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Fast Track School #3

Introduction to Solar-driven Water production & Treatment technologies and brine treatment processes
Technology benchmarking and Exploitation contents

Casa Cordovil, Universidade de Évora, Évora. 5th - 6th February, 2025

Benchmarking on PV-RO desalination

Brief introduction. Why PV-RO?	KPIs and comparative of final solutions	Products on the market and successful experiences	Challenges and future opportunities	Conclusions Q&A

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Why PV-RO desalination?

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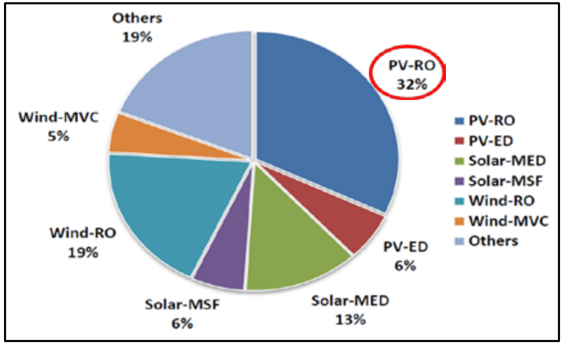
PV-powered RO is considered one of the most-promising forms of renewable-energy-powered desalination. A PV-RO plant was first investigated on a commercial scale in 1981 in Jeddah (Saudi Arabia), with a 3.2 m^3/d SWRO desalination plant coupled to an 8 kWp PV system.

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



Why PV-RO desalination?

Large market opportunities exist for solar powered RO desalination technologies in arid areas with solar and seawater resources. A challenge to realizing these markets is the variable nature of solar resources, which for the desalination plant can lead to:

- **High water costs due** to low capacity factors (CF). Potential solutions: energy storage (batteries), hybrid systems (PV + other RES/grid), variable operation with demand management and high-efficiency RO design.
- **Increased maintenance costs** due to repeated start-ups and shutdowns.

Competitive solutions using this coupling for isolated and water stressed places have been implemented worldwide.

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KPIs and comparative of final solutions

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PV-RO benchmarking refers to the process of evaluating and comparing the performance, efficiency, and cost-effectiveness of PV-RO desalination systems. This involves assessing key performance indicators (KPIs) such as water recovery rate, specific energy consumption (SEC), CAPEX, OPEX and levelized cost of water (LCOW) across different system designs, manufacturers, and operational environments.

Purpose of PV-RO Benchmarking

- ✓ Identify **best-performing** technologies for different feed water salinities or water production capacities.
- ✓ Optimize **PV-RO system design** for energy savings and cost reduction.
- ✓ Compare performance across different **climatic conditions** and regions.
- ✓ Guide **investment decisions** in sustainable desalination projects.

KPIs and comparative of final solutions

The benchmarking approach used is based on a **comparative analysis:**

- ❖ Compare different PV-RO systems based on performance and cost data.
- ❖ Use case studies of existing installations to evaluate effectiveness.

❖ Comparison of different PV-RO systems based on performance and cost data.

Most used key performance indicators:

1. Energy Efficiency:

- Specific Energy Consumption (SEC) (kWh/m³)
- Energy recovery efficiency (%)
- PV system performance ratio

2. **Water Production & Quality**:

- Permeate flow rate (m³/day)
- Recovery rate (%)
- Product water quality (TDS, use of chemicals, WHO compliance)

3. **Cost Metrics**:

- Capital Expenditure (CAPEX) per m³/day
- Operational Expenditure (OPEX) per m³
- Levelized Cost of Water (LCOW) (€/m³)
- Membrane replacement frequency & costs

4. **System Reliability & Sustainability**:

- Downtime & maintenance requirements
- Scalability & modularity
- Carbon footprint reduction

KPIs and comparative of final solutions

Benchmarking table comparing different PV-RO desalination systems based on key performance indicators.

