supply. In most cases the Feed Water Supply System will require a pumping system (motor and pump) which will consume part of the energy offered by the PV System.

Energy System Cost (ESC): The capital investment cost in €/year of the Energy System includes purchase and installation of the energy system. This includes PV panels, possible battery system (incl. battery replacement), as well as power conditioning system (inverters, controllers).

O&M cost (Running Cost, O&MC): Running cost (€/year) refer to the recurring cost of desalination systems. Includes: annual costs of labor, raw materials, consumables, etc, which are repeated year after year. Although they may differ from year to year, it is usually assumed that these differences are insignificant. Besides, in most cases, running costs are no more than a small proportion of total investment annual equivalent costs, but it counts as an important factor for the long term cost estimation. For methodological purposes, running costs are classified by nature (as above) and by system (Feed Water, Desalination, RES, Other).

Total cost of water produced (TCWP): is the cost of water (€/m^3) and varies according to the overall design.

Total cost of energy produced (TCEP): is the cost of the power install equipment (i.e. panels, batteries, power conditioning etc), to the potential energy consumed (€/kWh).

3. FUZZY SETS PROPOSED METHODOLOGY

The nature of parameters that affect desalination procedures includes many uncertainties. FL is characterized by generalizing classical two-valued logic for reasoning under nonlinear and uncertain conditions. It is therefore the most appropriate method in describing the human knowledge that contains vague concepts and huge amount of data.

- Since, precise comparisons between APVRO systems remains a great challenge to reduce the capital investment cost, the main objective of the fuzzy methodology in the current study is to develop a practical model to evaluate the best benefit to cost solution for the candidate system at a specific site.

The fuzzy inputs used for the evaluation of the benefit factor are listed as following:

- **Reference Yield (RY)**
- **Final PV System Yield (FPVSY)**
- **System Autonomy (SA)**
- **Performance Ratio (PR)**
- **Usage Factor (UF)**
- **Energy Savings (ES):**
- **Specific Energy Consumption (SEC)**

- **RO Hours of Operation (ROHO)**
- **Social Benefits (SB)**
- **Reliability Factor (RF)**

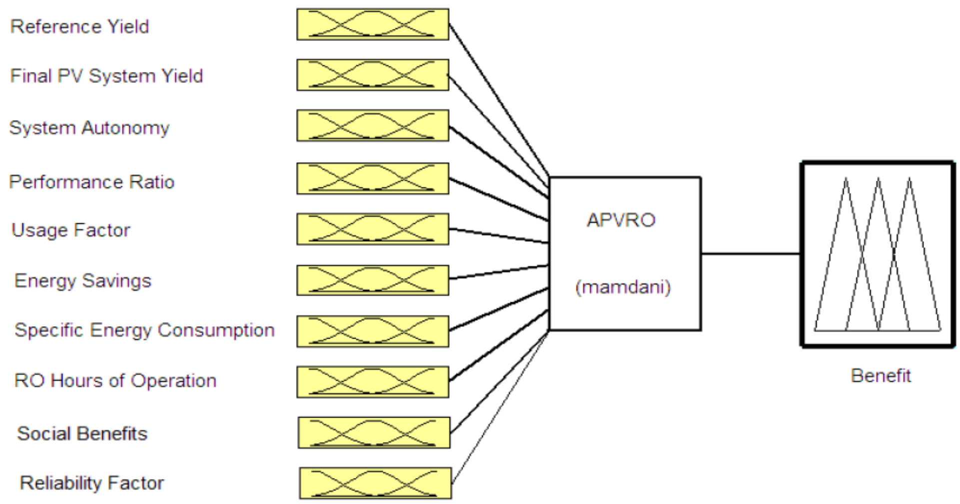


Fig. 3 **-** Fuzzy input/output combination for the System Benefit.

The fuzzy inputs used for the evaluation of the cost factor are listed as following:

- **Desalination system cost (DSC)**
- **Energy System Cost (ESC)**
- **O&M cost (Running Cost, O&MC)**
- **Total cost of water produced (TCWP)**
- **Total cost of energy produced (TCEP)**

