Technical University of Crete
Department of Electronic and Computer Engineering

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

Fanos O. Josephides

Supervisor

Prof. George Stavrakakis

Committee

Prof. Kostas Kalaitzakis

Ass. Prof. Denia Kolokotsa

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DECLARATION OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and in the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

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DEDICATION

This thesis is dedicated to my parents, Onoufrios and Paraskevi.

ACKNOWLEDGEMENTS

This thesis is written and submitted straight in English language in the scope of mutual cooperation through a research exchange program (“Research visits of academic researchers program, between Jordan and Greece”), that Greek government as well as Technical University of Crete (TUC) participated and accepted. Further, the bibliography used in this thesis is mainly referred to international publications, submitted by Greek and foreign researchers.

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LIST OF CONTENTS

ABSTRACT

The availability of clean drinking water is a development issue faced by billions of people in the developing and near-developed world. The global nature of this issue opens the door for the application of communal solutions, as was demonstrated by the discussions surrounding the Johannesburg global climate meeting where water issues were a key concern that all nations could come together to support. Energy has been recognized as important as water for the development of good standards of life because it is the force that puts in operation all human activities. Desalination is a proven technology capable of delivering small to large quantities of fresh water by separating dissolved minerals and impurities from seawater or other salty water.

Desalination is commonly used in rural or isolated areas with dry climates where traditional water supplies, such as dams or pumping from groundwater, are limited. Although potable water is essential to ensure life in this regions, the energy demands for desalination plants becomes a great socio-economic factor. The use of renewable energy can help to decrease the gas emissions, as the rising need for fresh water increases the demands for desalination plants.

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. Further, renewable energy technologies must be improved to satisfy future human needs and for environmental reasons as well. A fuzzy set methodology for optimum decision and comparison between several Autonomous PV-RO (APVRO) desalination plants driven by renewable (solar PV) energy has been investigated in order to specify a good benefit to cost solutions. Results as presented in this study indicate that fuzzy methodology can be used as a strong comparison tool for data manipulation and decision making.

The data was tested and validated through a case study scenario for Aqaba (Jordan) and Agia Napa (Cyprus).

CHAPTER 1

FUZZY LOGIC FUNDAMENTALS

1.1. Introduction

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. In contrast with "crisp logic", where binary sets have binary logic, the fuzzy logic variables may have a membership value of not only 0 or 1 as illustrated in **Fig. 1.1**. That is, the degree of truth of a statement can range between 0 and 1 and is not constrained to the two truth values of classic propositional logic [1]. Furthermore, when linguistic variables are used, these degrees may be managed by specific functions. Fuzzy logic emerged as a consequence of the 1965 proposal of fuzzy set theory by Lotfi Zadeh [2].

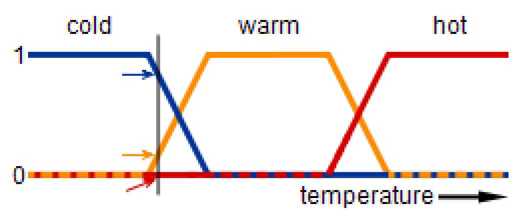


Fig. 1.1. – Illustration of fuzzy logic approach.

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. Today, fuzzy logic-based control systems, or simply fuzzy logic controllers (FLCs), can be found in a wide range of products, starting from washing machines to speedboats, from air condition units to auto-focus cameras. 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. However, the more complex a system, the less effective the mathematical model (Kirsten et al, 2002), (Zadeh, 1973).This is the fundamental concept that provided the motivation for fuzzy logic and is formulated by Lofti Zadeh, the founder of fuzzy set theory, as the Principle of Incompatibility [3].

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.

Fuzziness can be clearly necessary or beneficial at complex systems that are difficult or impossible to model, controlled systems by human experts, complex and continuous inputs and outputs, systems that use human observation as inputs or as the basis for rules and systems that are naturally vague, such as those in the behavioral and social sciences.

Fuzzy logic refers to the technologies and theories that use classes with unsharp boundaries include fuzzy arithmetic, fuzzy probability theory, fuzzy control [4-6], fuzzy decision analysis [7], fuzzy topology, fuzzy neural network theory, fuzzy mathematical programming [8], fuzzy pattern recognition, estimating applications [9], decision-making [10], etc.

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 (Jorge et al, 2000).

Fuzzy logic occupies wide range in decision making applications, fuzzy decision-making is a specialized, language oriented fuzzy system used to make personal and business management decisions [11], [12], such as purchasing decision applications. It has been used to make decisions to support system for securities trading in Fuji Bank in Japan (McNeill and Ellen, 1994).

The current research utilizes fuzzy logic to make decisions about Autonomous Photovoltaic (PV) Reverse Osmosis (RO) desalination plants through performance enhancement of both, solar energy utilization by renewable sources, and fresh water production through desalination. Further, this study restates that decisions should follow well optimum system designs at preferable solar sites, for future widespread applications.

1.2. Applications

Fuzzy systems have been used in a wide variety of applications in such diverse fields as taxonomy, topology, linguistics, automata theory, logic, control theory, game theory, information theory, psychology, pattern recognition, medicine, law, decision analysis, system theory and information retrieval, engineering, science, business, and more others. (i.e. military weapons) (Zadeh et al, 1975) (Passino and Yurkovich, 1998):

- Aircraft/spacecraft: Flight control, engine control, avionic systems, failure diagnosis, navigation and satellite attitude control.
- Automated highway systems: Automatic steering, braking, and throttle control for vehicles.
- Automobiles: Brakes, transmission, suspension, and engine control.
- Autonomous vehicles: Ground and underwater.
- Manufacturing systems: Scheduling and deposition process control.
- Power industry: Motor control, power control/distribution, and load forecasting [13].
- Process control: Temperature, pressure, and level control, failure diagnosis, distillation column control, and desalination processes [14], [15], [16], and [17].
- Robotics: Position control and path planning.

- Decision making applications: Business, purchasing, and power management.
- Renewable energy: solar and wind energy systems.
- Power plants systems [4].

1.3. Fuzzy models, Structure and operations

1.3.1. Fuzzy Sets

In traditional set theory, membership of an object belonging to a set can only be one of two values: 0 or 1. An object either belongs to a set completely or it does not belong at all. No partial membership is allowed **(Fig. 1.2(a)).** Crisp sets handle black-and-white concepts well, but usually they are not sufficient to realistically describe vague concepts. In our daily lives, there are countless vague concepts that we humans can easily describe, understand, and communicate with each other but that traditional mathematics fails to handle in a rational way.

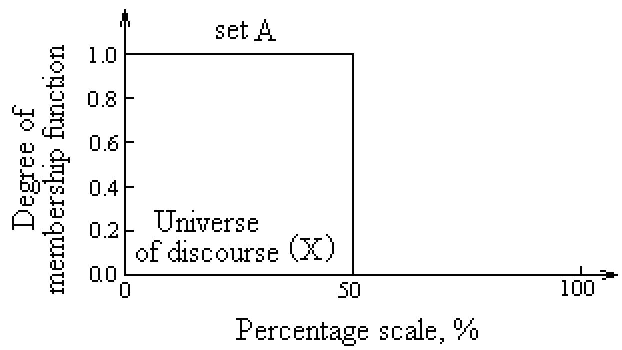
A fuzzy set can be simply defined as a set with fuzzy boundaries. The horizontal axis shown in **Fig 1.2 (a)** and **(b)** represent the universe of discourse, the range of all possible values applicable to a chosen variable. Let X be the universe of discourse and its elements be denoted as x. In classical set theory, crisp set A of X is defined as function fA(x) called the characteristic function of A as shown in **Fig. 1.2 (a)** and in the following equations.

$$fA(x) : X \rightarrow 0,1, \qquad (1.1)$$

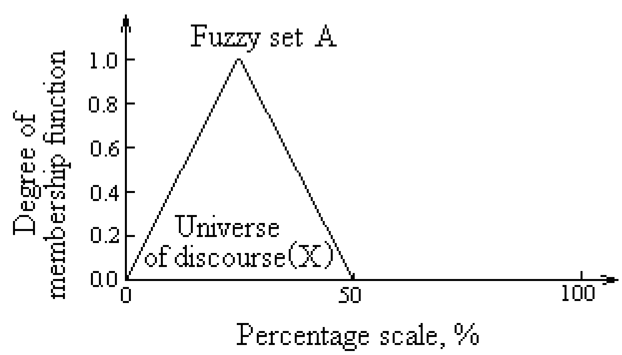
Where,

$$f_A(x) = \begin{cases} 1, & \text{if } x \in A \\ 0, & \text{if } x \notin A \end{cases}$$

This set maps universe X to a set of two elements. For any element x of universe X, characteristic function fA(x) is equal to 1 if x is an element of set A, and is equal to 0 if x not an element of A.



(a)



(b)

Fig. 1.2. - (a) Crisp and **(b)** Fuzzy sets

In the fuzzy theory **(Fig. 1.2 (b)),** fuzzy set A of universe X is defined by function μA(x) which represents the degree of belongingness to set A and called the membership function of set A.

$$\mu A(x): X \rightarrow [0,1], \tag{1.2}$$

Where,

$\mu A(x) = 1$ if x is totally in A;
$\mu A(x) = 0$ if x is not in A;
$0 < \mu A(x) < 1$ if x is partly in A.

Fuzzy sets theory generalizes 0 and 1 membership values of a crisp set to a membership function of a fuzzy set. A fuzzy set consists of a universe of discourse and a membership function that maps every element in the universe of discourse to a membership value between 0 and 1. At this set allows a continuum of possible choices. For any element x of universe X, membership function $\mu A(x)$ equals the degree to which x is an element of set A. This degree, a value between 0 and 1, represents the degree of membership, also called membership value, of element x in set A (Zadeh et al, 1975) (Negnevitsky, 2005).

1.3.2. Linguistic variables and hedges

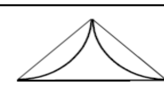
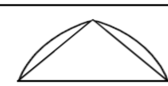
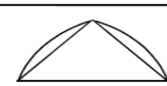
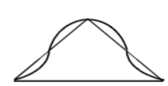
At the root of fuzzy set theory lies the idea of linguistic variables. A linguistic variable for fuzzy describes our daily speech words and adjectives, like tall, short, hot, cold, warm…etc.

The range of possible values of linguistic variables represents the universe of that variable. A linguistic variable carries with it the concept of fuzzy set qualifiers, called hedges. Hedges are terms that modify the shape of fuzzy sets. They include adverbs such as very, somewhat, quite, more or less and slightly. Hedges can modify verbs, adjectives, adverbs or even whole sentences to acquire more flexible design. They are used as:

- All purpose modifiers, such as very, quite or extremely.
- Truth-values, such as quite true or mostly false.
- Probabilities, such as or not very likely.
- Quantifiers, such as most, several or few.
- Possibilities, such as almost impossible or quite possible.

Hedges act as operations themselves. They are used to shrink or expand the fuzzy set as shown in **Table 1.1.** as follows (Negnevitsky, 2005):

Table 1.1. - Hedges in fuzzy logic

Hedge	*Mathematical Expression*	*Graphical Representation For the fuzzy set*
A little	$[\mu_A(x)]^{1.3}$	
Slightly	$[\mu_A(x)]^{1.7}$	
Very	$[\mu_A(x)]^{2}$	
Extremely	$[\mu_A(x)]^{3}$	
Very very	$[\mu_A(x)]^{4}$	
More or less	$\sqrt{\mu_A(x)}$	
Somewhat	$\sqrt{\mu_A(x)}$	
Indeed	$2\,[\mu_A(x)]^2$ if $0 \le \mu_A \le 0.5$ $1 - 2\,[1 - \mu_A(x)]^2$ if $0.5 < \mu_A \le 1$	

1.3.3. Fuzzy Logic Operations

In traditional set theory, there are binary logic operators AND (i.e. intersection), OR (i.e. union), NOT (i.e. complement), and so on. Fuzzy logic (AND, OR) operations are used in fuzzy controllers and models. Unlike the binary AND and OR operators whose operations are uniquely defined, their fuzzy counterparts are non-unique. Numerous fuzzy logic AND operators and OR operators have been proposed, some of them purely from the mathematics point of view. To a large extent, only the Zadeh fuzzy AND operator, product fuzzy AND operator, the Zadeh OR operator, and the Lukasiewicz OR operator have been found to be most useful for fuzzy control and modeling. Their definitions are as follows (Zadeh et al, 1975) (Ying, 2000):

Zadeh fuzzy logic AND operator:

$$\mu A \cap B(x) = \min(\mu A(x), \mu B(x)) \quad (1.3)$$

Product fuzzy logic AND operator:

$$\mu A \cap B(x) = \mu A(x) \times \mu B(x) \quad (1.4)$$

Zadeh fuzzy logic OR operator:

$$\mu A \cup B(x) = \max(\mu A(x), \mu B(x)) \quad (1.5)$$

Lukasiewicz (Probabilistic OR) fuzzy logic OR operator:

$$\mu A \cup B(x) = \min(\mu A(x) + \mu B(x), 1) = \mu A(x) + \mu B(x) - \mu A(x) \times \mu B(x) \quad (1.6)$$

Where max and min are the maximum operator and minimum operator, respectively.
The complement operation is also essential in fuzzy operations. It is defined as:

$$\mu \neg A(x) = 1 - \mu A(x) \quad (1.7)$$

The diagrams for the above operations are shown in Fig. 1.3 as follows:

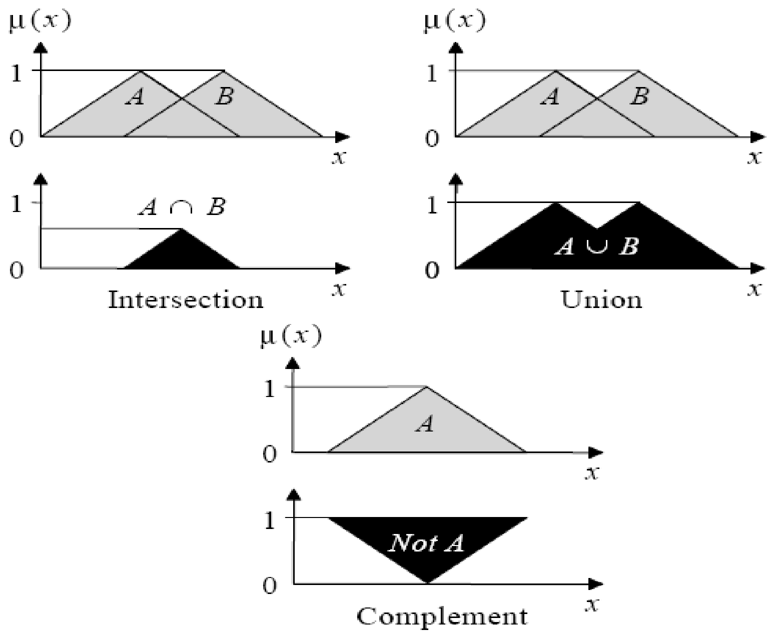


Fig. 1.3. - Operations of fuzzy sets

All of the fuzzy operations that presented in this section are supported by MATLAB Fuzzy Logic Toolbox (Mathworks, 2007), [18].

1.3.4. Fuzzy modeling

The main components for the fuzzy model are: fuzzification of inputs, inference mechanism with rule base that relates inputs to outputs, aggregation and defuzzification of output fuzzy set for crisp output calculation (Ying, 2000) **(Fig. 1.4).**

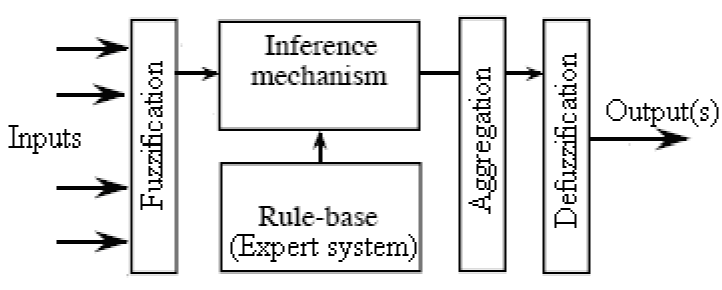


Fig. 1.4. - Main components for a fuzzy model (Ying, 2000).

1.3.4.1. Fuzzification

Fuzzification represents mapping the crisp values of the preprocessed inputs of the model into fuzzy sets, represented by membership functions. The degree of membership of a single crisp variable to a single fuzzy set is evaluated using membership function and can get the values from an interval ([0, 1]).

1.3.4.2. Rule base

The relationship between input and output variables are described in a rule base. Any rule consists of two parts: the IF part, called the antecedent (premise or condition) and the THEN part called the consequent (conclusion or action).

IF <antecedent>, THEN <consequent>

In general, a rule can have multiple antecedents joined by the keywords AND (conjunction), OR (disjunction) or a combination of both. However, it is a good habit to avoid mixing conjunctions and disjunctions in the same rule. It also can have multiple consequent as follows:

IF <antecedent 1>, AND/OR <antecedent 2>… AND/OR <antecedent n> THEN <consequent 1>, <consequent 2>… <consequent m>

The antecedent of a rule incorporates two parts: an object (linguistic object) and its value. The object and its value are joined by an operator. The operator identifies the object an assigns the value. Operators such as: is, are, is not, are not to assign a symbolic value to a linguistic object (Negnevitsky, 2005).

1.3.4.3. Inference engine

Aggregation is the process of unification of the outputs of all rules (Negnevitsky, 2005). The unification then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves all of the parts in **Fig. 1.3.**: **fuzzification**, **aggregation**, **rules** and **defuzzification**. There are two types of fuzzy inference systems (Mathworks, 2007): Sugeno-type and **Mamdani-type** (**Fig. 1.5 (a)** and **(b)**). These two types inference systems possess the same procedure but they vary somewhat in the way outputs are determined.

Mamdani's fuzzy inference method is the **most commonly seen** fuzzy methodology. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification **(Fig. 4.4b).** It is possible, and in many cases much more efficient, to use Sugeno method which employs single spikes as the output membership function rather than a distributed fuzzy set. This is sometimes known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set. It shortens the processing time and enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of a two-dimensional function. Rather than integrating across the two-dimensional function to find the centroid, weighted average of a few data points were used **(Fig. 1.5(a)).** In general, Sugeno-type systems can be used to model any inference system in which the output membership functions are either linear or constant (Mathworks, 2007).

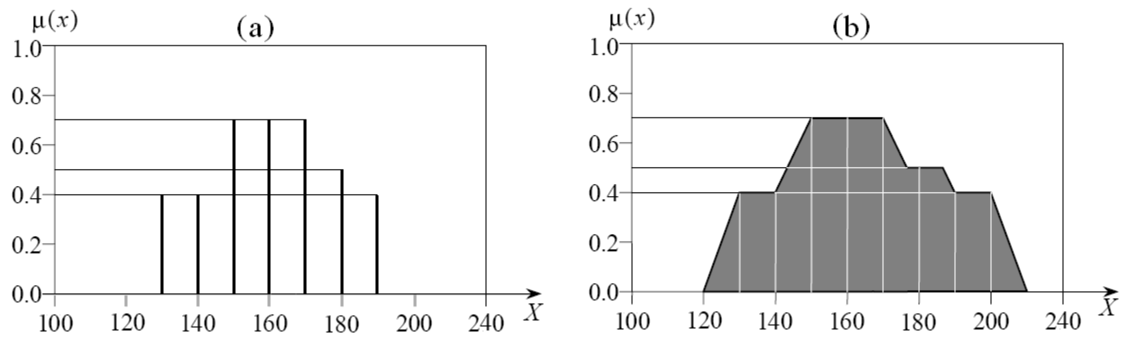


Fig. 1.5. - (a) Sugeno and **(b)** Mamdani fuzzy output.

The Mamdani method is widely accepted for capturing expert knowledge and it will be used in the current study. It allows us to describe the expertise decision in more intuitive, more human-1ike manner.

However, Mamdani-type fuzzy inference entails a substantial computational burden. On the other hand, the Sugeno method is computationally effective, which makes it attractive for dynamic nonlinear systems (Negnevitsky, 2005).

1.3.4.4. Aggregation

Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. Aggregation only occurs once for each output variable, just prior to the fifth and final step, defuzzification. The input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable. Notice that as long as the aggregation method is commutative (which it always should be), then the order in which the rules are executed is unimportant (Negnevitsky, 2005) (Mathworks, 2007).

1.3.4.5. Defuzzification

A defuzzifier analyzes the information provided by each of the rules and makes a decision from this basis. There are different methods for the calculation of crisp output of fuzzy system like Centroid average (CA), Center of gravity (COG), Maximum center average (MCA), Mean of maximum (MM), Smallest of maximum, etc (Passino and Yurkovich, 1998).

But the most popular aggregation method is centroid technique. It finds the point where a vertical line would slice the aggregate set into two equal masses. Mathematically this center of gravity (COG) can be expressed as

$$COG = \frac{\sum_{x=a}^{b} \mu_A(x) x dx}{\sum_{x=a}^{b} \mu_A(x) dx} \tag{1.8}$$

Where **a** and **b** are the boundaries on the X axis for the aggregated shape as shown in **Fig. 1.6**. (Negnevitsky, 2005):

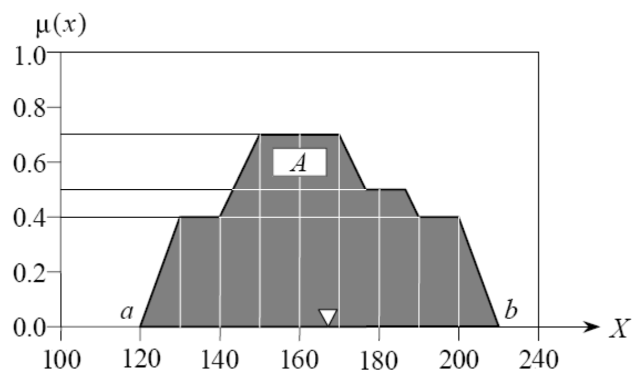


Fig. 1.6. - Defuzzification method.

Today, it is easier to build the fuzzy model using simulation programs techniques like MATLAB fuzzy toolbox, since it allows users to design, interact, monitor and modify their model through a mouse click rather than conventional fuzzy methods that use longitude formulas, so it can be categorized as a used friendly technique.

1.4. Fuzzy logic toolbox in MATLAB

The Fuzzy Logic Toolbox is a collection of functions, explained in the previous sections, integrated and built on the MATLAB numeric computing environment. It provides tools to create and edit fuzzy models within the framework of MATLAB, the toolbox provides a number of interactive tools that allow users to access many of the functions through a graphical user interface (GUI) in order to design, interact, monitor and modify their model through a mouse click rather than conventional fuzzy methods that use long formulas **(equations (1.1 – 1.8))** (Mathworks, 2007).

Fuzzy logic toolbox is consisted from the following main parts (Mathworks, 2007):

- Fuzzy Inference System (FIS) editor
- The membership function editor.
- The rule editor.
- The rule viewer.
- The surface viewer.

1.4.1. Fuzzy Inference System (FIS) editor.

Fuzzy inference is a method that interprets the values in the input vector and, based on user defined rules, assigns values to the output vector. The Fuzzy Logic Toolbox provides a set of GUI editors to build a FIS. The FIS Editor displays general information about a fuzzy inference system. **In Fig 1.7**, the top of the figure shows the names of each input variables and each output variable. The sample membership functions shown in the boxes are just icons and do not represent the shapes of the actual membership functions.

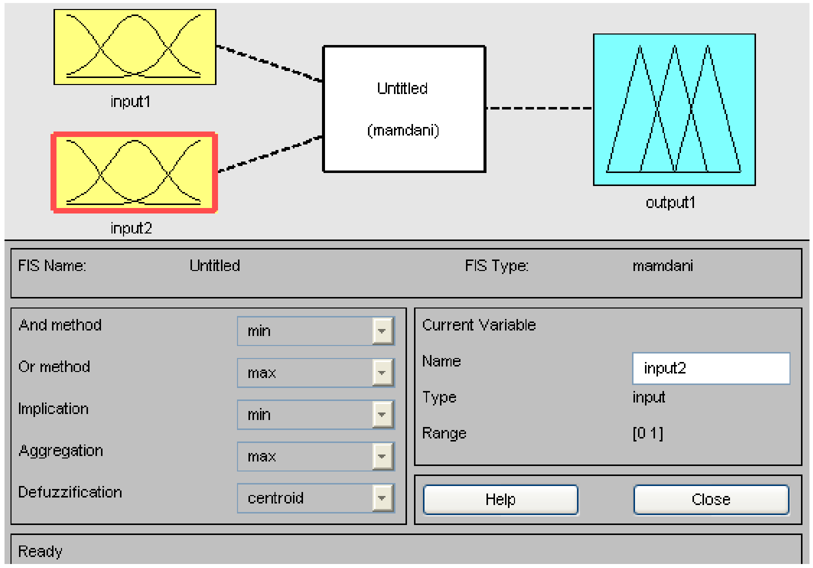


Fig. 1.7. - Fuzzy Inference System editor.

The FIS editor also determines the type of the used inference weather it is Mamdani or Sugeno style inference. The default inference engine is the Mamdani-style. The FIS editor also determines AND method and OR method type as discussed in **(1.3.3).**

1.4.2. Membership function editor

The Membership Function Editor is the tool display and edit all of the membership functions (MF) for the entire fuzzy inference system **(Fig. 1.8),** including both input and output variables. Membership function editor determines the name (linguistic variable), type (modifies the set, **Table 1.1**), number, range and coordinates of each fuzzy set.