Parameter	Small-Scale (5-50 m³/day)	Medium-Scale (50-500 m³/day)	Large-Scale (>500 m³/day)
Example Applications	Remote villages, disaster relief	Coastal communities, hotels	Industrial, municipal desalination
Feed water Type	Brackish* (1,000–10,000 mg/L)	BW/SW (10,000–35,000 mg/L)	Seawater (>35,000 mg/L)
Solar PV Capacity	5–50 kWp	50–500 kWp	500 kWp–10 MW
Energy Recovery	No ERD** / Simple Pump	Energy Recovery Device (ERD)	High-efficiency ERD (PX)
Specific Energy Consumption (SEC)	1.2–2.5 kWh/m³	2.5–4.0 kWh/m³	3.0–4.5 kWh/m³
Recovery Rate (%)	40–65%	40–50%	35–45%
Water Cost (LCOW, €/m³)	1.5–3.0 €/m³	1.0–2.0 €/m³	0.6–1.5 €/m³
System Cost (€/m³/day)	1,500–3,000 €	1,200–2,500 €	800–2,000 €
Battery Requirement	Optional (direct solar coupling)	Often required	Large battery or hybrid (grid backup, self-consumption)
Autonomy (Hours Operation)	6–8 hours (solar only)	8–12 hours	12–24 hours
Maintenance Complexity	Low (replace filters & membranes)	Medium (pumps, ERD maintenance)	High (SCADA, automation, chemical dosing)

* Small scale PV-SWRO systems are also available.

** ERD also available for SWRO systems above 11 m^3/d.

KPIs and comparative of final solutions

- Use case studies of existing installations to evaluate effectiveness:

Comparison Table

Parameter	Kitui, Kenya (Small-scale, Off-grid)	Abu Dhabi, UAE (Grid-Connected)	Singapore (Floating PV-RO)	Neom, Saudi Arabia (Large-Scale)
Capacity (m^3/day)	3	50	100	1,000
PV Capacity (kWp)	5	50	150	1,000
Feed water Type	Brackish Water	Seawater	Seawater	Seawater
Feed water TDS (mg/L)	3,500	40,000	38,000	42,000
Recovery Ratio (%)	40	35	40	45
SEC (kWh/m^3)	2.8	4.5	3.9	3.7
LCOW ($/$m^3$)	3.20	1.50	1.20	0.90
System Type	Off-grid, modular	Grid-backup hybrid	Floating PV-RO	Large-scale fixed PV-RO
Challenges	Low production, high LCOW	Grid dependence, high salinity	Installation complexity	High CAPEX, but low OPEX

KPIs and comparative of final solutions

Key Takeaways from Benchmarking

1. Small-scale off-grid systems are feasible for remote locations, modular systems with minimal maintenance required, but higher costs due to economies of scale.
2. Hybrid grid-connected systems are more reliable but depend on grid availability and have slightly higher energy consumption for SW desalination.
3. Floating PV-RO solutions optimize space and can achieve reasonable energy efficiency but require robust anchoring and wave resistance.
4. Large-scale PV-RO plants achieve the lowest LCOW due to economies of scale but require significant initial investment and are extensive in land use. Suitable for long-term water security.

KPIs and comparative of final solutions

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Products on the market and successful experiences

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- **ITC background in PV-RO desalination, FROM THE LAB TO THE LAND. PV-BWRO in Africa**

✓ Mature product. 5 systems installed in Africa
✓ Patent transferred to a Canary Islands company: http://www.drglobe.net/en/

DESSOL® units installed in Africa under real conditions (inland locations, brackish water):

Tunisia (Ksar Ghilène village): 10.5 kWp PV field connected to a 50 m³/d RO (batteries backup, without energy recovery). Commissioned in May 2006.

Products on the market and successful experiences

Dessol

Morocco (Essaouira and Ifni provinces) 3 x 4 kWp PV field + 2.2 kWp PV field connected to a 25 m³/d and 12 m³/d RO systems respectively (batteries backup, without energy recovery). Commissioned in May 2008.

Amellou

Tangarfa

Tasekra

Azla

- **DESSOL® units installed in Africa under real conditions** (coastal locations, sea water):

Cape Verde (Ribeira D. Joao, Maio island). Commissioned in June 2021.

PV field (25.2 kWp) with a battery bank (2280 Ah) to drive an existing SWRO desalination plant (120 m³/d), worked with a diesel group (60 kVA) that was maintained as a support system.