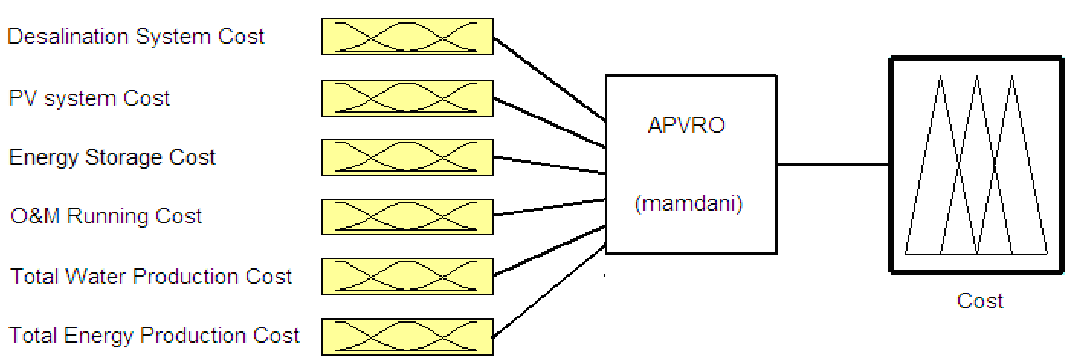


Fig. 4 **-** Fuzzy input/output combination for the System Cost.

The estimated weights for the above mentioned parameters are shown in Table 1 and Table 2 respectively, whiles the benefit and cost models are illustrated in Fig. 3 and Fig. 4 respectively.

Table 1 - APVRO System Benefits												
			Fuzzy Sets									
Main Parameters	**Symbol**	**Variable type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Range**	**Unit**	**Weights**
Reference Yield	RY	Input	VLL	VL	L	M	H	VH	VVH	1 - 8	hours/day	0.400
Final PV System Yield	FPVSY	Input	VLL	VL	L	M	H	VH	VVH	1 - 5	hours/day	0.400
System Autonomy	SY	Input	VLL	VL	L	M	H	VH	VVH	1 - 5	days	0.400
Performance Ratio	PR	Input	VLL	VL	L	M	H	VH	VVH	5 - 60	%	0.600
Usage Factor	UF	Input	VLL	VL	L	M	H	VH	VVH	10 - 90	%	1.000
Energy Savings	ES	Input	VLL	VL	L	M	H	VH	VVH	20 - 90	%	0.900
Specific Energy Consumption	SEC	Input	VLL	VL	L	M	H	VH	VVH	1 - 6	kwh/m3	0.800
RO Hours of Operation	ROHO	Input	VLL	VL	L	M	H	VH	VVH	3 - 12	hours/day	0.500
Social Benefits	SB	Input	VLL	VL	L	M	H	VH	VVH	5 - 50	m3/day/year	0.200
Reliability Factor	RF	Input	VLL	VL	L	M	H	VH	VVH	50 - 90	%	0.900
Benefit	**Benefit**	**Output**	**VLL**	**VL**	**L**	**M**	**H**	**VH**	**VVH**	**0 - 1**	_	_

Table 2 - APVRO System Cost												
			Fuzzy Sets									
Main Parameters	**Symbol**	**Variable type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Range**	**Unit**	**Weights**
Desalination System Cost	DSC	Input	VLL	VL	L	M	H	VH	VVH	$7 \times 10^3 - 100 \times 10^3$	€/year	0.900
PV System Cost	ESC	Input	VLL	VL	L	M	H	VH	VVH	$3 \times 10^3 - 60 \times 10^3$	€/year	0.538
Energy Storage Cost	ESC	Input	VLL	VL	L	M	H	VH	VVH	$3 \times 10^3 - 20 \times 10^3$	€/year	0.539
O&M Running Cost	O&MRC	Input	VLL	VL	L	M	H	VH	VVH	200 - 4000	€/year	0.339
Total Water Production Cost	TWPC	Input	VLL	VL	L	M	H	VH	VVH	1 - 10	€/m3	1.000
Total Energy Production Cost	TEPC	Input	VLL	VL	L	M	H	VH	VVH	8 - 80	c€/kWh	1.000
Cost	**Cost**	**Output**	**VLL**	**VL**	**L**	**M**	**H**	**VH**	**VVH**	**0 - 1**	_	_

The classical four steps for fuzzy implementation are shown below:

3.1. Determining the Linguistic Variables and the Fuzzy Sets

A sample of the fuzzy inputs/outputs combination is shown in Fig. 5. The 16 inputs and 2 outputs are divided each into seven fuzzy sets. This shows the degree in which the APVRO system's parameters, benefits or costs the investigate system design, with respect to the inputs situation. The linguistic declaration of each membership function is listed below:

- Very very low, (VVL).
- Very low, (VL).
- Low, (L).
- Moderate, (M).
- High, (H).
- Very high, (VH).
- Very very high, (VVH).