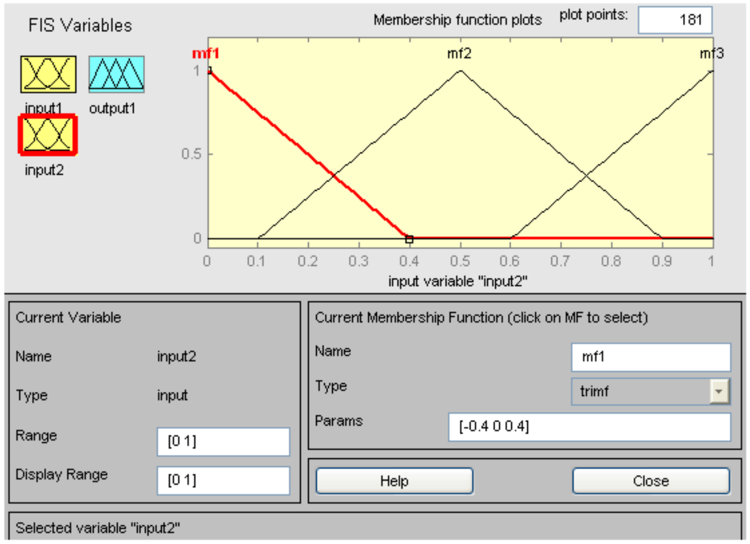


Fig. 1.8. - Membership function editor

1.4.3. The rule editor

The Rule Editor contains a large editable text field for displaying and editing rules. It also has landmarks similar to those in the FIS Editor and the Membership Function Editor, including the menu bar and the status line. The rules can be built using And/Or operators to map between the inputs and the output **(Fig. 1.9).**

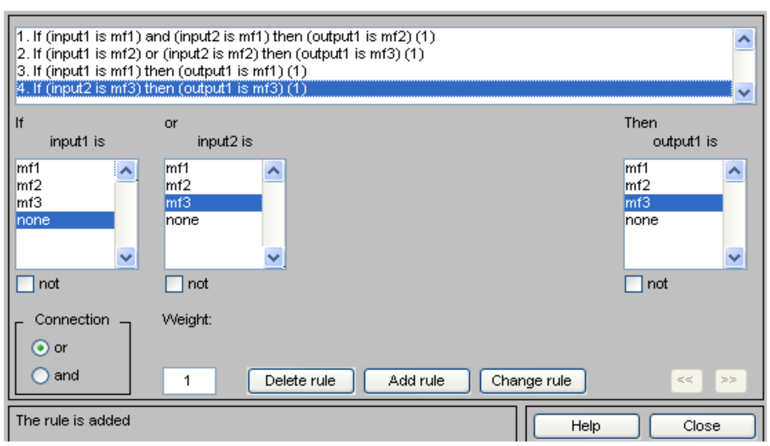


Fig. 1.9. - Rules editor

1.4.4. Rule viewer

The Rule Viewer displays a roadmap of the whole fuzzy inference process. It's based on the fuzzy rules described in the previous section. The three blocks in the first row in **Fig. 1.10** represent the antecedent and consequent of the first rule. There is a red index line across each input, it can be moved across the input range to determine its value or it can be entered and edited directly through the "Input" space shown in **Fig. 1.10.**

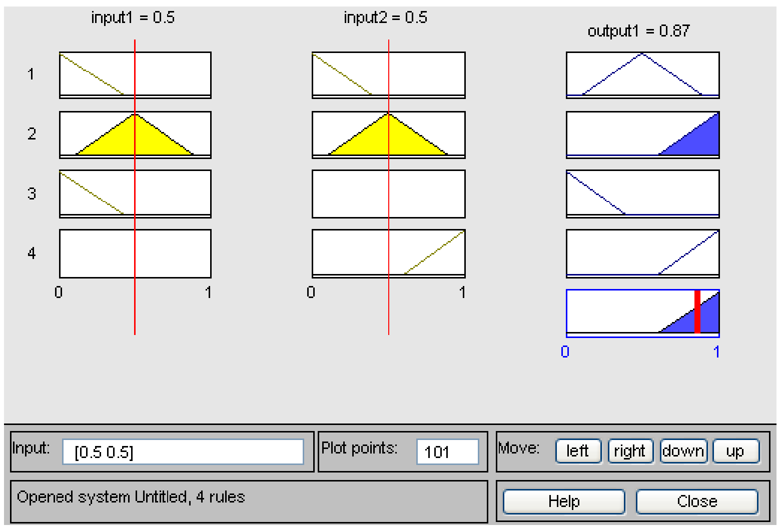


Fig. 1.10. - Rules viewer

1.4.5 Surface viewer

The surface viewer has a special capability that is very helpful in cases with two (or more) inputs and one output: the axes can be grabbed and repositioned to get a different three-dimensional view on the data. Variables in the surface viewer can be viewed in terms of each other in two or three variables at a time as shown in **Fig. 1.11.**

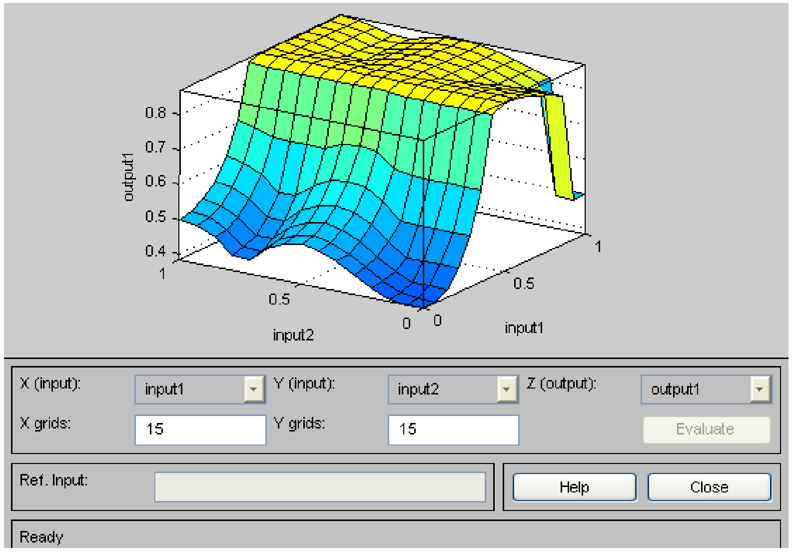


Fig. 1.11. - Rules viewer.

1.5. REFERENCES

- **See Chapter 6.**

CHAPTER 2

SOLAR ENERGY – PHOTOVOLTAICS

2.1. The photoelectric effect

Photovoltaics (PV) is the field of technology and research related to the application of solar cells **(Fig. 2.1).** The photoelectric cell uses the photovoltaic phenomenon to generate electrical energy using the potential difference that arises between materials when the surface of the cell is exposed to electromagnetic radiation. The photoelectric effect is the basic physical process by which a PV cell converts sunlight into electricity. When light shines on a PV cell, it may be reflected, absorbed, or pass right through. But only the absorbed light generates electricity. The energy of the absorbed light is transferred to electrons in the atoms of the PV cell. With their newfound energy, these electrons escape from their normal positions in the atoms of the semiconductor PV material and become part of the electrical flow, or current, in an electrical circuit. A special electrical property of the PV cell - what we call a “built-in electric field” - provides the force, or voltage, needed to drive the current through an external load.

Fig. 2.1. – Standard semiconductor photovoltaic cell, the most basic building block of a PV system.

To induce the built-in electric field within a PV cell, two layers of somewhat differing semiconductor materials are placed in contact with one another. One layer is an “n-type” semiconductor with an abundance of electrons, which have a negative electrical charge. The other layer is a “p-type” semiconductor with an abundance of “holes”, which have a positive electrical charge. Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p/n junction at their interface, thereby creating an electric field **(Fig. 2.2).** When n- and p-type silicon comes into contact, excess electrons move from the n-type side to the p-type side. The result is a buildup of positive charge along the n-type side of the interface and a buildup of negative charge along the p-type side. Because of the flow of electrons and holes, the two semiconductors behave like a battery, creating an electric field at the surface where they meet - what we call the p/n junction. The electrical field causes the electrons to move from the semiconductor toward the negative surface, where they become available to the electrical circuit. At the same time, the holes move in the opposite direction, toward the positive surface, where they await incoming electrons [1].

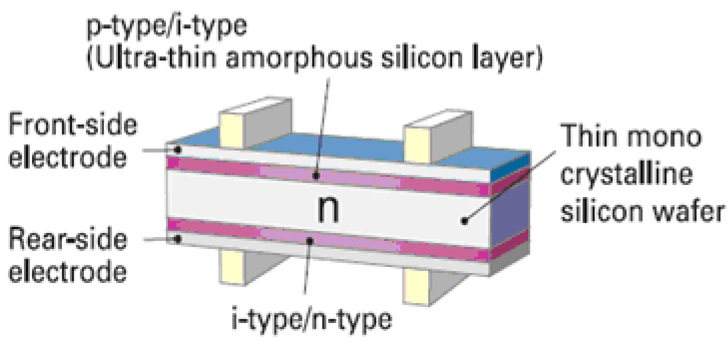


Fig. 2.2. – Typical solar cell photodiode [1].

2.2. PV current development

PV production has been doubling every 2 years, increasing by an average of 48% each year since 2002, making it the world’s fastest-growing energy technology, and then increased by 110% in 2008 [2]. At the end of 2008, the cumulative global PV installations reached 15,2 MW [3]. Roughly 90% of this generating capacity consists of

grid-tied electrical systems. Such installations may be ground-mounted or built into the roof or walls of a building, known as Building Integrated Photovoltaics (BIPV) [4]. Net metering and financial incentives, such as preferential feed-in tariffs for solar-generated electricity, have supported solar PV installations in many countries. Europe accounted for 82% of world demand in 2008. Spain's 285% growth pushed Germany into second place in the market ranking, while the US advanced to number three. Rapid growth in Korea allowed it to become the fourth largest market, closely followed by Italy and Japan.
In the assessment of PV demand in 2008, 81 countries contributed to the 5.95GW world market total [5], as illustrated in **Fig. 2.3.**

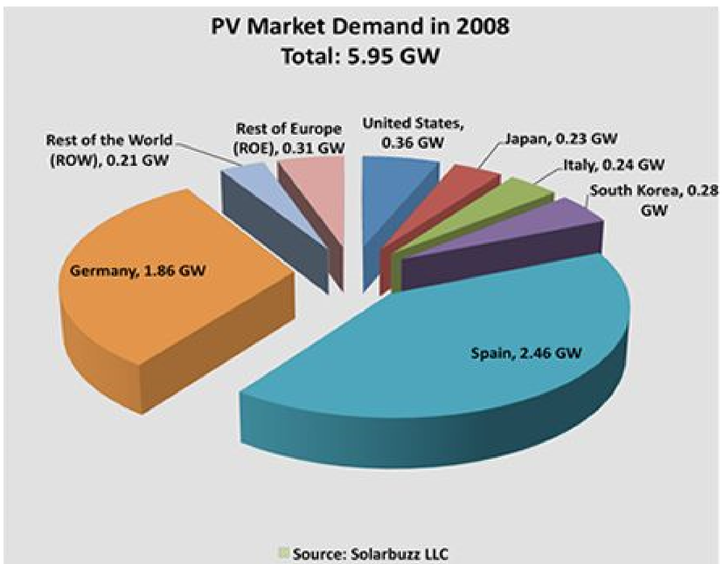


Fig. 2.3. – World solar PV market installations reached a record high of 5.95 GW in 2008, representing growth of 110% over the previous year [5].

The first practical application of PV was to power orbiting satellites and other spacecraft, but today the majority of PV modules are used for grid connected power generation. In this case an inverter is required to convert the DC to AC. There is a smaller market for off-grid power for remote dwellings, desalination plants, boats, recreational vehicles, electric cars, roadside emergency telephones, remote sensing, and cathodic protection of pipelines.

Cells require protection from the environment and are usually packaged tightly behind a glass sheet. When more power is required than a single cell can deliver, cells are electrically connected together to form PV modules, or solar panels. A single module is enough to power an emergency telephone, but for a house or a power plant the modules must be arranged in multiples as arrays. Although the selling price of modules is still too high to compete with grid electricity in most places, significant financial incentives in Japan and then Germany, Italy and France triggered a huge growth in demand, followed quickly by production. In 2008, Spain installed 45% of all photovoltaics, but a change in law limiting the feed-in tariff is expected to cause a precipitous drop in the rate of new installations there, from an extra 2500 MW in 2008 to an expected additional 375 MW in 2009 [6].

Perhaps not unexpectedly, a significant market has emerged in off-grid locations for solar-power-charged storage-battery based solutions. These often provide the only electricity available [7]. The first commercial installation of this kind was in 1966 on Ogami Island in Japan to transition Ogami Lighthouse from gas torch to fully self-sufficient electrical power.

World solar PV installations were 2.8 GWp in 2007, and 5.9 GWp in 2008, a 110% increase. The three leading countries (Germany, Japan and the US) represent nearly 89% of the total worldwide PV installed capacity. According to Navigant Consulting and Electronic Trend Publications, the estimated PV worldwide installations outlooks of 2012 are 18.8 GW. Notably, the manufacture of solar cells and modules had expanded in coming years.

Germany was the fastest growing major PV market in the world from 2006 to 2007. By 2008, 5.3 GWp of PV was installed, or 35% of the world total. The German PV industry generates over 10,000 jobs in production, distribution and installation. By the end of 2006, nearly 88% of all solar PV installations in the EU were in grid-tied applications in Germany. PV power capacity is measured as maximum power output under standardized test conditions (STC) in “Wp” (Watts peak). The actual power output at a particular point in time may be less than or greater than this standardized, or "rated", value, depending on geographical location, time of day, weather conditions, and other factors. Solar PV array capacity factors are typically under 25%, which is lower than many other industrial sources of electricity.

The EPIA/Greenpeace Advanced Scenario shows that by the year 2030, PV systems could be generating approximately 1.9 GW of electricity around the world. This means that, assuming a serious commitment is made to energy efficiency, enough solar power would be produced globally in twenty-five years' time to satisfy the electricity needs of almost 14% of the world's population.

Newer alternatives to standard crystalline silicon modules include casting wafers instead of sawing, thin film (CdTe, amorphous Si, mono-crystalline and poly-crystalline Si), concentrator modules, 'Sliver' cells, and continuous printing processes. Due to economies of scale solar panels get less costly as people use and buy more. As manufacturers increase production to meet demand, the cost and price is expected to drop in the years to come. By early 2006, the average cost per installed watt for a residential sized system was about US$ 7.50 (€ 5) to US$ 9.50 (€ 6.29), including panels, inverters, mounts, and electrical items.

The current market leader in solar panel efficiency (measured by energy conversion ratio) is SunPower, a San Jose based company. Sunpower's cells have a conversion ratio of 23.4%, well above the market average of 12-18%. However, advances past this efficiency mark are being pursued in academia and R&D labs with efficiencies of 42% achieved at the University of Delaware in conjunction with DuPont by means of concentration of light. The highest efficiency achieved without concentration is by Sharp Corporation at 35.8% using a proprietary triple-junction manufacturing technology in 2009.

2.2.1. Applications

- **Power stations:** As of October 2009, the largest PV power plants in the world are the Olmedilla Photovoltaic Park (Spain, 60 MW), the Strasskirchen Solar Park (Germany, 54 MW), the Lieberose Photovoltaic Park (Germany, 53 MW), the Puertollano Photovoltaic Park (Spain, 50 MW), the Moura photovoltaic power station (Portugal, 46 MW), and the Waldpolenz Solar Park (Germany, 40 MW). The largest photovoltaic power plant in North America is the 25 MW DeSoto Next Generation Solar Energy Center in Florida. The plant consists of over 90,000 solar panels. Topaz Solar Farm is a proposed 550 MW solar photovoltaic power plant which is to be built northwest of California Valley in the US at a cost of over US$1 billion (€0.7 billion). Built on 9.5 square miles (25 km2) of ranchland, the project would utilize thin-film PV panels designed and manufactured by OptiSolar in Hayward and Sacramento. The project would deliver approximately 1.1 GWh annually of renewable energy. The project is expected to begin construction in 2010, begin power delivery in 2011, and be fully operational by 2013. High Plains Ranch is a proposed 250 MW solar photovoltaic power plant which is to be built by SunPower in the Carrizo Plain, northwest of California Valley.

- **Building:** Building-integrated photovoltaics (BIPV) are increasingly incorporated into new domestic and industrial buildings as a principal or ancillary source of electrical power, and are one of the fastest growing segments of the photovoltaic industry. Typically, an array is incorporated into the roof or walls of a building and roof tiles with integrated PV cells can now be purchased. Arrays can also be retrofitted into existing buildings. In this case they are usually fitted on top of the existing roof structure. Alternatively, an array can be located separately from the building but connected by cable to supply power for the building. Where a building is at a considerable distance from the public electricity supply (or grid) - in remote or mountainous areas – PV may be the preferred possibility for generating electricity, or PV may be used together with wind, diesel generators

- **Transport:** PV has traditionally been used for auxiliary power in space. PV is rarely used to provide motive power in transport applications, but is being used increasingly to provide auxiliary power in boats and cars. Recent advances in solar race cars, however, have produced cars that with little changes could be used for transportation.

- **Stand-alone devices:** Until a decade or so ago, PV was used frequently to power calculators and novelty devices. Improvements in integrated circuits and low power LCD displays make it possible to power such devices for several years between batteries changes, making PV use less common. In contrast, solar powered remote fixed devices have seen increasing use recently in locations where significant connection cost makes grid power prohibitively expensive. Such applications include parking meters, emergency telephones, temporary traffic signs, and remote guard posts & signals.

- **Rural electrification:** Developing countries where many villages are often more than five kilometers away from grid power have begun using PV. In remote locations in India a rural lighting program has been providing solar powered LED lighting to replace kerosene lamps [8]. The solar powered lamps were sold at about the cost of a few month's supply of kerosene. Cuba is working to provide solar power for areas that are off grid. These are areas where the social costs and

- **Solar roadways:** A 45 miles (72 km) section of roadway in Idaho is being used to test the possibility of installing solar panels into the road surface, as roads are generally unobstructed to the sun and represent about the percentage of land area needed to replace other energy sources with solar power.

- **Desalination:** a widespread intention to couple photovoltaics - 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.

2.2.2. Economics

Grid parity [9], the point at which photovoltaic electricity is equal to or cheaper than grid power, is achieved first in areas with abundant sun and high costs for electricity such as in California and Japan.

Grid parity has been reached in Hawaii and other islands that otherwise use fossil fuel (diesel fuel) to produce electricity, and most of the US is expected to reach grid parity by 2015.

Other companies predict an earlier date: the cost of solar power will be below grid parity for more than half of residential customers and 10% of commercial customers in the OECD (Organization for Economic Co-operation and Development), as long as grid electricity prices do not decrease through 2010.

The fully-loaded cost (cost not price) of solar electricity is US$0.25/kWh (€0.17/kWh) or less in most of the OECD countries. By late 2011, the fully-loaded cost is likely to fall below US$0.15/kWh (€0.10/kWh) for most of the OECD and reach US$0.10/kWh (€0.07/kWh) in sunnier regions. These cost levels are driving three emerging trends:

- Vertical integration of the supply chain.
- Origination of power purchase agreements (PPAs) by solar power companies.
- Unexpected risk for traditional power generation companies, grid operators and wind turbine manufacturers.

Abengoa Solar has announced the award of two R&D projects in the field of Concentrating Solar Power (CSP) by the US Department of Energy that total over $ 14 million (€ 9.3 million). The goal of the DOE R&D program, working in collaboration with partners such as Abengoa Solar, is to develop CSP technologies that are competitive with conventional energy sources (grid parity) by 2015. Concentrating photovoltaics (CPV) could reach grid parity in 2011. In Sept 2009, Maharishi Solar Technology announces tie-up with Abengoa Solar.

Due to the growing demand for PV electricity, more companies enter into this market and lower cost of the PV electricity would be expected. Anwell Technologies Limited recently announced that its multi-substrate-multi-chamber PECVD targets to lower the cost to US$0.5 per watt in the future.

2.2.3. Financial incentives

The political purpose of incentive policies for PV is to facilitate an initial small-scale deployment to begin to grow the industry, even where the cost of PV is significantly above grid parity, to allow the industry to achieve the economies of scale necessary to reach grid parity. The policies are implemented to promote national energy independence, high tech job creation and reduction of CO2 emissions.

Three incentive mechanisms are used (often in combination):

- **Investment subsidies:** the authorities refund part of the cost of installation of the system.
- **Feed-in Tariffs (FIT):** the electricity utility buys PV electricity from the producer under a multiyear contract at a guaranteed rate [9].
- **Renewable Energy Certificates (RECs).**

With investment subsidies, the financial burden falls upon the taxpayer, while with feed-in tariffs the extra cost is distributed across the utilities' customer bases. While the investment subsidy may be simpler to administer, the main argument in favour of feed-in tariffs is the encouragement of quality. Investment subsidies are paid out as a function of the nameplate capacity of the installed system and are independent of its actual power yield over time, thus rewarding the overstatement of power and tolerating poor durability and maintenance. With feed-in tariffs, the financial burden falls upon the consumer. They reward the number of kilowatt-hours produced over a long period of time, but because the rate is set by the authorities, it may result in perceived overpayment. The price paid per kilowatt-hour under a feed-in tariff exceeds the price of grid electricity. Net metering refers to the case where the price paid by the utility is the same as the price charged. Where price setting by supply and demand is preferred, RECs can be used. In this mechanism, a renewable energy production or consumption target is set, and the consumer or producer is obliged to purchase renewable energy from whoever provides it the most competitively. The producer is paid via an REC. In principle this system delivers the cheapest renewable energy, since the lowest bidder will win. However, uncertainties about the future value of energy produced are a brake on investment in capacity, and the higher risk increases the cost of capital borrowed.

Financial incentives for photovoltaics have been applied in many countries, including Australia, China, Germany, Israel, Japan, and the United States. The Japanese government through its Ministry of International Trade and Industry ran a successful program of subsidies from 1994 to 2003. By the end of 2004, Japan led the world in installed PV capacity with over 1.1 GW.

In 2004, the German government introduced the first large-scale feed-in tariff system, under a law known as the 'EEG' (Erneuerbare Energien Gesetz) which resulted in explosive growth of PV installations in Germany. At the outset the FIT was over 3x the retail price or 8x the industrial price. The principle behind the German system is a 20 year flat rate contract. The value of new contracts is programmed to decrease each year, in order to encourage the industry to pass on lower costs to the end users. The program has been more successful than expected with over 1GW installed in 2006, and political pressure is mounting to decrease the tariff to lessen the future burden on consumers.

Subsequently in Europe [10], Spain, Italy, Greece, Cyprus (who enjoyed an early success with domestic solar-thermal installations for hot water needs) and France introduced feed-in tariffs. None have replicated the programmed decrease of FIT in new contracts though, making the German incentive relatively less and less attractive compared to other countries. The French and Greek FIT offer a high premium (EUR 0.55/kWh) for building integrated systems. California, Greece, France and Italy have 30-50% more insolation than Germany making them financially more attractive. The Greek domestic "solar roof" program (adopted in June 2009 for installations up to 10 kW) has internal rates of return of 10-15% at current commercial installation costs, which, furthermore, is tax free.

In 2006 California approved the 'California Solar Initiative', offering a choice of investment subsidies or FIT for small and medium systems and a FIT for large systems. The small-system FIT of $0.39 per kWh (far less than EU countries) expires in just 5 years, and the alternate "EPBB" residential investment incentive is modest, averaging perhaps 20% of cost. All California incentives are scheduled to decrease in the future depending as a function of the amount of PV capacity installed.

At the end of 2006, the Ontario Power Authority (OPA, Canada) began its Standard Offer Program (SOP), the first in North America for small renewable projects (10MW or less).

This guarantees a fixed price of $0.42 CDN (€ 0.27) per kWh over a period of twenty years. Unlike net metering, all the electricity produced is sold to the OPA at the SOP rate. The generator then purchases any needed electricity at the current prevailing rate (e.g., $0.055 per kWh). The difference should cover all the costs of installation and operation over the life of the contract. On October 1st, 2009, OPA issued a Feed in Tariff (FIT) program, increasing this fixed price to $0.822 per kWh.

The price per kilowatt hour or per peak kilowatt of the FIT or investment subsidies is only one of three factors that stimulate the installation of PV. The other two factors are insolation (the more sunshine, the less capital is needed for a given power output) and administrative ease of obtaining permits and contracts.

Unfortunately the complexity of approvals in California, Spain and Italy has prevented comparable growth to Germany even though the return on investment is better. In some countries, additional incentives are offered for BIPV compared to stand alone PV.

- France + € 0.25/kWh (€ 0.30 + 0.25 = € 0.55/kWh total)
- Italy + € 0.04-0.09 kWh
- Germany + € 0.05/kWh (facades only)

2.2.4. Environmental impacts

Unlike fossil fuel based technologies, solar power does not lead to any harmful emissions during operation, but the production of the panels leads to some amount of pollution [11]. This is often referred to as the energy input to output ratio. In some analysis, if the energy input to produce it is higher than the output it produces it can be considered environmentally more harmful than beneficial. Also, placement of PV affects the environment. If they are located where photosynthesizing plants would normally grow, they simply substitute one potentially renewable resource (biomass) for another. It should be noted, however, that the biomass cycle converts solar radiation energy to chemical energy (with significantly less efficiency than PV cells alone). And if they are placed on the sides of buildings (such as in Manchester) or fences, or rooftops (as long as plants would not normally be placed there), or in the desert they are purely additive to the renewable power base.

Life cycle greenhouse gas emissions are now in the range of 25-32 g/kWh and this could decrease to 15 g/kWh in the future. For comparison (of weighted averages), a combined cycle gas-fired power plant emits some 400-599 g/kWh, an oil-fired power plant 893 g/kWh, a coal-fired power plant 915-994 g/kWh or with carbon capture and storage some 200 g/kWh, and a geothermal high-temperature power plant 91-122 g/kWh. Only nuclear, wind and geothermal low-temperature are better, emitting 6-25 g/kWh, 11 g/kWh and 0-1 g/kWh on average. Using renewable energy sources in manufacturing and transportation would further drop carbon emissions. BP Solar owns two factories built by Solarex (one in Maryland, the other in Virginia) in which all of the energy used to manufacture solar panels is produced by solar panels.

One issue that has often raised concerns is the use of cadmium in cadmium telluride solar cells (CdTe is only used in a few types of PV panels). Cadmium in its metallic form is a toxic substance that has the tendency to accumulate in ecological food chains. The amount of cadmium used in thin-film PV modules is relatively small (5-10 g/m^2) and with proper emission control techniques in place the cadmium emissions from module production can be almost zero. Current PV technologies lead to cadmium emissions of 0.3-0.9 microgram/kWh over the whole life-cycle. Most of these emissions actually arise through the use of coal power for the manufacturing of the modules, and coal and lignite combustion leads to much higher emissions of cadmium. Life-cycle cadmium emissions from coal is 3.1 microgram/kWh, lignite 6.2, and natural gas 0.2 microgram/kWh. Note that if electricity produced by PV panels were used to manufacture the modules instead of electricity from burning coal, cadmium emissions from coal power usage in the manufacturing process could be entirely eliminated.

2.2.5. Energy payback time and energy returned on energy invested

The energy payback time is the time required to produce an amount of energy as great as what was consumed during production. The energy payback time is determined from a life cycle analysis of energy. The energy needed to produce solar panels will be paid back in the first few years of use.

Another key indicator of environmental performance, tightly related to the energy payback time, is the ratio of electricity generated divided by the energy required to build and maintain the equipment. This ratio is called the energy returned on energy invested (EROEI). Of course, little is gained if it takes as much energy to produce the modules as they produce in their lifetimes. This should not be confused with the economic return on investment, which varies according to local energy prices, subsidies available and metering techniques.

Life-cycle analyses show that the energy intensity of typical solar photovoltaic technologies is rapidly evolving. In 2000 the energy payback time was estimated as 8 to 11 years, but more recent studies suggest that technological progress has reduced this to 1.5 to 3.5 years for crystalline silicon PV systems.

Thin film technologies now have energy pay-back times in the range of 1-1.5 years (S. Europe). With lifetimes of such systems of at least 30 years the EROEI is in the range of 10 to 30. They thus generate enough energy over their lifetimes to reproduce themselves many times (6-31 reproductions, the EROEI is a bit lower) depending on what type of material, balance of system (BOS), and the geographic location of the system.

