Water desalination and the energy-water nexus

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MaLL
multiScale ModeLing Laboratory

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PRESENTATION OUTLINE

- Freshwater scarcity: What, where, why?
- A technology opportunity: Desalination
- A broader issue: Energy-Water nexus
- Perspectives: Sustainable desalination

FRESHWATER SCARCITY

What, where, why?

SUSTAINABLE DEVELOPMENT

In 2015, United Nations indicated **access to clean water and sanitation** as one of the *Sustainable Development Goals.*

WATER STRESS INDICATOR

SDG Indicator 6.4.2 - Water stress

- Water stress index:

$$WSI = \frac{G_{withdrawn}}{G_{available}},$$

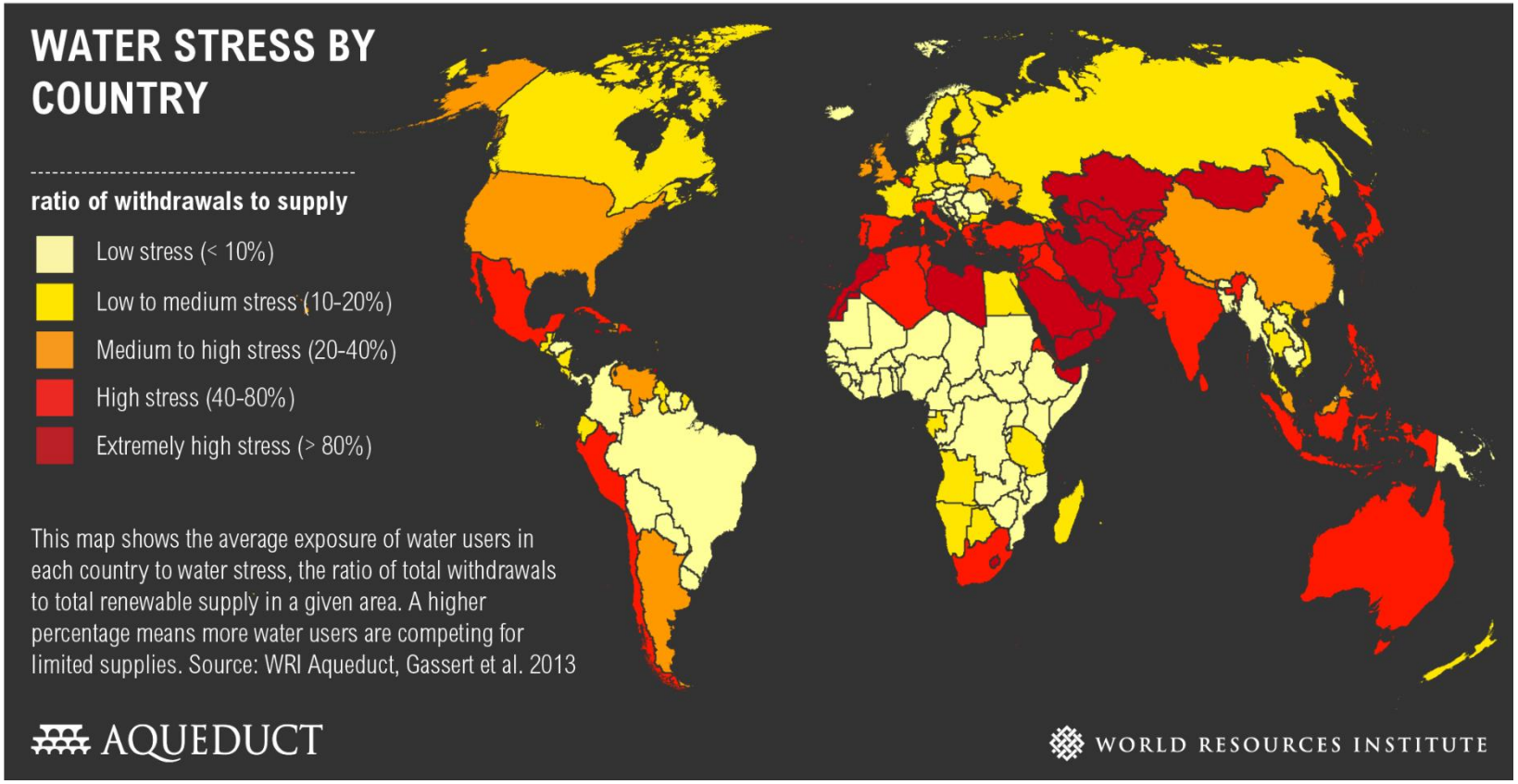
  where $G_{available}$ is computed after taking into account environmental water requirements.

- WSI provides knowledge on the **efficiency and sustainability of water usage**, to ensure that water resources support the world's ecosystems and continue to be available for future generations.

Source: FAO.org (2019)

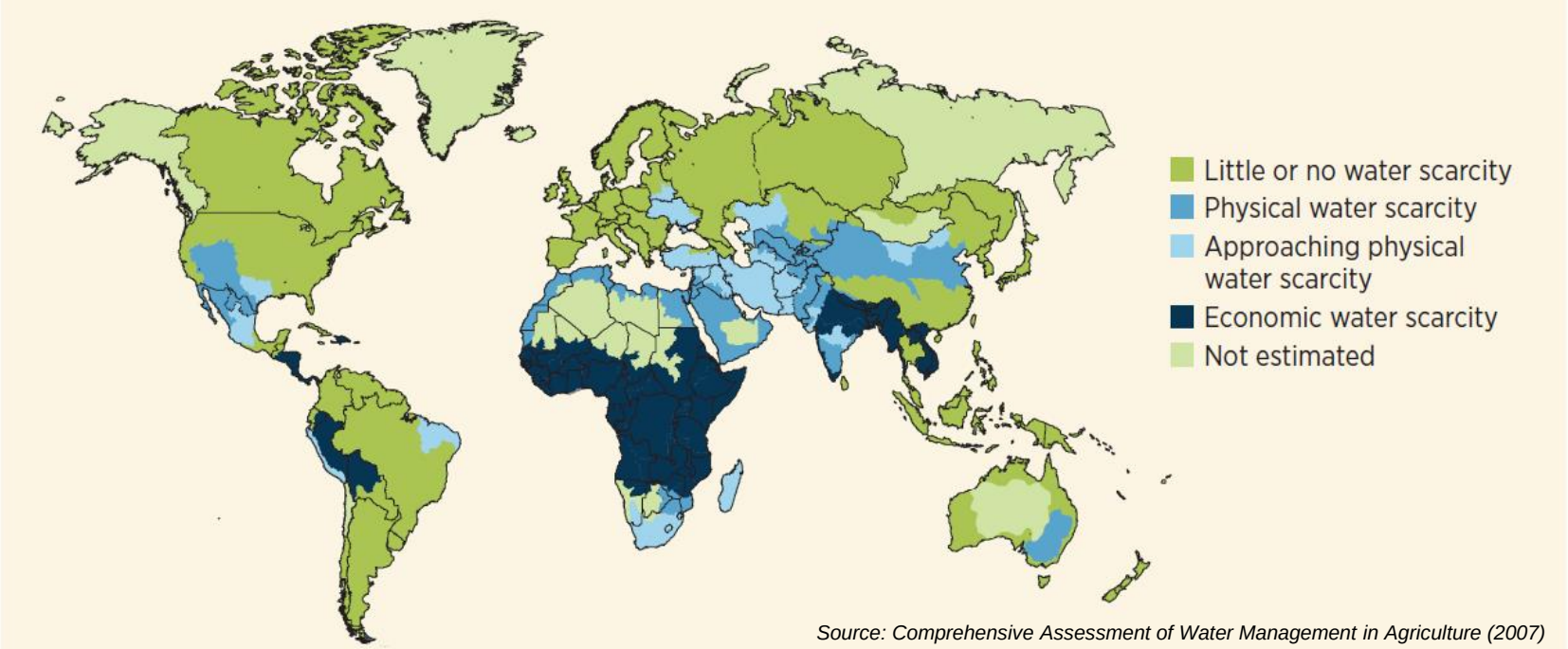
WATER STRESS MAP

Water stress is over 60% in **Western Asia, Central Asia and Northern Africa**, meaning that these regions face serious water stress, at least during parts of the year.



ECONOMIC WATER SCARCITY

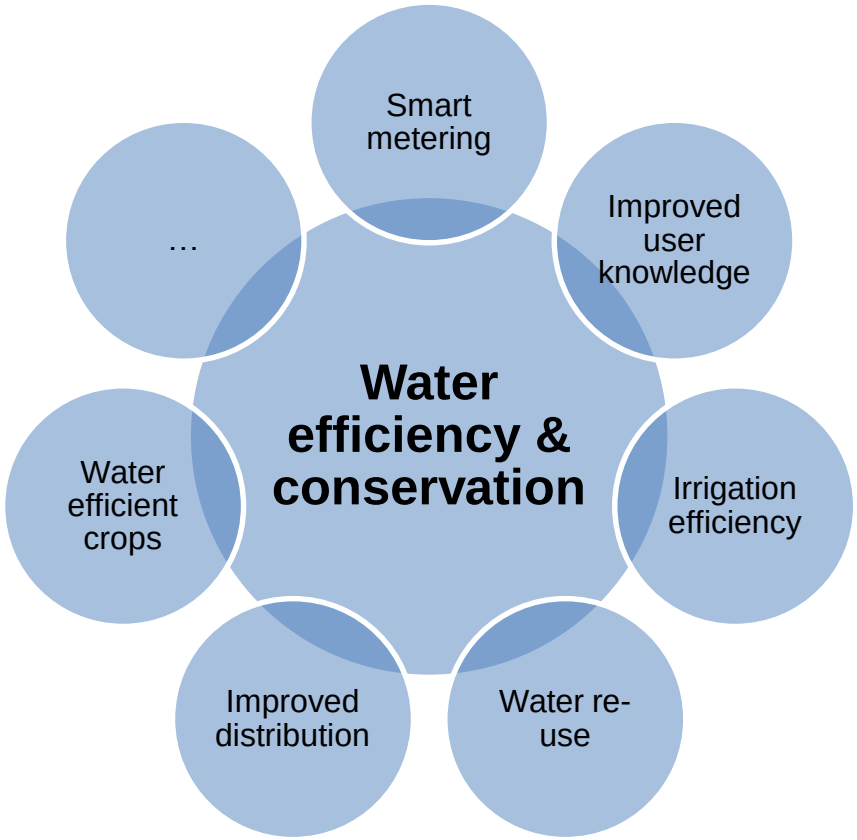
- Physical water stress is not the only reason affecting the actual freshwater supply. **Economic issues** (i.e. cost of water extraction, treatment, delivery) often play a serious role
- Overall, **one in ten people** worldwide has no access to drinking water [*WHO, 2012*] today. According to the latest FAO estimates, **1.8 billion people** will live in areas with absolute water scarcity by 2025