Products on the market and successful experiences

Dessol

- **Solar Water Solutions Oy Ltd** (Finland):

Adaptive No Voltage System (ANVS®) is an innovative approach that enables solar direct off-grid operation of reverse osmosis (RO) desalination systems. Key features:

Production capacities:

SW (from 17.2 to 312 m^3/d)
BW (from 29 to 492 m^3/d)

- ✓ Allows direct operation from PV power without inverters or batteries.
- ✓ Adjusts to varying solar power levels, optimizing pump speed and RO process efficiency.
- ✓ Uses high-efficiency energy recovery to reduce power consumption.
- ✓ Minimizes operational costs by eliminating battery-related expenses.
- ✓ Suitable for small to medium-sized desalination plants (e.g., 3 – 500 m^3/day).
- ✓ Ideal for off-grid communities, islands, and disaster relief areas.

Successful experiences: Over 300 small to medium-sized solar desalination units delivered to remote deserts and islands.

Products on the market and successful experiences

Kitui, Kenya.

- **Osmosun®** (France):

The OSMOSUN® technology may be installed fully off-grid, or as a grid tied system.

Production capacities:

- SWRO: from 1 to 2,000 m^3/d (the units are modular and may be combined in redundant production trains to reach up to 20,000 m^3).
- BWRO: from 5 to 2,000 m^3/d.

2016 First OSMOSUN unit implemented in Abu Dhabi as part of MASDAR Renewable Energy Desalination Program. The PV-SWRO desalination unit without battery achieved the lowest SEC 2.5 KWh/m^3.

Products on the market and successful experiences

Successful experiences: more than 40 OSMOSUN units in operation in 20 countries.

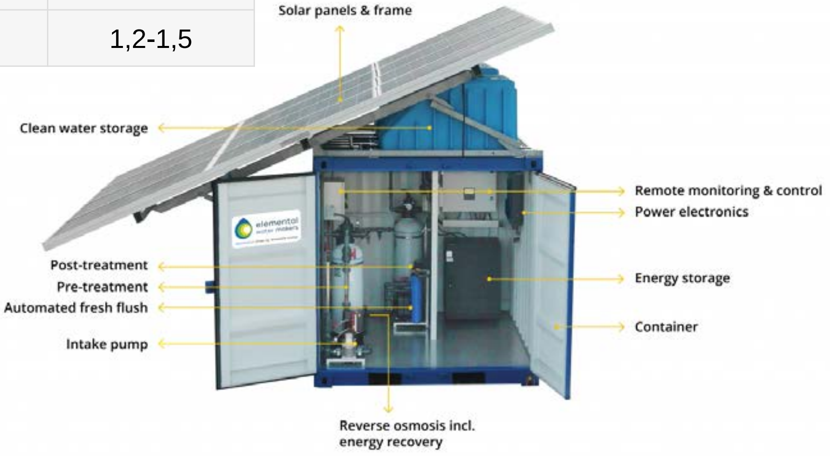
Location	**Type of system**	**Production capacity** (m^3/d)	**Beneficiaries**
Bora Bora, French Polynesia	SW, grid connected	240 m^3/d (80 m^3/d in off-grid mode)	10,000 inhabitants
Moia Moia, Cape Verde	BW, off-grid	50 m^3/d	28 families of farmers
Rodrigues Island, Mauritius	SW, grid connected	80 m^3/d (20 m^3/d in off-grid mode)	Hotel (84 rooms)
Witsand, South Africa	SW, grid connected	200 m^3/d (100 m^3/d in off-grid mode)	3,000 inhabitants
Gaza Province, Mozambique	BW, off-grid	Between 20 and 40 m^3/d by site	6 villages (7,200 inhab.)
Bethanie, Nambia	BW, off-grid	100 m^3/d	5,000 inhabitants
Wala, Rano, Vao and Atchin, Vanuatu	SW, off-grid	1.5 m^3/d	4 islands (3,000 inhab.)

- **Elemental Water Makers** (Netherlands):

Water production capacities between 3.8 – 100 m³/day.
Cost of desalinated SW 1-2 €/m³ (including investment, transportation, commissioning + training for maintenance, as well as the operational expenses for 15 years to come).

