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Fast Track School #1

Introduction to Solar-driven Water production & Treatment technologies and brine treatment processes
State of the Art

UNIPA Università degli Studi di Palermo, Palermo. 10th - 11th January, 2024

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State of the art of PV-RO

Solar PV driven RO desalination introduction	Basic theory of solar PV	RO process introduction. SWRO-BWRO differences	The need for solar desalination and its challenges	PV-RO key equipment, schemes and possible configurations	Costs and other non-technical aspects to take into account	Conclusions Q&A

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Solar PV driven RO desalination introduction

Palermo, Sicily. 10th - 11th January, 2024

The use of industrial desalination plants driven by renewable energy sources (RES) is a technique that has been implementing for more than four decades.

A solar PV powered RO plant was first investigated on a commercial scale in Saudi Arabia in 1981, when a 3.2 m^3/d SWRO desalination plant coupled to an 8 kWp PV system was installed in Jeddah.

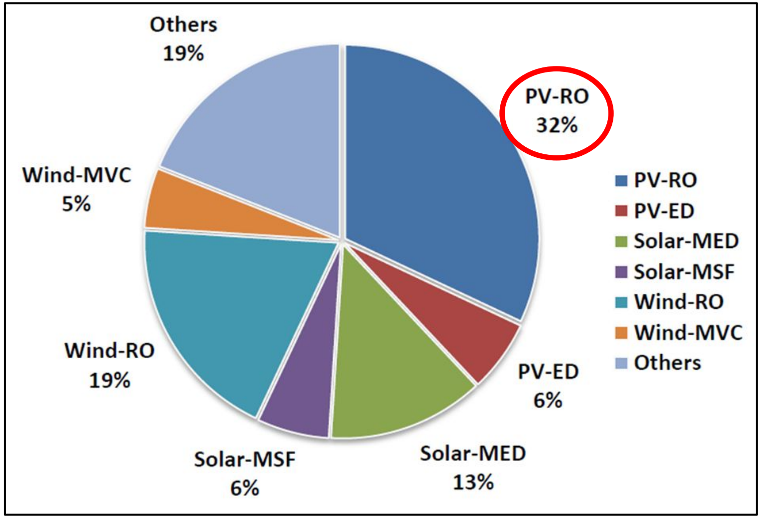
Although research on PV-RO desalination system began in the early 1980s (table below), its precise techno-economic feasibility has been assessed recently.

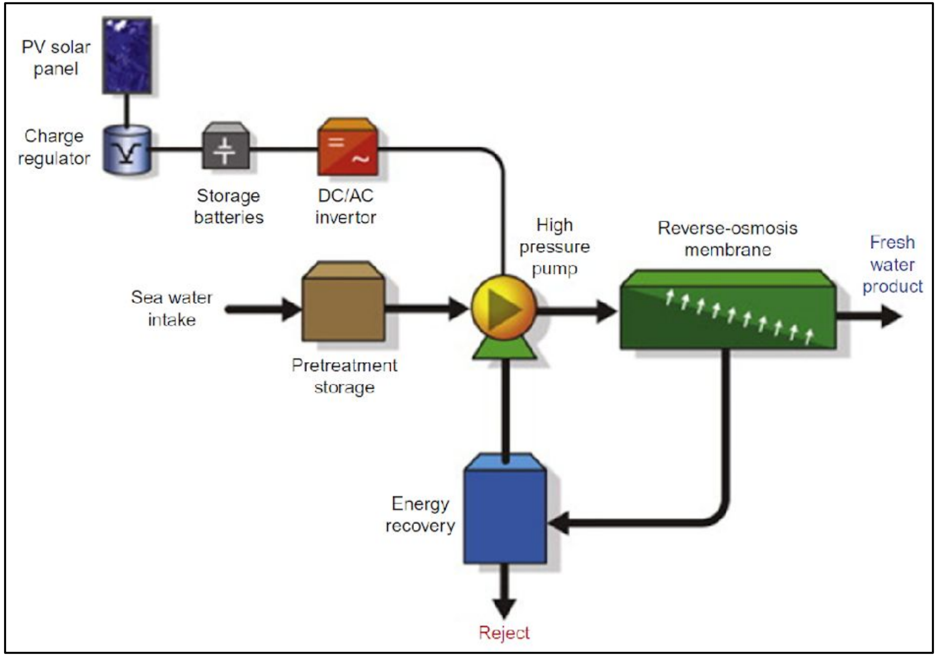
Solar PV driven RO desalination introduction

Table 1. Highlights of PV driven RO plant development.

Year	Event
1982	World's first solar PV driven SWRO plant (Boesch, 1982)
1985	Use of ERD (positive displacement pump) in PV-driven SWRO plant (Keeper et al., 1985)
1988	First PV driven BWRO plant (Effendi, 1988)
1998	Hybrid brackish water PV-RO plant with solar stills (Hasnain and Alajlan, 1998)
2001	Introduction of PV-powered brackish RO system without batteries (Joyce et al., 2001)
2003	First battery-less seawater PV-RO system (Thomson and Infield, 2003)
2006	First isolated PV-RO system for a community water supply (Baltasar et al., 2006)

PV-powered RO is considered one of the most-promising forms of renewable-energy-powered desalination.





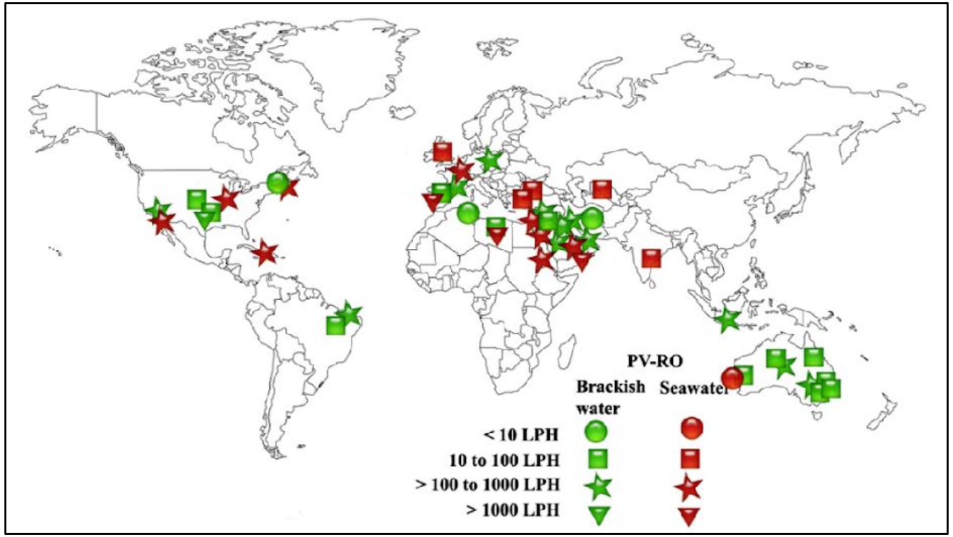
Schematic diagram of a PV-RO system with batteries

Solar PV driven RO desalination introduction

- Numerous studies focused on using solar PV energy to drive RO plants on a small scale.
- Almost 1/3 of the autonomous desalination systems installed are based on PV powered RO units. Both PV solar energy and RO are mature technologies with wide commercial network of manufacturers and suppliers.

Source: Renewable and Sustainable Energy Reviews. Volume 112, September 2019.

Geographical locations of seawater and brackish RO experimental setups powered by PV system.