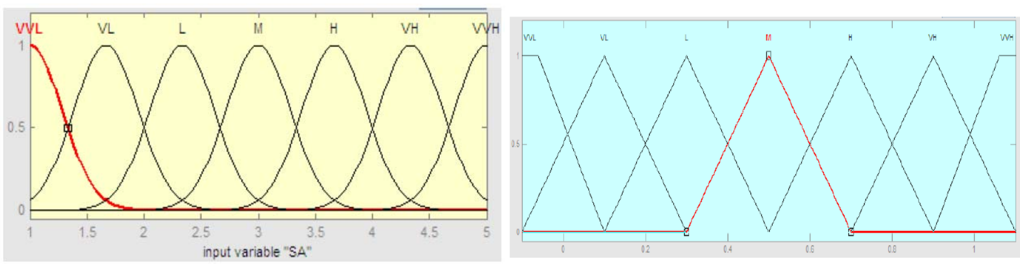


Fig. 5 – Sample of membership functions for the inputs/outputs of benefit and cost model.

3.2. Constructing Fuzzy Rules

In the current section, 70 fuzzy rules are used to determine the benefits, while 42 rules are used to determine the cost, based on the effects of weights for each input parameter [7].

3.3. Performing Fuzzy Inference into the System

The fuzzy inference is the process of formulating the mapping from a given input to output using fuzzy logic. The mapping then provides a basis from which decisions can be made or patterns discerned. The process of fuzzy inference involves membership functions, fuzzy logic operators, and if-then rules. This procedure is used to compute the mapping from the input values to the output values, and it consists of three sub-processes, fuzzification, aggregation, and defuzzification.

4. DISCUSSIONS

The meteorological data for needs of this case study have been taken from the Meteonorm while the various APVRO system designs has been configured using a software support tool (AUDESSY).

The proposed APVRO system is capable to produce 15 m^3/day. The system is designed to satisfy the needs at the MDP as shown in Fig. 6 and Fig. 7. It is sized to feed with fresh water, a community of 60 to 80 people (average 150 liter/day/person) in arid regions in Aqaba (Jordan) and/or Ag. Napa (Cyprus).

A recovery unit with recovery ratio ranging between 40 - 90% and a battery autonomy for one to five days (70 – 270 kWh) have also been tested in comparisons.

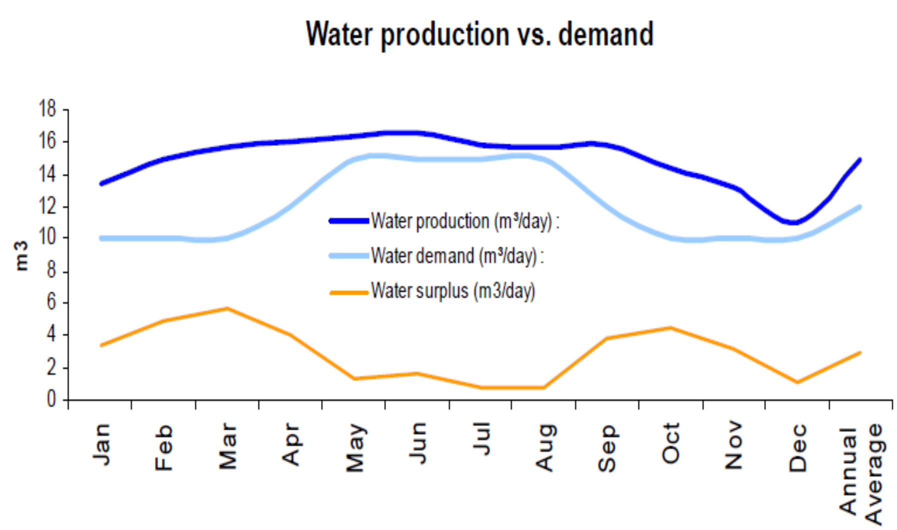


Fig. 6 - Water production versus demand, for a 15 m^3/day APVRO plant.