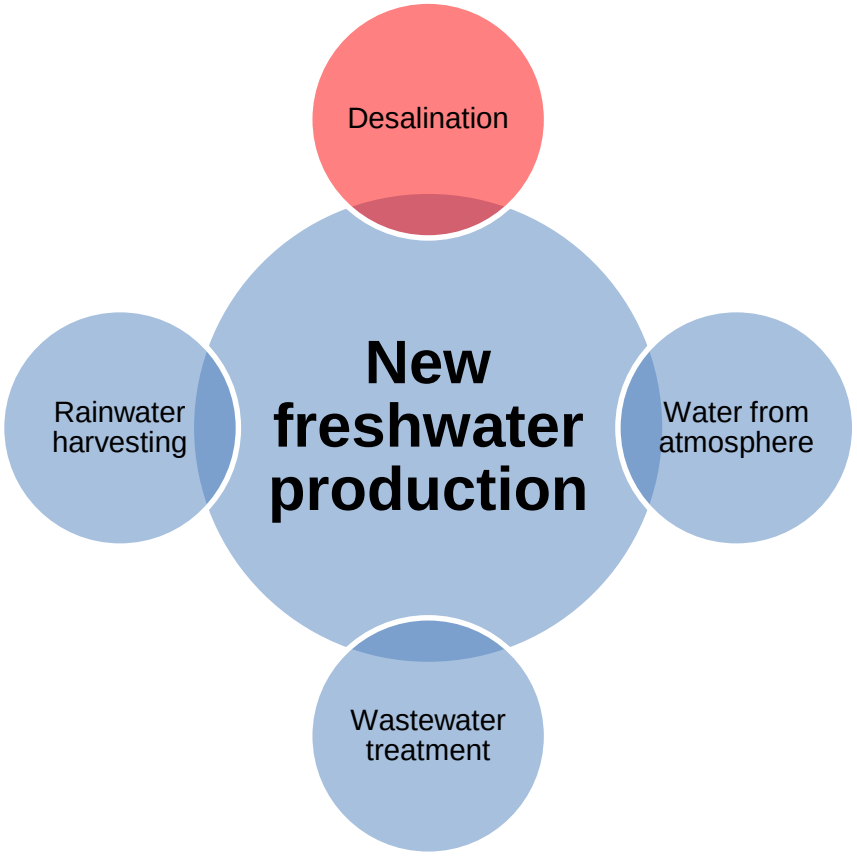
Source: Comprehensive Assessment of Water Management in Agriculture (2007)

COPING WITH WATER SCARCITY

Use better *current freshwater resources*



Use non-conventional *freshwater resources*



TECHNOLOGY OPPORTUNITY

Desalination

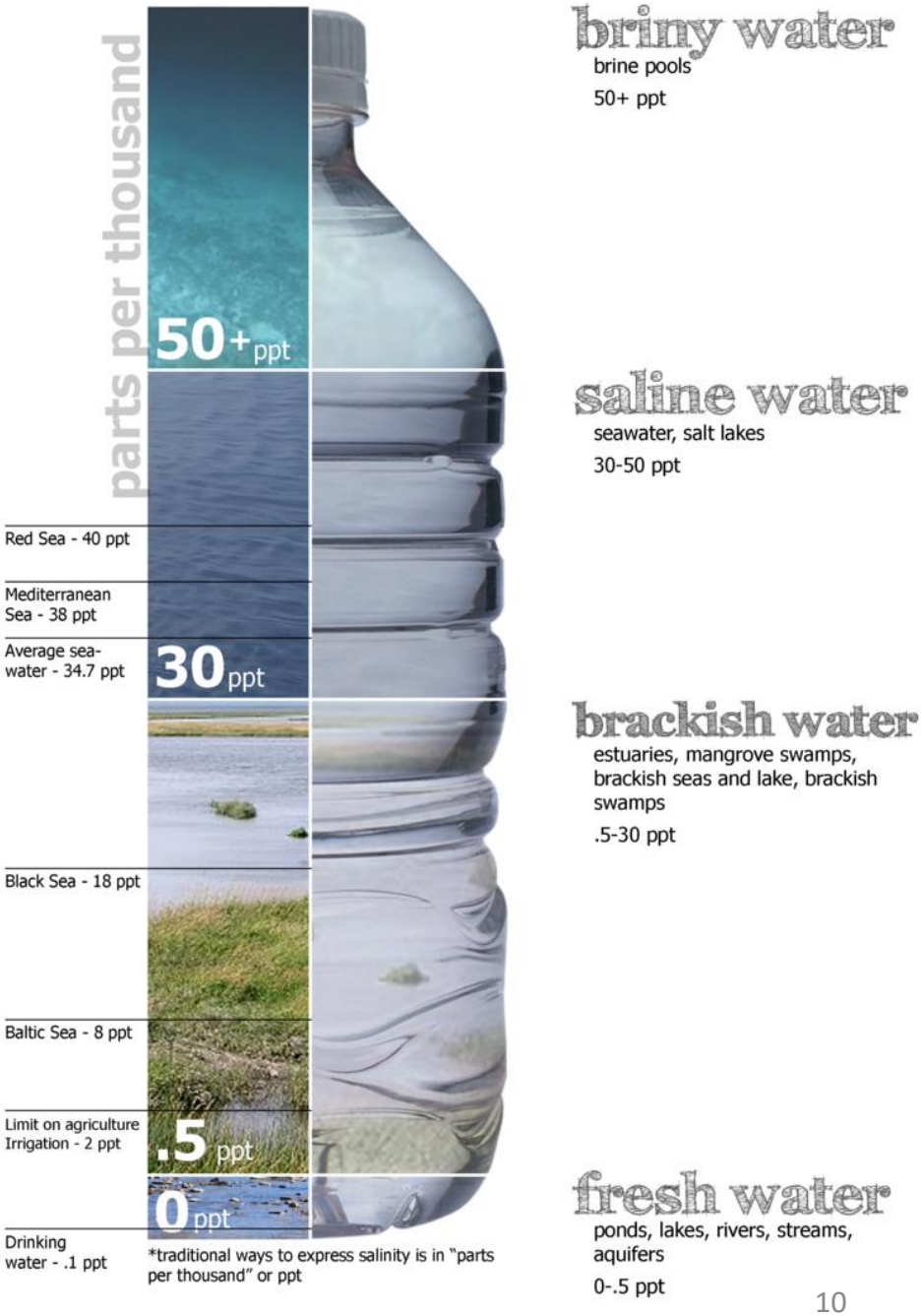
Technology opportunity

DESALINATION

- 75% of the Earth's surface is covered by water; **97.5% of that water is oceans**; only 1% is available for drinking

- **Desalination is the process of removing salt and other dissolved solids from water**, in order to produce water suitable either for human consumption (0.5 ppt) or agricultural purposes (2 ppt) and industrial processes

- Desalination not only pertains to sea and ocean water but also to **brackish water**

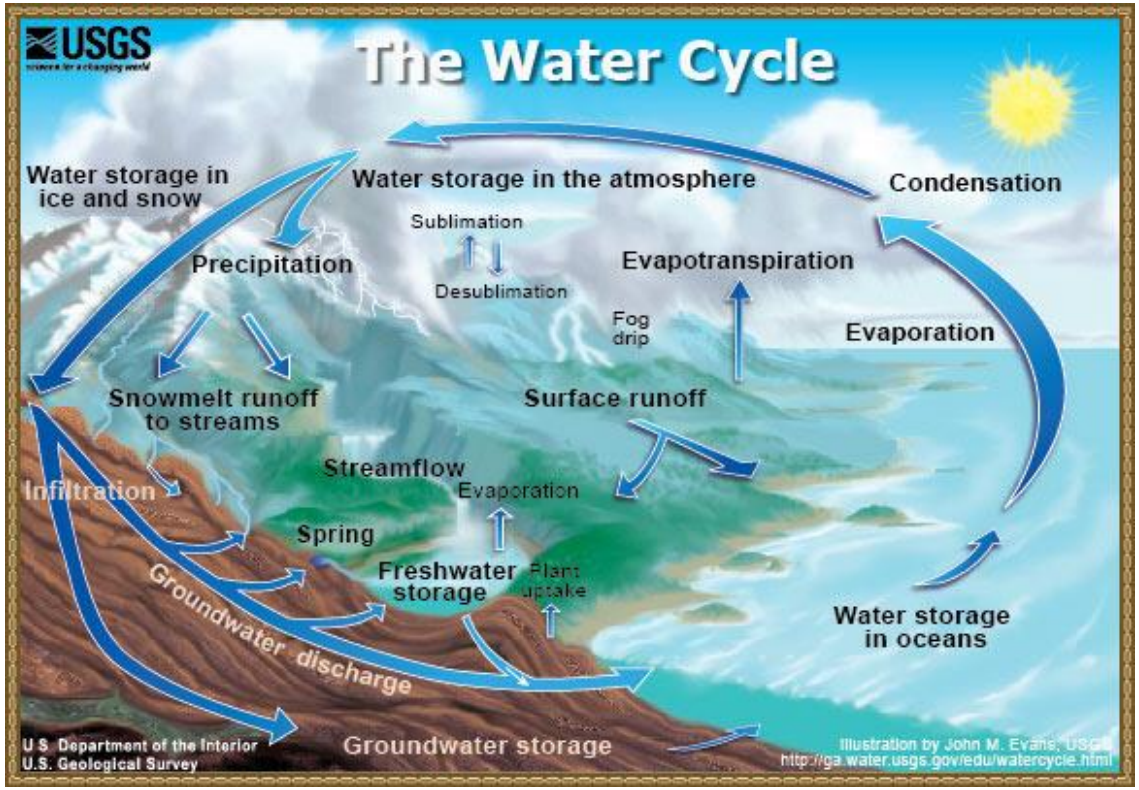


Source: Wikimedia, CC-BY 3.0

Technology opportunity

NATURAL «DESALINATION»