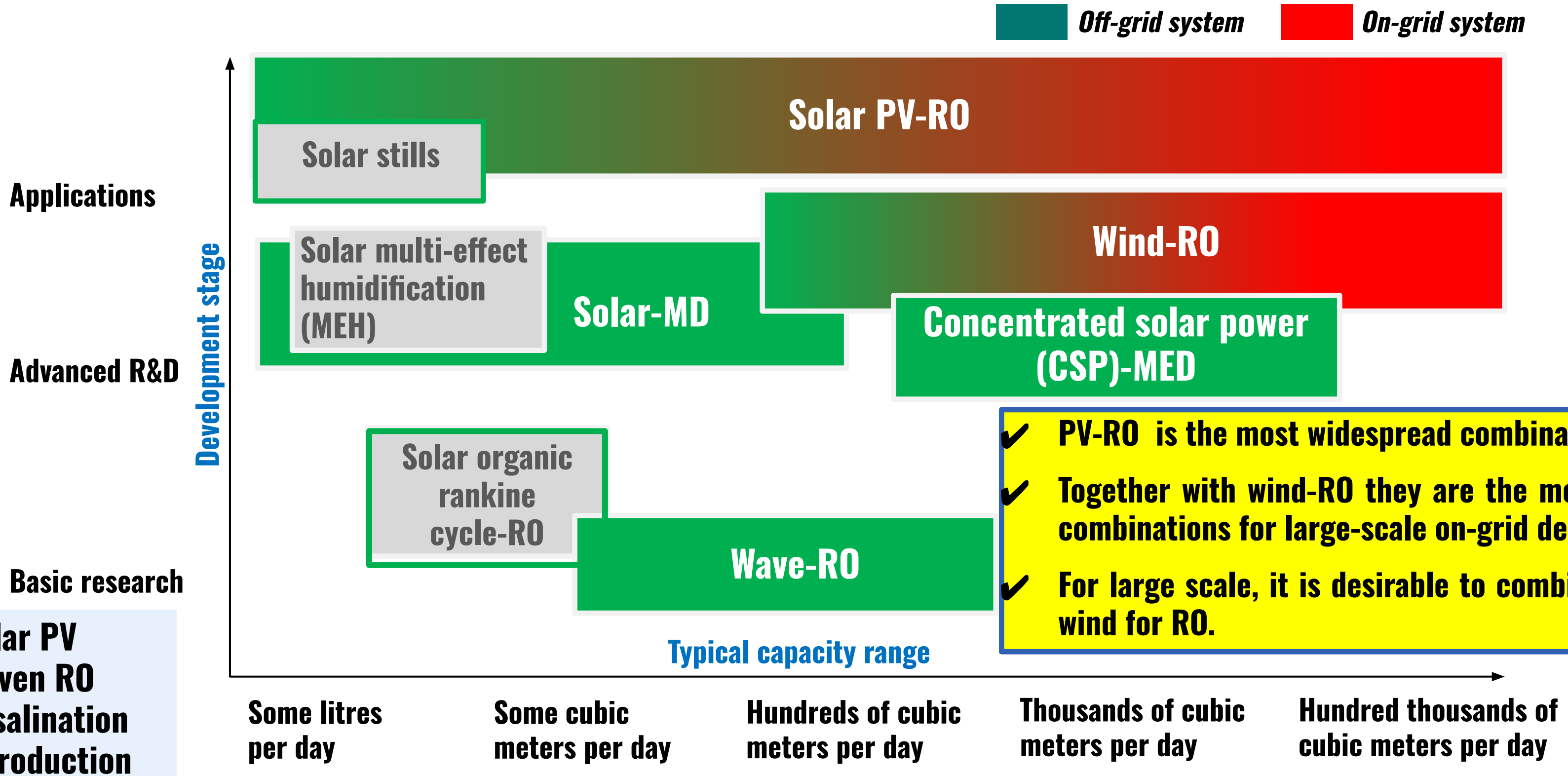
Selected specifications of currently installed solar PV powered RO plants.

Desalination plant location	Capacity (m^3/d)	Year	Feed water
California valley, USA	75	2012	Brackish water
Ben Guerdene, Tunisia	1,800	2013	Brackish water
Ras Laffan, Qatar	12,000	2013	Seawater
Aniwa Island, Vanuatu	96	2013	Seawater
Ambae Island, Vanuatu	96	2013	Seawater
Centro Morelos, Mexico	840	2014	Brackish water
Baja California, Mexico	48	2014	Brackish water
Fortaleza, Brazil	3,600	2014	Brackish water
Al Khafji, KSA (most recently)	60,000 (PV 20MW)	2023	Seawater

(Source: F.E. Ahmed et al., Solar powered desalination – Technology, energy and future outlook, Desalination 453 (2019) 54–76).

Solar PV driven RO desalination introduction

Development status and production capacity of desalination systems powered by RES



- ✔ PV-RO is the most widespread combination.
- ✔ Together with wind-RO they are the most mature combinations for large-scale on-grid desalination.
- ✔ For large scale, it is desirable to combine PV and wind for RO.

Solar PV driven RO desalination introduction

Source: adapted and updated from ProDes project.

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Basic theory of solar PV

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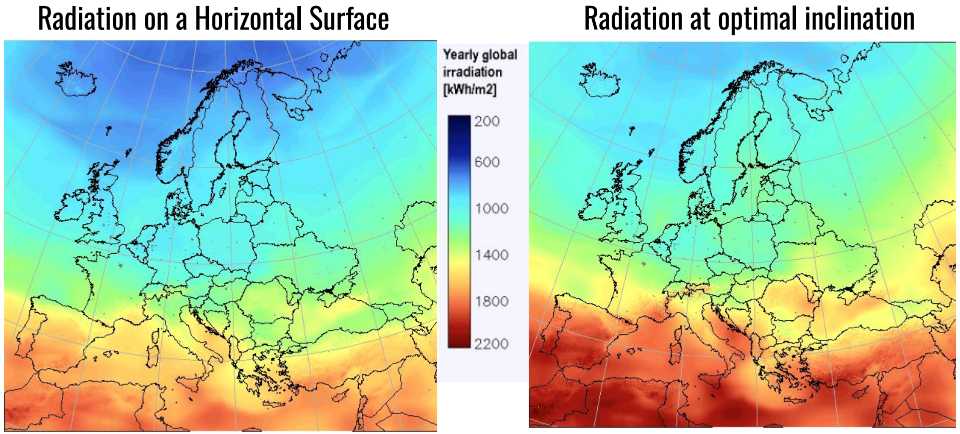
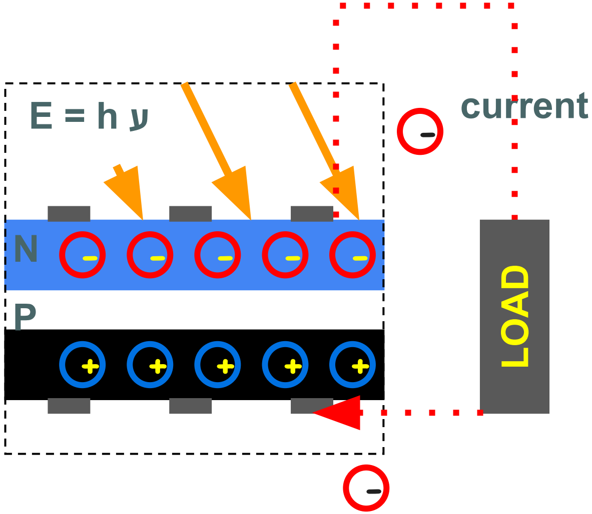
Solar radiation: solar energy received from the sun mainly depends on the location and the inclination of the reception device. The figures below show these effects.