2.2.6. Advantages and disadvantages

Advantages:

- The 89 petawatts of sunlight reaching the Earth's surface is plentiful - almost 6,000 times more than the 15 terawatts of average electrical power consumed by humans. Additionally, solar electric generation has the highest power density (global mean of 170 W/m^2) among renewable energies.
- Solar power is pollution-free during use. Production end-wastes and emissions are manageable using existing pollution controls. End-of-use recycling technologies are under development.
- PV installations can operate for many years with little maintenance or intervention after their initial set-up, so after the initial capital cost of building any solar power plant, operating costs are extremely low compared to existing power technologies.
- Solar electric generation is economically superior where grid connection or fuel transport is difficult, costly or impossible. Long-standing examples include satellites, island communities, remote locations and ocean vessels.
- When grid-connected, solar electric generation replaces some or all of the highest-cost electricity used during times of peak demand (in most climatic regions). This can reduce grid loading, and can eliminate the need for local battery power to provide for use in times of darkness. These features are enabled by net metering. Time-of-use net metering can be highly favorable, but requires newer electronic metering, which may still be impractical for some users.
- Grid-connected solar electricity can be used locally thus reducing transmission/distribution losses (transmission losses in the US were approximately 7.2% in 1995).
- Compared to fossil and nuclear energy sources, very little research money has been invested in the development of solar cells, so there is

Disadvantages:

- On the other hand, solar electricity is seen to be expensive. Once a PV system is installed it will produce electricity for no further cost until the inverter needs replacing. Current utility rates have increased every year for the past 20 years and with the increasing pressure on carbon reduction the rate will increase more aggressively. This increase will (in the long run) easily offset the increased cost at installation but the timetable for payback is too long for most.
- Solar electricity is not available at night and is less available in cloudy weather conditions from conventional silicon based-technologies. Therefore, a storage or complementary power system is required. However, the use of germanium in amorphous silicon-germanium thin-film solar cells provides residual power generating capacity at night due to background infrared radiation. Fortunately, most power consumption is during the day, so solar does not need to be stored at all as long to the extent that it offsets peak and “shoulder” consumption.
- Apart from their own efficiency figures, PV systems work within the limited power density of their location's insolation. Solar cells produce DC which must be converted to AC (using a grid tie inverter) when used in current existing distribution grids. This incurs an energy loss of 4-12%.

2.3. Technical study

A PV cell is a semiconductor device that produces electricity directly from photons (sunlight). A series of cells is interconnected on a panel, with electrical output ranging from 10 to 200 Wp typically. The function of the panel or module is to allow building integration and to protect the cells from the weather. Multiple panels may then be interconnected to form a string, and several strings may be used in parallel to form an array.

Silicon is the main semiconductor used in commercial cells [12]. Panels marketed are mostly made from mono-crystalline, poly-crystalline, or amorphous silicon cells. Many other materials are being developed but have not yet achieved the production level of silicon cells.

While conventional mono-crystalline cells have an efficiency of 13 to 16% and polycrystalline about 12 to 14%, relatively high efficiencies (about 18%) are achieved by using new mono-crystalline cells with embedded contacts and a grooved surface area. Amorphous silicon is the least efficient of the commercial silicon-based products. Its efficiency is in the 8 to 10% range when new, while instability of the material lowers efficiency to a stabilized efficiency of about 3 to 6% after a few months' exposure to sunlight. The efficiency of PV panel (n_p), is the ratio of electric power produced by a photovoltaic panel at any instant to the power of the sunlight striking the panel,

$$n_p = \frac{P_p}{G \times S} \tag{2.1}$$

$$n_p = \frac{E}{H \times S} \tag{2.2}$$

Where,

P_p = maximum power from PV panel, Wp

E = maximum energy from PV panel, kWh

S = total area of PV panel, m^2

G_i = total irradiance on the tilted PV plane, W/m^2

H_i = global direct irradiation on the PV array plane, kWh/m^2

The Watt-Peak (Wp), is the maximum electric power output produced by a PV panel illuminated under standard test conditions (STC) of 1000 watts of light intensity per square meter, for 25 °C ambient temperature and a spectrum similar to sunlight that passed through the atmosphere (air mass 1.5). Light conditions vary throughout the day and the PV array output will more or less vary accordingly. In the field, peak power only occurs occasionally, and as a yearly average, panels will produce no more than 20% of their rated output over a 24-hour period.

Among the other factors that affect the PV output, temperature is the most significant. In general rice in temperature reduces the performance of the PV array. In a similar way, when temperature drops, the voltage increases and PV panels produce more electricity.
For higher temperatures than those in STC, the efficiency of PV panel is reduced by a temperature coefficient σ_t. **Fig. 2.4** shows the variation in voltage due to variable temperature conditions. For STC σ_t = 1. The atmospheric dirt coefficient (σ_f) is the rate of electric power produced by the "dirty" surface of a PV panel to the electric power produced by the clean surface of a PV panel. Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing output. It is more realistic to estimate system output taking into account the reduction due to dust buildup in the dry season. A typical annual dust reduction factor to use is 93%. Thus, the energy produced by a PV panel is given:

$$E = H_i \times S \times n_p \times \sigma_t \times \sigma_f \qquad (2.3)$$

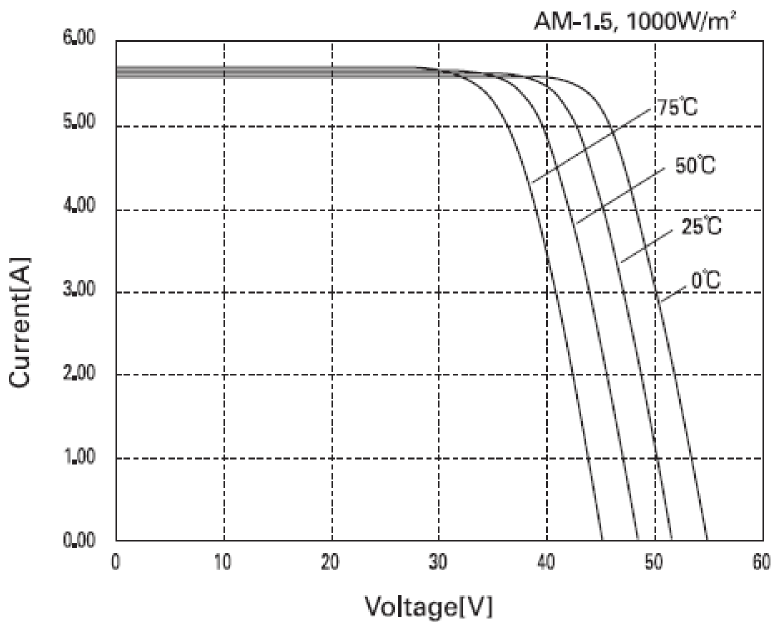


Fig. 2.4 – I-V curve of PV panel in STC. Variation in voltage due to variable temperature conditions.

The daily average energy production from PV panel is given by **equations (1), (2)** and **(3)** as follow:

$$E(kWh/d) = H_i(kWh/m^2\ d) \times \frac{P_p(kWp)}{1(kW/m^2)} \times \sigma_t \times \sigma_f \qquad (2.4)$$

The electrical characteristics and I-V curve of PV panel provided by manufactures are shown in **Table 2.1** and **Fig. 2.5**, respectively.

Table 2.1. - Electrical characteristics of PV panel	
Electrical Data	**Unit**
Maximum power (Pmax)	[W]
Max. power voltage (Vmp)	[V]
Max. power curent (Imp)	[A]
Open circuit voltage (Voc)	[V]
Short circuit current (Isc)	[A]
Warranted minimum power (Pmin)	[W]
Maximum over current rating	[A]
Output power tolerance	[%]
Maximum system voltage	[V]
Temperature coefficient of (Pmax)	[%/oC]
Voc	[V/oC]
Isc	[mA/oC]

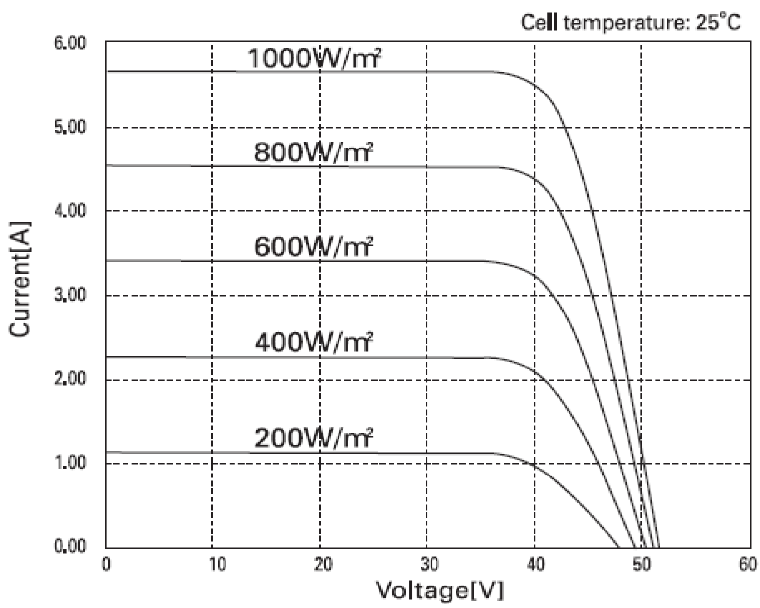


Fig. 2.5. – I-V curve of PV panel for variable irradiance.

2.4. PV systems standards

The achievement and maintenance of high performance of any system, in general, require an understanding and quantification of system losses across the operating period, which in turn requires the measurement and analysis of system performance, according to the needs of the system and the system user. 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 [13].

For that purpose a technical committee (TC82) was established in 1981. It is the most important international body regarding photovoltaic related standardization. The main tasks of TC82 are to prepare international standards for systems of photovoltaic conversion of solar energy into electrical energy and for all the elements in the entire photovoltaic energy system. TC82 has several working groups - each group is responsible for specific standardization related topic (glossary, non concentrating modules, BOS, PV energy storage systems and concentrator modules).

The IEC 61724 "Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis" standard [14-19], is introduced to characterize the long-term behavior of the suggested autonomous PV- RO system presented in this study (see **Chapter 5**). 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.

2.4.1 Energy balance equations and system performance indicators

The equations governing the energy balance of the different configuration systems as defined in the IEC-61724 Standard **(Fig. 2.5),** can be written in the following way [15]:

$$E_{in} = E_A + E_{BU} + E_{FU} + E_{FS} \tag{2.5}$$

$$E_{use} = E_L + E_{TU} + E_{TS} \tag{2.6}$$

Where:

E_{in} = The Energy IN the System

E_{use} = The Energy Used

E_{FU} = The Net Energy FROM Utility

E_{TU} = The Net Energy TO the Utility

E_{FS} = The Net Energy FROM Storage Unit

E_{TS} = The Net Energy to the Storage Unit

E_A = The Energy from PV array

E_{BU} = The Energy from Back-up Unit

E_L = Energy to the Load.

The Energy fraction (F_A) is defined as the total energy from PV Array to the total energy in the system.

$$F_A = E_A / E_{in} .$$

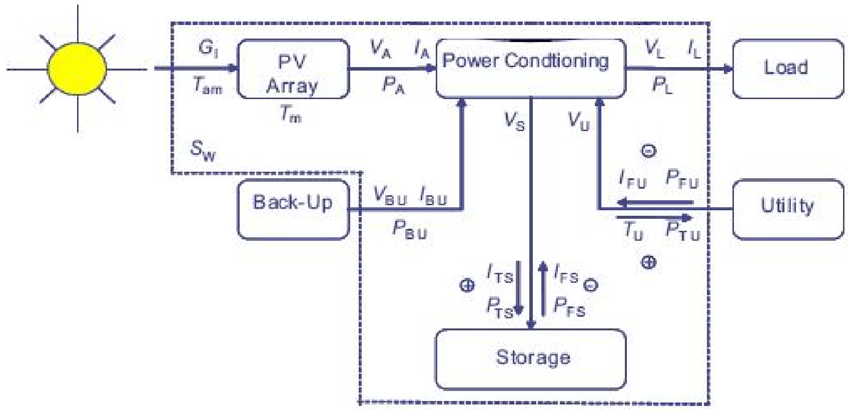


Fig. 2.5 – Real-time measured parameters defined in IEC-61724, [15].

As it was mentioned before, the analysis of the system presented in this study will follow the IEC-61724 International Standard. The real-time parameters (for measurements) are presented in **Table 2.2.**

Table 2.2 - Real-time parameters		
Parameter	**Symbol**	**Unit**
Metereological		
Daily global irradiation on the PV array plane	H_i	$Wh/m^2/day$
Total irradiance on the tilted PV plane	G_i	W/m^2
Ambient temperature	T_{am}	^oC
Atmospheric Pressure	P_A	*Atm.*
Relative Humititive	*Hum*	%
PV array		
Output voltage	V_A	V

Output current	I_A	A
Output power	P_A	W
Module temperature	T_m	^oC
Slope angle of the tracker	ϑ_{T}	*Degrees*
Azimuth angle of the tracker	ϑ_{A}	*Degrees*
Energy storage		
Operating voltage	V_s	V
Current to storage	I_{TS}	A
Current from storage	I_{FS}	A
Power to storage	P_{TS}	W
Power from storage	P_{FS}	W
Load		
Load voltage	V_L	V
Load current	I_L	A
Load power	P_L	W

Utility		
Voltage	V_U	V
Current to the utility	I_{TU}	A
Current from the utility	I_{FU}	A
Power to the utility	P_{TU}	W
Power from the utility	P_{FU}	W
Back-up sources		
Output voltage	V_{BU}	V
Output current	I_{BU}	A
Output power	P_{BU}	W

To compare PV systems, normalized performance indicators are used: e. g. energy yields (normalized to nominal power of the array), efficiencies (normalized to PV array energy) and performance ratio (normalized to inplane irradiation).

The most appropriate performance indicators of a PV system are:

The **final yield** ($Y_{f,A}$) is the energy (kWh) delivered to the load per day and kWp ($hours/day$). The **reference yield** ($Y_{r,A}$) is based on the inplane irradiation and represents the theoretically available energy per day and kWp ($hours/day$). The

performance ratio (PR) is the ratio of PV energy actually used to the energy theoretically available (i.e. $Y_{f,A}/Y_{r,A}$). 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.

From the performance analysis of 260 PV plants in the IEA-PVPS Task 2 database [20], the following annual performance ratios can be expected for the different types of systems:

- Grid-connected PV systems. PR = 0.6 - 0.8
- Stand-alone systems without back-up. PR = 0.1 - 0.6
- Stand-alone systems with back-up. PR = 0.3 - 0.6

The distribution of annual performance ratio calculated from 170 grid-connected PV systems shows that the PR significantly differs from plant to plant and ranges between 0.25 and 0.9 with an average PR value of 0.66. It was found that well maintained PV systems operating well show an average PR value of typically 0.72 at an availability of 98 %. A tendency of increasing annual PR values during the past years has been observed. Despite good results, which have been obtained in many of the grid-connected systems, the investigation of the operational behaviour of the reported PV systems has identified further potential for optimization. The performance analysis of data from stand-alone and hybrid systems has revealed that operational performance is not only depending on the component efficiency, but also on system design and load pattern Annual performance ratios range from 0.2 to 0.6 for off-grid applications depending on whether they have a back-up system or not and from 0.1 to 0.25 for off-grid professional systems, which are often oversized for reliability reasons.

Stand-alone systems: The performance analysis of stand-alone systems in terms of performance ratio has shown that in contrast to grid-connected systems, the PR alone cannot be used to describe the proper operation of stand-alone systems from a technical point of view [21],[22].

For the above reason, two new parameters have been introduced to characterize the performance of stand-alone systems:

The **matching factor** (MF_A) is the product of the performance ratio and the array fraction (F_A) and indicates how the PV generated energy matches the electrical load while using a back-up contribution (SAS) or energy from the grid (GCS). The matching factor is valuable for all hybrid systems (F_A less than one) and for grid-connected systems with a considerable contribution from the grid (F_A less than one).

The **usage factor** (UF_A) 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. E_{pot} is a measured energy quantity, which differs from E_{pot} for all SAS, presenting PV array disconnection due to a fully charged battery. The derived parameters, as shown **Table 2.2**, are presented in **Table 2.3**.

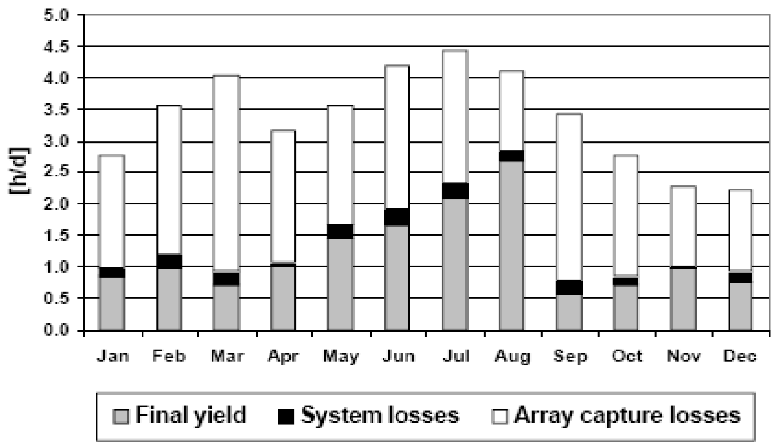
Table 2.3 - Derived parameters			
Parameter	**Symbol**	**Equation**	**Unit**
Electrical energy quantities			
Net energy from the PV array*	E_A	$E_A = \sum_{\tau} P_A$	Wh
Net energy from the back-up generator	E_{BU}		Wh
Net energy to the storage	E_{TS}		Wh
Net energy from storage	E_{FS}		Wh
Net energy to the utility	E_{TU}		Wh
Net energy from the utility	E_{FU}		Wh
Load efficiency	n_{LOAD}		*Dimensionless*
Energy fraction from the PV array	F_A	$F_A = E_A / E_{in}$	*Dimensionless*
Energy fraction from the back-up gen.	F_A	$F_{BU} = E_{BU} / E_{in}$	*Dimensionless*
Total energy in the system	E_{in}	$E_{in} = E_A + E_{BU} + E_{FU} + E_{FS}$	Wh
Total energy used	E_{use}	$E_{use} = E_L + E_{TU} + E_{TS}$	Wh
Net energy to the load	E_L		Wh

Table 2.3 (continue) - Derived parameters			
Parameter	**Symbol**	**Equation**	**Unit**
BOS component performance			
BOS efficiency	n_{LOAD}	$n_{LOAD} = \frac{E_{in}}{E_L}$	%
System performance indices			
PV array yield	Y_A	$Y_A = E_A / P_{A,N}$	h/day
Final PV system yield	$Y_{f,A}$	$Y_{f,A} = E_{A,use} / P_{A,N}$	h/day
Reference yield for the PV array*	$Y_{r,A}$	$Y_{r,A} = \int_{\tau} G_i dt / G_{STC}$	h/day
Normalized losses			
PV array capture losses	$L_{c,A}$	$L_{c,A} = Y_{r,A} - Y_A$	h/day
PV BOS losses	$L_{BOS,A}$	$L_{BOS,A} = Y_A - Y_{f,A}$	h/day
Performance ratio for the PV array	PR	$PR = Y_{f,A} / Y_{r,A}$	$Dimensionless$
System efficiencies			
Average PV array efficiency*	$n_{A,mean}$	$n_{A,mean} = E_A \Big/ \int_{\tau} G_i \times A_a \, dt$	%
Global PV array generation efficiency*	$n_{A,tot}$	$n_{A,tot} = E_{use,A_{\tau}} \Big/ \int_{\tau} G_i \times A_a \, dt$	%
Matching factor			
PV matcing factor	MF_A	$MF_A = PR \times F_A$	$Dimensionless$
Usage factor			
PV usage factor	UF_A	$UF_A = E_A / E_{pot}$	$Dimensionless$

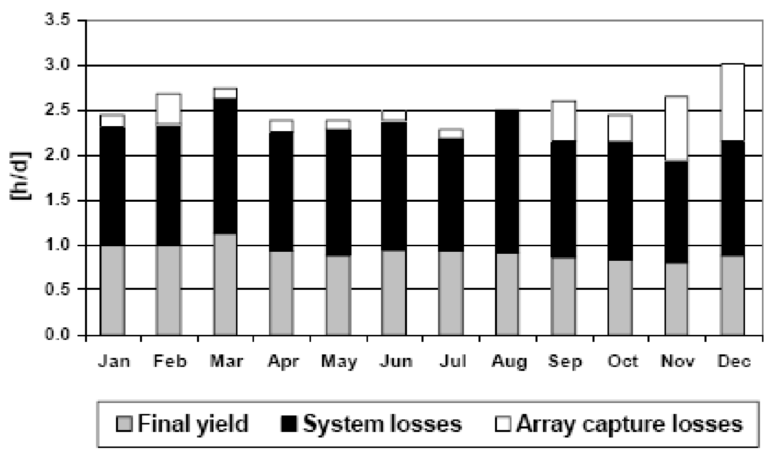
* The sub index τ, appearing in many of the parameters presented in the standard denoting the reporting period.

* h/day unit may be more illustrative expressed as ($kW\,h/day$) real/ (kW) assigned.

An illustration of system performance indicators of two different SAS is shown in **Fig. 2.6 (a)** and **(b).**



(a)



(b)

Fig. 2.6. - Indices of performance for two different SAS with (a) PR = 0.31 and UF = 0.45 and (b) PR = 0.31 and UF = 0.9 [14].

If the PV array is of too low size for the considered application, the PV system will show a very high value of PR, but at the same time the user will sometimes not be supplied with electricity. An oversized system has to face frequent array disconnection affecting directly the PR value. For SAS systems without a back-up generator, the PV array is often oversized for reliability reasons. Hybrid systems, present higher PR values but also higher capital investment and maintenance. In **Fig. 2.7** a range of PR values for PV-only and hybrid systems is illustrated.

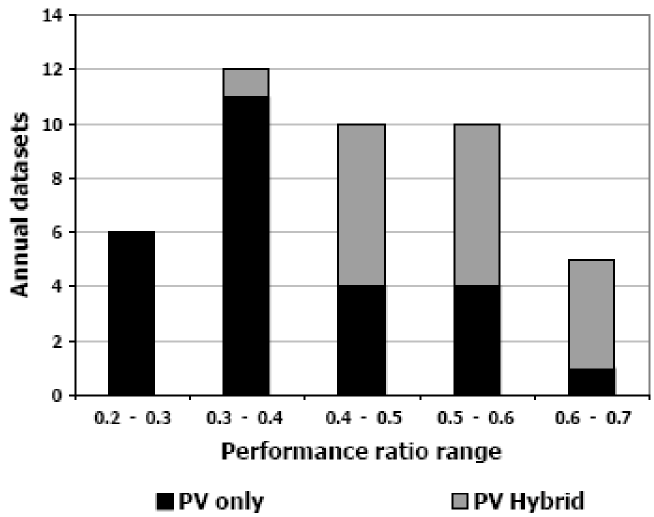


Fig. 2.7 - Range of PR values for PV-only and hybrid systems.

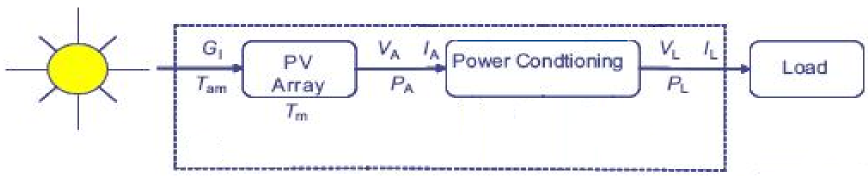
Finally, a detailed analysis concerning the operation of stand-alone systems will necessitate:

- More detailed and more reliable monitoring campaigns, which are feasible even for small remote systems with the development of integrated data loggers.
- Several years of measurement to better appreciate the evolution of user behaviour over time.
- The use of simulation tools to evaluate the influence of new component sizes or new regulation strategies to increase the system performance.

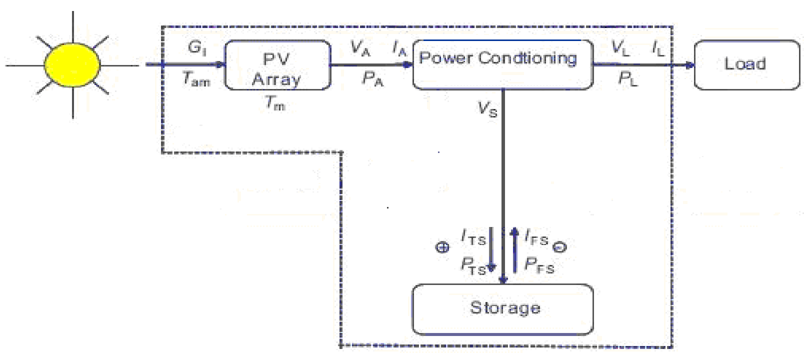
2.5. Stand-alone systems types

Stand-alone systems are usually categorized into three types, depending on whether they use battery storage and/or back-up generators. **Fig. 2.8 (a), (b)** and **(c),** illustrates these three categories [23].

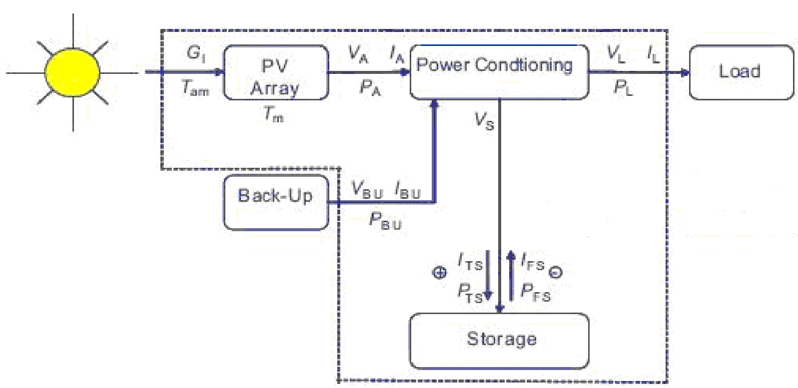
A PV array is generally mounted in a fixed position at an appropriate tilt angle, facing towards the equator. The main advantages of this approach is that minimize human intervention, but it also limits the performance. Different ways of improving the performance have been tried and these include manual tilting, tracking arrays and use of concentrators or reflectors. The main disadvantage of these systems, however, is that they have mechanical moving parts that require maintenance. Furthermore, the cost of the system is increased significantly.



(a)



(b)



(c)

Fig. 2.8. - **(a)** Only PV, **(b)** PV- Batteries, and **(c)** PV-Back-up-generator-Batteries.

2.6. Component Sizing and matching [24-26].

A first simple, yet crucial, step in the design of stand-alone PV system is the load assessment. Although straight forward, this step is too often not carried out carefully enough, leading to a suboptimal operation of the PV system. Overestimating the load will ensure a reliable supply of electricity, but the cost of the system will be unnecessarily high. On the other hand, underestimating the load can lead to an unreliable power supply, increased ageing of the batteries and unexpected use of a back-up diesel generator (if it is used). At worst, the system may fail to supply a critical load. Consequently, all loads must be properly evaluated, both in terms of power and duty cycle (number of hours per day, in a certain period). This indicates the daily energy needs.

The maximum demand assessment is also important as the system must be sized to have the capacity to power the load. This requires an evaluation of the maximum power that might be required at any time (worst case). Since high values will result in a more expensive system (more storage and possibly a larger inverter would be required), it is wise to consider managing the loads either by reducing demand peaks or by matching demand peaks to renewable energy input peaks.

2.6.1. Battery

For the applications requiring energy during periods of low sunlight or at night, a storage medium must be used to ensure the autonomy of the system. Most stand-alone systems require storage. The usual storage equipment used with stand-alone PV systems is rechargeable batteries. The following is a brief overview of the different types of battery used with PV systems.

Two battery technologies are generally found in PV systems: lead-acid and nickel-cadmium. Both can be found in a variety of sizes and capacity. Nickel-cadmium batteries present some technical advantages over lead-acid and are preferred for some applications.

However, they are 3-4 times more expensive per unit of energy stored and consequently lead-acid batteries are more commonly used.

Lead-acid and nickel-cadmium batteries are divided in two categories: open units (often referred as ‘vented’) and sealed units (also called ‘valve-regulated’). When overcharged, batteries produce hydrogen and oxygen and there is also a consequential loss of water. In open batteries that loss needs to be made up from time to time. Sealed units, when properly operated, will minimize this loss. For this reason, these are generally considered to be ‘maintenance-free’ batteries. However, if they are mistreated and overcharged, a valve will let the battery vent, which will result in a permanent loss, since water cannot be added to this units.