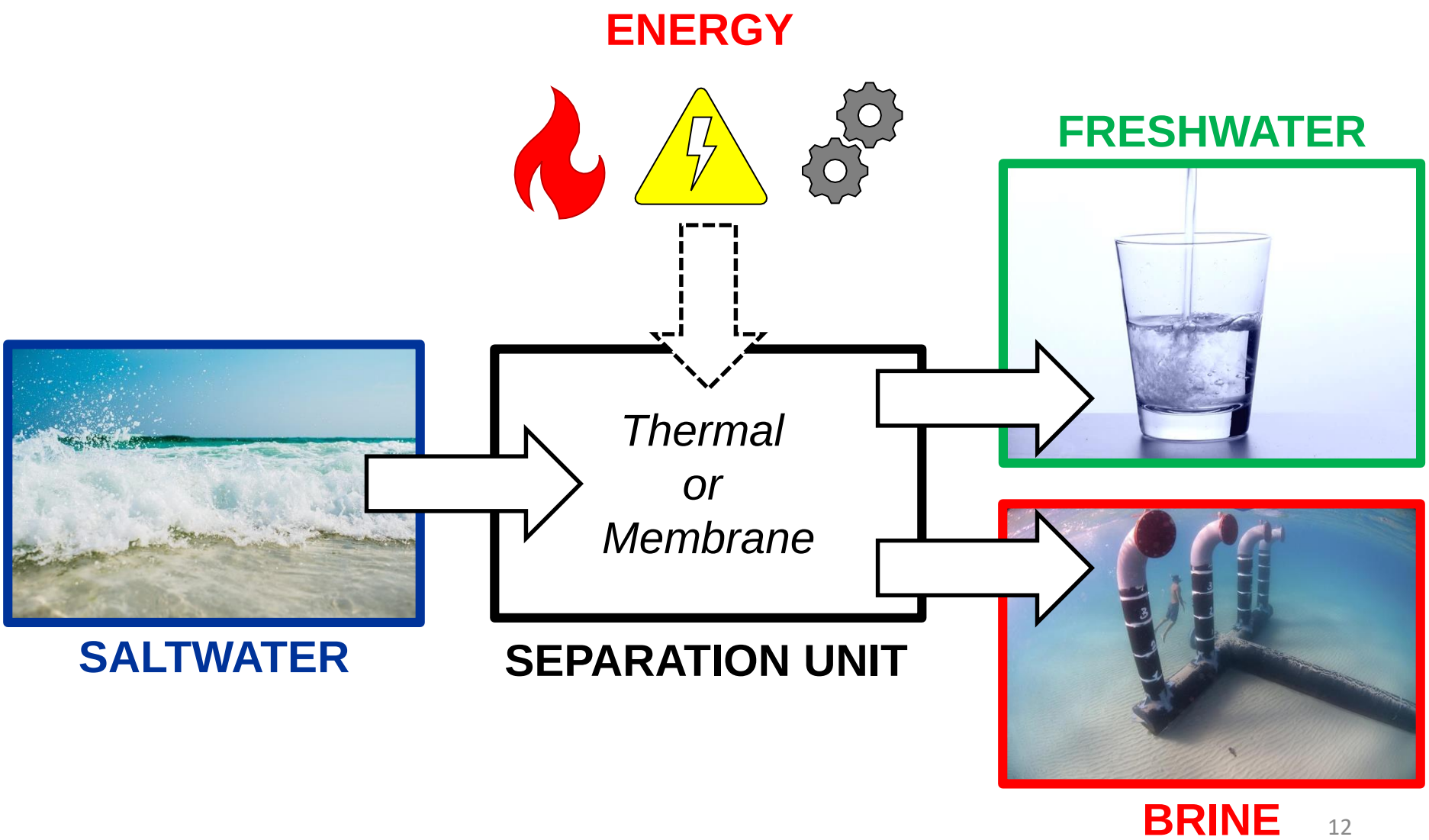
1. Evaporation
2. Condensation
3. Precipitation
4. Collection



505000 km^3 of water falls as **precipitation** each year (900 mm/year) » 5000 km^3 of global freshwater **consumption** each year » 32 km^3 of freshwater **by desalination** each year