Source: JRC publications (http://ec.europa.eu/dgs/jrc/index.cfm?id=2020)

Solar PV energy is based on the electric conversion of solar radiation on a solar cell, by means of the **photovoltaic effect**:



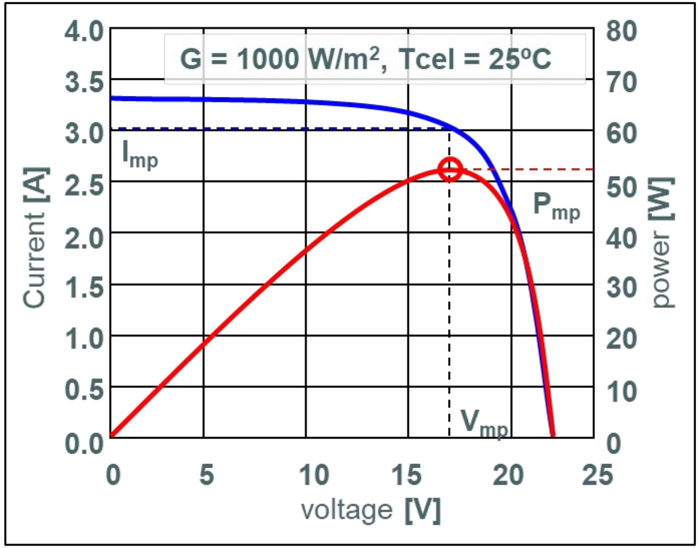
Free electrons created by absorption of photons are in excess in the N layer of a semi-conductor, migrating to P layer through an external circuit, thus creating an electric current.

Basic theory of solar PV

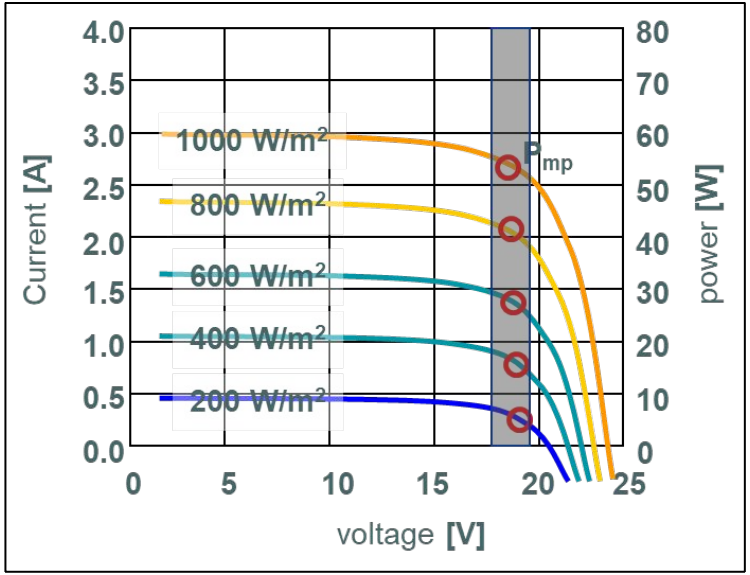
Solar cells are connected in series to form a PV module.

PV modules are connected in series or parallel to assemble a Solar PV field with the required current and voltage.

Current – Voltage curve



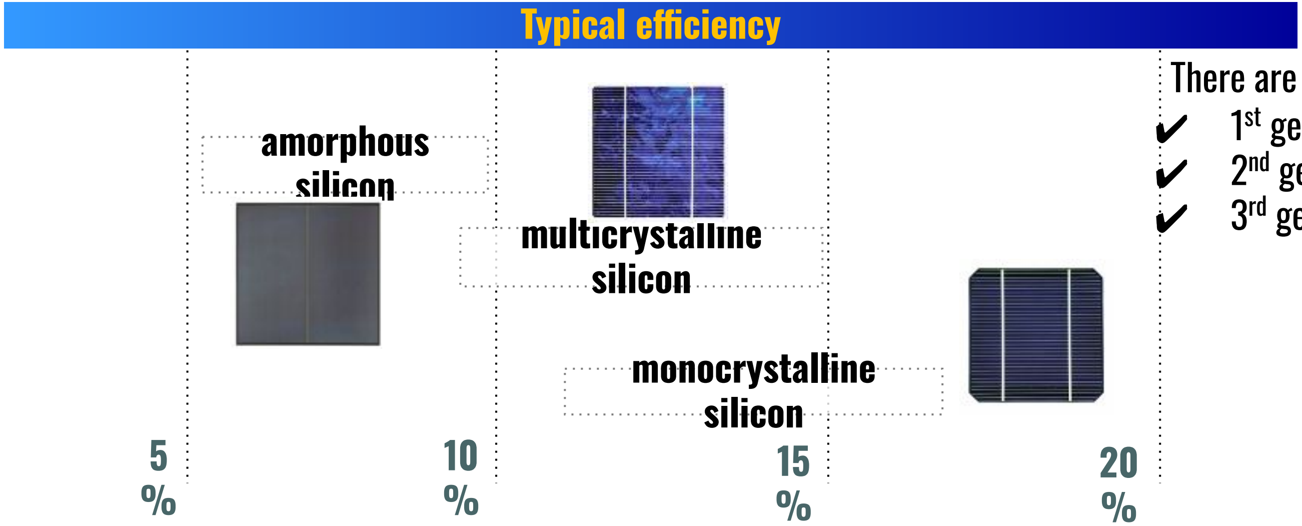
The current and power produced by a PV cell vary according to its voltage under given temperature and irradiation conditions. Under reference irradiation and temperature conditions, the characteristic I-V curves can be obtained (left figure).



Basic theory of solar PV

The values under reference conditions are called Peak or reference values: Peak power (Pmp), Current at peak power (Imp), Voltage at peak power (Vmp). The effect of solar radiation on the I-V curve is presented in the right figure.

Efficiency of solar cells



There are three generations of PV cells:

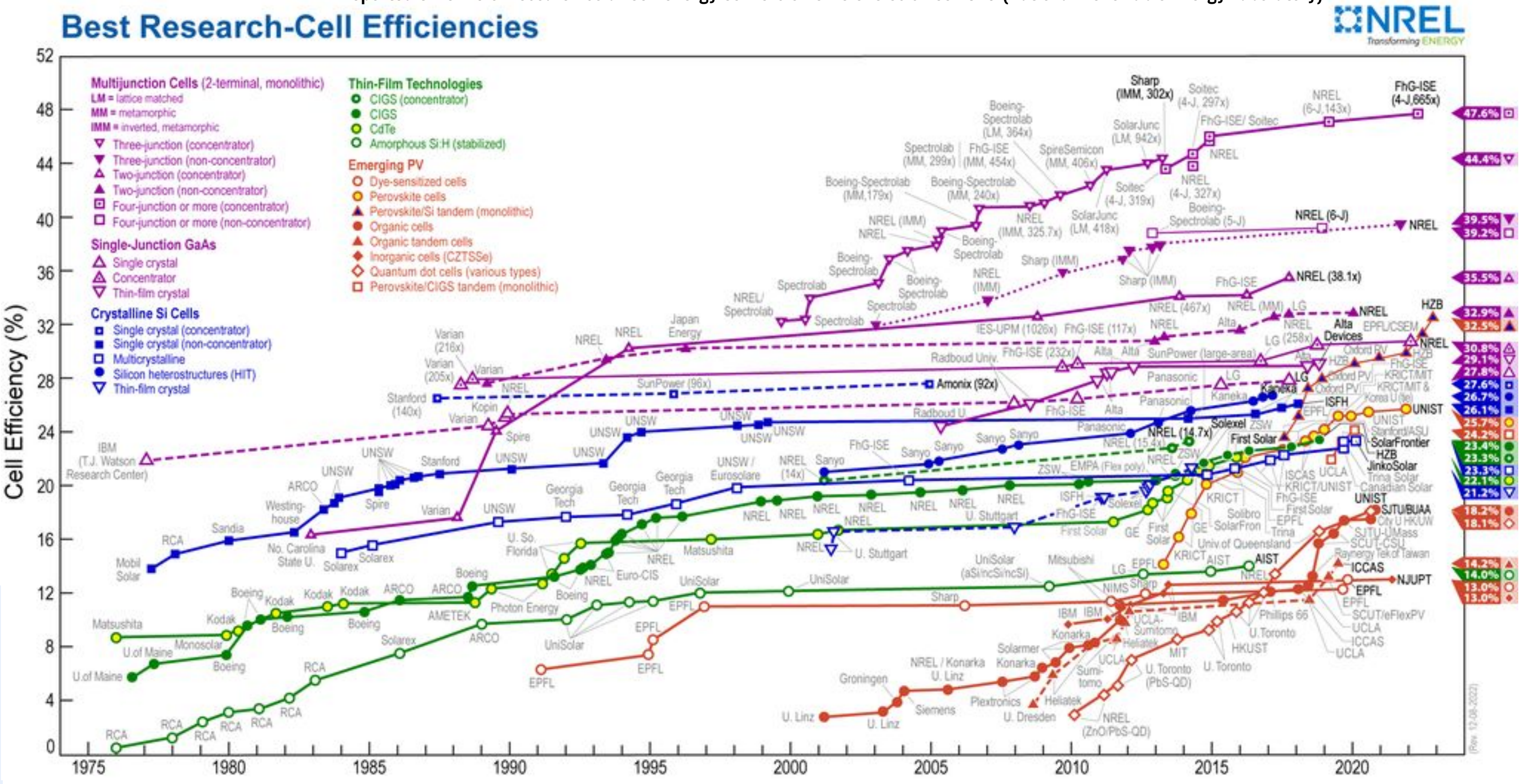
- ✔ 1st generation: crystalline silicon (c-Si);
- ✔ 2nd generation: amorphous silicon thin-film (TF);
- ✔ 3rd generation: Nano-PV