Other characteristics, such as the construction of the plate and type of electrolyte, make some batteries more appropriate under certain operating conditions. For instance, solar-powered telecommunication systems include batteries designed to provide back-up power. Their duty cycle involves frequent and relative light discharges compared to batteries used in most other duty cycles. Starter batteries, as applied in vehicles, are designed to accommodate frequent sharp, but shallow discharges. Batteries designed for renewable-energy systems must withstand regular deep discharging. Because batteries are designed to suit a particular duty cycle, it is important that correct type of battery is selected for a given application. Some manufacturers provide an indication of the battery life as a function of the number of cycles and the depth of discharge. The system design will need to take into account the efficiency of energy storage by the battery. The energy returned upon discharge is lower than the energy supplied upon charging because the battery voltage is higher during charging than during discharge. Some charge may also lose in the battery, principally during gassing. The overall energy efficiency of most lead-acid batteries is like to be in the range between 85 and 90%.

Although specialized PV batteries are now becoming available on the market, most batteries that are currently installed in PV systems are standard components originally intended for conventional application, or adapted from them to suit the particular mode of operation envisaged for the PV system.

2.6.1.1. Battery Capacity

Batteries are rated by Amp-hour (Ah) capacity. The capacity is based on the amount of power needed to operate the loads and how many days of stored power will be needed due to weather conditions. In theory, a 100 Ah battery will deliver one Amp for 100 hours or roughly two Amps for 50 hours before the battery is considered fully discharged. If more storage capacity is required to meet a specific PV application requirement, then batteries can be connected in parallel. Higher voltages can be obtained through series wiring. Some available configurations are shown in **Fig. 2.9**.

Many factors can affect battery capacity, including rate of discharge, depth of discharge (DOD), temperature, age, and recharging characteristics. Fundamentally, the required capacity is also affected by the size of the load.

Since it is easy to add PV modules to an existing PV system, a commonly held misconception is that the entire PV system is modular as well. However, manufacturers generally advise against adding new batteries to an old battery bank. Older batteries will degrade the performance of new batteries (since the internal cell resistance is greater in old batteries) and could result in reduced system voltage when wired in series. In addition, if we were to add batteries to an existing system, we would probably add them in parallel to increase Amp-hour capacity and maintain system voltage. Also it’s advisable to minimize excessive “paralleling” because this increases the total number of cells, thereby increasing the potential for failure from a bad cell. It is also recommended to initially specify a slightly larger battery capacity than is needed because batteries lose their capacity as they age. However, if we greatly oversize the battery bank, it may remain at a state of partial charge during periods of reduced insolation. This partial charge state can cause shortened battery life, reduced capacity, and increase sulfation.
Consequently battery capacity should be determined by the overall load profile.

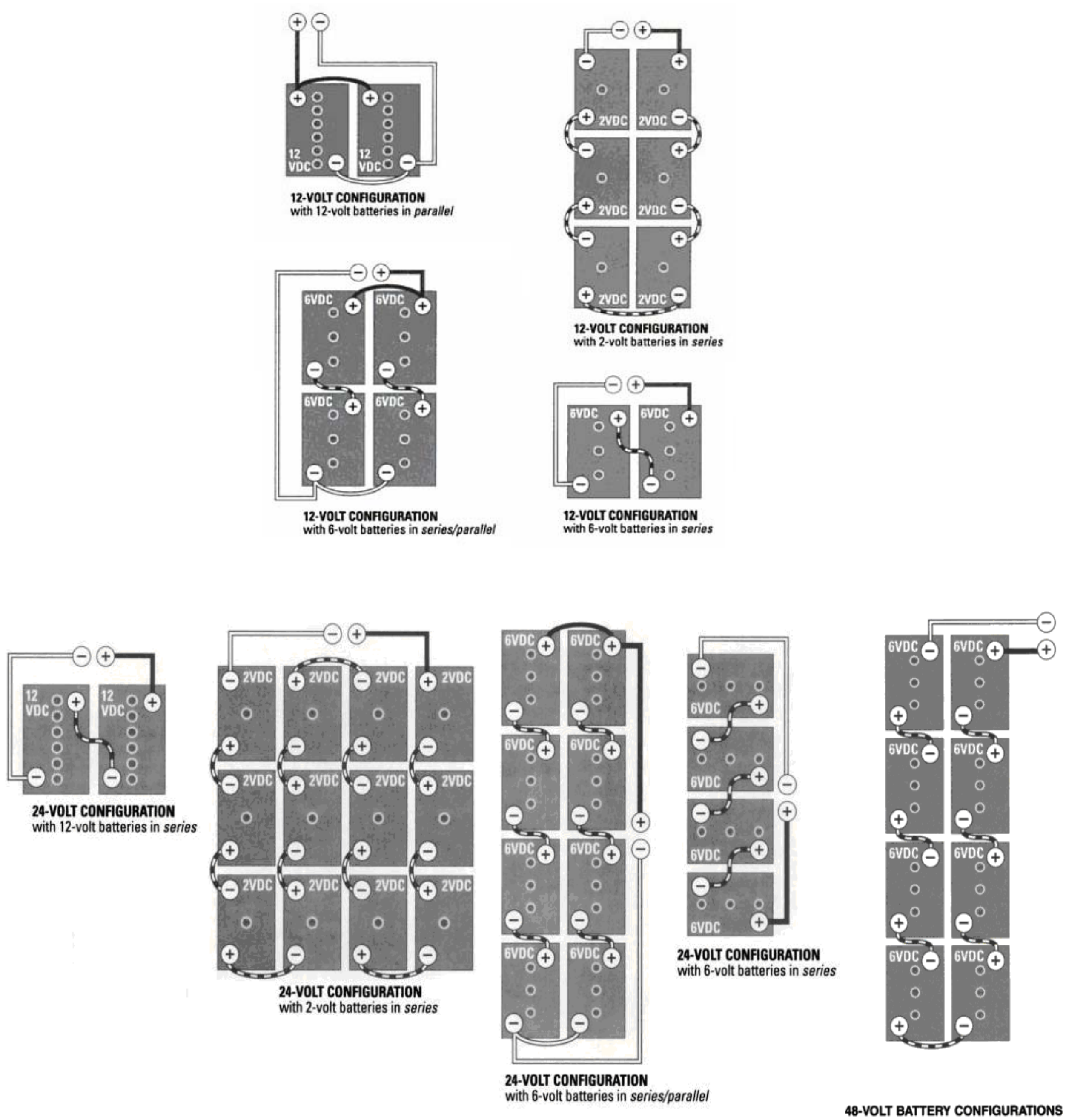


Fig. 2.9. - Some available battery configurations [24].

2.6.1.2. Rate and Depth of Discharge

The rate at which the battery is discharged directly affects its capacity. If the battery is discharged quickly, less capacity is available. Conversely, a battery that is discharged slowly will have a greater capacity. A common battery specification is the battery's capacity in relation to the number of hours that it is discharged. For example, when a battery is discharged over 20 hours, it is said to have a discharge rate of C/20 or capacity at 20 hours of discharge. If a battery is discharged over 5 hours, the discharge rate is C/5. Note that the C/5 discharge rate is four time faster than the C/20 rate. Most batteries are rated at the C/20 rate.

Similar consideration should be taken when charging batteries. Most flooded lead-acid batteries should not be charged at more than the C/5 rate. Gel-cell, however should never be charged at higher than a C/20 rate.

Thus, DOD refers to how much capacity will be withdrawn from battery resulting in battery life which is directly related to how deep the battery is cycled. For example, if a battery is discharged to 50% every day, it will last about twice as long as if is cycled to 80%. Lead-acid batteries should never be completely discharged, even though some deep cycle batteries can survive this condition the voltage will continually decrease. Nickel-cadmium batteries, on the other hand, can be totally discharged without harming the battery and hold their voltage. When the nickel-cadmium is fully discharged it may reverse polarity potentially harming the load. A manufacturer's specification sheet will list the maximum DOD for any battery. The most practical number to use when designing a system is 50% DOD for the best storage versus cost factor. The previous mentioned are summarized in two equations:

$$C_N = \frac{E}{n \times D_d \times V_0} \qquad (2.1)$$

$$P_b = \frac{n \times C_N \times V_0}{24 \times \mu} \tag{2.2}$$

Where:

C_N = Battery capacity, Ah

E = Energy produced from PV, kWh

n = Battery efficiency

D_d = Depth Of Discharge (DOD)

V_0 = Battery voltage, V

P_b = Battery Power, kW

μ = Autonomy days, d

2.6.1.3. Environmental Conditions

Batteries are sensitive to their environment and are particularly affected by temperature of that environment. Higher voltage charge termination points are required to complete charging as a battery's temperature drops and vice versa. Controllers with a temperature compensation feature can automatically adjust charge voltage based on a battery's temperature.

2.6.2. The power-conditioning equipment

2.6.2.1. Inverters

Alternating current (AC) is easier - in terms of performance - to transport over a long distance and has become the conventional modern electrical standard. Consequently, most common appliance or loads are designed to operate on AC. PV and batteries are well known that operate and store direct current (DC). AC and DC are, by nature fundamentally incompatible. Therefore, a “bridge” – an inverter – is needed between the two.

Historically, inverters have been a weak link in PV systems. Early inverters were unreliable and inefficient, imposing large penalties on overall system performance. System inefficiencies were compounded by the fact that most AC appliances used large amounts of power. Recent improvements in inverters and appliances have reduced this penalty and made inverters a viable “bridge” between DC power sources and AC load requirements.

The fundamental purpose of a PV system inverter is to change DC electricity from PV modules and batteries to AC electricity, and finally to power AC loads. Inverters can also feed electricity back into the grid (grid-tied).

Over the years, inverter manufacturers have used different technologies to convert low voltage DC electricity to higher voltage AC. The first inverters used a basic transistor to abruptly switch the polarity of the DC electricity from positive to negative at close 50 or 60 times per second (frequency in Hz), creating a square wave form and then passes through a transformer to increase the voltage. A transformer increases (or decreases) the voltage, by passing electricity through a primary transformer coil and then to the secondary transformer coil. If, the number of windings in the secondary coil is greater than the number in the primary coil, then the voltage in the secondary coil will increase directly proportionate to the number of winding in each coil. Stand-alone inverter transformers are designed to increase voltage up to 230 volts alternating current (VAC) depending upon the country in which they will be used.

The advent of sophisticated integrated circuits, field effect transistor, and high-frequency transformers has allowed the creation of lighter, more efficient inverters that produce a waveform closer to a true sine wave. Thus, instead of converting the low voltage DC directly to i.e. 230VAC they use a computerized multi-step process with variable time cycles.

2.6.2.2. Inverter - Operating principles

A system designer should know the optimal features of an inverter when choosing one. Inverter features include the following:

- High efficiency. The inverter should convert 80% or more of the incoming DC input into AC output.
- Low standby losses. The inverter should be highly efficient when no loads are operating.
- High surge capacity. The inverter should provide high current required to start motors or run simultaneous loads.
- Frequency regulation. The inverter should maintain 50 or 60 Hz over a variety of input conditions.
- Harmonic distortion. The inverter should “smooth out” unwanted output peaks to minimize harmful heating effects on appliance.
- Ease of servicing. The inverter should contain modular circuitry that is easily replaced in the field.
- Reliability. The inverter should provide dependable long-term low maintenance.
- Automatic warning or shut-off. The inverter should contain protective circuits that guard the system.
- Power correction factor. The inverter should maintain optimum balance between the power source and load requirements.
- Low weight. The inverter should facilitate convenient installation and service.
- Battery charging capability. Many PV systems have backup AC power source, such as a generator, to charge the batteries. A battery charging capability on an inverter allows the generator to charge the batteries through the inverter (by converting the AC to DC with appropriate voltage) instead of through a separate battery-charging component.
- Low cost. The inverter’s price should fit the system budget.

In addition to the primary functions listed above, the following are desirable features for an inverter:

- Remote control operation: The inverter can be programmed and monitored from a remote location with special unit.
- Load transfer switch: Manual load switching allows an inverter to meet critical loads in case of failure. This is design to increase system reliability in systems that have multiple inverters.
- Capability for parallel operation: In some systems it is advantageous to use multiple inverters. Those inverters can connect in parallel to service more loads at the same time.
- Capability for series operation: In systems with multiple inverters, this feature enables the inverter to operate higher voltage loads.

2.6.2.3. Inverter types

There are two categories of inverters. The first category is synchronous or grid-tied inverters, which are used with grid connected PV systems. The second category is stand-alone or static inverters, which are designed for independent, utility-free power systems and are appropriate for remote PV installations. Some inverters may have features from both types to facilitate future utility-connected options.
Another classification for inverters is the type of waveform they produce. The three most common waveforms **(Fig. 2.10)** include the following:

Square wave. Are used to switch the DC input into a step-function or ‘square’ AC power and they are used for appliance with low capabilities.
Modified square wave. This type of inverters uses effect transistors (FET) or silicon-controlled rectifiers (SRC) to switch DC input to AC output. This style of inverters is more appropriate for operating a wide variety of loads and standard electronic equipment but is less effective than the sine wave inverters.

Sine wave. Are used to operate sensitive electronic hardware that requires high quality waveform.

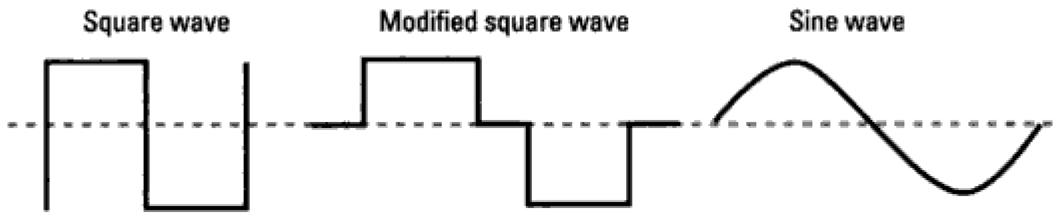


Fig. 2.10. - The three most common inverters waveforms

2.6.2.4. Inverter specifications

Most inverters will list some if not all of the following specifications:

- **Watts Output:** This indicates how many watts of power the inverter can supply during standard operation. It is important to choose an inverter that will satisfy a system's peak load requirements. However, system designers should remember that over-sizing the inverter could result in reduced system efficiency and increased system cost.
- **Voltage Input or Battery Voltage:** This figure indicates the DC input voltage that the inverter requires to run, usually 12, 24, or 48 V. The inverter voltage must match the nominal PV system voltage.
- **Surge Capacity:** Most inverters are able to exceed their rated wattage for limited periods of time. This is necessary to power motors that can draw up to seven times their rated wattage during start up. As a rough "rule of thumb" minimum, surge requirements of a load can be calculated by multiplying the required watts by three.
- **Frequency:** Inverters should provide 50Hz for Europe countries and 60Hz for US.

- **Voltage Regulation:** This figure indicates how much variability will occur in the output voltage. Better units will produce a near constant output voltage.
- **Efficiency:** if inverter will operate frequently, high efficiency unit is essential. Many inverter manufacturers claim high efficiency. However, inverters may only be efficient when operated at or near certain outputs. Therefore, it is usually wise to choose a unit rated at a high efficiency over a broad range of loads. Fig. 2.11 shows a sample efficiency curve of a 4 kW inverter which is most efficient operating at 400 W.

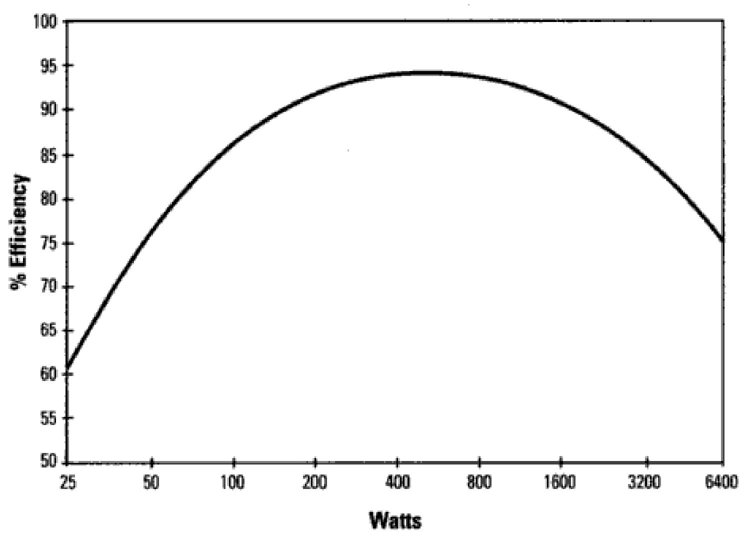


Fig. 2.11 - A sample efficiency curve of a 4 kW inverter.

2.6.3. Controllers

The PV control is a voltage regulator. The primary function of controller is to prevent the battery from being overcharged. Many PV controls also protect a battery from being overly discharged by the DC load. When the batteries are fully charged, the control will stop or decrease the amount of current flowing from the PV array into the battery. When the batteries are being discharged to a low level, many controllers will shut off the current flowing from the battery to the load(s).

2.6.3.1 Controllers type

Charge controls come in many sizes, typically from just a few Amps to as much as 60 Amps. Higher amperage units are available, but rarely used. If high currents are required, two or more PV controllers can be used. When using more than one controller, it is necessary to divide the array into sub-arrays. Each sub-array will be wired into its own controller and then they will all be wired into the same battery bank. There are four different types of PV controls:

- **Shunt controls.** Are designed for very small systems. They prevent overcharging by "shunting" or bypassing the batteries when they are fully charged. The shunt controller's circuitry monitors the battery voltage and switches excess current through a power transistor when a pre-set full charge value is reached. This acts like a resistor and converts the excess power into heat. Shunt controllers have heat sinks with fins that help to dissipate heat. These controllers may also incorporate a blocking diode to prevent current from draining back from batteries through the solar array. Shunt controllers are simply designed and inexpensive. They must be exposed to open air to provide the ventilation required from the cooling fins. Their disadvantages are their limited load handling capability and ventilation requirements.
- **Single-stage controls.** Single-stage controllers prevent battery overcharging by switching the current off when the battery voltage reaches a pre-set value called the charge termination set point (CTSP). The array and battery are automatically reconnected when the battery reaches a lower preset value called the charge resumption set point (CRSP). Some manufacturers incorporate a built-in timer to cycle the constant voltage charge during the end of the charging process to "top-off" the battery bank. Single-stage controllers use a sensor to break the circuit and prevent reverse current flow at night, instead of using a block diode. These controllers are small and inexpensive, eliminating the need for bulky heat

- **Multi-stage controls.** These devices automatically establish different charging currents depending on the battery's stage charge. The full array current is allowed to flow when battery is at low state of charge. As the battery bank approaches full charge, the controller dissipates some of the array power so that less current flows into the batteries. This charging approach is said to increase battery life. Like shunt controllers, heat is generated by the dissipation of power, requiring that multi-stage controllers be properly ventilated. These controllers generally have a relay type switch that prevents reverse "leakage" at night.
- **Pulse controls.** These provide a "topping off" charge by rabidly switching the full charging current on and off when the batter voltage reaches a fully charge state (the pre-set charge termination point). The length of charging current pulse gradually decreases as battery voltage rises. Blocking diodes may be used in these controllers.

2.6.3.2. Controllers - features & specification

A PV system controller must much the system voltage. Secondly, a controller must be cable of handling the maximum load current (amperage) that will pass through the controller. Thirdly, a controller must be able to handle the maximum PV array current.
This feature can be provided by the maximum power point tracker (MPPT) often integrated as a function in the charge controller. The National Electric Code (NEC) requires that the PV array current should not be more than 80% of controller rating. Thus, we can use the maximum array Amps at short circuit current (which is greater than the operating Amps) plus 25% safety margin to conservatively determine this figure. Some PV manufacturers specify a generic battery voltage that the controller begins charging or stop charging. These set points may be fixed or field-adjustable.

2.7. REFERENCES

- **See Chapter 6.**

CHAPTER 3

DESALINATION

3.1 Overview

According to the World Health Organization (WHO), water scarcity affects one in three people around the globe [1]. Even in the developed countries, water shortages are expected during the next decade. As the world faces growing water scarcity challenges, the need for conservation and recycling of water is more important than ever before.

Water use has been growing at more than twice the rate of population increase in the last century. By 2025, 1.8 billion people will be living in countries or regions with water scarcity, and two-thirds of the world population could be under stress conditions, as stated by the Food and Agriculture Organization of the United Nations.

As the Middle East grapples with growing demand for sustainable supplies of clean water, water reuse and desalination has become an increasingly critical strategy [2]. The Middle East and North Africa region has 5 percent of the world's population and less than 1 percent of the world's available water supply. Water scarcity is a major threat to the region's standard of living. Furthermore, severe drought usually generates a general malaise in populations which are already affected by a number of social and poverty problems, which often lead to significant and uncontrolled emigration towards richer countries, especially if one takes into account the increasing economic and lifestyle gap between north and south Mediterranean countries. Emigration could be contained if basic life needs were guaranteed to the population in their homelands, particularly potable water supply. Abundant solar energy combined with desalination could provide a sustainable source of potable water. Unfortunately, a lot of research has to be done in that field to provide population with inexpensive fresh water. As a result, desalination technologies are emerging as a vital solutions to the region's and the world's water shortage challenges. With proper treatment, seawater, brackish water and wastewater can be reused for beneficial purposes such as drinking water, agricultural and landscape irrigation, industrial processes and similar uses, enabling communities and countries to stretch limited freshwater supplies.

Desalination among other water treatment technologies has major benefits and has to be studied further. Factors that have the largest effect on the cost of desalination are feed water quality (salinity levels), product water quality, site, energy costs as well as economies of scale [3][4]. Seawater desalination is being applied at 58% of installed capacity worldwide, followed by brackish water desalination accounting for 23% of installed capacity. **Fig. 3.1** outlines the global desalting capacity by feed water sources.

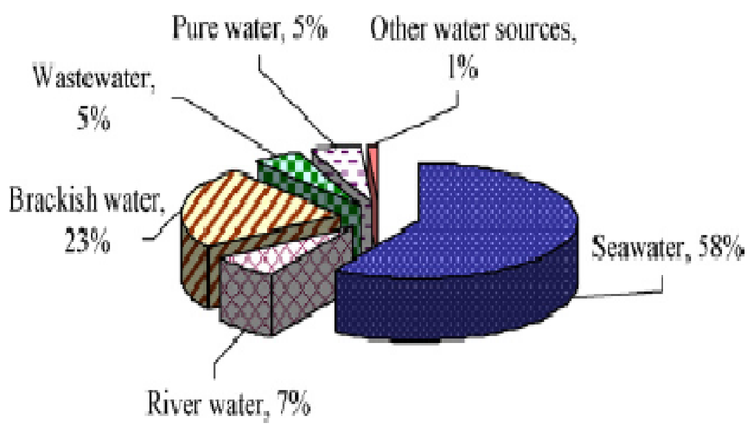


Fig 3.1. - Global water sources [3].

The real problem in erecting desalination technologies is the optimum economic design and evaluation of the combined plants in order to be economically viable for remote or arid regions. 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. Reverse osmosis is becoming the technology of choice with continued advances being made to reduce the total energy consumption and lower the cost of water produced [5].

As the technology grows, more efficient reverse osmosis (RO) systems are being developed, and RO systems are currently available from small to large capacities (capable of purifying a few liters of water per day to several thousand cubic meters for conventional water supplies).

The only nearly inexhaustible sources of water are the oceans. Their main drawback, however, is their high salinity. Therefore, it would be attractive to tackle the water-shortage problem with desalination of this water. According to World Health Organization (WHO), the permissible limit of salinity in water is 500 parts per million (ppm) and for special cases up to 1000 ppm, while most of the water available on earth has salinity up to 10,000 ppm, and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts. Excess brackishness causes the problem of taste, stomach problems and laxative effects. The purpose of a desalination system is to clean or purify brackish water or seawater and supply water with total dissolved solids within the permissible limit of 500 ppm or less. This is accomplished by several desalination methods that will be analysed in this chapter.

Desalination processes require significant quantities of energy to achieve separation of salts from seawater. This is highly significant as it is a recurrent cost, which few of the water-short areas of the world can afford. Many countries in the Middle East, because of oil income, have enough money to invest in and run desalination equipment. People in many other areas of the world have neither the cash nor the oil resources to allow them to develop in a similar manner. The installed capacity of desalinated water systems in year 2000 was about 22 million m^3/day, which is expected to increase drastically in the next decades. The dramatic increase of desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption and environmental pollution caused by the use of fossil fuels. It has been estimated that the production of 22 million m^3/day requires about 203 million tons of oil per year (about 8.5 EJ/yr or 2.36×1012 kWh/yr of fuel). Given concern about the environmental problems related to the use of fossil fuels, if oil was much more widely available, it is questionable if we could afford to burn it on the scale needed to provide everyone with fresh water.

Given current understanding of the greenhouse effect and the importance of CO2 levels, this use of oil is debatable. Thus, apart from satisfying the additional energy demand, environmental pollution would be a major concern. If desalination is accomplished by conventional technology, then it will require burning of substantial quantities of fossil fuels. Given that conventional sources of energy are polluting, sources of energy that are not polluting will have to be developed. Fortunately, there are many parts of the world that are short of water but have exploitable renewable sources of energy that could be used to drive desalination processes.

Solar desalination is used by nature to produce rain, which is the main source of fresh water supply. Solar radiation falling on the surface of the sea is absorbed as heat and causes evaporation of the water. The vapour rises above the surface and is moved by winds. When this vapour cools down to its dew point, condensation occurs and fresh water precipitates as rain. All available man-made distillation systems are small-scale duplications of this natural process.

Desalination of brackish water and seawater is one of the ways of meeting water demand. Renewable energy systems produce energy from sources that are freely available in nature. Their main characteristic is that they are friendly to the environment.

Production of fresh water using desalination technologies driven by renewable energy systems is thought to be a viable solution to the water scarcity at remote areas characterized by lack of potable water and conventional energy sources like heat and electricity grid. Worldwide, several renewable energy desalination pilot plants have been installed and the majority has been successfully operated for a number of years. Virtually, all of them are custom designed for specific locations and utilize solar, wind or geothermal energy to produce fresh water. Operational data and experience from these plants can be utilized to achieve higher reliability and cost minimization. Although renewable energy powered desalination systems by the time cannot compete with conventional systems in terms of the cost of water produced, they are applicable in certain areas and are likely to become more widely feasible solutions in the near future.

In this chapter, a description of the various methods used for seawater desalination is presented. Only methods, which are industrially matured, are reviewed. There are, however, other methods, like freezing and humidification/dehumidification methods, which are not included in this work as they are developed at a laboratory scale and have not been used on a large-scale for desalination. Special attention is given to the use of renewable energy systems in desalination. Among the various renewable energy systems, the ones that have been used, or can be used, for desalination are reviewed. These include solar thermal collectors, solar ponds, photovoltaics, wind turbines and geothermal energy.

3.2 Desalination and Energy

Energy has been recognized as important as water for the development of good standards of life because it is the force that puts in operation all human activities. Desalination is a proven technology capable of delivering small to large quantities of fresh water by separating dissolved minerals and impurities from seawater or other salty water. Desalination is commonly used in rural or isolated areas with dry climates where traditional water supplies, such as dams or pumping from groundwater, are limited. Although potable water is essential to ensure life in this regions, the energy demands for desalination plants becomes a great socio-economic factor. The use of renewable energy can help to decrease the gas emissions, as the rising need for fresh water increases the demands for desalination plants [5].