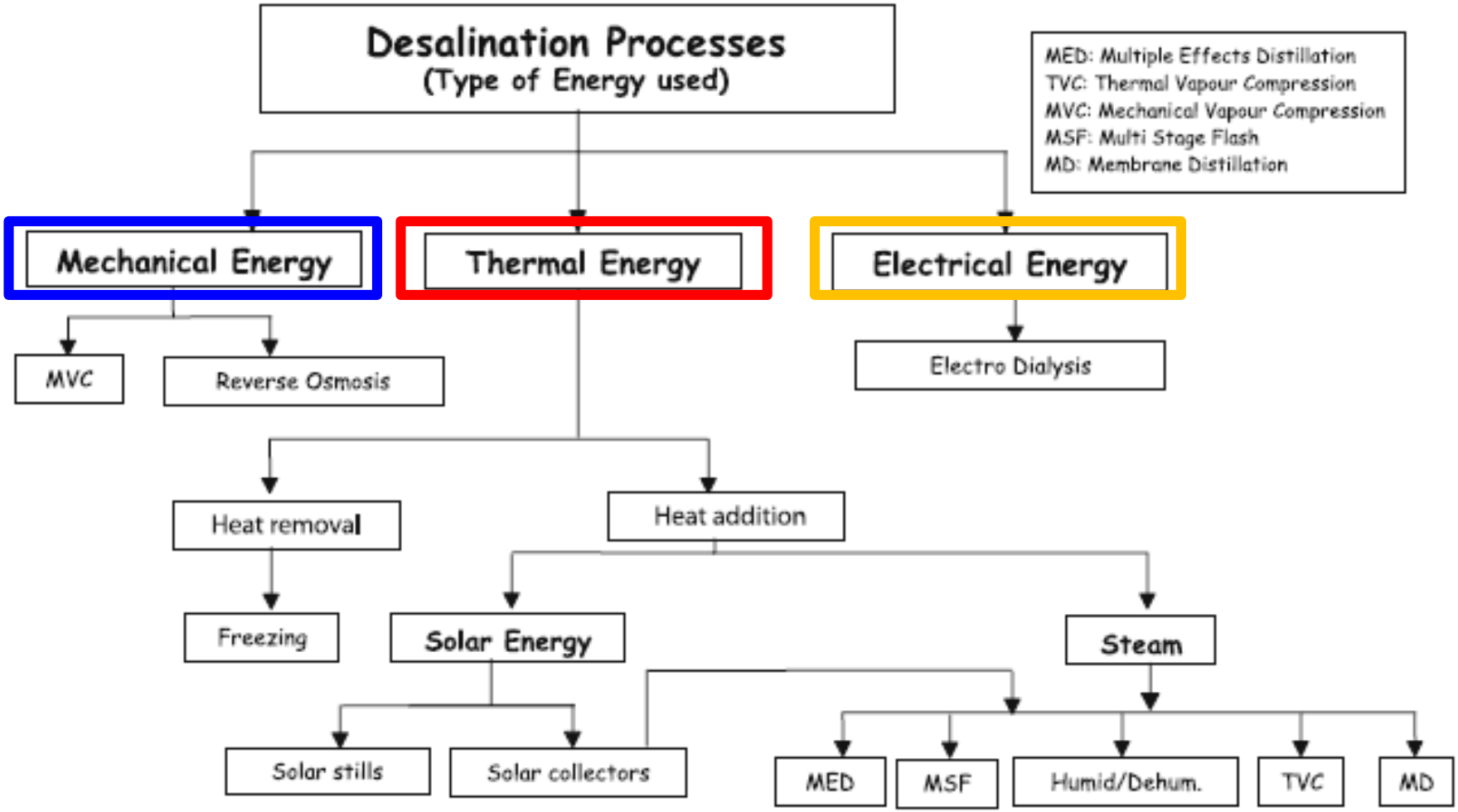
Technology opportunity

GENERAL SCHEME



Technology opportunity

DESALINATION TECHNOLOGIES



Source: Cipollina et al., Seawater desalination, Springer, 2009

Technology opportunity

THERMAL PROCESSES

SALTWATER

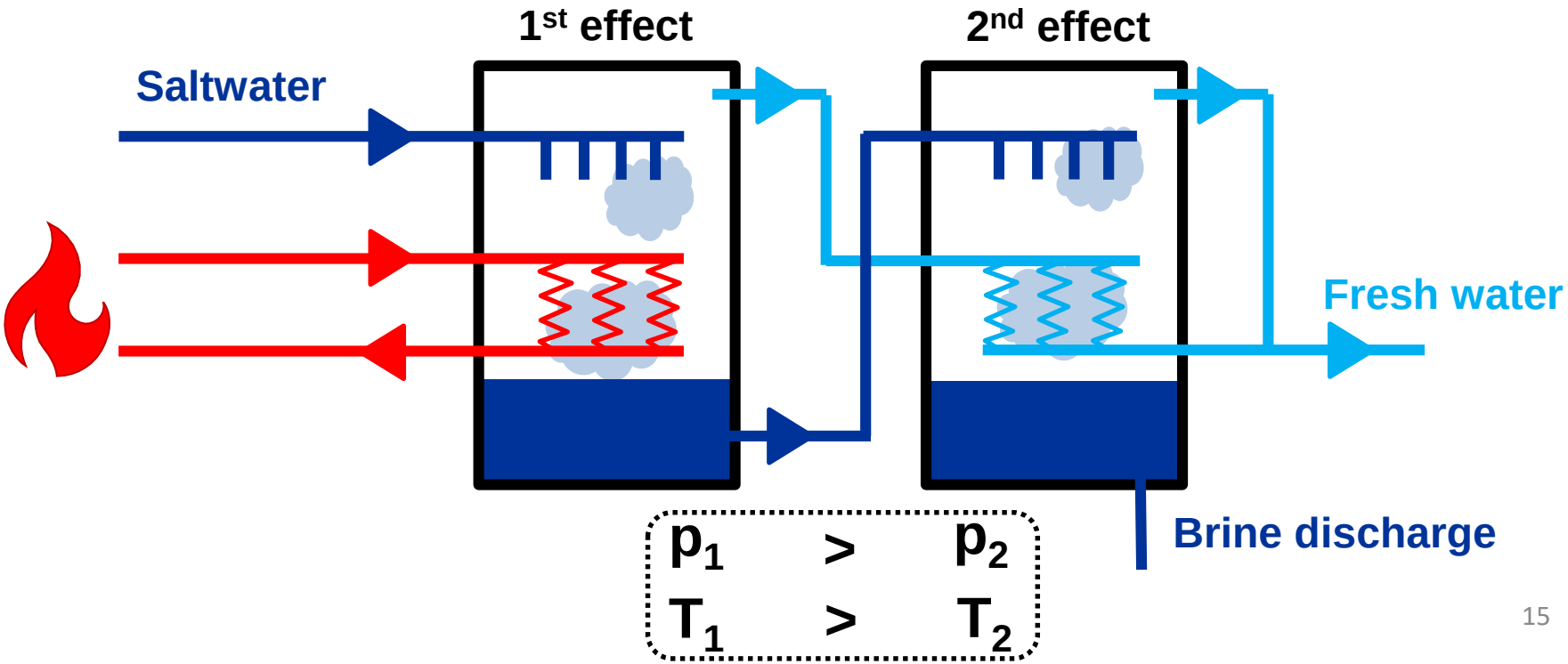
EVAPORATION

CONDENSATION

Technology opportunity

THERMAL SYSTEMS: MED/MSF

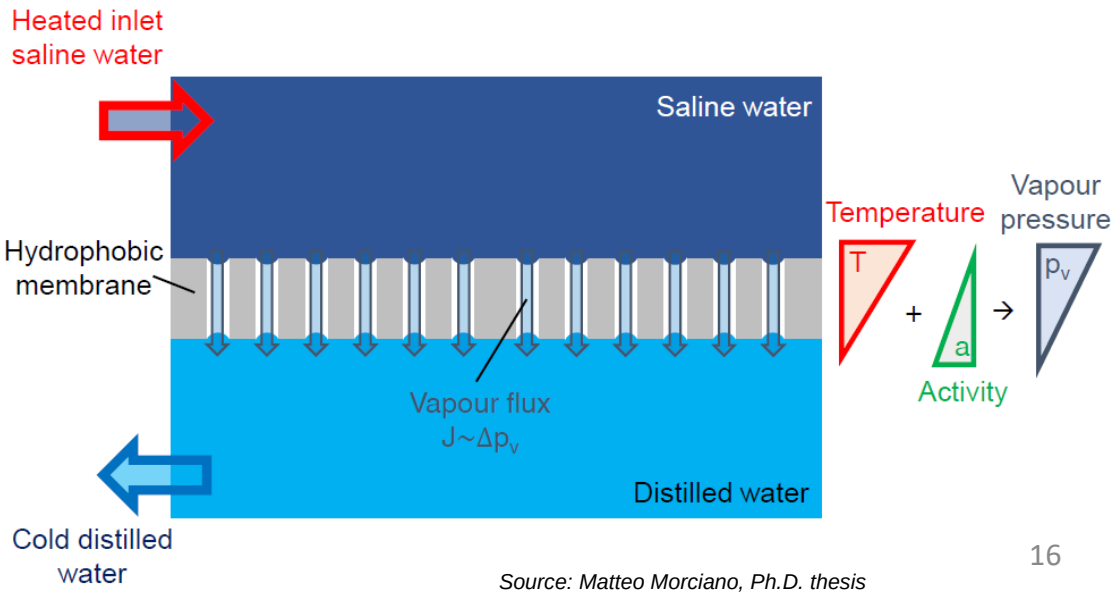
- **ISSUE:** Thermodynamic limit of **single-effect** evaporation/condensation process — 670 kWh/m^3
- **SOLUTION:** **Multi-effect** process, to "re-use" the latent heat of condensation — ≈10 kWh/m^3



Technology opportunity

MEMBRANE DISTILLATION

- **Membrane distillation** is a thermally driven separation process, in which separation is driven by **phase change**
- A **hydrophobic membrane** (e.g. PTFE-Teflon) displays a barrier for the liquid phase, allowing the **vapour phase** (e.g. water vapour) to pass through the membrane's pores
- Both industrial waste heat and solar thermal energy are used to power MD processes (up to **30 kWh/m^3** water desalination efficiency)
- The driving force of the process is given by a **partial vapour pressure difference** triggered by a (limited) **temperature difference**

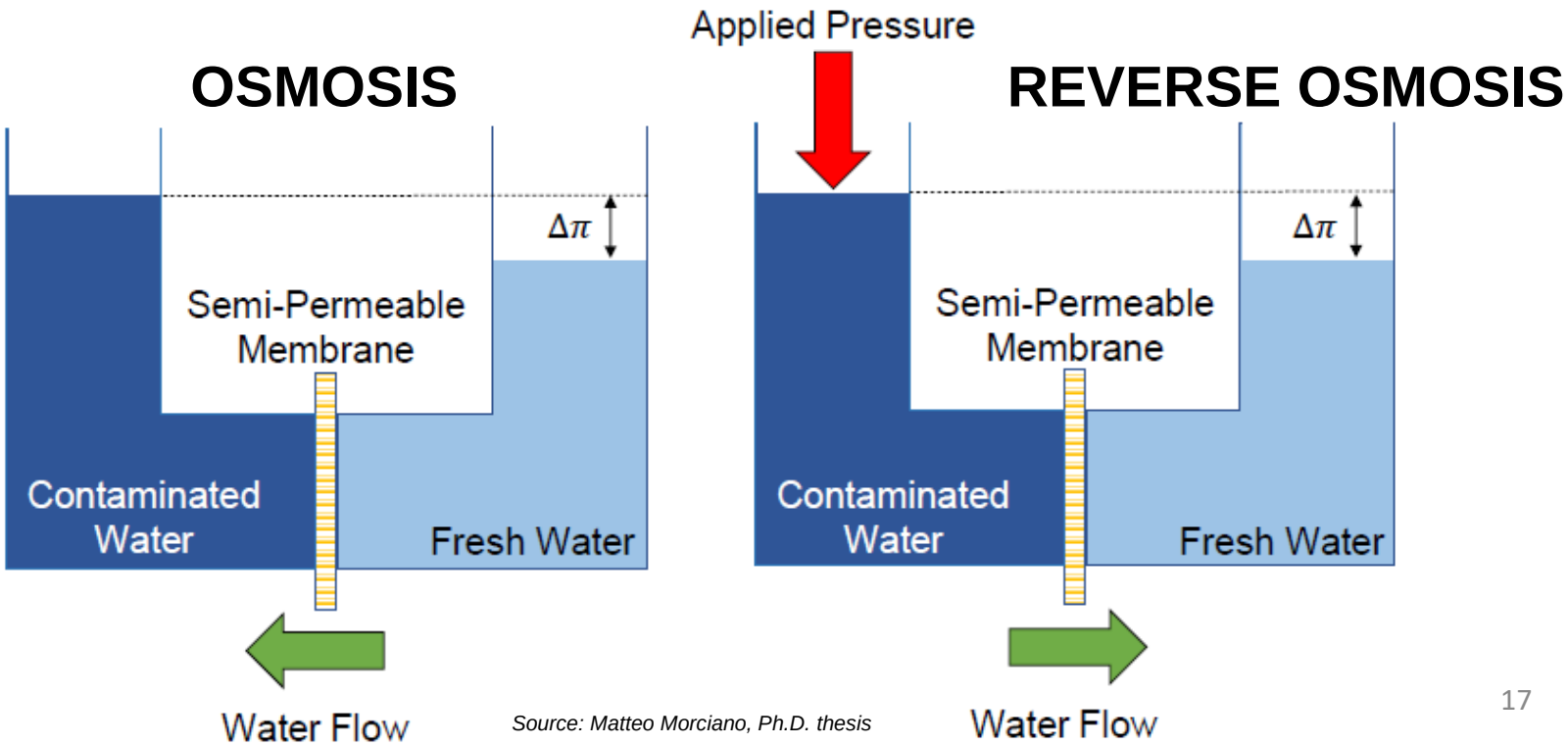


Source: Matteo Morciano, Ph.D. thesis

Technology opportunity

REVERSE OSMOSIS

- In the normal **osmosis process**, the solvent naturally moves from an area of low salt concentration, through a membrane, to an area of high salt concentration, driven by **osmotic pressure** ($\Delta\pi$).
- Applying an **external pressure** to reverse the natural flow of pure solvent, thus, is **reverse osmosis**. The process is similar to other membrane technologies, but **RO membranes are nanoporous** (10^{-9} m)