Basic theory of solar PV

In today's market, the most common material used for PV cells is crystalline silicon. The overall efficiency of a PV system totally depends on temperature of the cells, in a way that the efficiency decreases with a rise in operating temperature.

Current research activities have achieved high efficiencies (close to 40 %) in prototypes tested in laboratories.

Reported timeline of research solar cell energy conversion efficiencies since 1976 (National Renewable Energy Laboratory)



Basic theory of solar PV

The world record for solar cell efficiency is **47.1%**, set in 2019 by multi-junction concentrator solar cells developed at National Renewable Energy Laboratory (NREL), Golden, Colorado, USA. This record was set in lab conditions, under extremely concentrated light. The record in real-world conditions is also held by NREL, who developed triple junction cells with a tested efficiency of **39.5%**

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RO process introduction. SWRO-BWRO differences

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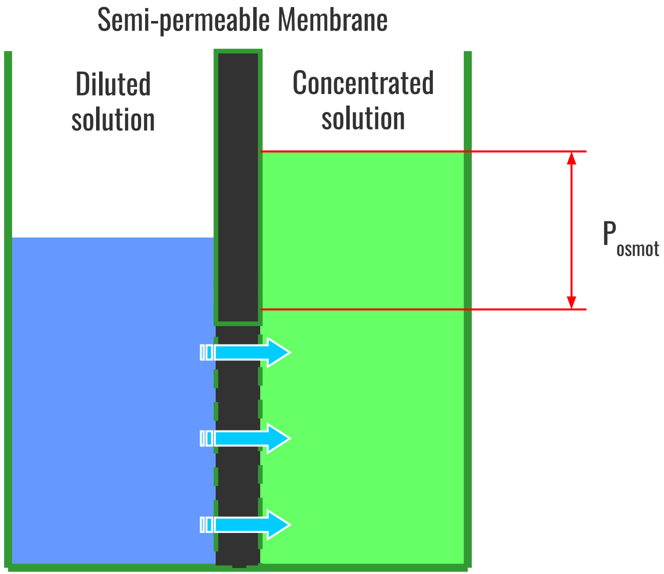
Salinity [g/l]	Molarity (≈NaCl) [mol/l]	P T=25°C [atm]
5	0.086	4
10	0.172	8
35	0.603	29
50	0.862	42
70	1.207	59

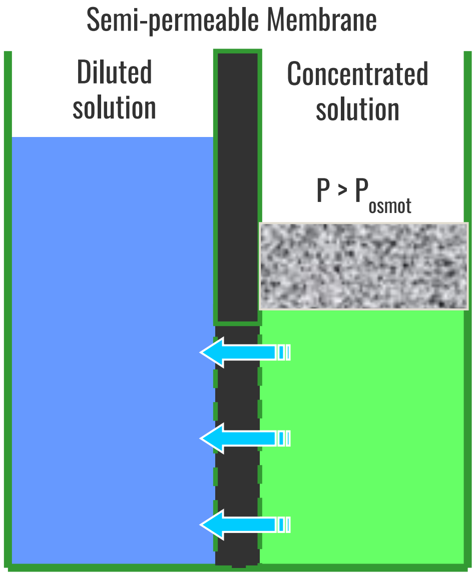
RO process introduction. SWRO-BWRO differences

Osmosis



Natural phenomenon that occurs when matter is exchanged between two solutions with different concentrations separated by a semi-permeable membrane. The concentrations of these two solutions become balanced spontaneously, without the need for energy.

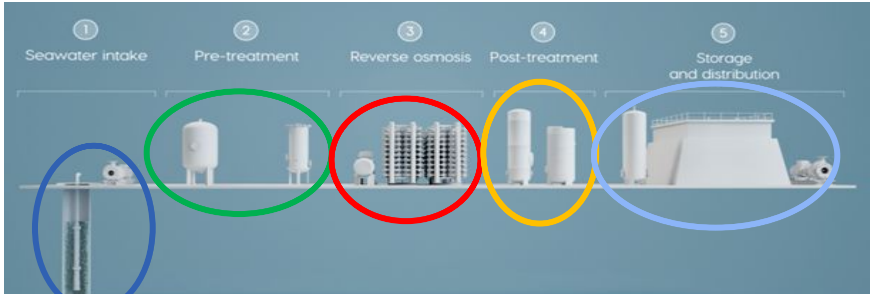
Reverse Osmosis



This process can be reversed artificially by applying energy. If we apply a force to a volume of seawater containing a high salt content and pass it through a semi-permeable membrane, we obtain water with a very low salt concentration on one side and highly concentrated water, called brine, on the other.

Reverse Osmosis is the most widespread and sustainable membrane desalination technology available today.

Typical SWRO desalination plant flow diagram



SWRO plant scheme (ACIISI, 2023)

The desalination process begins with the **seawater intake**, mainly done through open intakes or beach wells.

Open intakes allow for larger water flows to be collected, and are the most used for large desalination plants. However, the quality of the water they provide varies over time. Well system provides a better and more stable water quality, thanks to natural filtration process that occurs in the ground.

Seawater must be pre-treated, to a greater or lesser extent, depending on the type of intake and the physicochemical properties of the water. Physical and chemical **pre-treatment** are made. A dual media filtration (20 microns) followed by a cartridge filtration (5 microns).

Although the technological development of RO has made it possible to reduce the use of chemicals, the use of antiscalant is still common to prevent the deposition of salts on the membranes when operating at high recovery rates.

RO process introduction. SWRO-BWRO differences

RO is the heart of the desalination process. The system consists of HPP, RO racks composed of a series of pressure vessels housing usually 7 RO membranes placed in series, and an ERD (with a booster pump in the case of isobaric ERDs).