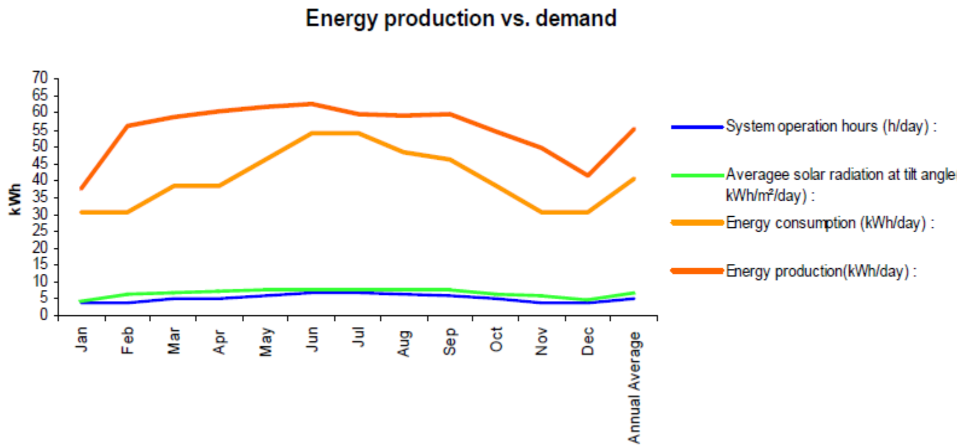


Fig. 7 - Energy production versus consumption, for a 15 m^3/day APVRO plant.

In Fig. 8 the results of comparison between 8 different APVRO systems has been carried out, based on daily average solar radiation data (kWh/kWp), in Aqaba region. The systems have been optimized for different recovery ratios and battery sizes. Recovery Ratio and battery sizing are important design factors that need to be study further [15, 16]. Fuzzy model results have shown that, as recovery ratio increases, benefit increases, while cost decreases with respect to candidate design benefits (Fig 8). However, benefits can be limited, even if the recovery ratio is high, due to a component mismatching (i.e. battery).

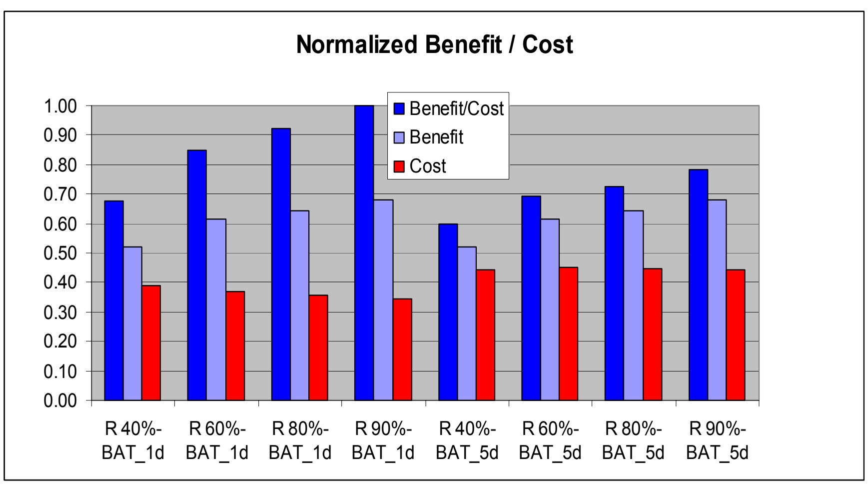
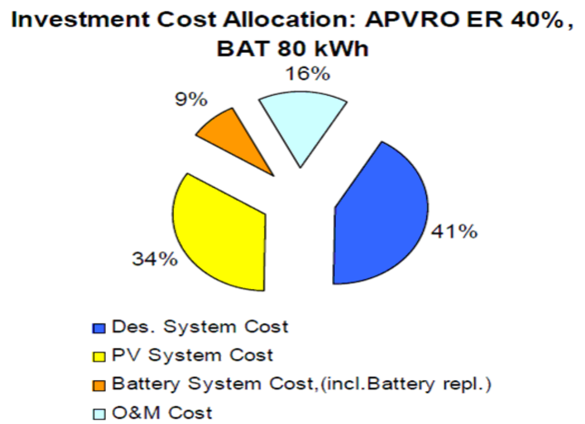
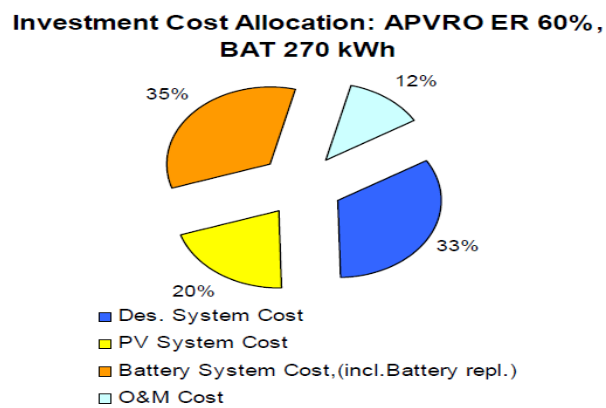


Fig. 8 **-** Normalized Benefit to Cost Ratio (site: Aqaba').