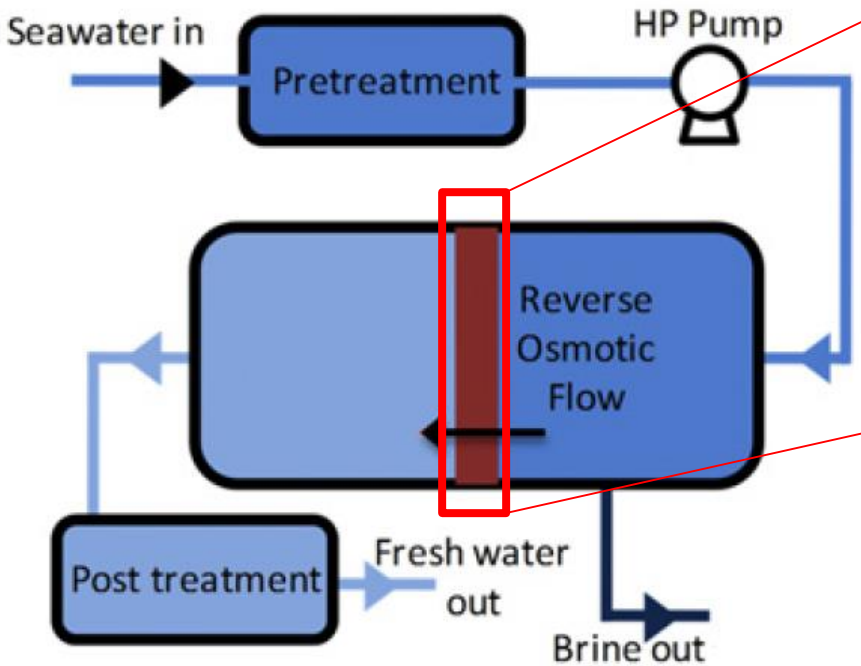


Source: Matteo Morciano, Ph.D. thesis

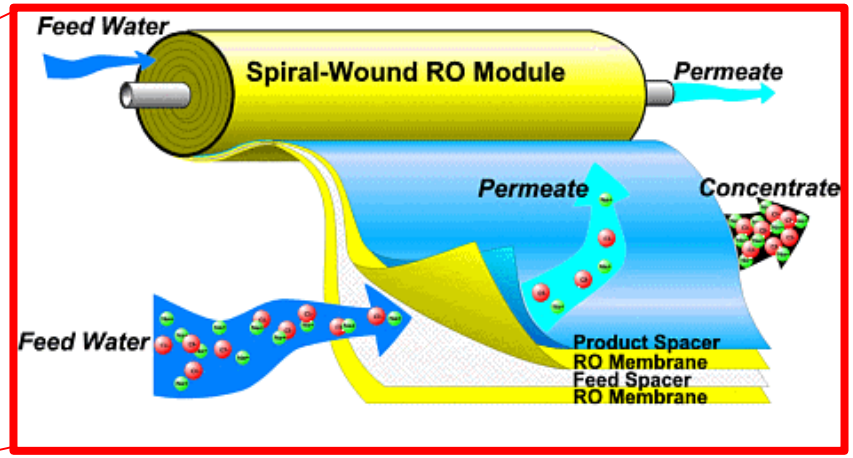
Technology opportunity

MECHANICAL SYSTEMS: RO

Working principle



RO membrane



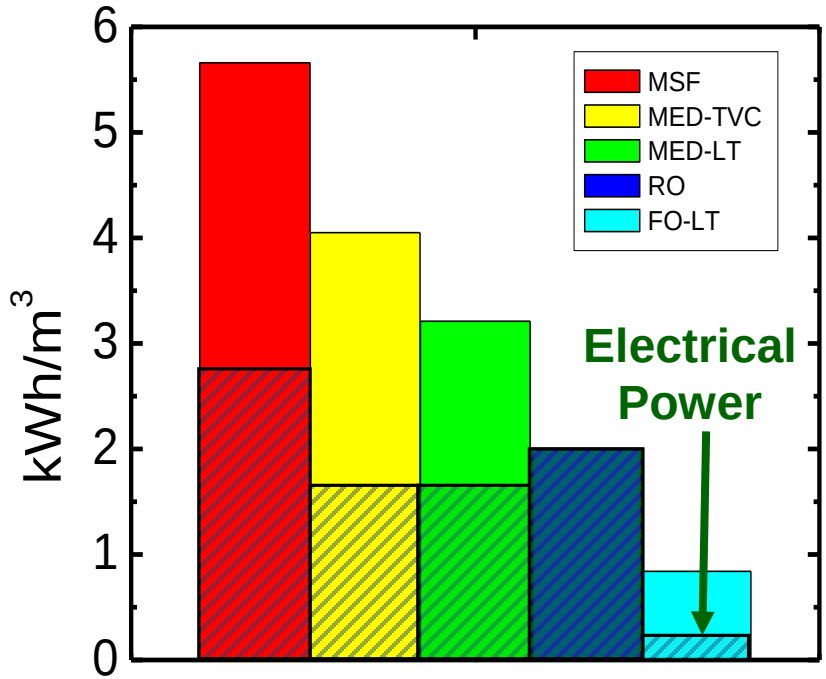
- Materials for membranes:
  - Aromatic polyamide
  - Cellulose acetate
  - Carbon nanotube
  - Zeolite
- Main design parameters:
  - Permeability
  - Salt Rejection

Technology opportunity

PROS AND CONS OF RO

PROs

- **Cheapest** desalination technology for large plants
- Most **energy-efficient** technique



Source: McGinnis and Elimelech, Desalination, 207 (2007) 370-382.

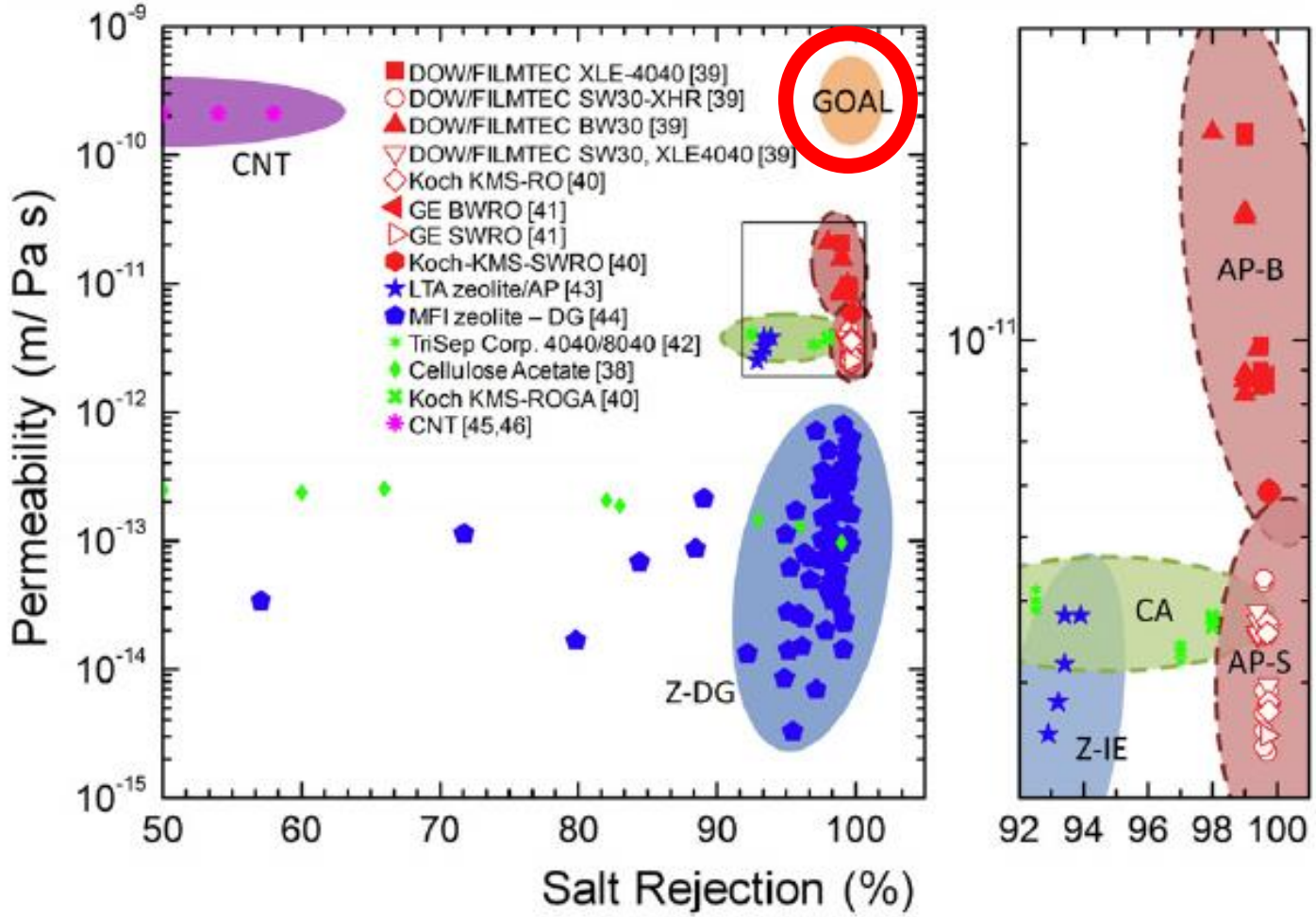
CONs

- Membranes are **specific** to the type of feed water
- Intensive **maintenance** of membranes; **large plants** and capital costs are required
- RO uses electricity, i.e. a form of energy with high "value"; **thermal processes could work with low-grade heat sources** instead