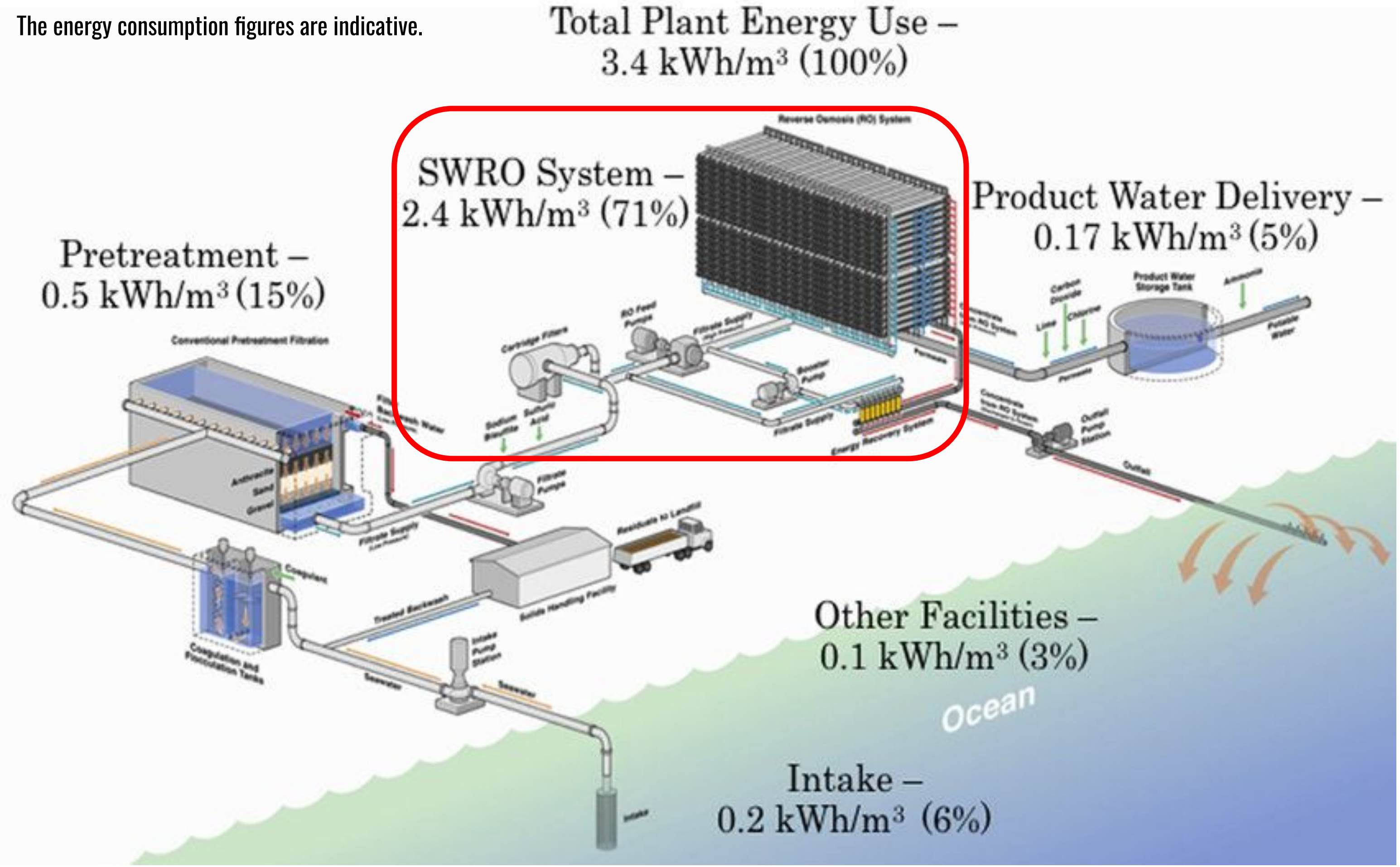
Typical operating values for SW desalination: P = 50 to 60 bar (lower in BW), recovery rate 40 to 45% (higher in BW), SEC = from 2 to 3 kWh/m^3 (lower in BW).

Desalination process culminates with the **post-treatment.** Permeate is corrosive and must be remineralised to achieve a balance in which pH, alkalinity and calcium levels become homogeneous and stable during the water **distribution**.

The most used remineralization technique is CO_2 injection, together with calcite beds to add CO_3Ca to the water, so adjusting the pH and increasing its hardness and alkalinity. After remineralization, if water is intended for human consumption, chlorination is carried out in the distribution tank.

Energy use breakdown of typical SWRO desalination plant

The energy consumption figures are indicative.



RO process introduction. SWRO-BWRO differences

Source: (Nikolay Voutchkov, 2018). Review of the currently most efficient SWRO plants

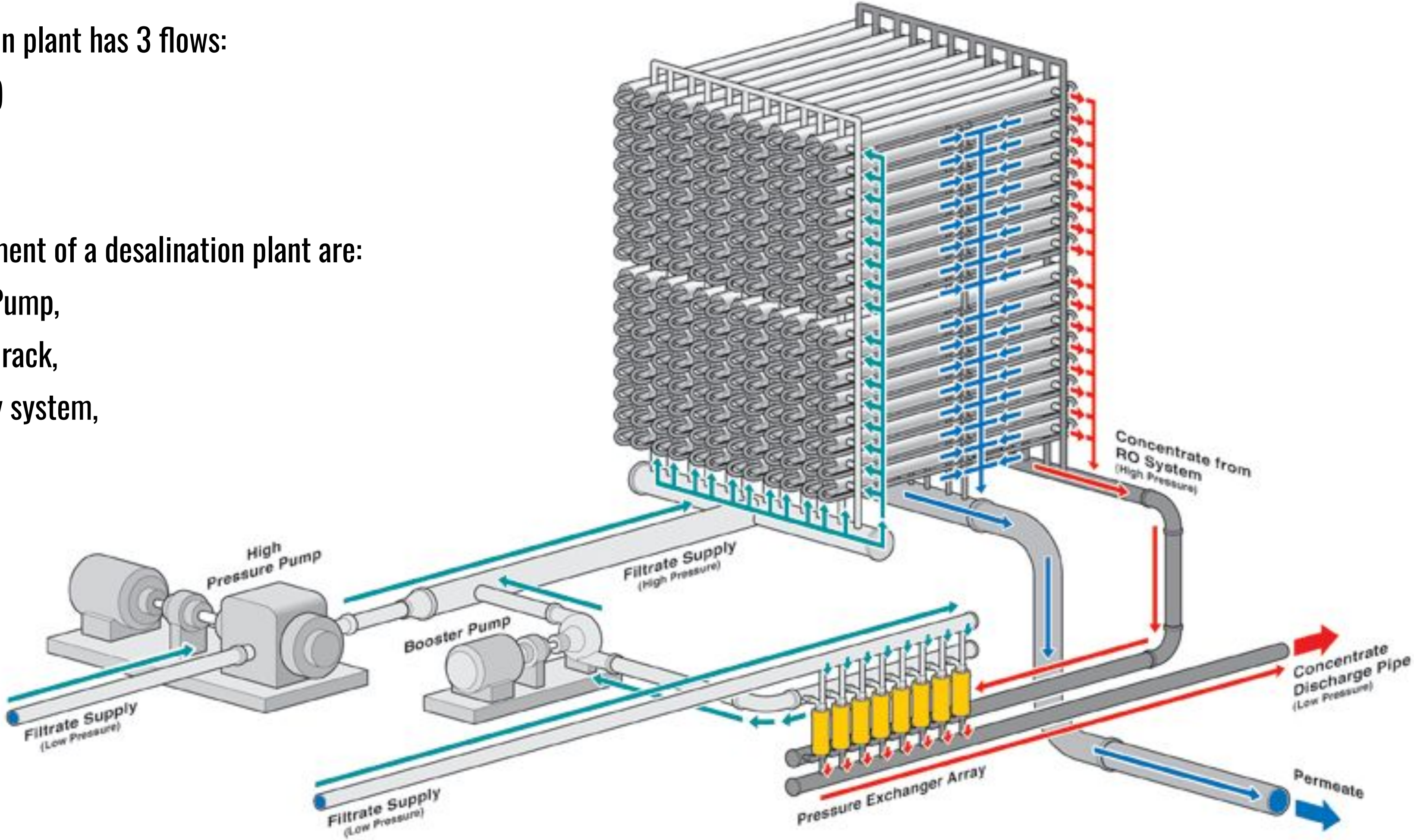
A RO desalination plant has 3 flows:

- feed (light blue)
- product (blue)
- brine (red)

The main equipment of a desalination plant are:

- High Pressure Pump,
- RO membranes rack,
- Energy recovery system,
- Booster pump.