3.3 Desalination Processes

A wide variety of desalination technologies effectively removes salts from salty water, producing a water stream with low concentration of salt (the product stream) and another with a high concentration of remaining salts (the brine or concentrate). Most of these technologies rely on either distillation (thermal processes through phase-change) or membranes (or single-phase) to separate salts from the product water [6]. Thus, desalination techniques may be classified into the following categories:

- phase-change or thermal processes and
- membrane or single-phase processes.

In the phase-change or thermal processes, the distillation of seawater is achieved by utilizing a thermal energy source. The thermal energy may be obtained from a conventional fossil-fuel source, nuclear energy or from a non-conventional solar energy source or geothermal energy. In the membrane processes, electricity is used either for driving high-pressure pumps or for ionization of salts contained in the seawater.

Commercial desalination processes based on thermal energy are multi-stage flash (MSF) distillation, multiple effect distillation (MED) and vapour compression (VC), which could be thermal (TVC) or mechanical (MVC). MSF and MED processes consist of a set of stages at successively decreasing temperature and pressure. MSF process is based on the generation of vapour from seawater or brine due to a sudden pressure reduction when seawater enters an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure. This process requires an external steam supply, normally at a temperature around 100 ^{o}C. The maximum temperature is limited by the salt concentration to avoid scaling and this maximum limits the performance of the process. **Fig. 3.2** shows a schematic diagram of a basic MSF desalination process. On MED, vapours are generated due to the absorption of thermal energy by the seawater. The steam generated in one stage or effect is able to heat the salt solution in the next stage because the next stage is at a lower temperature and pressure. **Fig. 3.3** shows a schematic diagram of horizontal tubes in MED plant. The performance of the MED and MSF processes is proportional to the number of stages or effects. MED plants normally use an external steam supply at a temperature of about 70 ^{o}C. On TVC and MVC, after initial vapour is generated from the saline solution, this vapour is thermally or mechanically compressed to generate additional production as illustrated in **Fig. 3.3.**

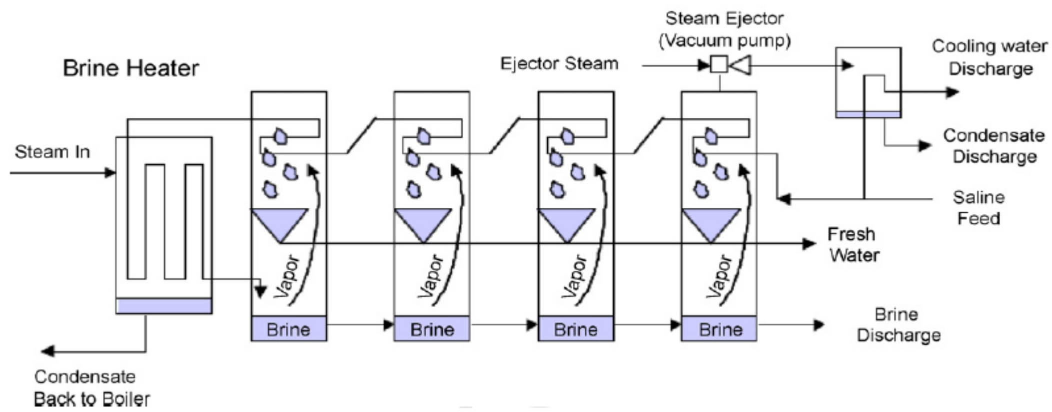


Fig. 3.2. - Schematic diagram of a basic multi-stage flash (MSF) desalination process [5].

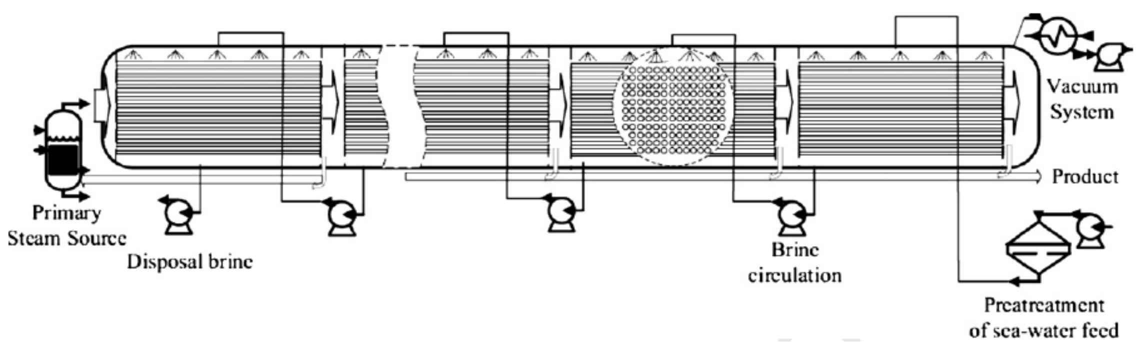


Fig. 3.3. - Schematic diagram of horizontal tubes in multi-effect distillation (MED) plant [5].

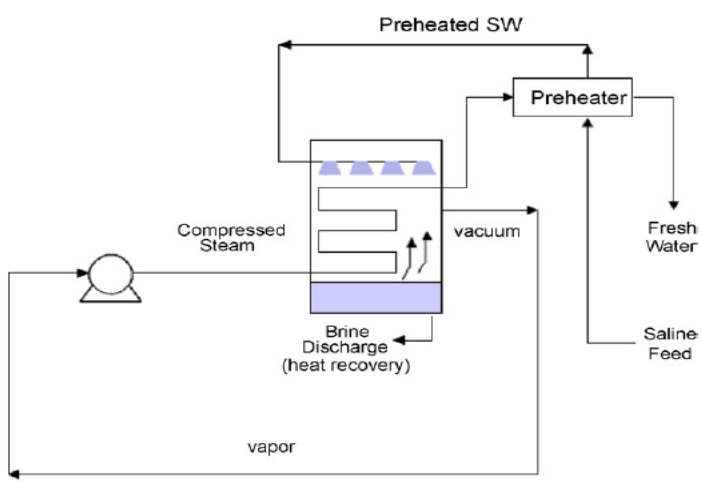


Fig. 3.4. - Schematic diagram of single stage mechanical vapour compression (MVC) [5].

MED plants tend to have smaller number of effects than MSF stage. Usually 8-16 effects are used in typical large plants, due to relation of the number of effects with the performance ratio. The performance ratio (water production to stream consumption) of the MED plant is approximately equal to the number of effects minus 1 (N-1). For an 8:1 performance ratio plant, the number of effects needed in a MED plant would be 9. This is much lower than in an equivalent MSF plant. The smaller number of effects in MED plants contributes to savings in capital cost compared with MSF [7].

Not only distillation processes involve phase change, but also freezing and humidification/dehumidification processes [8]. The conversion of saline water to fresh water by freezing has always existed in nature and has been known to man for thousands of years. In desalination of water by freezing fresh water is removed and leave behind concentrated brine. It is a separation process related to the solid– liquid phase change phenomenon. When the temperature of saline water is reduced to its freezing point, which is a function of salinity, ice crystals of pure water are formed within the salt solution. These ice crystals can be mechanically separated from the concentrated solution, washed and re-melted to obtain pure water. Therefore, the basic energy input for this method is for the refrigeration system. Humidification/dehumidification method also uses a refrigeration system but the principle of operation is different. The humidification/dehumidification process is based on the fact that air can be mixed with large quantities of water vapour. Additionally, the vapour carrying capability of air increases with temperature. In this process, seawater is added into an air stream to increase its humidity. Then this humid air is directed to a cool coil on the surface of which water vapour contained in the air is condensed and collected as fresh water. These processes, however, exhibit some technical problems which limit their industrial development.

The other category of industrial desalination processes does not involve phase change but membranes [9]. These are the reverse osmosis (RO) and electrodialysis (ED). The first one requires electricity or shaft power to drive the pump that increases the pressure of the saline solution to that required. The required pressure depends on the salt concentration of the resource of saline solution and it is normally around 70 bar for seawater desalination.

ED also requires electricity for the ionization of water which is cleaned by using suitable membranes located at the two appositively charged electrodes as shown in **Fig. 3.5**. Both of them, RO and ED, are used for brackish water desalination, but only RO competes with distillation processes in seawater desalination.

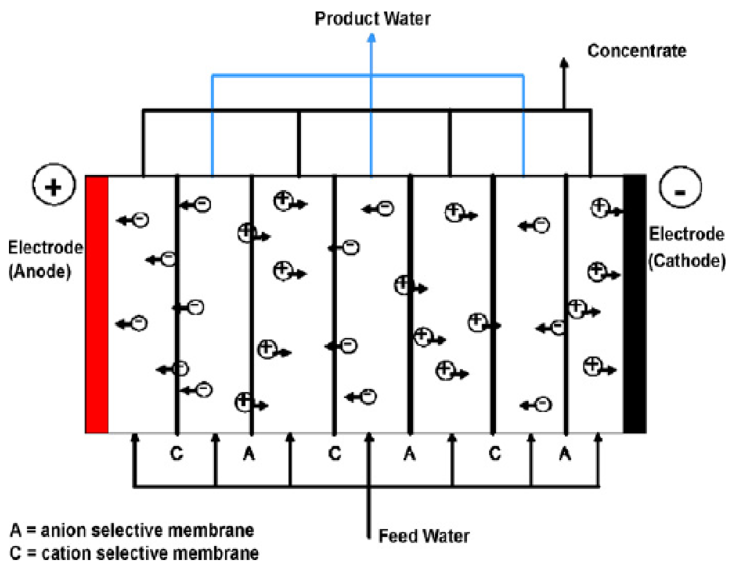


Fig. 3.5 - Principle of electrodialysis (ED), under constant DC current field.

The dominant processes are MSF and RO, which account for 44 and 42% of worldwide capacity, respectively. The MSF process represents more than 93% of the thermal process production, while RO process represents more than 88% of membrane processes production [10]. In **Fig 3.6** a comparison between desalination processes is presented.

Process	Recovery and Total dissolved solids	Pros	Cons
RO	30–60% recovery possible for single pass (higher recoveries are possible for multiple pass or waters with lower salinity)	Lower energy consumption	Higher costs for chemical and membrane replacement
		Relatively lower investment cost	Vulnerable to feed water quality changes
		No cooling water flow	Adequate pre-treatment a necessity
		Simple operation and fast start-up	Membranes susceptible to biofouling
		High space/production capacity	Mechanical failures due to high pressure operation possible
	<500 mg/L TDS for seawater possible and <less 200 mg/L TDS for brackish water	Removal of contaminants other than salts achieved	Appropriately trained and qualified personnel recommended
		Modular design	Minimum membrane life expectancy around 5–7 years
		Maintenance does not require entire plant to shutdown	
ED/EDR	85–94% recovery possible	Energy usage proportional to salts removed not volume treated	Only suitable for feed water up to 12,000 mg/L TDS
	140–600 mg/L TDS	Higher membrane life of 7–10 years	Periodic cleaning of membranes required
		Operational at low to moderate pressures	Leaks may occur in membrane stacks
			Bacterial contaminants not removed by system and post-treatment required for potable water use
MSF	25–50% recovery in high temperature recyclable MSF plant	Lends itself to large capacity designs	Large capital investment required
		Proven, reliable technology with long operating life	Energy intensive process
		Flashing rather than boiling reduces incidence of scaling	Larger footprint required (land and material)
	<50 mg/L TDS	Minimal pre-treatment of feed water required	Corrosion problems if materials of lesser quality used
		High quality product water	Slow start-up rates
		Plant process and cost independent of salinity level	Maintenance requires entire plant to shut-down
		Heat energy can be sourced by combining with power generation	High level of technical knowledge required
			Recovery ratio low
MED	0–65% recovery possible	Large economies of scale	High energy consumption
		Minimal pre-treatment of feed water required	High capital and operational cost
		Very reliable process with minimal requirements for operational staff	High quality materials required as process is susceptible to corrosion
	<10 mg/L TDS	Tolerates normal levels of suspended and biological matter	Product water requires cooling and blending prior to being used for potable water needs
		Heat energy can be sourced by combining with power generation	
		Very high quality product water	
VCD	~50% recovery	Developed process with low consumption of chemicals	Start-up require auxiliary heating source to generate vapour
	possible	economic with high salinity (>50,000 mg/L)	Limited to smaller sized plants
		Smaller economies of scale (up to 10,000 m^3/d)	Compressor needs higher levels of maintenance
	<10 mg/L TDS	Relatively low energy demand	
		Lower temperature requirements reduce potential of scale and corrosion	
		Lower capital and operating costs	
		Portable designs allow flexibility	

Fig 3.6. - Comparison between desalination processes [5].

Solar energy can be used for seawater desalination either by producing the thermal energy required to drive the phase-change processes or by producing electricity required to drive the membrane processes. Solar desalination systems are thus classified into two categories, i.e. direct and indirect collection systems. As their name implies, direct collection systems use solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and one for desalination). Conventional desalination systems are similar to solar systems since the same type of equipment is applied. The prime difference is that in the former, either a conventional boiler is used to provide the required heat or mainly electricity is used to provide the required electric power, whereas in the latter, solar energy is applied. The most promising and applicable renewable energy systems (RES) desalination combinations are shown in **Fig. 3.7.**

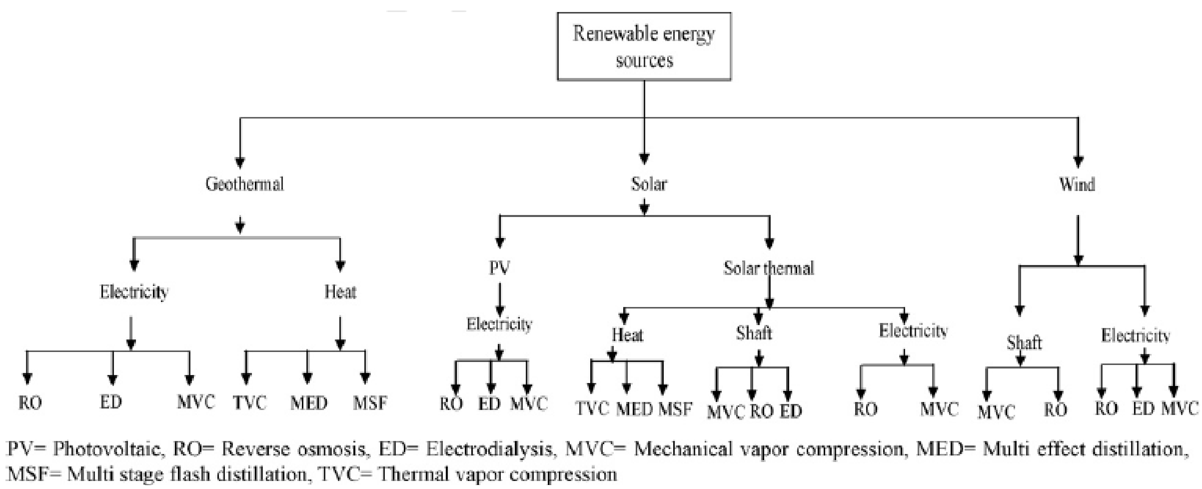


Fig. 3.7 - Possible technological combinations of the main renewable energies and desalination methods.

Over the last two decades, numerous desalination systems utilizing renewable energy have been constructed. Almost all of these systems have been built as research or demonstration projects and were consequently of a small capacity. It is not known how many of these plants still exist but it is likely that only some remain in operation. The lessons learnt have hopefully been passed on and are reflected in the plants currently being built and tested. A list of installed desalination plants operated with renewable energy sources is given by Tzen and Morris [11].

3.4 Status and Progress in desalination powered by RES

The most investigated modes of coupling between RES and desalination processes utilize the direct or indirect sun rays or wind to produce fresh water are indicated in **Fig. 3.8.**

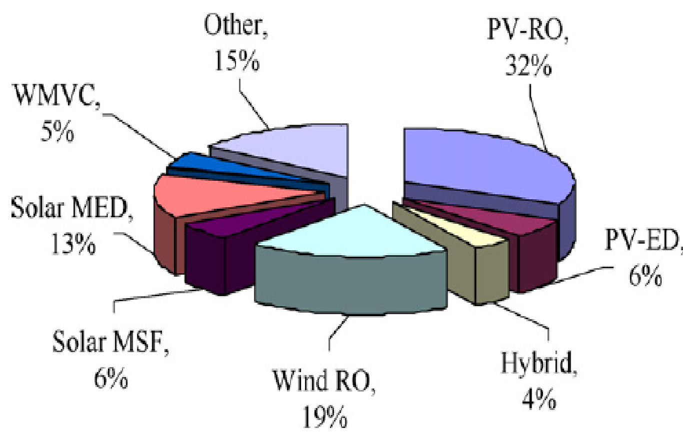


Fig. 3.8 - Distribution of renewable energy powered desalination technologies.

Despite the highly available renewable energy solutions solar desalination is one of the most promising technologies and reverse osmosis (RO) systems combined with the most mature renewable energy technologies can be economically viable in the nearer future for covering the water needs in small isolated communities. A lot of attempts have been carried out worldwide in this aspect [12-18].

3.5. REFERENCES

- **See Chapter 6.**

CHAPTER 4

REVERSE OSMOSIS

4.1. Osmosis process

Osmosis is a separation process that uses pressure to force a solvent through a membrane that retains the solute on one side and allows the pure solvent to pass to the other side. More formally, it is the process of forcing a solvent from a region of high solute concentration through a membrane to a region of low solute concentration by applying a pressure in excess of the osmotic pressure.

Reverse osmosis systems depends on the properties of semi-permeable membranes which, when used to separate water from a salt solution, allow fresh water to pass into the brine compartment under the influence of osmotic pressure as shown in **Fig 4.1.** If a pressure in excess of this value is applied to the salty solution, fresh water will pass from the brine into the water compartment.

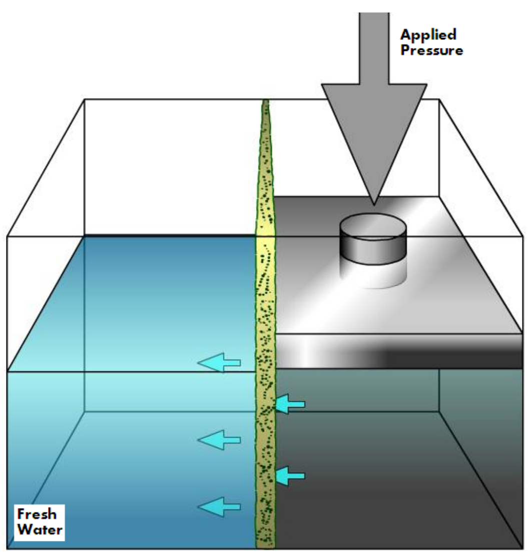


Fig. 4.1 – The osmosis process

The output of RO systems is about 500–1500 liter per day per square meter of membrane, depending on the amount of salts in the raw water and the condition of the membrane. The membranes are in effect very fine filters, and are very sensitive to both biological and non-biological fouling. To avoid fouling, careful pre-treatment of the feed is necessary before it is allowed to come in contact with the membrane surface.

One method used recently for the pre-treatment of seawater before directed to RO modules is nano-filtration (NF). NF is primarily developed as a membrane softening process which offers an alternative to chemical softening. The main objectives of NF pre-treatment are [1], [2]:

1. Minimize particulate and microbial fouling of the RO membranes by removal of turbidity and Bacteria.
2. Prevent scaling by removal of the hardness ions.
3. Lower the operating pressure of the RO process by reducing the feed water total dissolved solids (TDS) concentration.

Theoretically, the only energy requirement for an RO system is to pump the feed water at a pressure above the osmotic pressure. In practice, higher pressures must be used, typically 40–80 atm, in order to have a sufficient amount of water pass through a unit area of membrane [3]. According to this process, the feed is pressurized by a high-pressure pump and made to flow across the membrane surface. Part of this feed passes through the membrane, where the majority of the dissolved solids are removed. The remainder, together with the remaining salts, is rejected at high pressure as shown in **Fig. 4.2.** In larger plants, it is economically viable to recover the rejected brine energy with a suitable brine turbine. Such systems are called energy recovery reverse osmosis (ER-RO) systems. Typical, energy recovery devices for small RO units are listed below:

- PX Pressure Exchanger (ERI)
- Clark pump (Spectra)
- Ultra Whisper (Sea Recovery) and
- Ingeniatec system

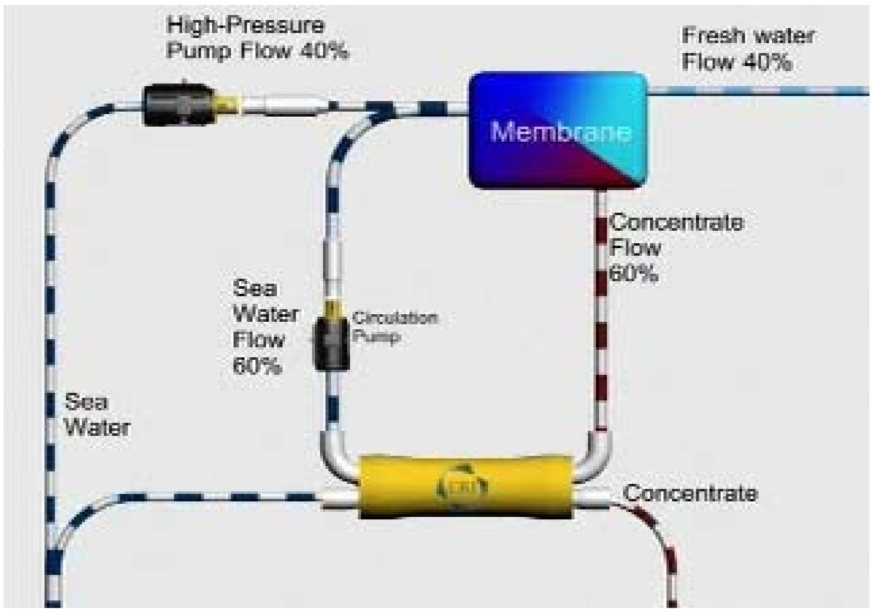


Fig. 4.2 – Typical RO system design.

4.1.1 The desalination system and tank size [4]

The desalination system size is characterized by its daily product water production. The system size simply can be calculated from the following equation,

$$Q_p = \frac{Q_f \times R}{100} \tag{4.1}$$

Where:

R = the recovery rate, %

Q_p = the product water flow rate, m3/day

Q_f = the feed water flow rate, m3/day

The value of Q_p is already known as the daily water demand at a specific month, hence Q_f could be calculated easily from the same equation.

A water storage tank is required to supply the water demanded when the system cannot operate for sufficient time to provide the water demanded due to lack of solar radiation and insufficient battery charge. In effect all fresh water produced is directed into the tank while water demand is supplied directly from the bottom of the tank. Therefore the tank is playing the role of a water “buffer”, which secures continuity of water supply and storage of energy in the form of fresh water produced. Most likely water tank sizes, measured in daily water needs (m3) of the Most Demanding Period (MDP), range between 1 to 5 days. The tank size is calculated by multiplying the water autonomy days by the maximum daily water demand at the most demanding month. The fact that there is some 10% at the tank bottom not used due to dirt concentration, the tank size will be sized 10% larger.

$$T_S = \frac{W_d \times A_{days}}{0.9} \tag{4.2}$$

Where:

T_S = tank size, m3

W_d = daily water needs, m3/day

A_{days} = water autonomy, days

4.2. Reverse osmosis system modeling

4.2.1. Water and salt transport in RO systems [5]

The osmotic pressure, P_{osm} of the solution can be determined experimentally by measuring the concentration of dissolved salts in solution:

$$P_{osm} = 1.19(T + 273) \times \sum m_i \tag{4.3}$$

Where:

P_{osm} = Osmotic pressure, psi, bar (not in SI)

T = Temperature, oC

$\sum m_i$ = sum of molar concentration of all constituents in a solution, TDS*

* Molarity is defined as moles of solute per litre of solution

An approximation of P_{osm} may be made by assuming that 1000 ppm (TDS) equals about 0.76 bar of osmotic pressure.

The rate of water passage through a semi-permeable membrane is:

$$Q_W = \left(\Delta\Pi - \Delta P_{osm}\right) \times K_w \times \frac{S}{d} \tag{4.4}$$

Where:

Q_W = Rate of water flow through the membrane, m3/sec

$\Delta\Pi$ = Hydraulic pressure differential across the membrane, psi (bar)

ΔP_{osm} = Osmotic pressure differential across the membrane, psi (bar)

K_w = Membrane permeability coefficient for water, %

S = Membrane area, m2

d = Membrane thickness, mm

The above equation could be simplified by,

$$Q_W = (NDP) \times A \quad (4.5)$$

Where:

Q_W = Rate of water flow through the membrane, m3/sec

NDP = Net driving pressure, psi, (bar)

A = A constant for each membrane material type

* Note: The NDP required for any given membrane application in RO, is a function of both the osmotic pressure change and hydraulic resistance,

$$NDP = P_F + \Pi_P - \Pi_F - \Pi_P$$

The rate of salt through the membrane is defined by

$$Q_S = \Delta C \times K_S \times \frac{S}{d} \quad (4.6)$$

Where,

Q_S = Flow rate of salt through the membrane, m3/sec

ΔC = Salt concentration differential across the membrane

K_S = Membrane permeability coefficient for salt

S = Membrane area, m2

d = Membrane thickness, mm

The above equation could be simplified by,

$$Q_S = B \times \Delta C \quad (4.7)$$

Where:

Q_S = Flow rate of salt through the membrane, m3/sec

ΔC = Salt concentration differential across the membrane or the driving force for the mass transfer of salts.

B = A constant for each membrane type

The above equations (4.5), (4.6) and/or (4.7) show that for a given membrane,

The rate of water flow through a membrane is proportional to the net driving pressure differential across the membrane.

The rate of salt flow is proportional to the concentration differential across the membrane.

The salinity of the permeate water depends on:

$$C_P = \frac{Q_S}{Q_W} \tag{4.8}$$

Where:

C_P = Salt concentration in the permeate water

Q_S = Flow rate of salt through the membrane, m3/sec

Q_W = Water flow rate through the membrane, m3/sec

The salt passage through the membrane is:

$$SP = \frac{C_P}{C_{fm}} \times 100\% \tag{4.9}$$

Where:

SP = Salt passage through the membrane, %

C_P = Salt concentration in the permeate water, mg/L

C_{fm} = Mean salt concentration in feed stream, mg/L

Thus, the salt rejection is given:

$$SR = 100\% - SP \tag{4.10}$$

4.2.2. Water Recovery ratio

Recovery ratio, (R) is an important parameter in the design and operation of RO systems. Recovery ratio affects the salt passage and product flow and is defined as follow:

$$R = \frac{Q_P}{Q_f} \times 100\% \qquad (4.11)$$

Where:

Q_P = Permeat flow rate, m3/sec

Q_f = Feed water flow rate, m3/sec

Concentration Factor (CF) is the salinity of the concentrate divided by the salinity of the plant feed water:

$$CF = \frac{1}{1 - R} \qquad (4.12)$$

Concentration Polarization Factor (CPF). As water flows through the membrane and salts are rejected by the membrane, a boundary layer is formed near the membrane surface in which the salt concentration exceeds the salt in the bulk solution. The CPF is defined as:

$$CPF = \frac{C_S}{C_b} \qquad (4.13)$$

Where:

C_S = Salt concentration at the membrane surface

C_b = Bulk concentration

4.2.3 Energy Requirements

The energy requirements for RO depend directly on the concentration of salts in the feed water end, to a lesser extent, on the temperature of the feed water. Because no heating or phase change is necessary for this method of separation, the major use of energy is for pressurizing the feed water. Power consumption of RO desalination process is the lowest among the commercial desalination methods. RO facilities are even more economical for desalinate brackish water because energy consumption versus feed water salinity decreases as the salt content of the source water decreases.