Technology opportunity

TARGET: BETTER MEMBRANES

$$\dot{Q} = K \cdot \Delta p \cdot S$$

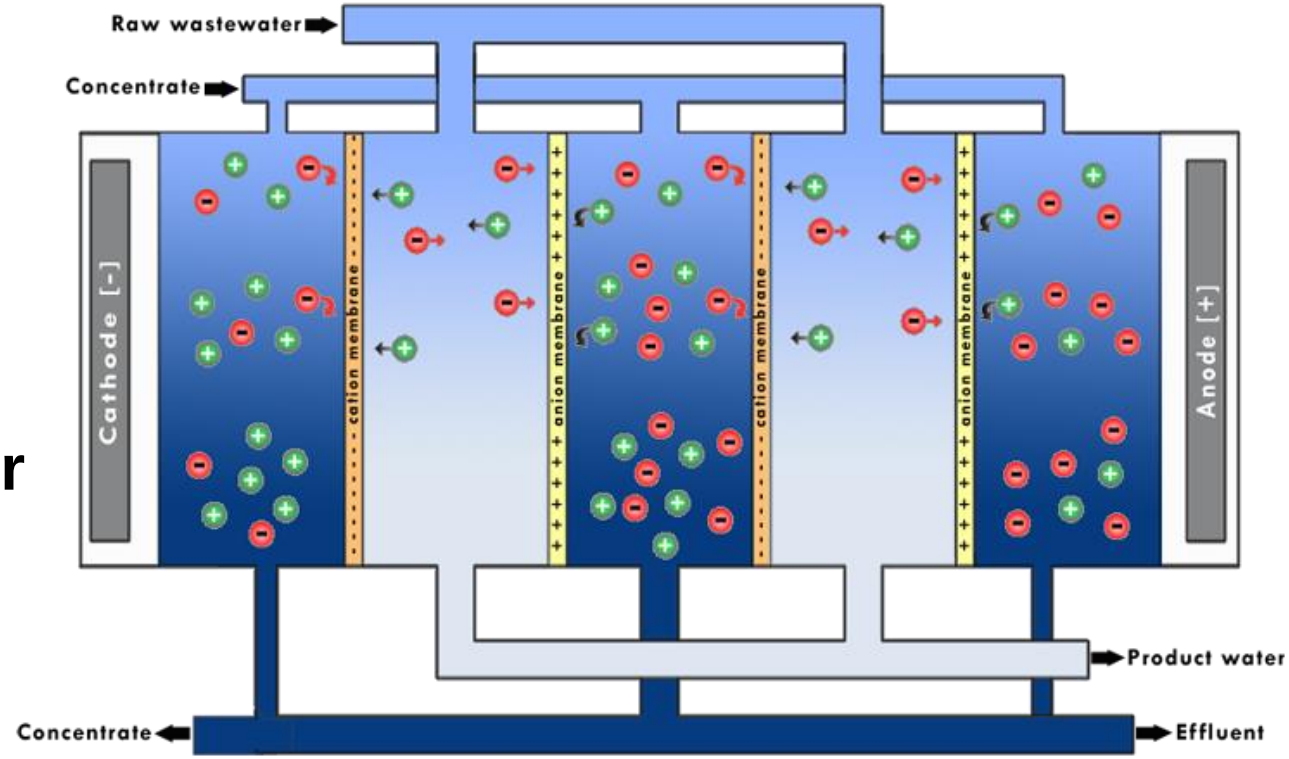


$$\text{SALT REJECTION} = \frac{m_{salt}^{out}}{m_{salt}^{in}}$$

Technology opportunity

ELECTRICAL SYSTEMS: EO

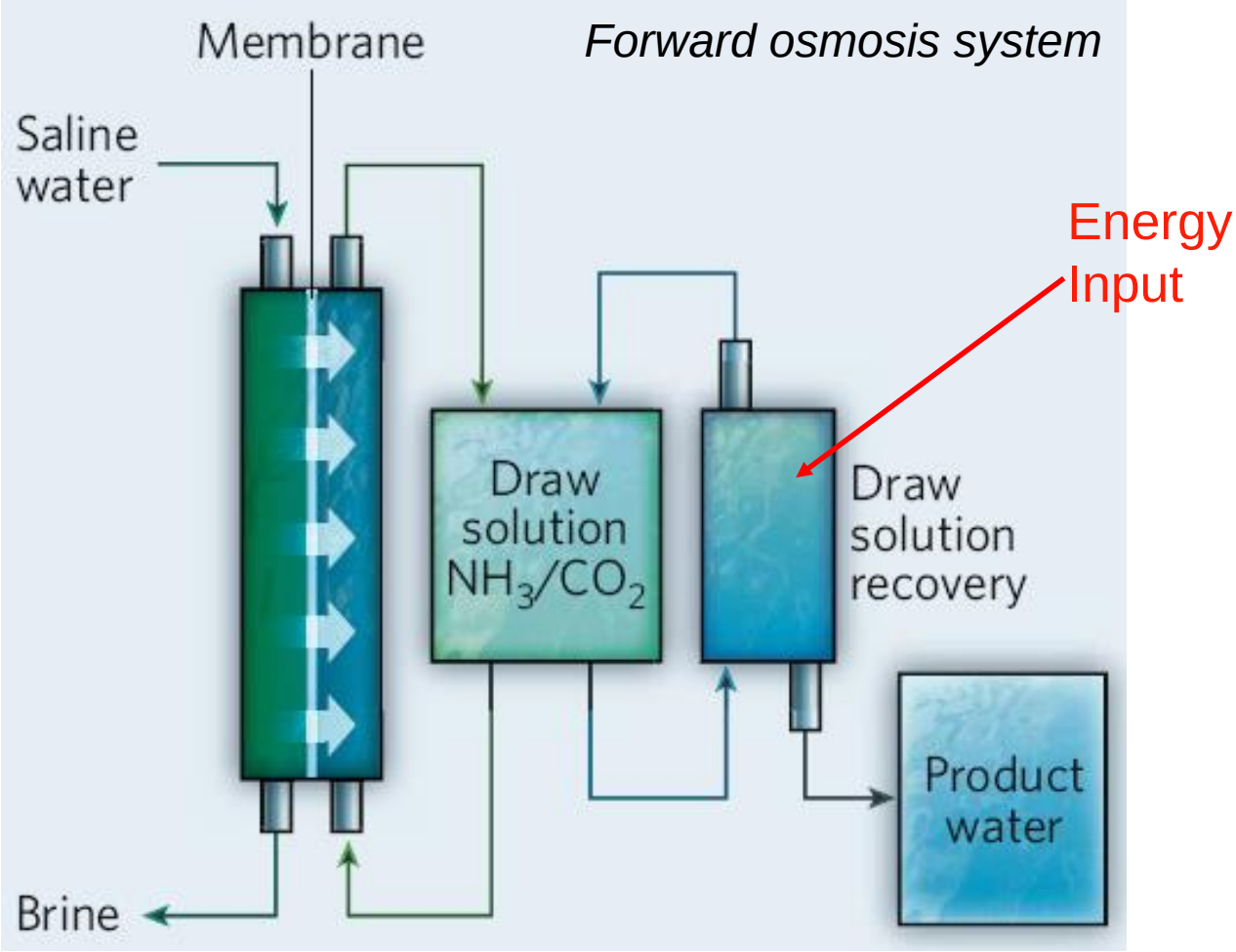
- **Electrodialysis uses** an **electrical potential** to drive ions (e.g. Na+, Cl-) through a membrane leaving water behind
- Membrane attracts salt ions leaving behind clean water
- Considerably expensive compared to other method, but particularly efficient with **brackish water** (e.g. saline wells in NW India)



Technology opportunity

OTHER SYSTEMS

- Forward osmosis
- Freezing desalination
- Thermal/Mechanical vapor compression (TVC/MVC)



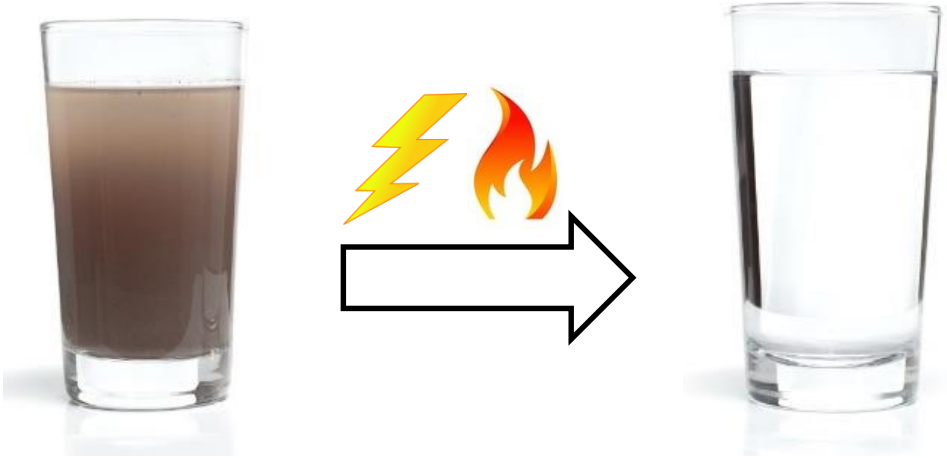
Source: McCutcheon, McGinnis, and Elimelech, Desalination, 174 (2005) 1-11.

BROADER ISSUE

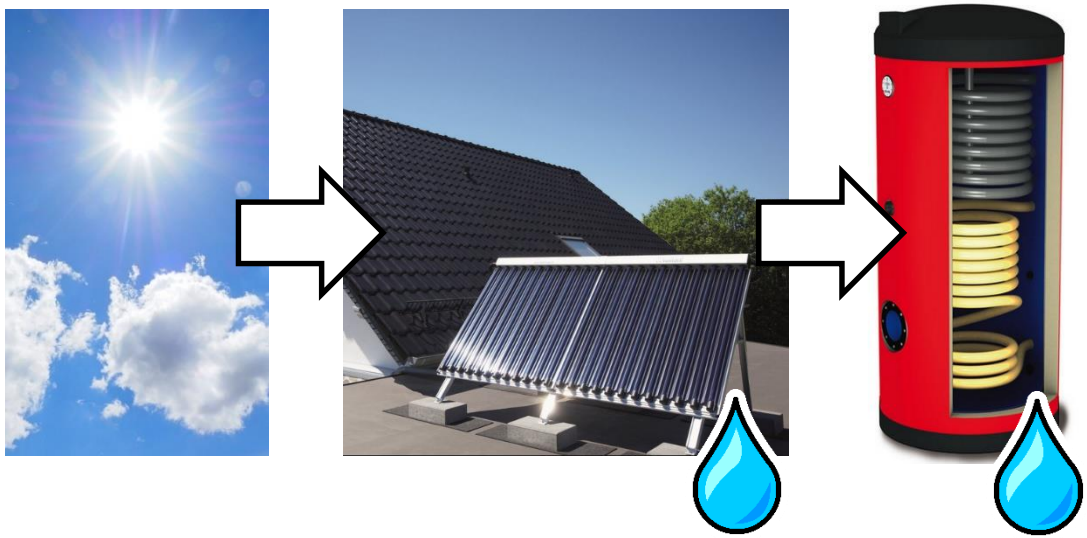
Energy-water nexus

ENERGY-WATER NEXUS

Energy is required to extract, treat, and deliver *water*



Water is used in multiple phases of *energy* production, transport and storage



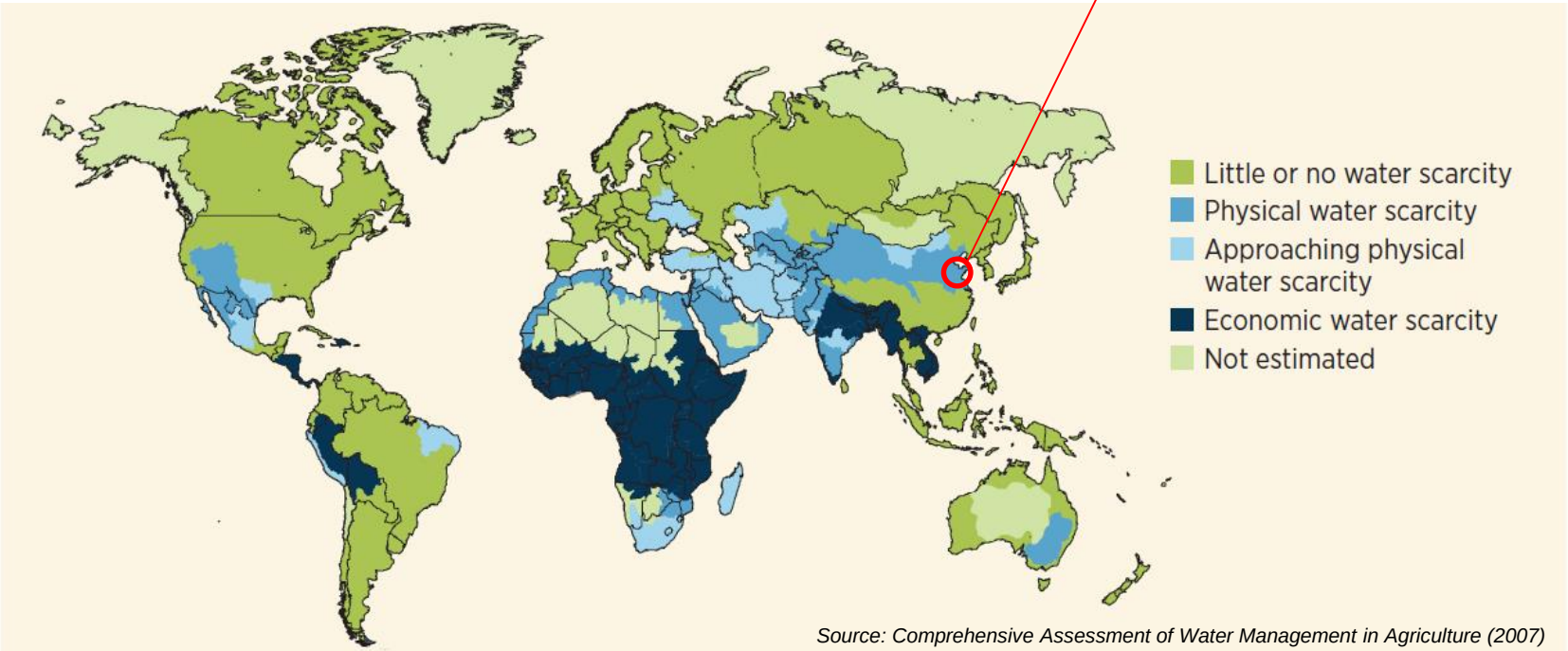
EXAMPLE: DESALINATION IN QINGDAO

China has a water crisis - how can it be solved?