Water production (m³/d)	3.8	10	20	50	100
Container size (ft)	8 ft	8 or 20 ft	20 ft	40 ft	40 ft
Solar energy (kWp)	4.5	10.3	20.4	46.3	93.8
SEC (kWh/m³)	3.0	2.7	2.7	2.7	2.7
Feed water TDS (ppm)	3,000-40,000	3,000-40,000	3,000-40,000	3,000-40.000	3,000-40,000
LCOW (€/m³)	4-5	2-3	1,5-2,5	1,3-2,0	1,2-1,5

Products on the market and successful experiences



- **Genius Watter** (Italy):

Off-grid, battery-less solar powered SW and BW desalination systems with production capacities from 20 to 3,000 m^3/day.

The whole system can run even with low sunlight levels (less than 200 W/m^2, from around 8h in the morning to 17h), it can harness up to 90% of the available PV power.

Successful experiences:

Boa Vista, Cape Verde:

- Beneficiaries: Varandinha association farmers and the nearby community of 250 people.
- 73kWp off-grid PV system.
- BWRO production capacity: 75 m^3/d (58 m^3/d for farming, and 17 m^3/d for the community).

Products on the market and successful experiences

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Challenges and future opportunities

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Several **challenges** (technical & economic) need to be addressed to enhance PV-RO feasibility, efficiency, and cost-effectiveness.

Challenges and future opportunities

Technical Challenges	
Variable Solar Energy Supply	• Solar irradiance fluctuations leads to unstable power supply for RO operation. • Direct PV-RO coupling requires advanced power management to ensure steady operation. • Energy storage (batteries) or hybrid systems are often necessary, adding complexity and cost.
Energy Storage Limitations	• Batteries increase system reliability but have limited lifespans and require replacements. • High costs, low energy efficiency, and degradation make battery integration a challenge.
RO System Efficiency and Energy Demand	• RO desalination is an energy-intensive process, requiring HPP and ERD. • Energy demand depends on feed water salinity (e.g., SW at 38,000 mg/L TDS needs ~3-4 kWh/m^3). • Optimizing energy use while ensuring consistent water production is a major design challenge.
Membrane Fouling and Maintenance	• SW and BW contain organic matter, biofouling agents, and scaling compounds, leading to membrane clogging. • Frequent cleaning increases operational downtime and maintenance costs. • Advanced membranes with anti-fouling coatings and improved pre-treatment methods are required for long-term reliability.
System Design and Scalability	• PV-RO systems must be custom-designed based on solar availability, water demand, and salinity levels. • Scaling up from small units to larger systems requires higher capital investment and optimized energy-water balancing. • Decentralized systems can be challenging to manage without skilled operators.
Brine Disposal and Environmental Impact	• RO systems generate high-salinity brine, which can harm local ecosystems if improperly discharged. • Sustainable brine management strategies, such as mineral recovery or brine concentration, require additional infrastructure and costs.

Challenges and future opportunities

Economic Challenges	
High Capital Costs	• PV-RO desalination has a high initial investment due to solar panels, batteries, HPPs, and membranes. • In off-grid locations, costs increase due to transportation and infrastructure development. • The total installed cost can range from 2,000–5,000 €/kW of PV capacity, depending on system size and location (whole system).
LCOW Considerations	• The target LCOW of 1.5€/m³ is challenging due to energy costs, maintenance, and system depreciation. • Achieving cost-competitiveness with conventional diesel-powered RO or grid-connected solutions requires optimized energy efficiency.
Cost of Energy Storage and Backup Systems	• Batteries significantly increase project costs (typically 200-400 €/kWh for lithium-ion). • Alternative energy storage (e.g., pumped hydro, flywheels) is not always feasible in remote areas. • Hybrid PV-wind or PV-diesel systems require additional investment and operational complexity.
Limited Access to Financing and Incentives	• Many PV-RO projects in developing regions struggle with lack of government subsidies or financial incentives. • Private investment is limited due to high perceived risks and long payback periods (typically 5-10 years). • Innovative financing models (e.g., power purchase agreements, microfinancing) are needed for widespread adoption.
Supply Chain and Spare Parts Availability	• Remote areas often lack local suppliers for PV-RO components. • Importing spare parts (e.g., RO membranes, pumps, inverters) leads to long delivery times and increased costs. • Skilled technicians for system maintenance may not be readily available.
Operational and Maintenance (O&M) Costs	• Regular membrane replacement, pump maintenance, and cleaning chemicals add recurring expenses. • Lack of trained personnel increases risk of system failures and efficiency losses. • Remote monitoring and automation can help but require additional investment in IoT and control systems.