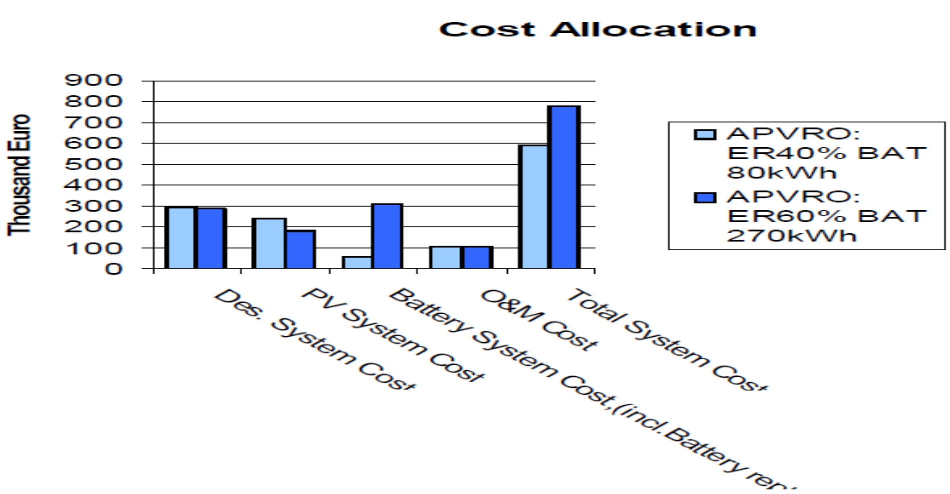
Further, a cost comparison between system with recovery ratio 40% and 60%, and battery storage unit, with autonomy 1 and 5 days are illustrated in Fig. 9 (a),(b) and (c), respectively.



(a)



(b)



(c)

Fig. 9 – Investment cost allocation. **(a)** APVRO system with recovery ratio 40% and battery capacity 80 kWh and **(b)** APVRO system with recovery ratio 60% and battery capacity 270 kWh and **(c)** Cost allocation in thousand € for the two candidate APVRO designs.

Finally a comparison based on two identical systems designs is carried out in order to decide which site between Aqaba and Agia Napa is the most beneficial. The result, as it was expected, designate Aqaba having the most benefits due to higher average solar irradiation as shown in Fig. 10.

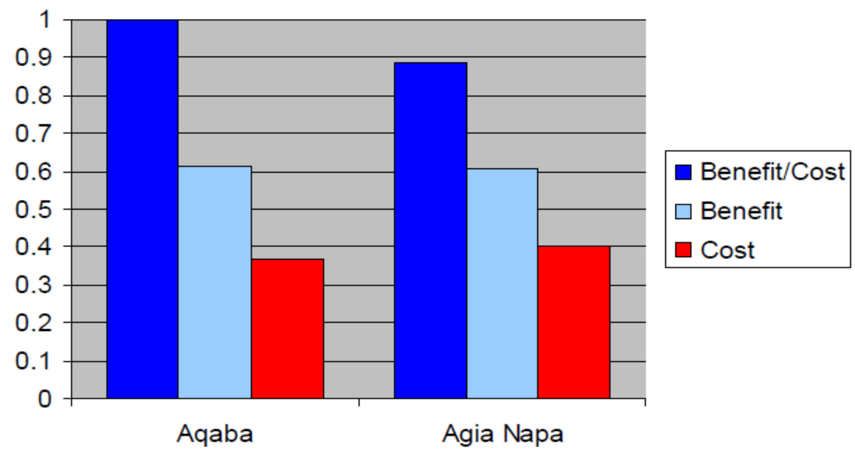


Fig. 10 - Normalized Benefit to Cost Ratio for site decision.

5. CONCLUSIONS

This study highlights the importance of the use of alternative technologies for water desalination plants. The reverse osmosis remains the cheapest option for both low and high production capacities in comparison to other technologies. However, it is important to restate that desalination cost is extremely depending on specific site, availability of energy, energy recovery, and capacity as well as to the overall system design.

More experimental work needs to be carried out to study the continuous performance of the APVRO system. Fuzzy set methodology is a proven powerful tool for analysis while well optimum system design at preferable solar sites can extend future widespread applications.

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