Image: REUTERS/Aly Song

Qingdao (China)

9.046 million people

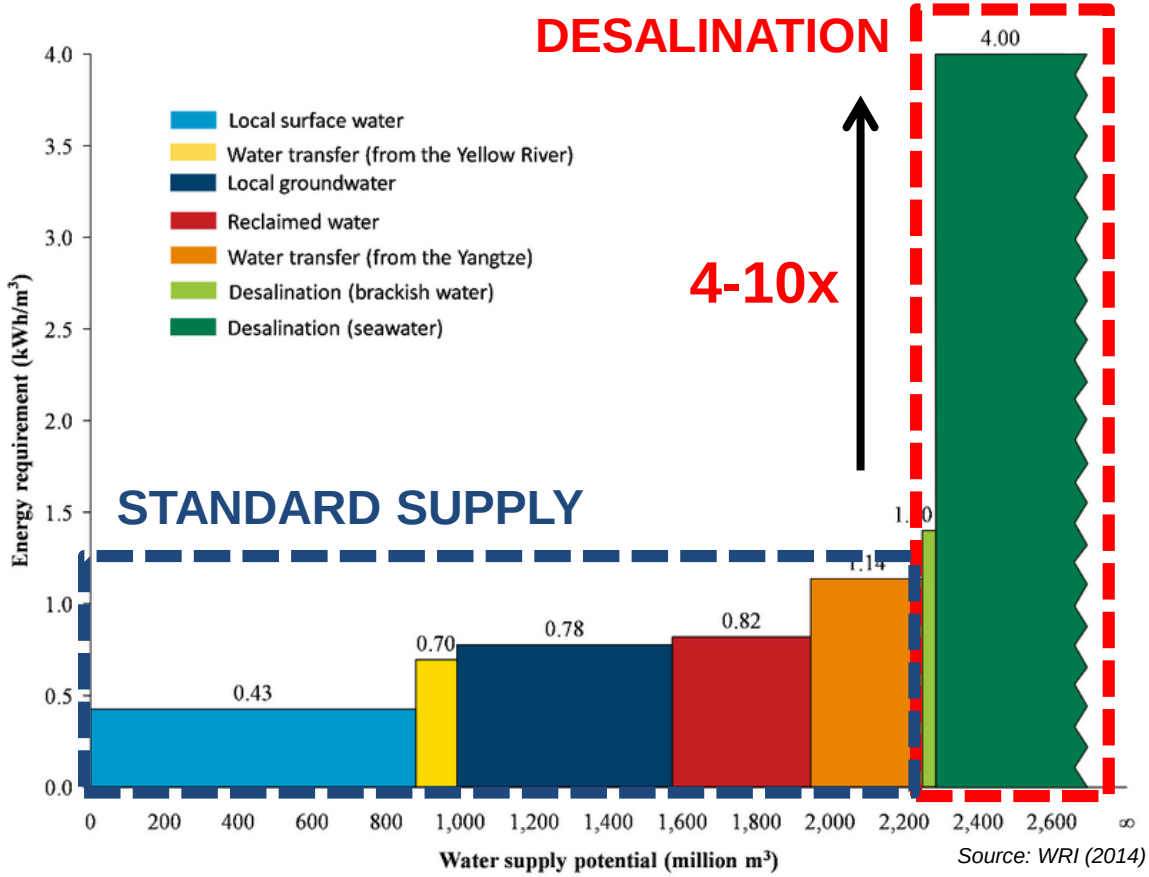


Source: Comprehensive Assessment of Water Management in Agriculture (2007)

DESALINATION ENERGY

- A **desalination plant** was constructed for the water needs of 500,000 people (5.5% Qingdao population)

- The desalination plant requires **electricity** (4 kWh/m^3), namely **4-10 times more** than standard water supply



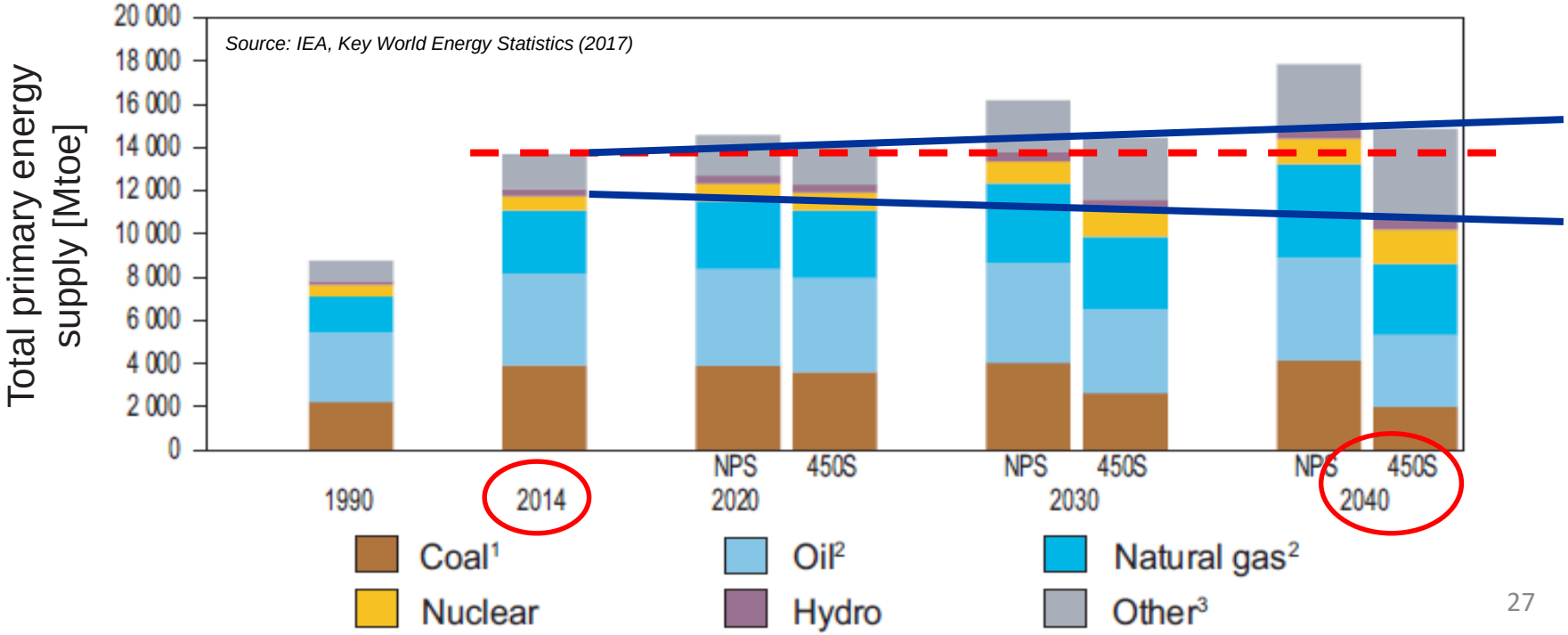
Source: WRI (2014)

⇨ Issue: desalination is energy-intensive

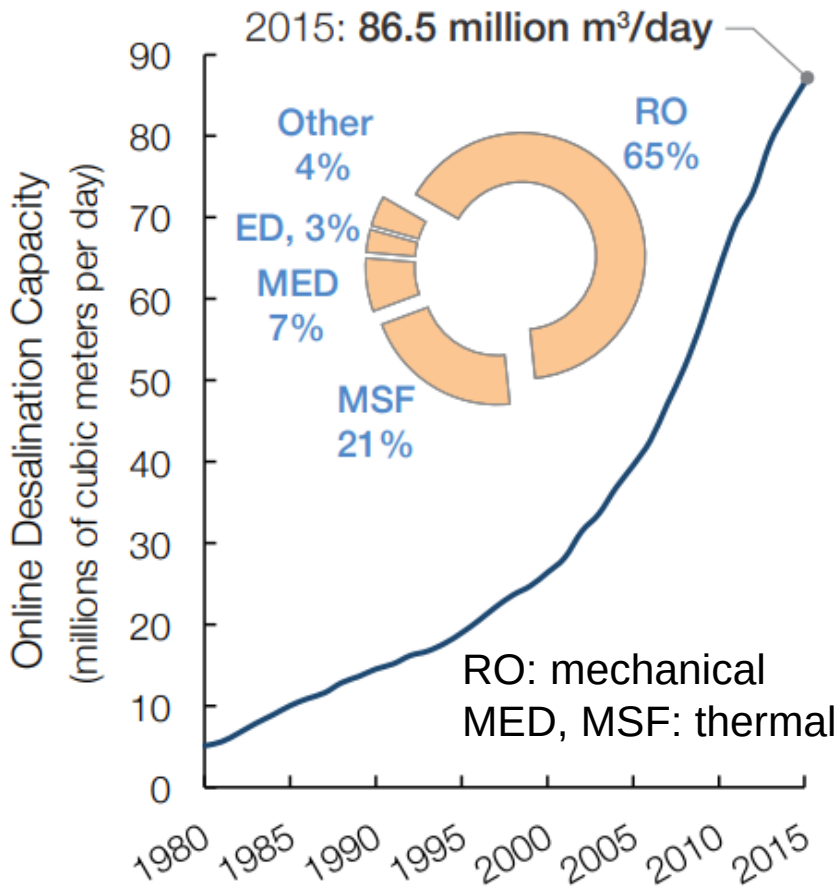
ENERGY OUTLOOK

To comply with the recent policies to **limit** average **temperature increase to 2 °C**, IEA predicts that in 2040:

- World total primary energy supply should keep almost **constant** respect to 2014 (i.e. *Energy efficient processes*)
- Other sources of energies should **more than double** their primary energy supply (i.e. *Use of renewable energies*)



DESALINATION OUTLOOK



Source: J.K. Lienhard, Low Carbon Desalination, MIT

Open technological issues :

- **Reducing** the use of expensive **fossil fuels** (60% of the water cost), by means of **energy efficient** technologies and **renewable sources**
- **Reducing pollution**:
  - ✓ 75 million tons of CO_2 per year
  - ✓ Huge amounts of chemicals are used in the industrial process (such as antiscalants, biocides, cleaning chemicals, etc.
- Need of **diversification** for future global energy crisis
- Need of standalone technology to **help remote (off-grid) and poor areas**

ISSUES OF CONVENTIONAL DESALINATION

Reduce impact on marine habitants

- Brine released back into ocean has potential to kill marine life
- Release chemicals (used for pre-treatment and cleaning) which harms marine life
- Discharged waste has potential to rise water temperatures, affecting the habitants