PV-RO desalination sector presents significant **opportunities** for technological advancements, cost reductions, and expanded deployment, particularly in off-grid and water-scarce regions.

Challenges and future opportunities

Future opportunities in the PV-RO sector	
Technological Advancements	• **High-Efficiency Solar Panels**: ✓ Emerging perovskite-silicon tandem solar cells offer efficiencies above 30%, reducing land and panel requirements. ✓ Bifacial solar panels can capture reflected sunlight, increasing energy yield. • **Direct PV-RO Coupling** (Without Batteries): ✓ Using variable-speed HPPs and ERDs allows direct coupling of PV and RO without battery storage. ✓ Smart control algorithms can adjust system operation based on solar availability. ✓ Reducing battery reliance significantly lowers capital and maintenance costs. • **Advanced Membrane Technologies**: ✓ Graphene-based and carbon nanotube membranes offer higher permeability and anti-fouling properties. ✓ Biomimetic membranes inspired by aquaporins allow for energy-efficient water filtration. ✓ Self-cleaning membranes reduce fouling and extend membrane lifespan. • **Hybrid Energy Integration**: ✓ PV-Wind-RO systems provide a more reliable energy mix by compensating solar intermittency. ✓ Hydrogen-based storage could serve as a future alternative to batteries. • **Digitalization and Smart Monitoring**: ✓ IoT-based remote monitoring and AI-driven predictive maintenance can enhance system efficiency and reduce downtime. ✓ Smart sensors can optimize water production based on real-time solar availability and demand.

Future opportunities in the PV-RO sector	
Economic and Market Expansion	• **Declining Costs of PV and RO Components**: ✓ Solar PV module costs continue to decline, making PV-RO more cost-competitive. ✓ Mass production of HPPs and ERDs will further reduce system costs. ✓ Membrane improvements will extend lifespans and lower replacement costs. • **Modular and Decentralized Systems**: ✓ Containerized PV-RO solutions provide plug-and-play options for remote communities. ✓ Scalable micro grid-integrated RO plants can serve both households and industries. • **Green Financing and Carbon Credits**: ✓ Growing emphasis on decarbonization and net-zero goals creates funding opportunities for PV-RO projects. ✓ Carbon credits and water credits could provide additional revenue streams. ✓ Public-private partnerships (PPPs) can enhance affordability and accessibility. • **Water-Energy-Food Nexus**: ✓ PV-RO desalination for agriculture can support food production in arid regions. ✓ Solar-powered greenhouses using desalinated water can boost crop yields. ✓ Integrated aquaponics and desalination could be a sustainable food production model.

Challenges and future opportunities

Future opportunities in the PV-RO sector	
Sustainable and Environmental Innovations	• **Sustainable Brine Management:** ✓ Innovations in brine treatment, such as zero-liquid discharge (ZLD) and mineral recovery, can reduce environmental impact. ✓ Using brine for salt production, aquaculture, or other applications can create additional value. • **Climate Adaptation and Disaster Resilience:** ✓ Solar-powered mobile desalination units can provide emergency water supply after natural disasters. ✓ PV-RO can support drought-prone regions by offering climate-resilient water sources.
Policy and Infrastructure Development	• **Government Incentives and Policy Support:** ✓ Incentives such as feed-in tariffs (FiTs) for renewable desalination can accelerate adoption. ✓ Policies encouraging water-energy integration can attract investments. ✓ International aid and development funds can support off-grid PV-RO in water-scarce regions. • **Expansion into Emerging Markets:** ✓ Africa, South Asia, and the Middle East present high demand for off-grid desalination solutions. ✓ Rural electrification programs can integrate PV-RO for water security. ✓ Decentralized PV-RO plants can serve island nations and remote coastal communities.

Challenges and future opportunities

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Conclusions

- 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 and products already available on the market.
- 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

- PV-RO desalination holds great potential for sustainable and decentralized water production, particularly in arid and off-grid regions.
- While **challenges** such as high initial costs, energy storage, and membrane fouling remain, **advancements** in solar efficiency, membrane technology, direct PV-RO coupling and smart monitoring can drive down costs and enhance feasibility.
- Sustainable brine management, modular designs, and green financing will further enhance its competitiveness.

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Q&A