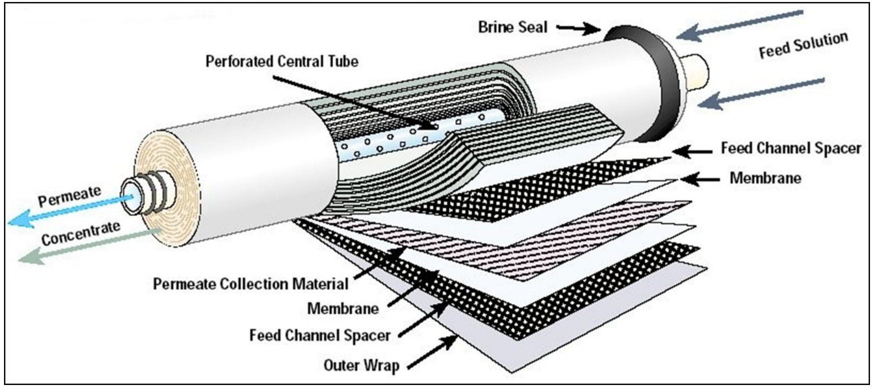
RO process introduction. SWRO-BWRO differences



Factors influencing RO Specific Energy Consumption (SEC) and improvements of technology

The **main factors affecting the SEC** in the RO process are:

- Product water quality
- Type of Energy Recovery Device (ERD)
- Type of High Pressure Pumps (HPP)
- Operating conditions



The **main improvements** in RO processes:

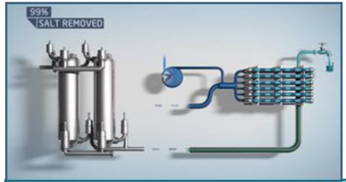
- Efficiency of membranes (the so-called last generation membranes)
- Technology of Energy Recovery Devices (ERD)
- Use of Positive Displacement Pumping in High Pressure
- Use of Variable Frequency Devices (VFD)

RO process introduction. SWRO-BWRO differences

Developments and improvements of ERD

TURBOCHARGER = 3.15 kWh/m^3

PELTON = 4.14 kWh/m^3

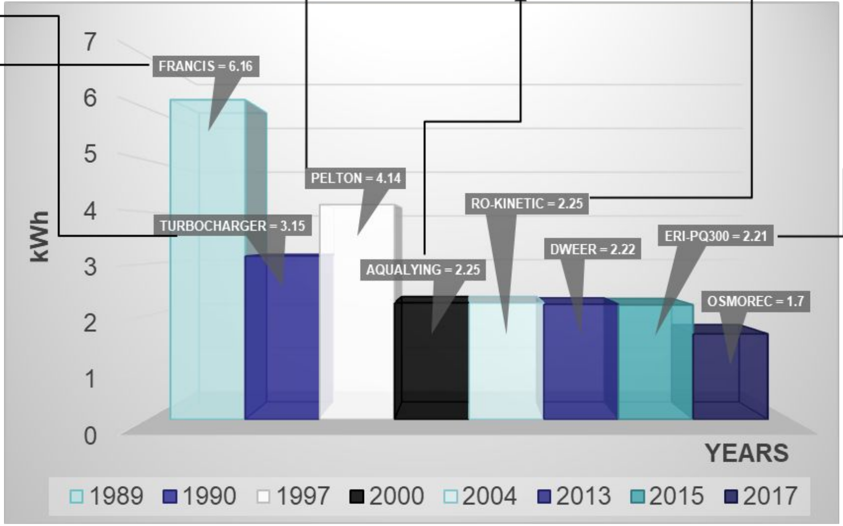


AQUALYNG = 2.25 kWh/m^3

RO-KINETIC = 2.25 kWh/m^3

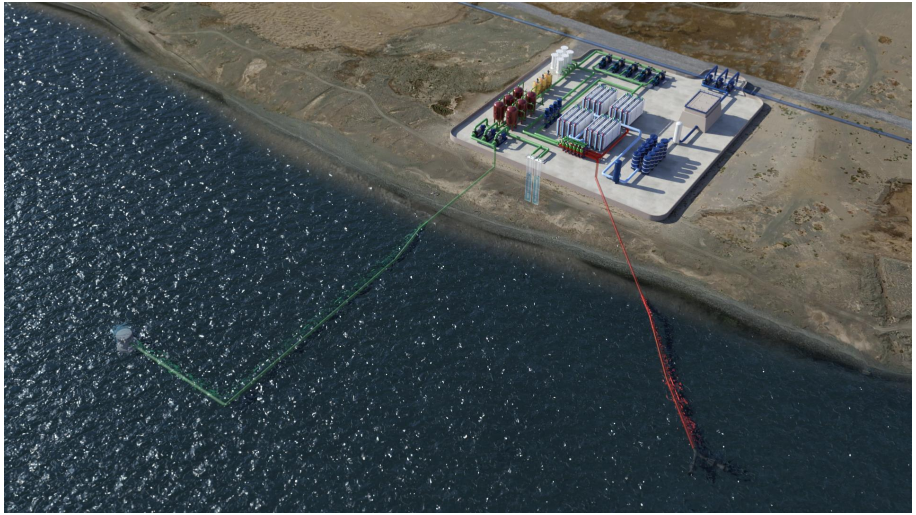
PX-Q300 = 2.21 kWh/m^3

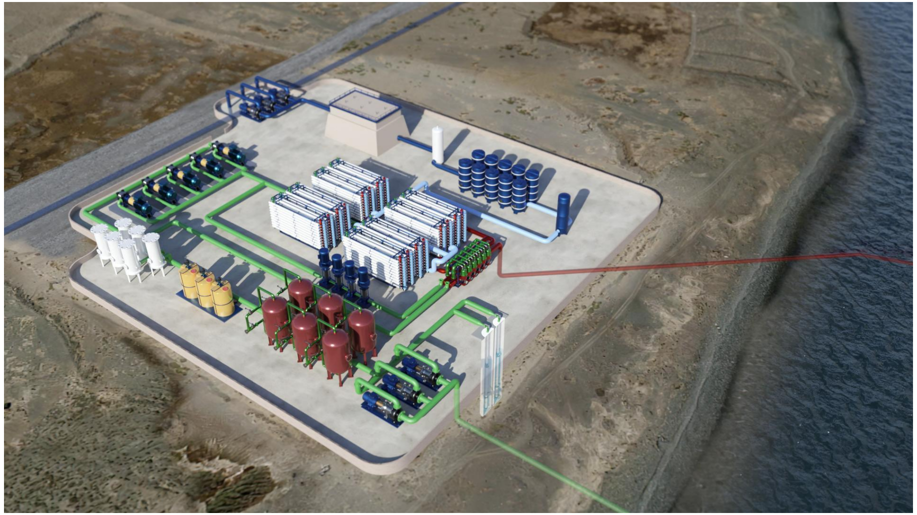
FRANCIS = 6.16 kWh/m^3



SALINO = 1.98 kWh/m^3

RO process introduction. SWRO-BWRO differences





Hyper realistic 3D Video on the operation of a SWRO desalination plant.