The main load of an RO unit is the high-pressure pumps. In seawater systems, usually the high-pressure pumping unit provides the major contribution (85%) to the combined power consumption of the process. Other loads are:

- Booster pump
- Dosing pumps
- Membrane cleaning pump
- Permeate pump

The efficiencies of pumps, electric motors and power recovery devices have been improved considerably during the last few years. Due to this improvements, power consumption in the range of 3-4 kWh/m3 is quite common in seawater desalination systems.

4.2.3.1 Booster pump (feed pump)

The power required to run a booster pump is given by

$$P_{bp} = \frac{\rho \times g \times h \times Q_f}{n_p} \tag{4.14}$$

Where:

P_{bp} = Booster pump power, kW

ρ = Feed water density at 25 ^{o}C, kg/m^3

g = Acceleration due to gravity, 9.81 m/sec^2

h = Manometric height, m

Q_f = Feed flow rate, m^3/sec

n_p = Pump efficiency, %

4.2.3.2 High-pressure pump

The power required to run a high-pressure pump is given by

$$P_{HPP} = \frac{P_f \times Q_f}{n_p} \tag{4.15}$$

Where:

P_{HPP} = Power of HPP, kW

P_f = Feed pressure, N/m^2

Q_f = Feed flow rate, m^3/sec

n_p = Pump efficiency, %

4.2.3.3 Membrane cleaning pump

The power required to drive the pump for the flushing procedure after the shutdown of the plant is:

$$P_{MFP} = \frac{P \times Q}{n_p} \tag{4.16}$$

Where:

P_{MFP} = Power of flushing pump, kW

P = Pressure, N/m2

Q = Flow rate, m3/sec

n_p = Pump efficiency, %

4.2.3.4. Energy recovery

The reject brine from the RO membranes is passed through the energy recovery unit **(Fig. 4.3)** where its pressure energy is directly transferred to a portion of the incoming raw seawater at up to 95% efficiency. This feed water stream, nearly equal in volume to the reject stream, then passes through a small booster pump, which makes up for hydraulic losses through the RO system. This feed water now stream joins the feed water stream from the main high pressure pump; it does not pass through the high-pressure pump. This is significant because now the main pump is sized to match the permeate flow, not the full flow. The booster pump also makes up the small volume of brine lost through the recovery device hydrostatic bearing. 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. The unit has one moving part, a shaftless ceramic rotor with multiple ducts; it is hydrostatically suspended within a ceramic sleeve. The rotor effects an exchange of pressure from brine to seawater through direct contact displacement with negligible losses [6]. **Fig. 4.3** illustrates a typical energy recovery unit.

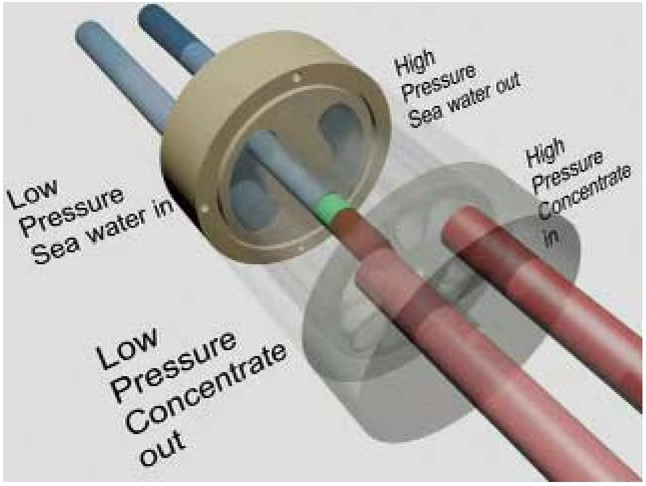


Fig. 4.3 – Design of a typical energy recovery unit

The fraction of power, recovered by the power recovery device, depends on the type and efficiency of the power recovery equipment used. Energy recovery devices leave the pressure vessel at about 1 to 5 bar less than the applied pressure from the high-pressure pump. Thus, the power recovered (P_R) by an energy recovery device is:

$$P_R = \mathrm{Pr}_b \times Q_b \times n_t \tag{4.17}$$

Where:

P_R = Power recovered, kW

Pr_b = Brine pressure, N/m2

Q_b = Brine flow rate, m3/sec

n_t = Turbine efficiency, %

4.2.4. Specific Energy Consumption

The energy consumption (kWh) per m3 of water produced is:

$$E_{spec} = \frac{\left(P_{bp} + P_{HPP} - P_R\right) \times 24(hours)}{Q_P} \tag{4.18}$$

Where:

P_{bp} = Booster pump power, kW

P_{HPP} = Power of HPP, kW

P_R = Power recovered, kW

Q_P = Permeate flow rate, m3/day

4.5. Autonomous Reverse Osmosis Desalination Systems

Autonomous Desalination Systems (ADS) are water desalination systems powered by Renewable Energy Sources (RES) [7-9]. Such systems are usually small and most of them utilize membrane technology. They are friendly to the environment and are viable in the long future. On the other hand, the energy they use is not cheap, due to the high cost of almost all renewable energy sources and the restricted availability due to weather conditions, [10-15] etc. However, they can be economically attractive under specific conditions (e.g. remote areas, use of waste energy, etc.).(ERI)

Renewable energy supply and water demand in each period are the main determinants of the size of the ADS, which will be sufficiently large to satisfy demand at any period [16]. It is apparent that the sizing of the complete system will have to be estimated at the Most Demanding Period (MDP), in which water demand is relatively high while renewable energy supply is low. If the system is large enough to satisfy demand in the MDP, then it will comfortably satisfy the rest of the periods [manual].

Cost Analysis of ADS leads to the estimation of the cost of a liter or a cubic meter of fresh water and calculates the contribution of each cost item to the total cost. This identifies immediately the most important cost items and attracts the attention of the researcher, the planner, the user, to what should first be examined for possible improvement and sensitivity analysis. The cost of an autonomous desalination system (ADS) can easily be divided into at least five cost categories as follows:

- Renewable Energy system cost. This is the cost of supporting Renewable Energy Source (RES), supplying all the energy needs for the desalination unit, feed water pumps and brine disposal.
- Desalination system cost. This is the cost of the Desalination unit itself.
- Feed Water system cost. This is the cost of Feed Water system and pre-treatment, including all necessary investment and related expenses required for the supply of brackish or sea water to the desalination main system.
- Brine Water system disposal cost. This could be anything from minimal to very expensive depending upon specific conditions.
- Other non allocated system costs.

4.5.1. Renewable Energy System cost

The Renewable Energy System, exploiting the energy of the sun, the wind, etc. is supplying the desalination and supporting systems with the required energy in order to function properly. The investment cost of the Renewable Energy System includes purchase and installation of the system. As the availability of the Renewable Energy Source (RES) involves an element of uncertainty, each ADS may have an associated battery system [], which, in combination with the fresh water storage system, smooth the fluctuations of the RES.

4.5.2. Desalination System Cost

The cost of the Desalination System consists of the purchase and installation cost of all the pieces of equipment required for the actual desalination. This may include some kind of pre-treatment items, the desalination unit itself, 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 Autonomous Desalination 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. However, the size of the tank is limited by the size of the desalination system and cost effectiveness considerations which must be taken into account before sizing the water storage.

4.5.3. Feed water supply system cost

.The required investment and running cost of this part of the system depends very much on the nature of each case, the elevation and horizontal distance of the water source to the desalination machine, the type and size of the piping system, etc. 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 Renewable Energy System of the configuration (RES). Drilling for underground water may be the most important cost item under this heading. Depending upon the depth of the water basin it could be anything between a few hundred to many thousand Euros. The cost of borehole and associated fixed equipment is treated very much like the costs of desalination and RES system costs.

4.5.4. Brine water disposal system cost

The brine water which remains after desalination, should be disposed in a way that does not harm the feed water or the environment in general. In the case of sea water source, brine can be re-directed to the sea based on detailed environmental study. However, in the case of drilling underground water, brine has to be sent back into the ground, sometimes in depths much deeper than the feed water location. The cost of Brine Water disposal is very much siting dependent and has to be studied for each individual case for a meaningful estimation of the environmental impact and required expense.

4.5.5 Other costs

Other costs under this heading are mainly costs of buildings, constructions or equipment supporting the operation of the ADS. Costs of other equipment are handled at exactly the same manner as other investment categories. In the case that an investment in this category is shared with other uses, only the proportion corresponding to the ADS use is considered.

4.6. RO economic parameters

In this section an optimization algorithm for cost evaluation is suggested [1] in order to obtain the desired plant life and reliability with minimum cost.

The major components of desalinated water production cost and their expired range in commercial RO plants are given in **Table 4.1**. The contribution of capital recovery cost varies between 30% to 50% of cost, of water produced, depending on several variables like plant size, site, process type, etc. Energy is usually the major component cost over the useful service life of RO plants, which usually extends up to 30 years for major plants. The O&M cost ranges 15% to 30%, depending mainly on plant capacity [17]. It is the purpose of this section to discuss the impact of key parameters that affect RO desalination plant production cost. **Table 4.2** describes briefly the main cost for Autonomous RO desalination systems.

Table 4.1 - Typical range of desalinated water production cost components

Component	Contribution, %
Capital recovery cost	30 - 50
Energy cost	30 - 50
O&M (labour, spares, membranes, chemicals, etc.)	15 - 30

Plant capital and water production costs decrease significantly as plant capacities increase up to about 12,000 m3/day for brackish water and 20,000 m3/day for seawater RO. Beyond these limits, costs decrease only slightly with increasing plant size. Desalination plants require major initial capital outlays that need to be depreciated over plant service life which could be 30 years. Hence, the cost of capital has a significant impact on water production cost since capital contribution is usually 30% to 50% of water production cost.

Energy contribution to the water production cost can range from about 30% to 50% depending on energy cost, process type and design. The energy input for RO desalination is a function of water salinity and plant design. For producing 1 m^3 of desalinated water, RO requires approximately 6-7 kWh of electric energy. This energy consumption rate can be reduced by a minimum 30% using energy recovery devices connected to the brine stream.

The source and quality of feed water are an important cost factor. The cost of desalting seawater can be from three to as much as seven times more expensive than brackish water when using RO desalination [18]. The cost and availability of water storage, water transfer and other infrastructure required for building a desalination plant or delivering its water can be a major cost component. Such costs are mainly related to the plant location and size.

In the case of seawater desalting, RO plants require about two times the amount of water they produce. Seawater intake costs include intake pipes or channels, screens, intake basins and seawater pumps with all auxiliary equipment. This cost indicates that the seawater intake is an expensive component in the plant [19]. Therefore, due consideration has to be given to the design and location of the intake as well as to the location of the plant. The main purpose of seawater intake systems is to provide good quality feed water free from seaweed, shells, sand and contamination through hydrocarbons. To avoid seaweed, the intake mouth should preferable be installed more than 15 m below sea level to avoid suction of this matter. This may result in intake pipes of 2km length offshore.
Also, to reduce pollution through hydrocarbons the intake should be installed several meters below the lowest sea wave level. Due to increasing sea coast pollution, simple onshore intakes with short channels are becoming less and less possible. Seawater intake is one of the vital components of the plant, so it should have a stand-by capacity. Intake pipes may be installed on the ground of the seabed but also above the sea level with a vacuum-based siphon system. Compared to an open seawater intake, beach wells are preferred if plant location and ground conditions allow their use.

The reliability of the continuing trouble-free operation of RO plants is a key consideration related directly to the water production cost. The reliability of any desalination plant is a function of proper operation and good design. Proper operation depends on operators' experience, skills and training. Good design should compensate for or prevent operation errors through sufficient instrumentation and control. Computer and digital controls allow full plant automation, which is highly desirable to increase reliability of large plants. It is a common practice in large RO plants to expect a load factor of 90% or better. With good design and operation, plant availability may exceed 95% of the time over 1 year. All plants need some shut-down time for routine maintenance, which accounts for the remaining percentage. A common approach to increase plant availability is to have spares or duplicate copies of key items installed or in store ready for use when the operating item fails. This practice will increase the initial capital cost. The best approach to increase plant reliability is through proper process design for the available water at the given site. Pre-treatment of feed water before the brine desalting component is an important consideration in plant design [19]. Pre-treatment usually involves several filters and chemical injections and may require clarifiers, activated carbon or other equipment depending on the chemistry and quality of the feed water.

The useful service life of RO desalination is defined as the years over which the plant produces the water quantity and quality it is designed for. Usually plants are designed for a service life of 20 to 30 years. The selection of material and equipment specification can have a great impact on the capital and the operation and maintenance costs required over the life of the plant.

The O&M costs such as, labour, membranes, chemicals, spare parts and consumables usually range 15% to 30% of water production cost depending on plant size, process type and design, etc. Labor costs may be up to 5 to 20% for small to large RO plants. Plant automation will reduce the cost of labour with the additional advantage of increased plant reliability. The annual cost of spare parts is usually about 1% to 2% of the capital cost of the plant, excluding membrane replacement. Membrane life expectancy has continuously been improved since the 1970s. Most membrane manufacturers now provide a 5-year warranty, and the average expected life may exceed 7 years for a well designed and operated plant. Membranes cost about 15% to 20% of the cost of capital for large seawater RO plants, and their replacement about 10% of the water production cost for large RO plants [19]. Chemicals may reach 10% of water production costs. Chemical consumption can greatly be reduced by proper process optimization for any given site.

4.6.1 A Mathematical formulation and an optimization algorithm

The capital cost, C_C in € is given by the relation:

$$C_C = C^*_{CS} \times P_{CS} \qquad (4.19)$$

Where:

C_C = Investment cost, €

C_{CS} = Specific investment cost, €/m^3/day

P_{CS} = Plant capacity, m^3/day

The annual recovery of capital cost C_A in € is given by:

$$C_A = C_{RF} \times C_C \qquad (4.20)$$

Where:

C_{RF} = Annual recovery factor of investment with interest i for n periods (i.e. years), €

$$C_{RF} = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{4.21}$$

The specific annual recovery of capital cost, in €/m^3 is given by:

$$C_{AS} = \frac{C_A}{P_A} \tag{4.22}$$

Where P_A is the annual production of desalinated water in m^3 given as follow:

$$P_A = 365 \times LF \times P_{CS} \tag{4.23}$$

Where:

LF = Water production load factor, %

By substitute the **equations. (l), (2)** and **(5)** into **(4),** the specific annual recovery of capital cost is given by:

$$C_{AS} = \frac{C_{RF} \times C_{CS}}{365 \times LF} \tag{4.24}$$

The specific energy cost E_{CS} in €/m^3 is given by:

$$E_{CS} = E_S \times E_T \qquad (4.25)$$

Where:

E_S = Specific Energy Consumption (Plant), kWh/m^3

E_T = Specific cost of electricity, €/kWh

For stand-alone systems instead of specific cost of electricity (E_T) it is more suitable to use rated power cost N_{CP} in €/kW. Thus the equation (4.25) can be written as follow,

$$E_{CS} = E_S \times \frac{N_{CP}}{T_{peak}} \qquad (5.26)$$

Where:

E_S = Specific energy consumption, kWh/ m^3

N_{CP} = Rated power cost, €/kW

T_{peak} =Sum of equal peak hours, h

The specific O&M costs consist of two components: the fixed O&M cost and the variable O&M cost. The fixed O&M costs include labour, spare parts, membrane replacement, administration and overhead. The variable O&M costs include chemicals. The fixed O&M cost O_C , (except for the membrane replacement cost) in €/m^3/day is given by:

$$O_C = \frac{A}{P_{CS}} \qquad (4.27)$$

Where:

A = The fixed O&M cost, €

The specific fixed O&M cost O_{CS} in €/m^3 is given by:

$$O_{CS} = \frac{O_C}{365 \times LF} \tag{4.28}$$

Where:

O_C = Fixed O&M cost (excluding membrane replacement Cost), €/m^3/day

The membrane replacement cost M_C, in €/m^3/day is given by:

$$M_C = \frac{M \times M_E \times M_P}{P_{CS}} \tag{4.29}$$

M = Unit cost of membrane, €/element

M_E = Total number of the installed membrane elements

M_P = Annual replacement ratio of membranes, %

The specific membrane replacement cost M_{CS} in €/m^3 is given by:

$$M_{CS} = \frac{M_C}{365 \times LF} \tag{4.30}$$

The specific cost of chemicals H_{CS} in €/m^3 depends mainly on the design, the feed water quality and chemicals prices.

Thus, the specific cost of water production C_j, in €/m^3 is given by:

$$C_j = (C_{AS})_j + (E_{CS})_j + (O_{CS})_j + (M_{CS})_j + (H_{CS})_j \tag{4.31}$$

Where j is the candidate RO scheme. The optimum solution can then be obtained by:

$$\text{Least Cost Solution} = \min [\ C_j\ ] \tag{4.32}$$

* A useful equation for estimating the specific investment cost (for different plant capacity) usually referred to as economy of scale is given below:

$$C_{CS} = 4428.2 \times (P_{CS})^{-0.1941} \tag{4.33}$$

Fig. 4.3, Fig. 4.4, Fig. 4.5 and **Fig. 4.6** illustrate the overall conclusions.

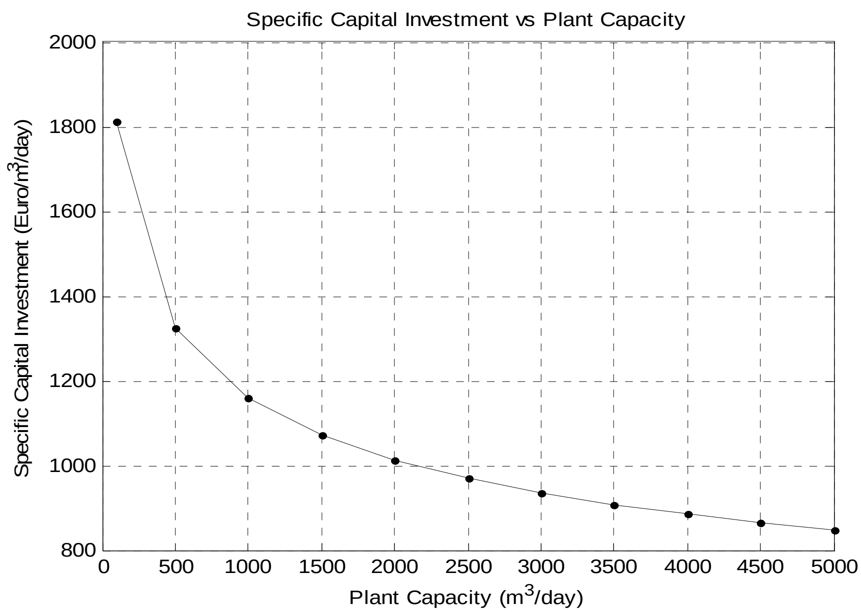


Fig. 4.3 – Specific Capital Investment vs. Plant Capacity

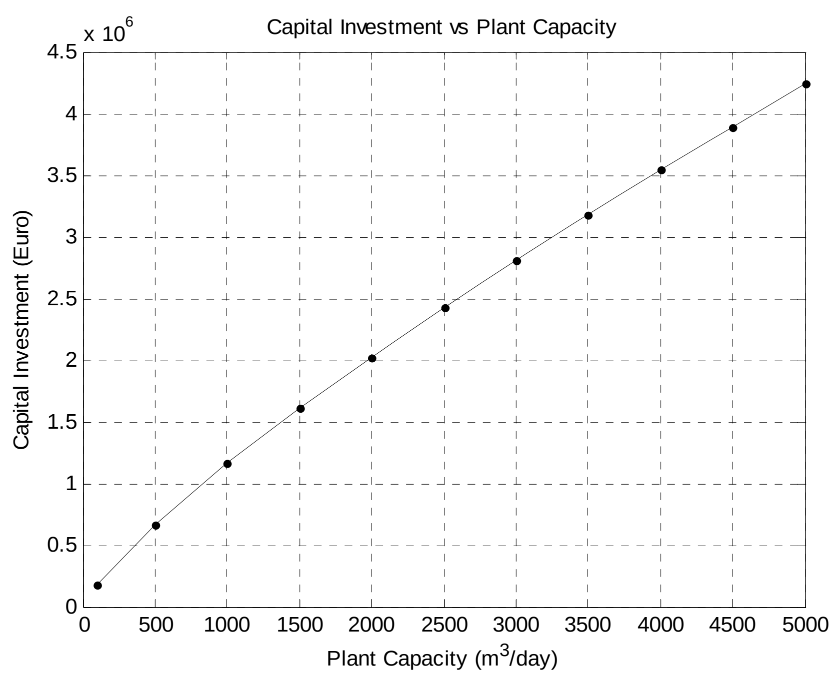


Fig. 4.4 – Capital Investment vs. Plant Capacity

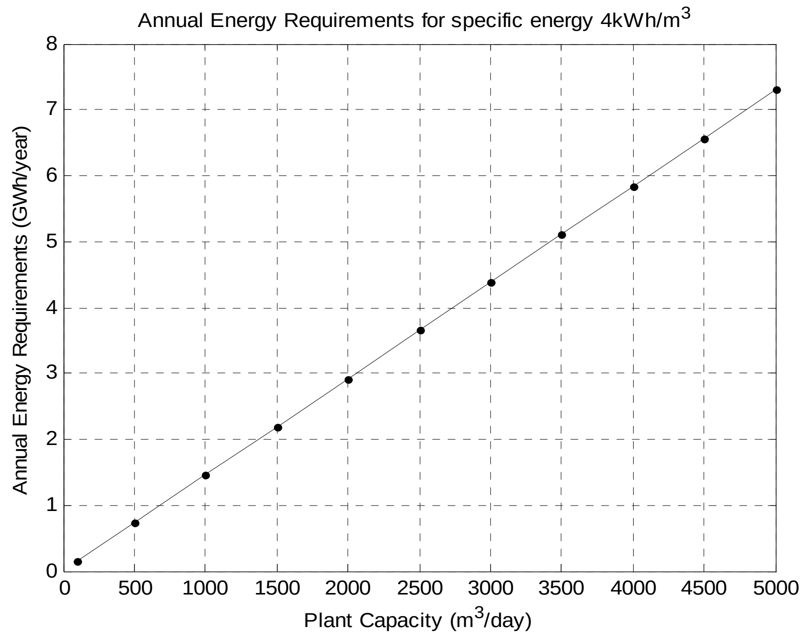


Fig. 4.5 – Annual Energy Requirements for specific energy 4kWh/m^3

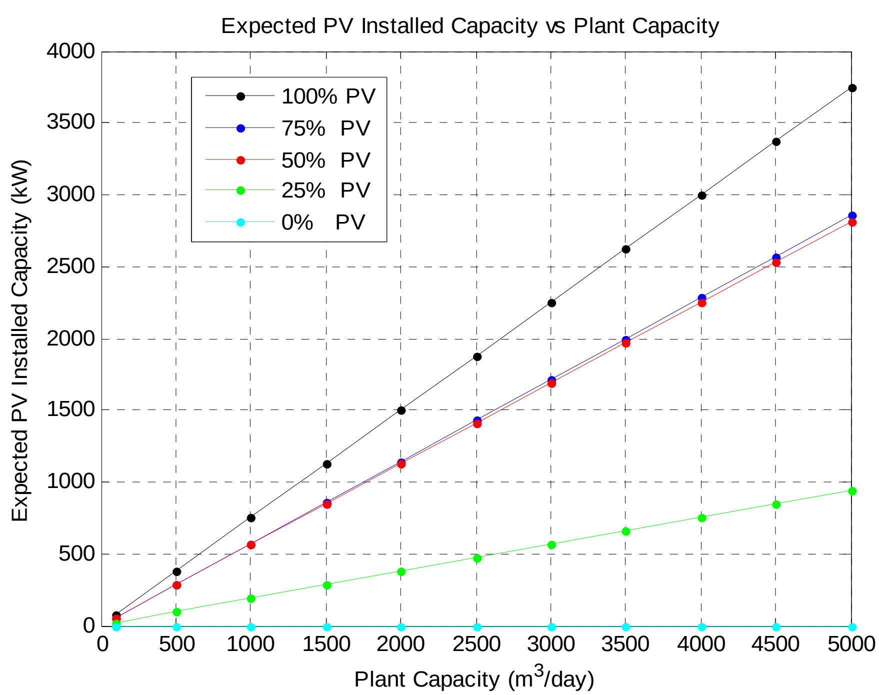


Fig. 4.6 – Expected PV Installed Capacity vs. Plant Capacity

4.7. REFERENCES

- **See Chapter 6.**

CHAPTER 5

Fuzzy Set Proposed Methodology to Compare Between Different Autonomous PV-RO Desalination Plants: A Case Study Scenario.

5.1. Introduction

The analyses carried out so far have not been able to provide a strong basis for comparing the overall efficiency and viability of different autonomous desalination plants. Reverse osmosis is becoming the technology of choose while the continuous reduction in the cost of photovoltaics, including fresh water shortages, can increase the need for more compact desalination system (hybrid or autonomous). As a result, comparison tools should be developed to achieve higher reliability and cost minimization in order to ensure further sustainability. The main objective of the current study is to develop a Benefit to Cost model, by using a fuzzy set methodology that can achieve as much as accurate results. The results are presented through a case study view, for two different sites, Jordan (Aquaba) and Cyprus (Agia Napa). As it is stated in **Chapter 1**, fuzzy logic has the ability to absorb the human experience, contain a large amount of data and infer the desired actions (decisions).

The advantages of using fuzzy logic include the following:

- Fuzzy method uses fuzzy sets that enabled us to condense a large amount of data into smaller set of variable rule.
- Fuzzy logic controllers are based on heuristics and therefore able to incorporate human intuition and experience (Cirstea et al, 2002).

5.2. A Fuzzy proposed method.

In the present study an Autonomous PV-RO (APVRO) system with batteries is suggested to cover the water needs of a small community in Aqaba (Jordan) and/or Agia Napa (Cyprus). A fuzzy set methodology for system sizing and site comparison will also be present.

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 [1][2].

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 [3] [4].

The APVRO system 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 [5][6]. **Fig. 5.1** illustrates the APVRO system design flowchart while **Fig. 5.2** illustrates system design from the energy point of view.

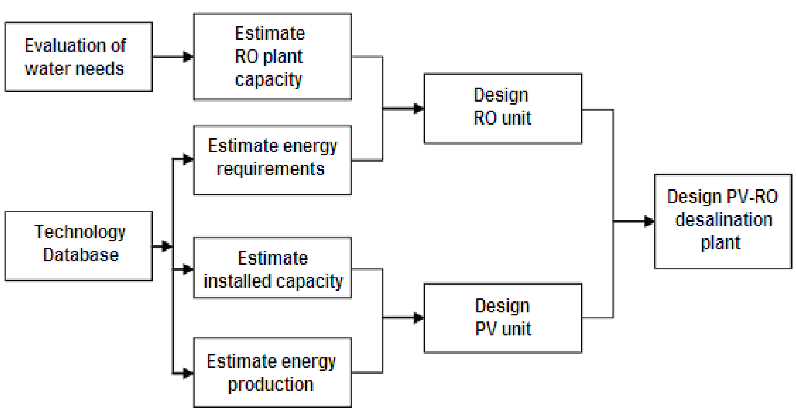


Fig. 5.1 – APVRO system design flowchart.