RO process introduction. SWRO-BWRO differences

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The need for solar desalination and its challenges

Palermo, Sicily. 10th - 11th January, 2024

The use of RO desalination has grown in response to water scarcity. Despite steady improvements in energy efficiency, RO desalination remains an energy-intensive process. Renewable energy is an attractive solution to:

- ✔reduce RO plants' carbon footprint,
- ✔decrease their running costs,
- ✔eliminate the link between water prices and fuel costs.

Whereas the power output of solar-PV field is intermittent and fluctuating, commercial RO plants are designed to work at constant flow, pressure and power level.

The plant adaptability to RES can be improved, matching the load to the available power by means of:

The need for solar desalination and its challenges

- **Plant configuration** (modular desalination plant design). Different RO racks or pressure vessels in the same rack can be connected/disconnected based on the available energy.
- **Operational strategy** (variable-speed operation). Using a variable frequency drive to change the HPP speed according to the available power. Positive displacement pumps are suitable for variable-speed operation, as they offer consistent efficiency at varying flowrates.
- An accurate **control system** design.
- Including a **backup system** (connection to electric grid, energy/water storage system or diesel generator).

- Two **main technical challenges** to be faced when operating RO plant in discontinuous way:

  - **Shortened RO membrane lifetime.**

Negative: continuous start-ups, shutdowns, flow variation and pressure fluctuations can lead to mechanical fatigue with a negative impact on membrane lifetime and performance.

Positive: after numerous studies there are contradictory opinions; some authors report shorter lifetimes while others highlight improvements in performance, arguing that turbulence improves the diffusion through the membrane and decreases the effect of concentration polarization leading to increased permeate flux and quality.

  - **Reduced performance of ERDs.**

Positive: unlike centrifugal devices, isobaric devices can operate at nearly constant efficiency with a varying flow rate making them more suitable for variable operation. Additionally, their decoupled operation from the HPP offers a great advantage for variable operation, as it allows the independent variation of membrane flux and recovery.

Negative: however, the negative effects of mixing and leakage on overall performance could worsen under variable operation due to increased pressure and flow fluctuations.

The need for solar desalination and its challenges

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PV-RO key equipments, schemes and possible configurations

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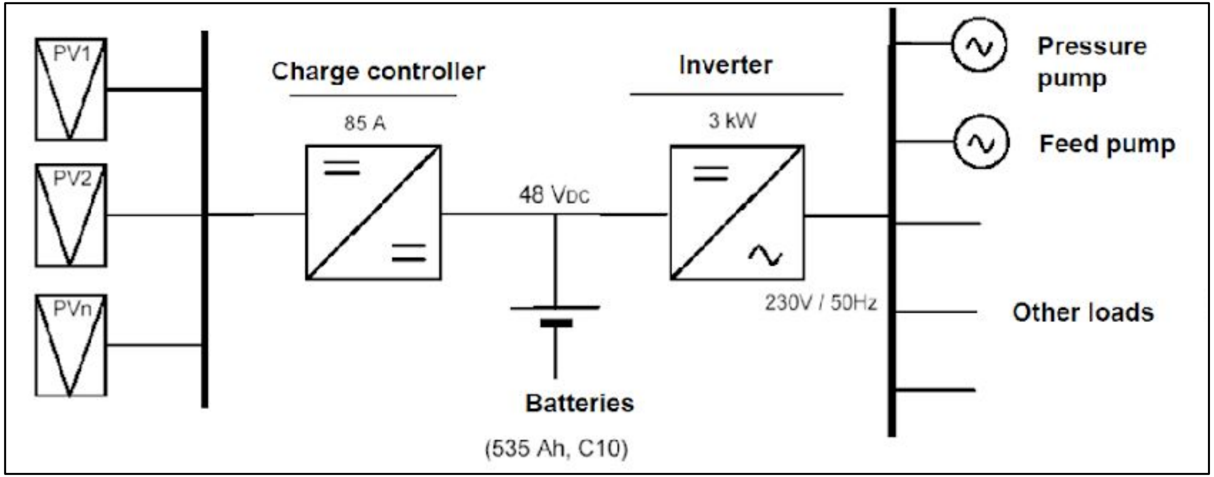
PV & RO Coupling (diagram)

Some figures about the size of equipment have been included as a reference.



PV-RO key equipment, schemes and possible configurations

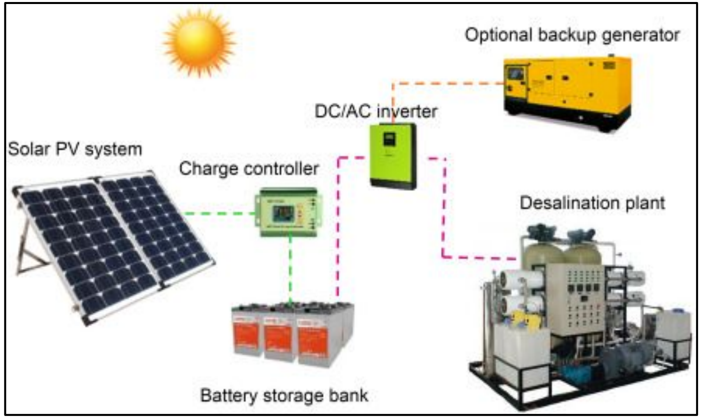
- ✔ The DC voltage produced by the PV field goes to the batteries through a charge controller to guarantee the good operation of the batteries.
- ✔ Energy from the batteries is converted into AC in the inverter to supply electricity to the different loads.

The core components of a solar-PV system are PV panel, charge controller, battery pack, DC/AC inverter. These equipment should be added to a PV module to supply energy to a desalination plant.

Two configurations are possible: stand alone or grid connected PV-RO plants.

PV-RO key equipment, schemes and possible configurations

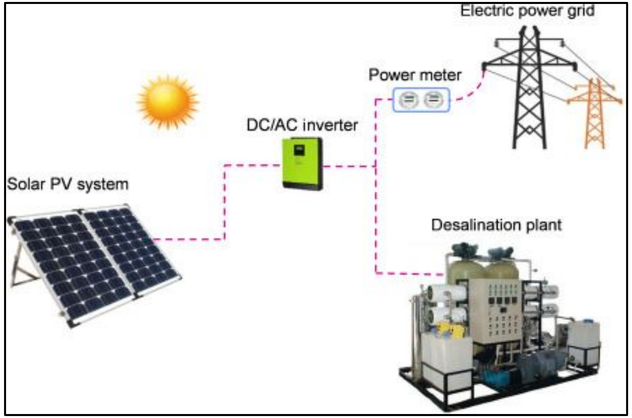
OFF-GRID PV-RO desalination: all the energy required by the desalination plant is supplied by RES.



Use of RES isolated from a power grid (off-grid / micro-grid):

- Small/medium desalination plant capacities.
- Storage of water/energy to overcome the variability of the energy resource.
- High investments depending on the m^3 produced.
- It requires a control system to optimize the use of the energy resource.
- It can be hybridized and/or combined with diesel.

ON-GRID PV-RO desalination: RES supplies a percentage of the energy required per year (30-60% depending on the type of RES). Surplus energy can be sold back to the grid in some cases.

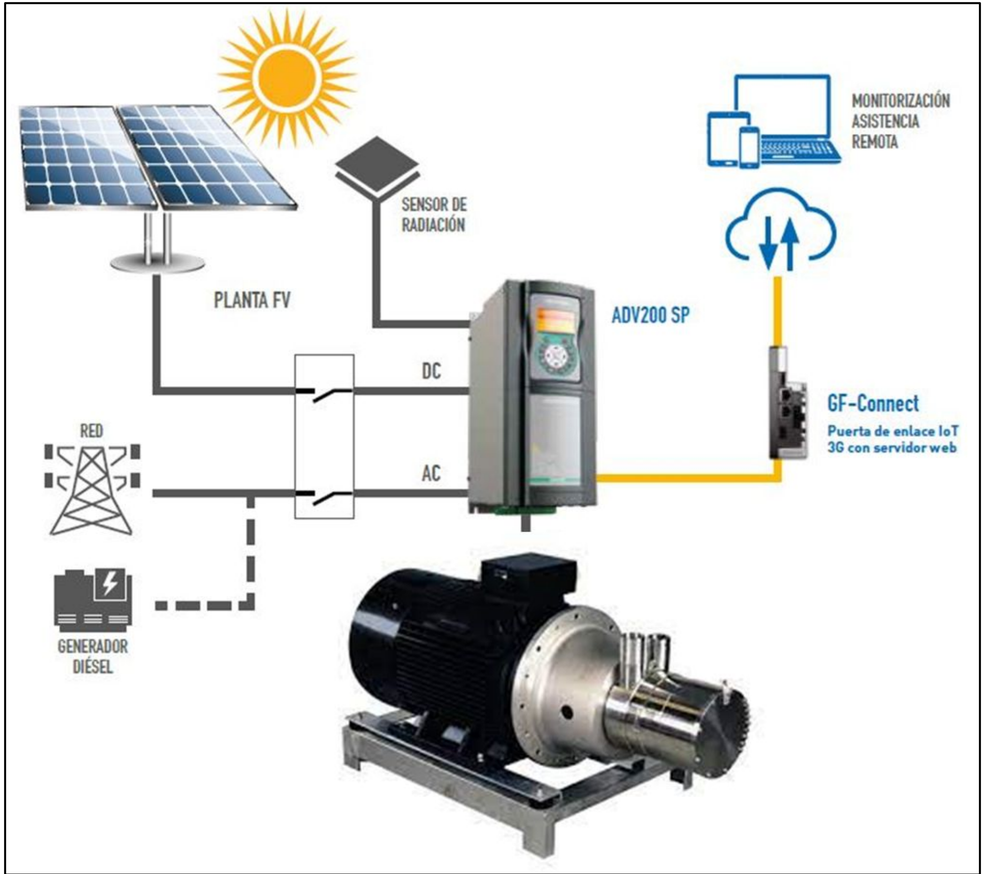


RES connected to a power grid (self-consumption or net balance)

- Medium and large production capacities.
- Water storage to meet demand.
- It requires a control system to manage the load.
- Sale of energy. Economic viability due to the sale of the resource.
- Existing regulatory constraints.

Source: Photovoltaic Solar Energy Conversion. Technologies, Applications and Environmental Impacts. Chapter 8 - Applications of solar PV systems in desalination technologies, S. Gorjian et altres. 2020, Pages 237-274.

Zero discharge using the VFD DC bus: PV connected to the DC bus of the HPP variable frequency drive of the RO plant, without batteries. Operating the PV-RO desalination plant pseudo-connected to the electrical grid.



- ✔ Savings of 25 to 30% of electrical energy from the grid.
- ✔ 100% use of solar energy.
- ✔ Solar PV field voltage adapted to the inverter voltage.

PV-RO key equipment, schemes and possible configurations

PV-RO with battery back-up system vs. battery-less system

PV-RO with constant production capacity (batteries)		PV-RO with variable production capacity (battery-less)	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Simpler control system. RO plant of less complexity Higher water production per year for the same PV field. Greater operation stability which means fewer breakdowns (less stops per year) Lower-scale desalination plant dimension. Guarantees stable water production. Lower water storage capacity required. Long term lower OPEX.	Higher space requirement. Higher investment cost in PV panels. Higher investment cost in battery capacity (89%). Higher investment cost in electrical installation (20%). Higher maintenance costs (batteries/PV).	Lower investment cost in PV panels and batteries (for 24/365 control). Lower investment cost in electrical installation. Lower maintenance costs (batteries/PV). Less space requirement.	Higher desalination plant investment: due to variability of operation a higher production scale plant is needed for guaranteeing a daily production. Needs greater water storage capacity. Lack of understanding of the behavior and life of RO membranes operating under variable conditions during several years.

PV-RO key equipment, schemes and possible configurations

Source: lessons learnt from a case study carried out by the ITC at Pozo Izquierdo testing facilities in Gran Canaria.

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Costs and other non-technical aspects to take into account

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Non-technical aspects of a PV-RO desalination project include:

- ✔ Economic aspects
- ✔ Environmental aspects
- ✔ Social, political and legal aspects

DESALTED WATER COST

The current water cost for a small-scale SWRO-grid connected desalination plant is around **1 – 1.3 €/m³** produced (considering 0.14 €/kWh).

During the last decade, **PV module costs** have been reduced considerably. This is a clear benefit over the PV-RO investment costs, where the ratio of **isolated peak power installed** has decreased from **10 €/Wp** (in 2007) to **2.0-3.5 €/Wp** (including panels, converters, power control, batteries and place).

Costs and other non-technical aspects to take into account

Depending of the scale and energy required, for a PV-RO-batteries system the cost of the water produced is estimated from **1.5 – 4.0 €/m³ (brackish – sea water)**. Lower than prices that an isolated local population could paid for freshwater nowadays: **3 - 10 €/m³**.

It is a competitive cost in isolated areas where the cost of desalinated water produced with a diesel generator or a weak electrical grid could reach 2 €/m³ produced (24/365).

- Cost of RE desalination systems is high in comparison with conventional desalination costs.
- Lack of a clear market and risk understanding, water pricing structures and lack of investment funding are the main economic barriers for the development of RE desalination.
- RE desalination does not generate the atmospheric pollution of fossil fuel energy sources, required for the energy supply of conventional desalination.
- Use of chemical products in desalination units can lead to toxicity effects. Salinity, temperature and density of brine flow must be taken into account for evaluating the environmental impact.
- Social aspects are a key factor when a RE desalination project is carried out in a developing country. It is essential to involve all the local actors.
- Generation of tools to improve the trust of decision makers and investors on RE desalination.

Costs and other non-technical aspects to take into account

Recommendations for desalination projects with RES:

- Simple and robust designs, adapted to local conditions (tailor-made project).
- Development of the specific control system, programmed for each particular case (reduces maintenance, maximizes water production and extends the useful life of the equipment).
- In the case of localization in developing countries, include the participation of local entities in the project, in order to consider all aspects, not only the technical elements, but also the social and economic conditions.

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Conclusions

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- PV-powered RO desalination is mature for commercial implementation; the technical feasibility of different design concepts has been demonstrated in a large number of case studies.
- Competitive solutions using this coupling for isolated and water stressed places have been implemented worldwide.
- Due to its modularity, RO can be adapted to the available energy, easy operation (a control system is required).
- The PV panels costs reduction has motivated an acceleration of its implementation.
- PV-RO connected to the grid can be an excellent solution to industrial places (reduction of 25-35% OPEX).
- Challenge: the connection with isolated micro-grids and the control of the energy loads.

Conclusions

State-of-the-art, battery-less systems that couple the PV modules directly to variable speed DC pump motors seem to have the highest potential for energy-efficient and cost-effective small-scale PV-RO desalination. However, the long-term performance and reliability of such systems has not yet been sufficiently tested.

Disadvantages: high initial investment cost. Low local capacitation in isolated areas.

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Q&A

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