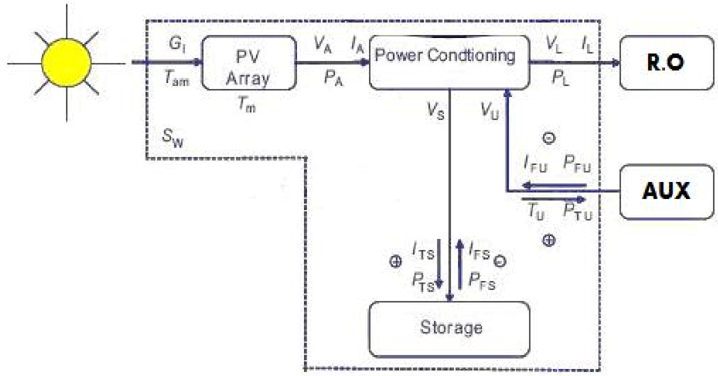


Fig. 5.2 – APVRO system design from the energy point of view.

5.2.1. Variables definitions and fuzzy sets

The input variables were extracted using a detail research on various publications concerning PV performance standards and desalination methods, as they are described in previous chapters. In this section the most important parameters **(Fig. 5.2),** are presented. For further details refer to **Chapter 2 (Table 2.2)** and **Chapter 4**.

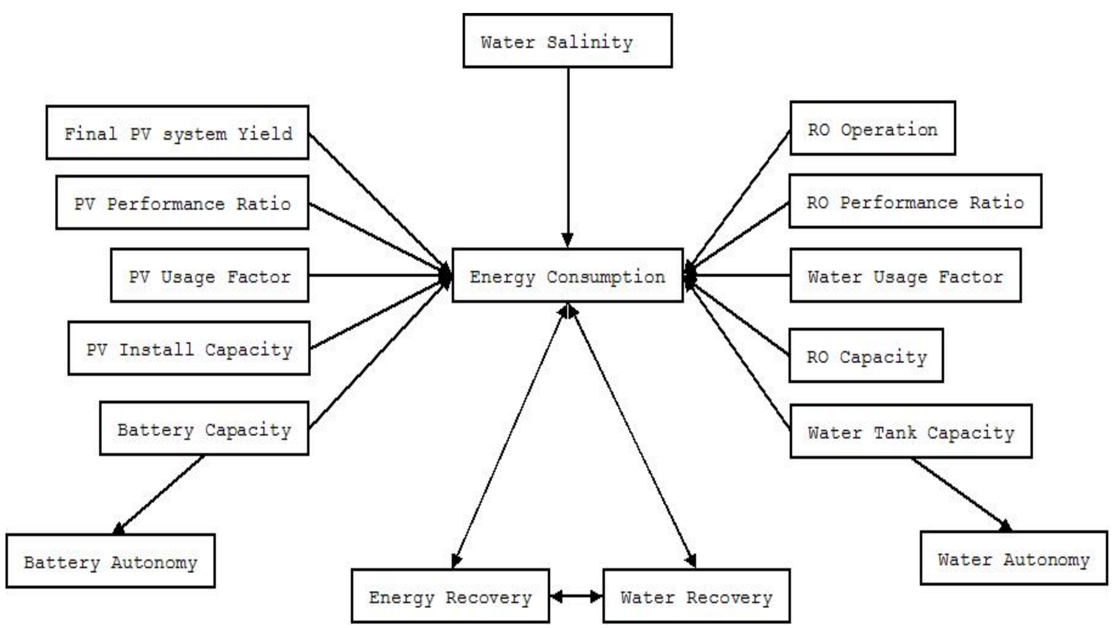


Fig. 5.3 – Schematic diagram of the main parameters of an Autonomous PV-RO desalination system (APVRO).

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.

$$Y_{r,A} = \int_{\tau} G_i \, dt / G_{STC} \qquad (5.1)$$

Final PV System Yield (FPVSY): The final PV system yield ($Y_{f,A}$) is the energy used by the system, to the total PV power in ($hours/day$), as described in **equations 2.5** and **2.6** in **Chapter 2**, and shows how the load (RO unit), utilize the energy from PVs.

$$Y_{f,A} = E_{A,use} / P_{A,N} \qquad (5.2)$$

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 (section 2.4.1). 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:

$$PR = Y_{f,A} / Y_{r,A} \qquad (5.3)$$

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. E_{pot} is a measured energy quantity, which differs from E_{pot} for all stand-alone (SAS), presenting PV array disconnection due to a fully charged battery **(section 2.4.1).** It is given as follow:

$$UF_A = E_A / E_{pot} \tag{5.4}$$

Energy Savings (ES): is the percentage (%), which describes the energy savings due to the recovery device system (section 4.2.3.4).

Specific Energy Consumption (SEC): is the energy consumption per m^3 of water produced (section **4.2.4**.). 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): is the average total water production (i.e. m^3/day) over a specified period. It is the real plant capacity parameter **(equation 4.1).**

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.

$$RF = \frac{W_{Sur}}{W_{Sur,MDP}} \tag{5.5}$$

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 ADS 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. However, the size of the tank is limited by the size of the desalination system and cost effectiveness considerations which must be taken into account before sizing the water storage. For the purposes of this study the feed water system is included in the capital investment of the DSC. The required investment of this part of the system depends very much on the nature of each case, the elevation and horizontal distance of the water source to the RO machine, the type and size of the piping system, etc. 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, as well as power conditioning system (inverters, controllers).

Energy Storage Cost (ESC): is the cost (€/year) of batteries. Battery replacement (average 5 to 7 years) is included in the energy storage cost.

O&M cost (Running Cost, O&MC): Running cost (€/year) refer to the recurring costs of desalination systems. Includes: annual costs of labour, 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. Some of these costs are identified to each part of the system, i.e. they are allocated to the various cost categories as defined above. Some other costs, for example labour costs that cannot easily be allocated, are categorized as Overheads. Overheads are included in the O&M cost for the purposes of this study. For methodological purposes, running costs are classified by nature (as above) and by system (Feed Water, Desalination, RES, Other) [7].

Total cost of water produced (TCWP): is the cost of water (€/m^3) and varies according to the overall design. See also **section 4.6.1** for details.

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).

The estimated weights for the above mentioned parameters, are shown in **Table 5.1** and **Table 5.2** respectively, while the benefit and cost models are illustrated in **Fig. 5.3** and **Fig 5.4** respectively.

Table 5.1 – APVRO System Benefit													
			Fuzzy Sets										
Main parameters	**Symbol**	**Variable type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Range**	**Unit**	**Weights**
Reference Yield	RY	Input	VVL	VL	L	M	H	VH	VVH	1-8	hours/day	0.400
Final PV System Yield	FPVSY	Input	VVL	VL	L	M	H	VH	VVH	1-5	hours/day	0.400
System Autonomy	SA	Input	VVL	VL	L	M	H	VH	VVH	1-5	days	0.400
Performance Ratio	PR	Input	VVL	VL	L	M	H	VH	VVH	5 - 60	%	0.600
Usage Factor	UF	Input	VVL	VL	L	M	H	VH	VVH	10-90	%	1.000
Energy Savings	ES	Input	VVL	VL	L	M	H	VH	VVH	20-90	%	0.900
Specific Energy Cons.	SEC	Input	VVL	VL	L	M	H	VH	VVH	1 - 6	kWh/m3	0.800
RO Hours of Operation	ROHO	Input	VVL	VL	L	M	H	VH	VVH	3 - 12	hours/day	0.500
Social Benefits	SB	Input	VVL	VL	L	M	H	VH	VVH	5 - 50	m3/day/year	0.200
Reliability Factor	RF	Input	VVL	VL	L	M	H	VH	VVH	50 - 90	%	0.900
Benefit	**Benefit**	**Output**	**VLL**	**VL**	**L**	**M**	**H**	**VH**	**VVH**	**0 - 1**	**-**	**-**

Table 5.2 – 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	VVL	VL	L	M	H	VH	VVH	7*103-100*103	€/year	0.900	
PV System Cost	ESC	Input	VVL	VL	L	M	H	VH	VVH	3*103-60*103	€/year	0.538	
Energy Storage Cost	ESC	Input	VVL	VL	L	M	H	VH	VVH	3*103-20*103	€/year	0.539	
O&M Running Cost	O&MRC	Input	VVL	VL	L	M	H	VH	VVH	200-4000	€/year	0.339	
Total Water Production Cost	TWPC	Input	VVL	VL	L	M	H	VH	VVH	1- 10	€/m3	1.000	
Total Energy Production Cost	TEPC	Input	VVL	VL	L	M	H	VH	VVH	8 - 80	c€/kWh	1.000	
Cost	Cost	Output	VLL	VL	L	M	H	VH	VVH	0 - 1	-	-	

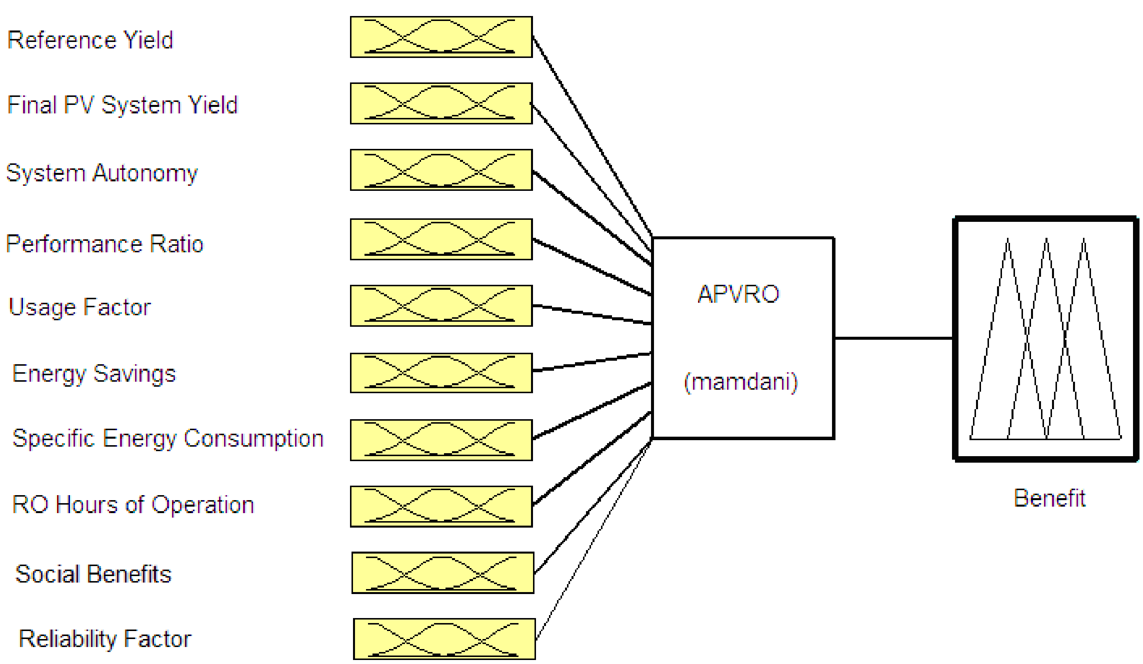


Fig. 5.3. - Fuzzy input/output combination for the System Benefit.

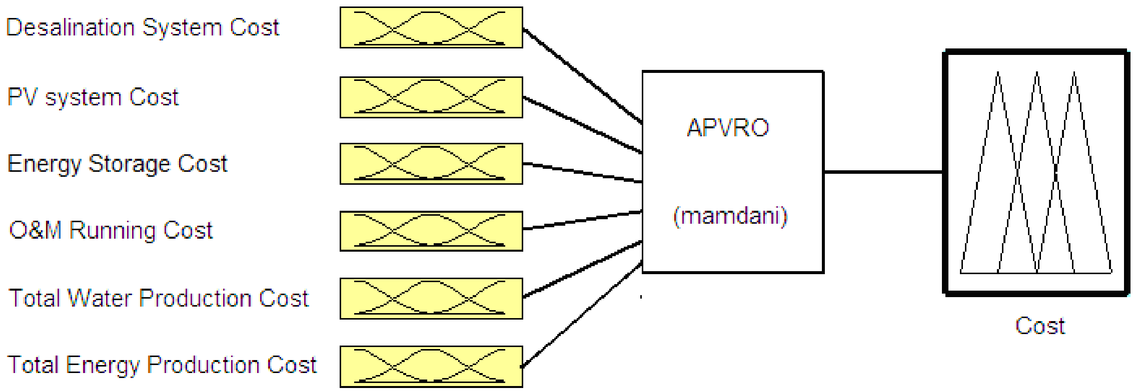


Fig. 5.4. - Fuzzy input/output combination for the System Cost.

The 16 inputs and 2 outputs are divided each into seven fuzzy sets. This shows the degree in which the Autonomous PV-RO system 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).

The output intervals (fuzzy sets) are shown in **Fig. 5.5.**

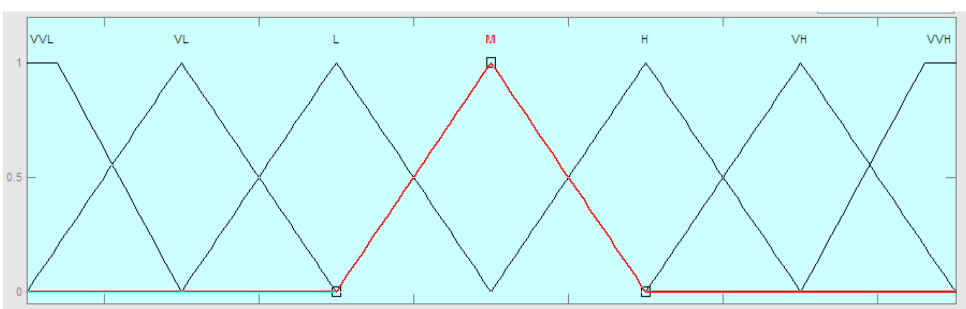


Fig. 5.5. - Membership functions for the outputs of benefit and cost model.

The tuned values [8] of the output **(Fig. 5.5)** are falling within 0 to 1 represent the minimum and the maximum benefit or cost limits, respectively.

The membership functions of the main input parameters are shown in **Fig. 5.6** to **Fig. 5.12** as follows:

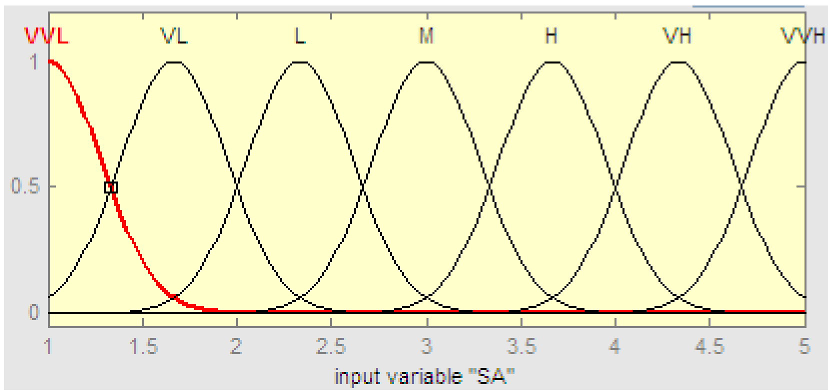


Fig. 5.6 - Membership functions for the system autonomy (SA) input in days.

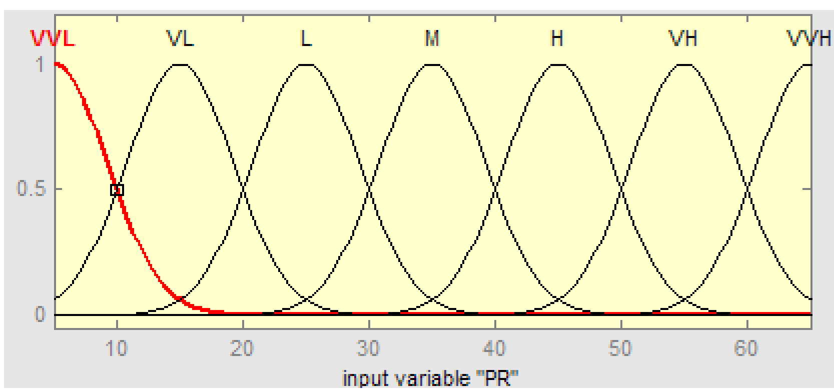


Fig. 5.7 - Membership functions for the performance ratio (PR) input in %.

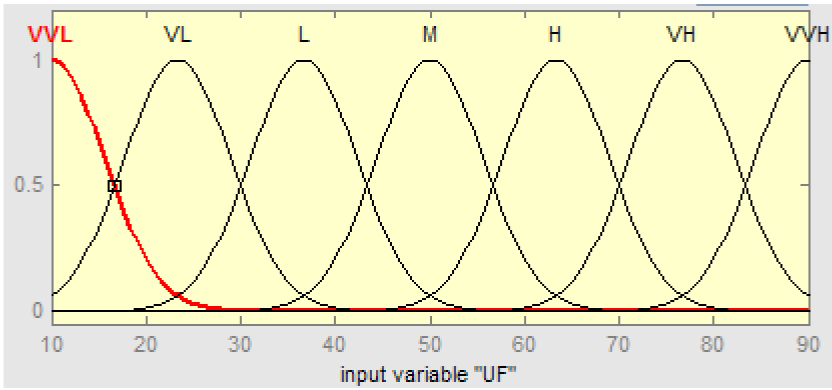


Fig. 5.8 - Membership functions for the usage factor (UF) input in %.

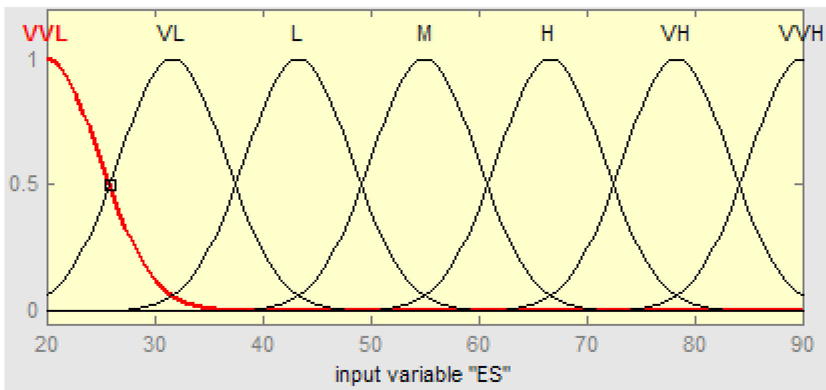


Fig. 5.9 - Membership functions for the energy savings (ES) input in %.

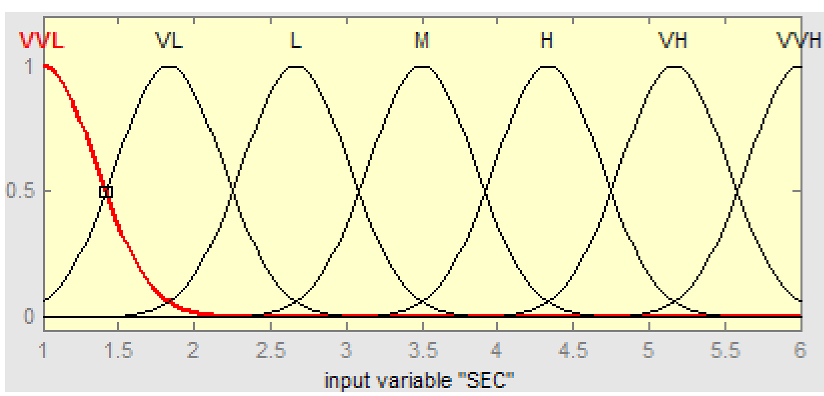


Fig. 5.10. - Membership functions for the specific energy consumption (SEC) input in kWh/m3.

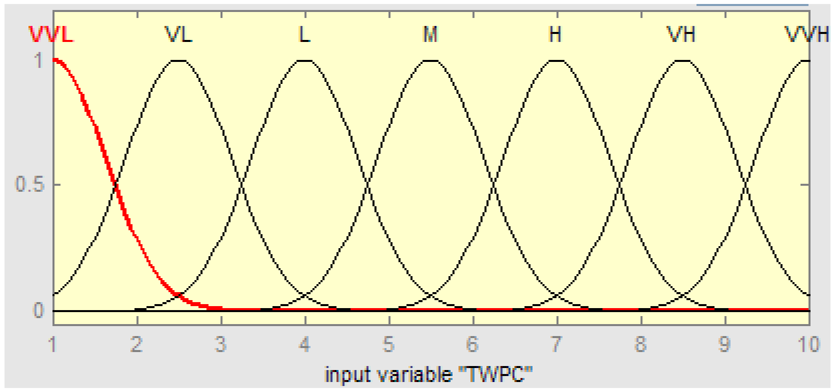


Fig. 5.11. - Membership functions for the total water production cost (TWPC) input in €/m3.

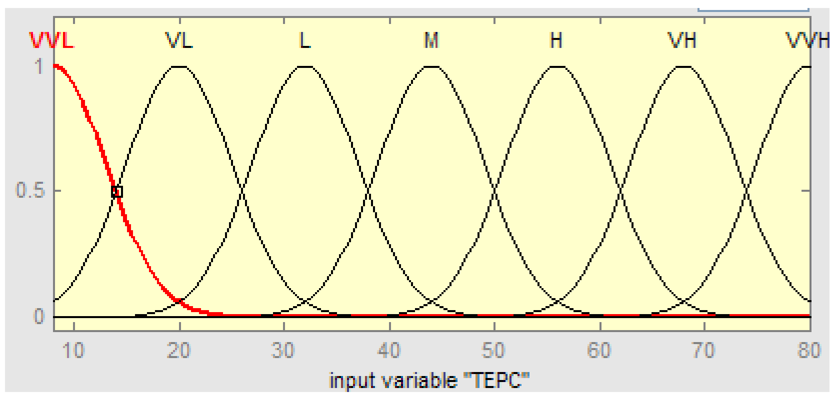
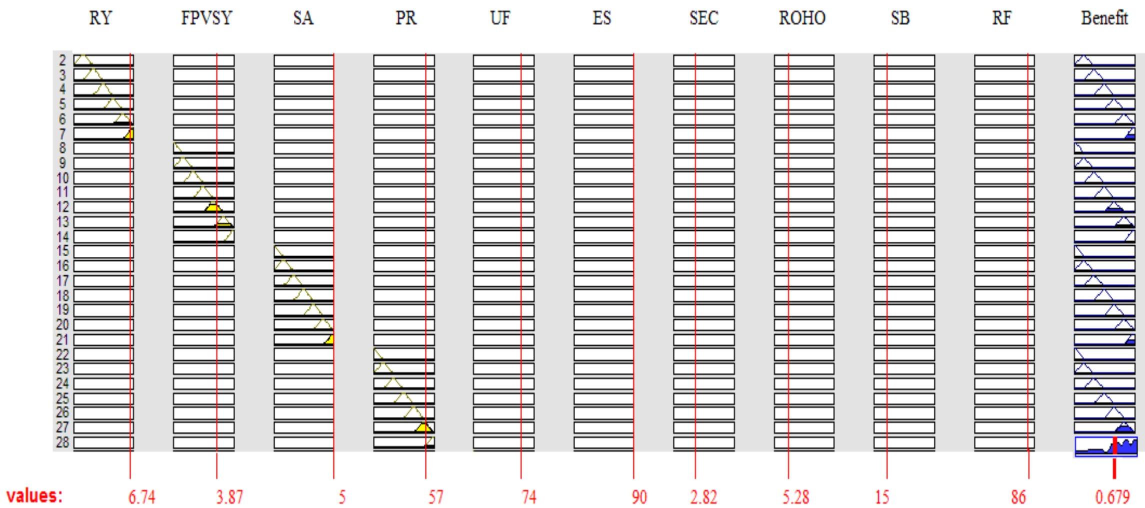


Fig. 5.12. - Membership functions for the total energy production cost input (TEPC) in c€/kWh.

5.2.2. 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 effect of different parameters weights [9], as shown in **Fig. 5.13.**



. **Fig. 5.13.** - Determining the Benefits using fuzzy logic

5.2.3. Performing fuzzy inference into the system

As it is mentioned in **Chapter 1 (section 1.4.1),** fuzzy inference is the process of formulating the mapping from a given input to an 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 (The MathWorks, 2007).

This procedure is used to compute the mapping from the input values to the output values. It is consisted of three sub-processes, fuzzification, aggregation and defuzzification as shown in **Fig. 5.14.**

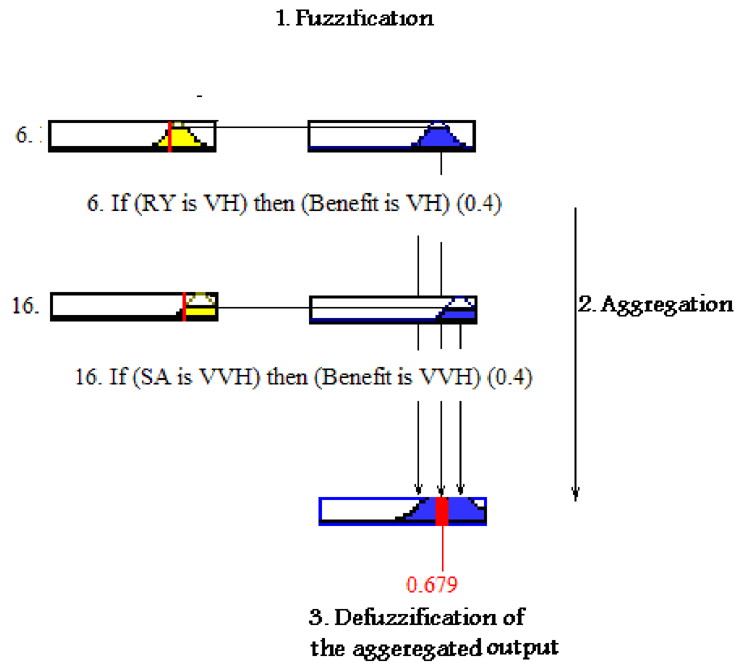


Fig. 5.14. - Fuzzy implementation sequence.

The “activated” sets due to fuzzification sub-process will be aggregated in the next step to form the combined shape shown in Fig. 5.14, after that, it will be defuzzified to get a crisp number (i.e. Benefit = 0.679), the rules in the MATLAB toolbox are shown in **Fig. 5.15.**

5. If (RY is H) then (Benefit is H) (0.4)
6. If (RY is VH) then (Benefit is VH) (0.4)
7. If (RY is VVH) then (Benefit is VVH) (0.4)
8. If (FPVSY is VVL) then (Benefit is VVL) (0.4)
9. If (FPVSY is VL) then (Benefit is VL) (0.4)
10. If (FPVSY is L) then (Benefit is L) (0.4)
11. If (FPVSY is M) then (Benefit is M) (0.4)
12. If (FPVSY is H) then (Benefit is H) (0.4)
13. If (FPVSY is VH) then (Benefit is VH) (0.4)

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32. If (UF is M) then (Benefit is M) (1)
33. If (UF is H) then (Benefit is H) (1)
34. If (UF is VH) then (Benefit is VH) (1)
35. If (UF is VVH) then (Benefit is VVH) (1)
36. If (ES is VVL) then (Benefit is VVL) (0.9)
37. If (ES is VL) then (Benefit is VL) (0.9)
38. If (ES is L) then (Benefit is L) (0.9)
39. If (ES is M) then (Benefit is M) (0.9)
40. If (ES is H) then (Benefit is H) (0.9)
41. If (ES is VH) then (Benefit is VH) (0.9)

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65. If (RF is VL) then (Benefit is VL) (0.9)
66. If (RF is L) then (Benefit is L) (0.9)
67. If (RF is M) then (Benefit is M) (0.9)
68. If (RF is H) then (Benefit is H) (0.9)
69. If (RF is VH) then (Benefit is VH) (0.9)
70. If (RF is VVH) then (Benefit is VVH) (0.9)

Fig. 5.15 - Fuzzy rules.

5.3. Case study: Results and Discussion

5.3.1. System Sizing

The proposed APVRO system is capable to produce 15 m^3/day.The current system utilize a recovery unit with recovery ratio 60% and a battery autonomy for one day (50 kWh). It is sized to feed with fresh water, a community of 60 to 80 people (average 150 liter/day/person) in Jordan (**Fig. 5.17)** and **(Fig. 5.18). Table 5.3** to **Table 5.5**, shows the main system design parameters - as defined in previous section **(5.1.1)** - used as inputs to the fuzzy model.

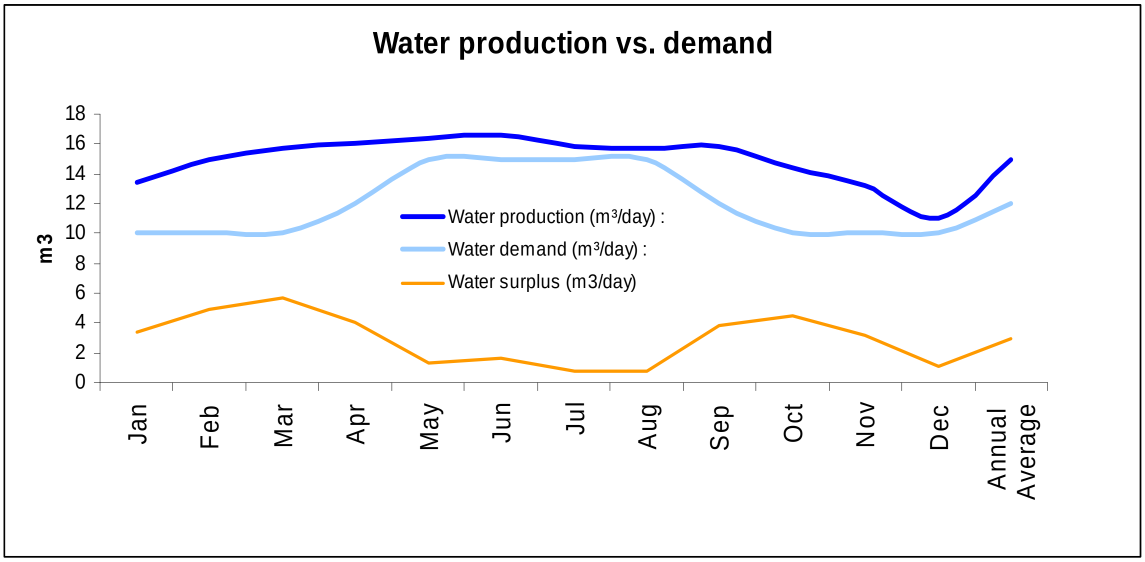


Fig. 5.17 - Water production versus demand, for a 15 m^3/day APVRO plant.

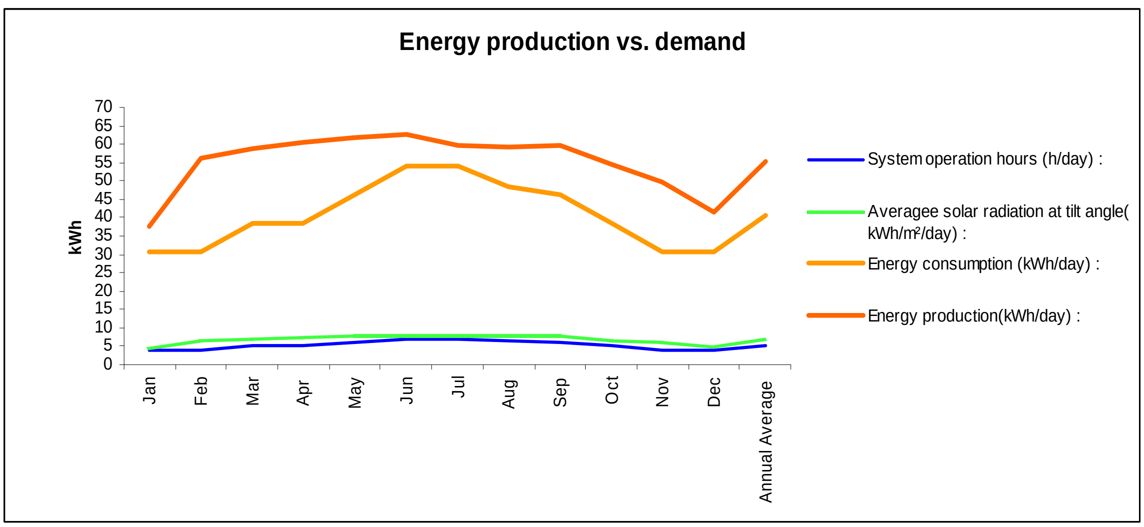


Fig. 5.18 - Energy production versus consumption, for a 15 m^3/day APVRO plant.

Table 5.3 – System description	
Technical	**Unit**
System water recovery (%)	60
High-pressure-pump motor power (KW)	6.28
Total RO power (KW)	6.93
System overload power (KW)	7.70
System Energy required (kWh/day)	33.89
System voltage (V)	24
Energy required (Ah)	1412
Water autonomy days	5
Battery Autonomy(days)	1
High pressure pump flow rate (m³/h)	4.17
High pressure pump pressure (psi)	550
Dynamic Head (m)	50

Table 5.4 – Component size and cost				
Component	Size	Life (yrs)	Cost (€)	Description
FW Electric Motor (kW)	0.75	10	233	
Feed Water Pump(m3/hr)	7.00	8	700	
PV panels(kW)	10.00	25	50000	47 modules (60m^2), eff: 16.09%, type: mono c-Si, 205 Wp/ panel
Inverter (kW)	10.00	10	10000	
Battery Capacity(kWh)	70.00	7	7000	2259.25 Ah (equal)
Main Des Syst. (m3/day)	70.00	20	105000	ncl.HPP,excl.membranes& filters
Fresh Water Tank (m³)	75.00	30	800	

Table 5.5 - Other derived parameters		
Parameter	**Unit**	**Size**
Total Water Demand	(m^3/year)	4320
Total Water Production	(m^3/year)	5270
Total Water Production Cost (TWPC)	(€/m^3)	5.27
Total Energy Production Cost (TEPC)	(€/kWh)	0.34
Daily Water Production	(m^3/day)	15.00
Daily Energy Production	kWh/day	55.00
Energy Consumption	kWh/m^3	3.77

In **Fig. 5.17** a comparison between 8 different APVRO systems has been carried out, based on daily average solar radiation data (kWh/kWp), in Aqaba. 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 [10-15]. Fuzzy model results have shown that, as recovery ratio increases, benefit increases, while cost decreases with respect to candidate design benefits **(Fig 5.19).** However, benefits can be limited, even if the recovery ratio is high, due to a component mismatching (i.e. battery).

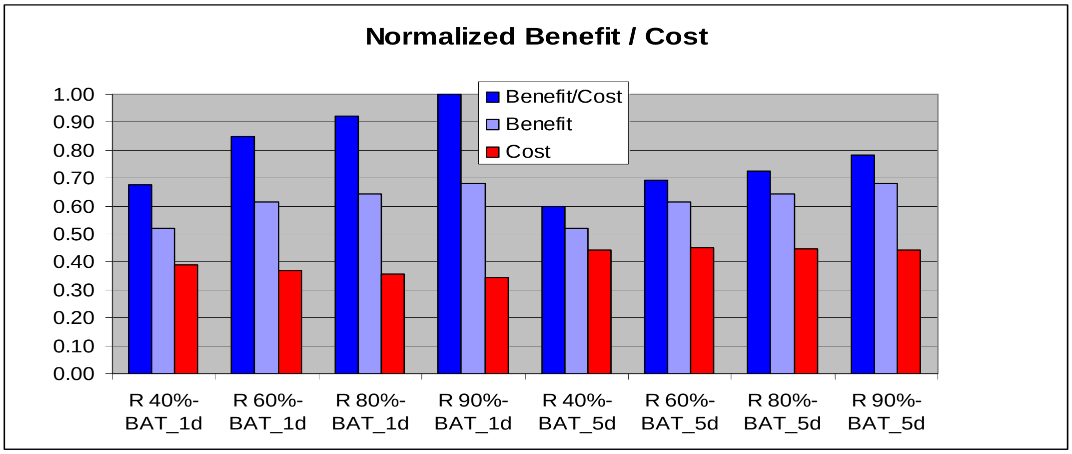
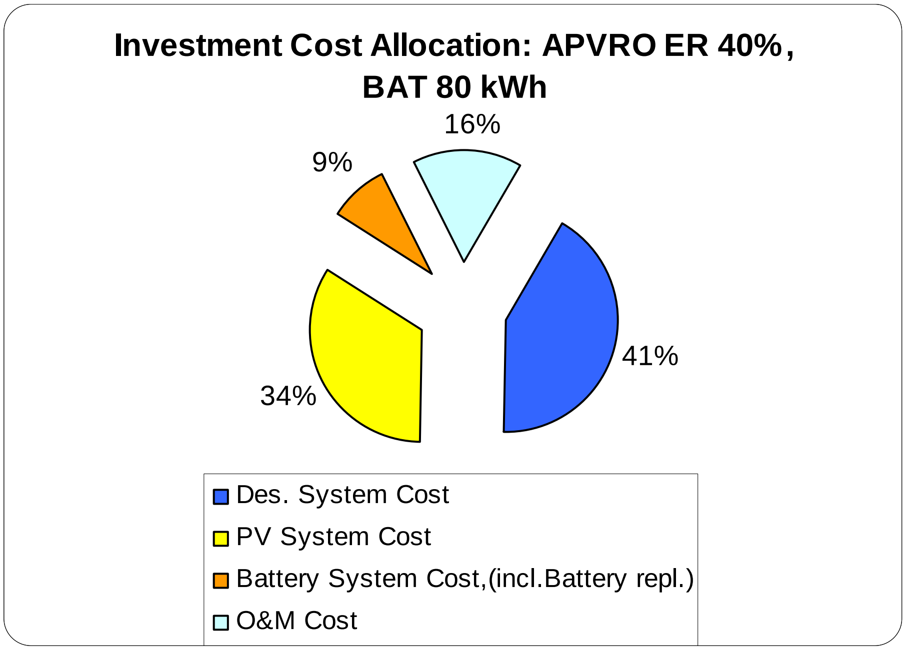
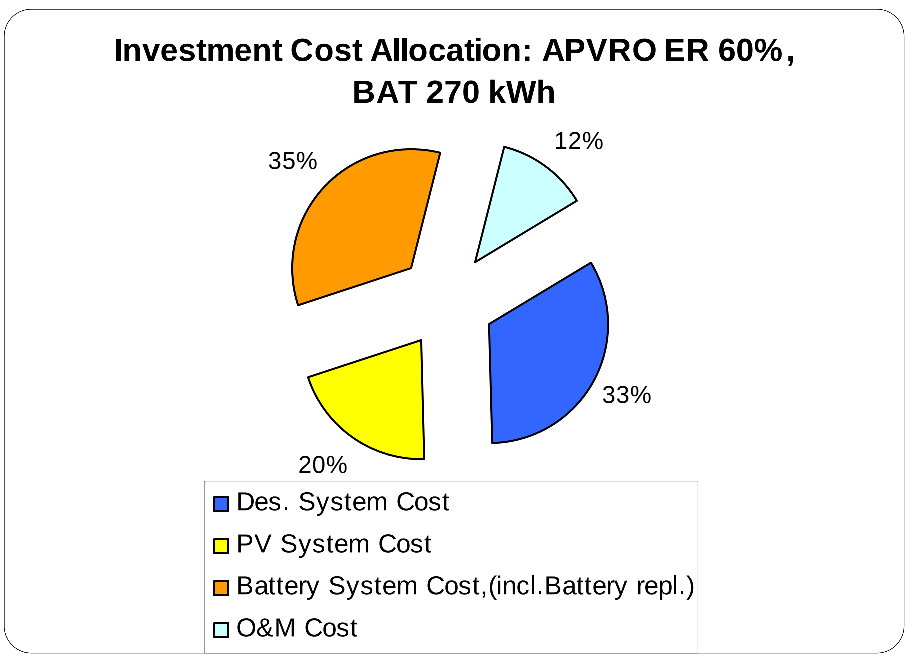


Fig. 5.17 – Normalized Benefit to Cost Ratio 8 systems configurations using a fuzzy set methodology. (site: Aqaba').

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. 5.18 (a)** and **(b),** respectively.



(a)



(b)

Fig. 5.18 - 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.

- **Note:** Battery installation cost including battery replacement are given separately to the main O&M cost. O&M cost includes membrane replacement, filters, chemicals, labour and/or other O&M cost.

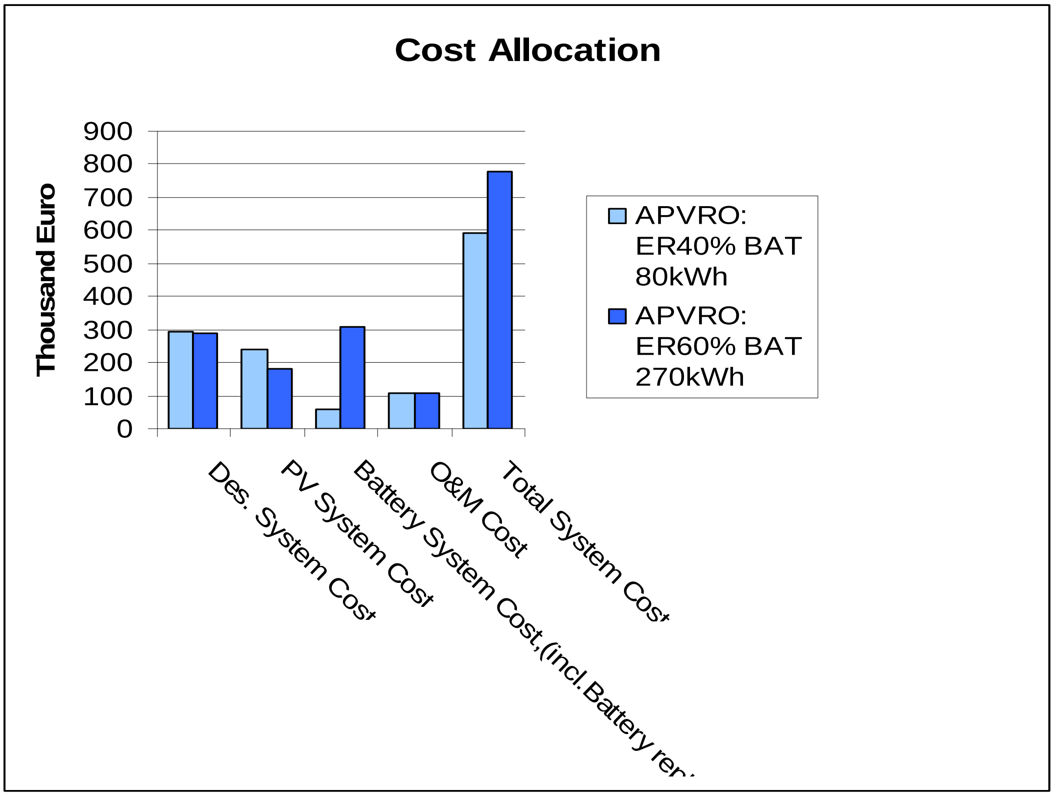


Fig. 5.19 - Cost allocation in thousand € for the two candidate APVRO designs.

5.3.2. Site decision

The same methodology (for evaluating APVRO: ER 60%, BAT 80 kWh) was follow to indicate the most beneficial site. Results show that Aqaba site is 10% more beneficial than Agia Napa due to a higher utilization of solar radiation. Also, a 5% increase in the cost was observed, as total cost of energy increased. The final system balance is presented in **Table 5.6**.

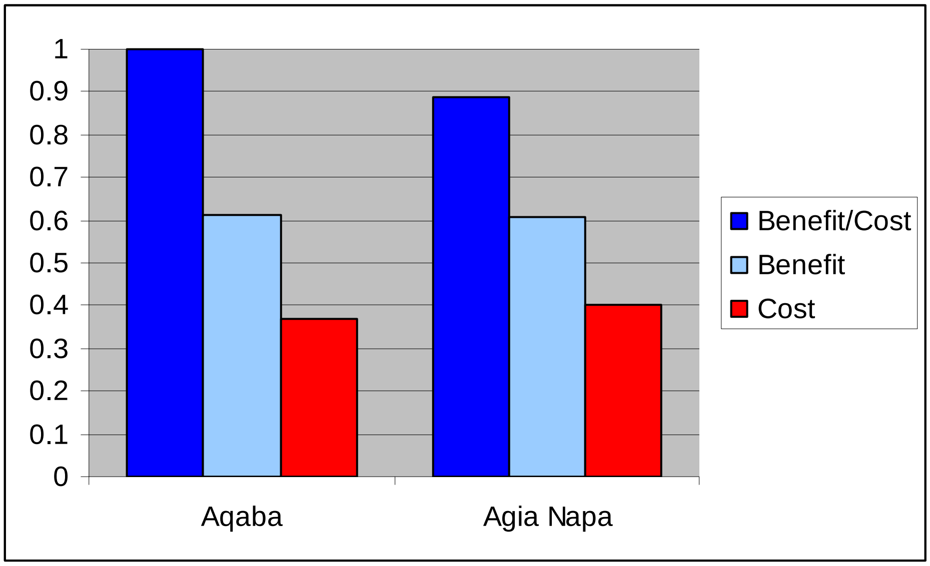


Fig. 5.20 - Normalized Benefit to Cost Ratio for site decision.

Table 5.6 - Energy vs. Water Balance of the System		
	APVROS (Aqaba)	**APVROS (Agia Napa)**
Total cost of water production (€ / m^2)	5.27	5.14
Total cost of energy production (€ / kWh)	0.34	0.42

****

5.4. Conclusion

More experimental work needs to be carried out to study the continuous performance of the APVRO systems. Fuzzy set methodology can be a powerful tool for analysis and decision making problems as well as for real-time system control including desalination. The current research utilizes fuzzy logic to make decisions about Autonomous Photovoltaic (PV) Reverse Osmosis (RO) desalination plants through performance enhancement of both, solar energy utilization by renewable sources, and fresh water production (consumption) through desalination. Further, this study restates that decisions should follow well optimum system designs at preferable solar sites for future widespread applications.

5.5. REFERENCES

- **See Chapter 6.**

CHAPTER 6

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6.4. Chapter 4

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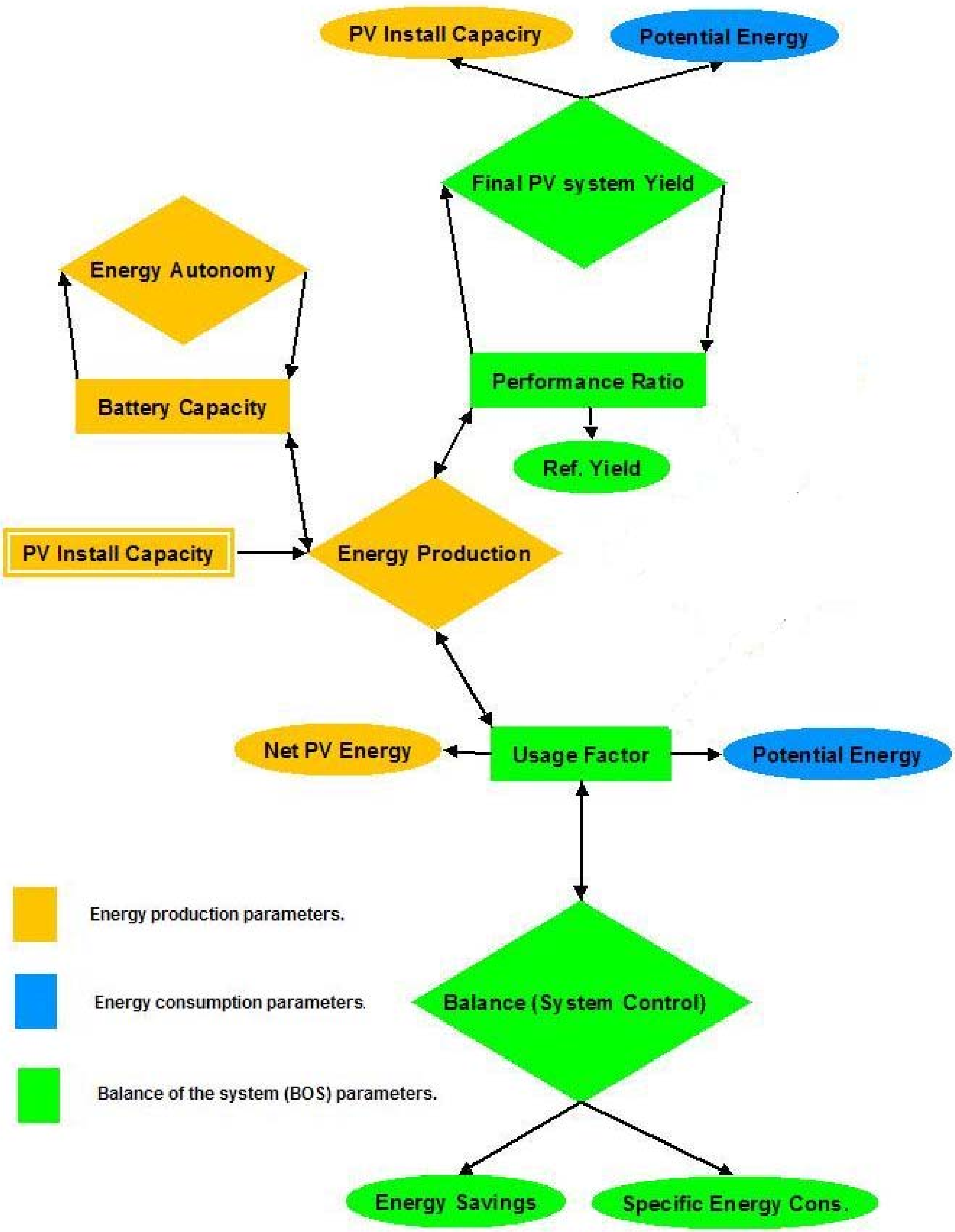
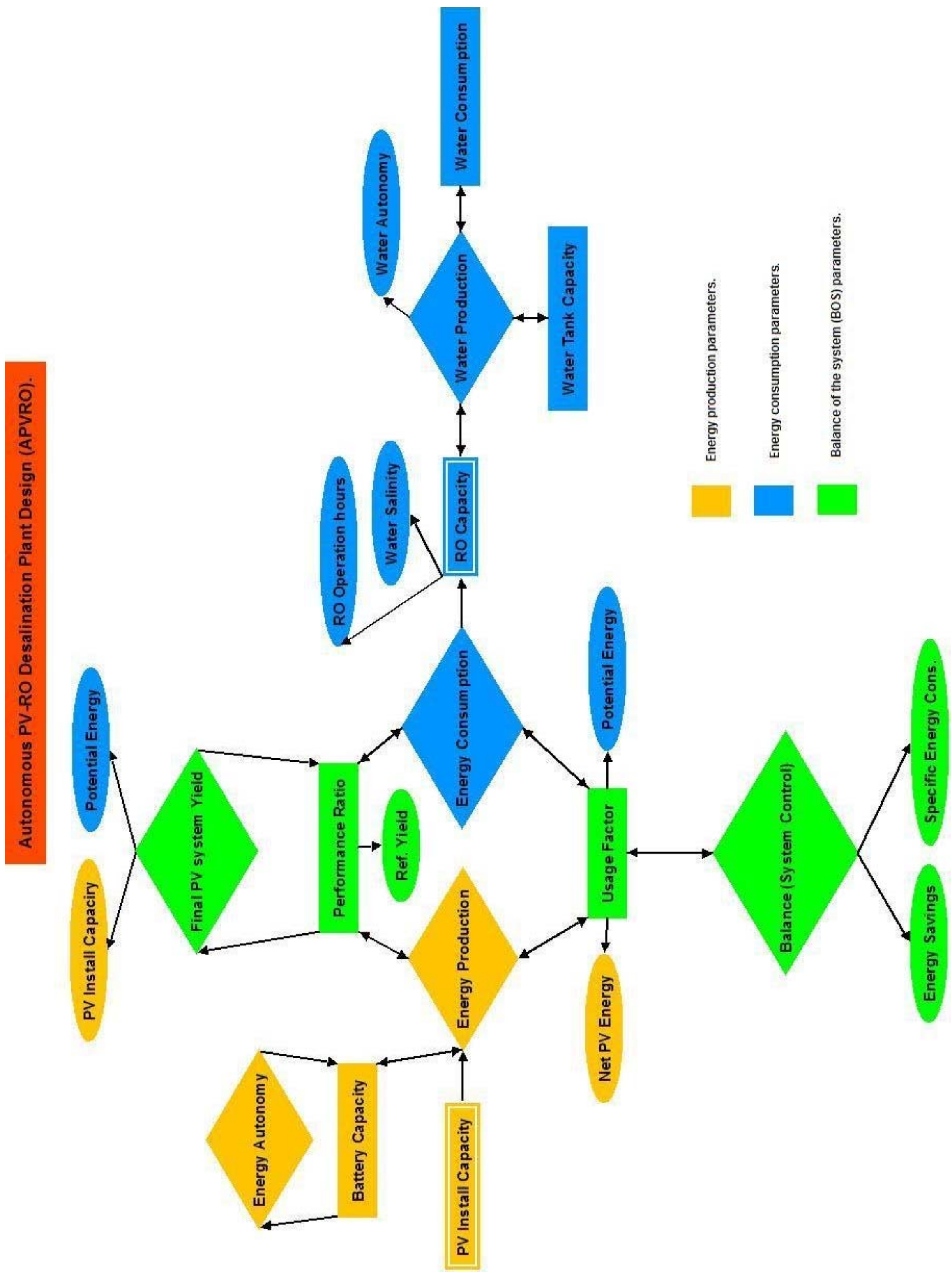
APPENDIX

- **Entity Relational Models For APVRO system Design:**




PV Install Capaciry
Potential Energy
Final PV system Yield
Performance Ratio
Ref. Yield
RO Operation hours
Water Salinity
Water Autonomy
Energy Consumption
RO Capacity
Water Production
Water Consumption
Water Tank Capacity
Usage Factor
Potential Energy
Energy production parameters.
Energy consumption parameters.
Balance of the system (BOS) parameters.
Balance (System Control)
Energy Savings
Specific Energy Cons.


Autonomous PV-RO Desalination Plant Design (APVRO).
PV Install Capaciry
Potential Energy
Final PV system Yield
Energy Autonomy
Battery Capacity
Performance Ratio
Ref. Yield
Energy Production
Energy Consumption
PV Install Capacity
RO Operation hours
Water Salinity
RO Capacity
Water Autonomy
Water Production
Water Consumption
Water Tank Capacity
Net PV Energy
Usage Factor
Potential Energy
Balance (System Control)
Energy Savings
Specific Energy Cons.
Energy production parameters.
Energy consumption parameters.
Balance of the system (BOS) parameters.