Reduce energy consumption

- Plants produce large amounts of greenhouse gasses due to high energy needs

Reduce land use

- Most desalination plants are located by the sea shore

PERSPECTIVES
Sustainable desalination

SUSTAINABLE DESALINATION

SUSTAINABLE ENERGY

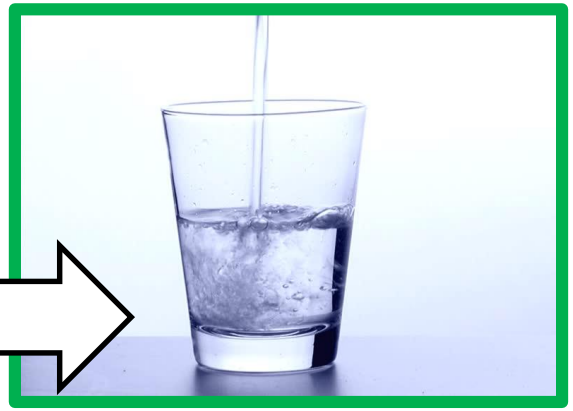
- **Renewable energy** (electricity, heat)
- Recovered heat

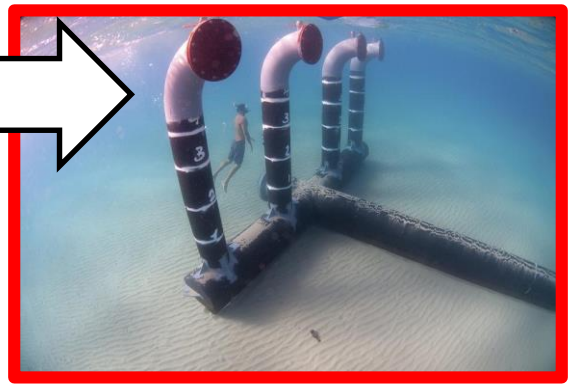
SALTWATER

Thermal or Membrane

SEPARATION UNIT

FRESHWATER

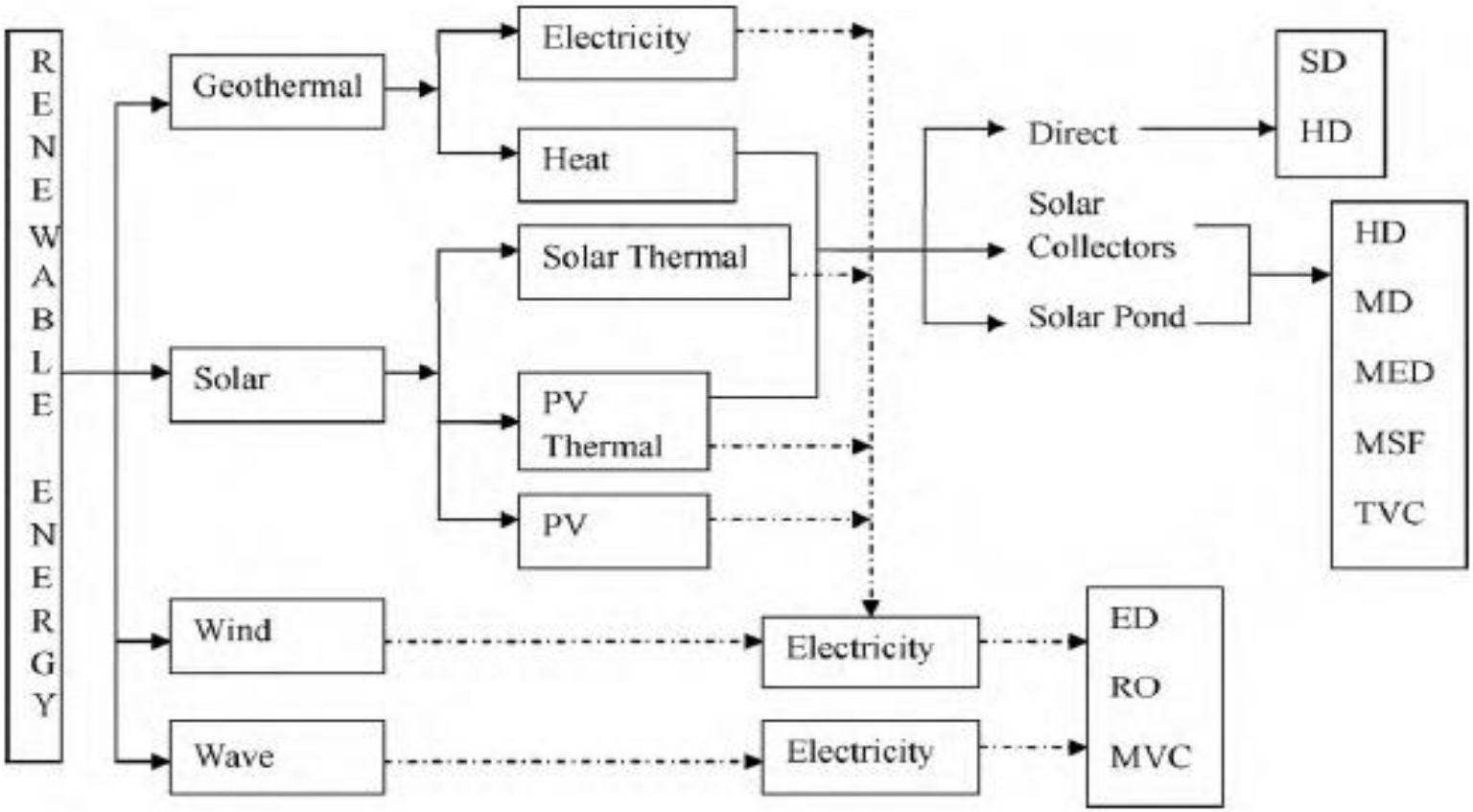




BRINE

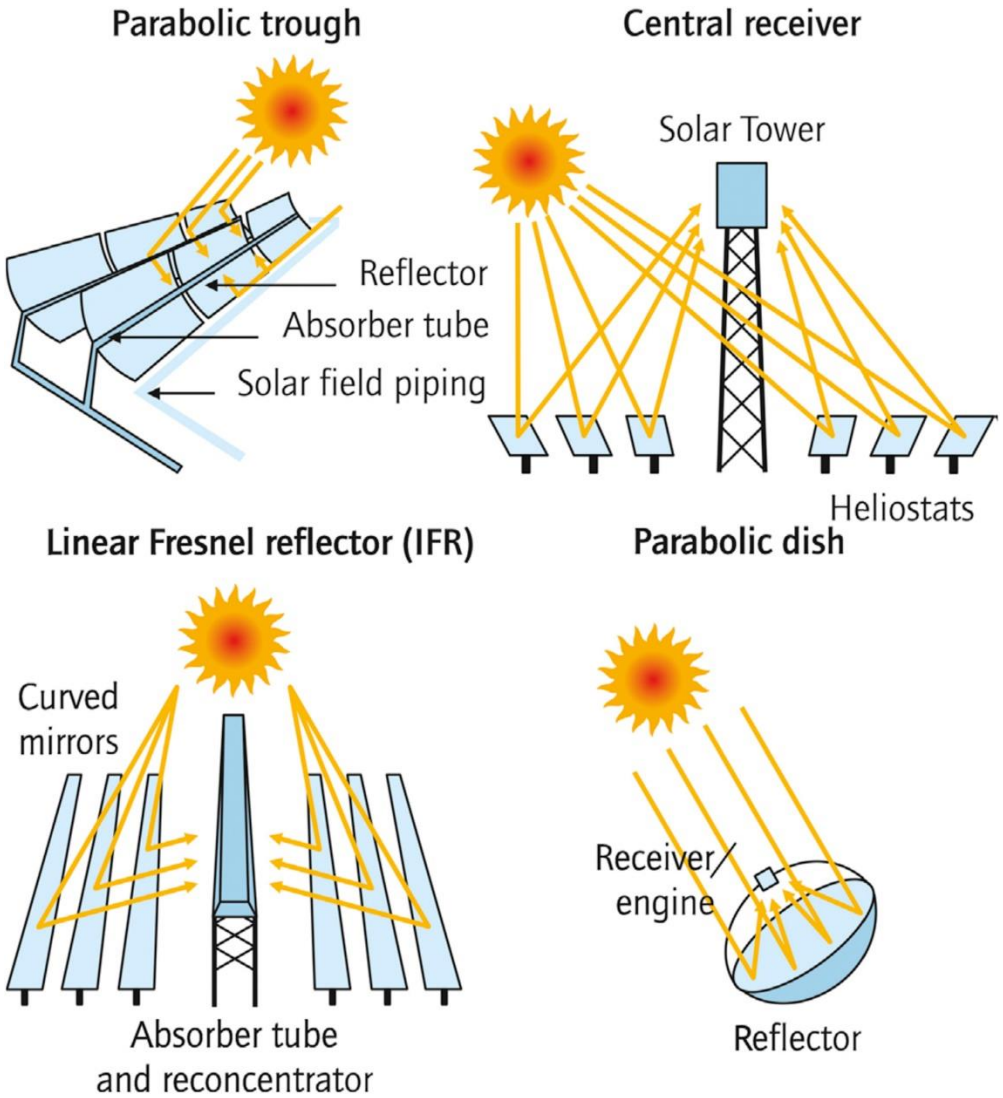
RENEWABLE ENERGY DESALINATION

Coupling renewable energy sources to conventional desalination technologies



Source: Gude et al., Renewable and sustainable approaches for desalination, RSER, 2010

CONCENTRATED SOLAR POWER



Source: Fuqiang et al., RSER, 2017

Solar energy

↓

Concentrated solar energy

↓

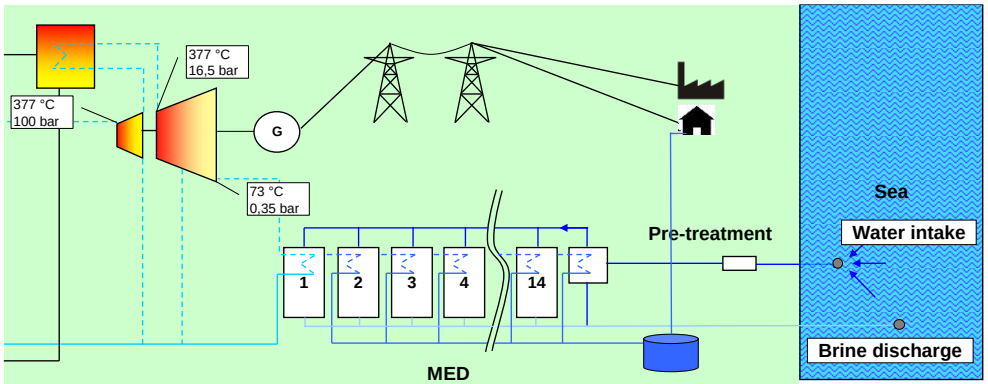
Thermal energy

↙ ↘

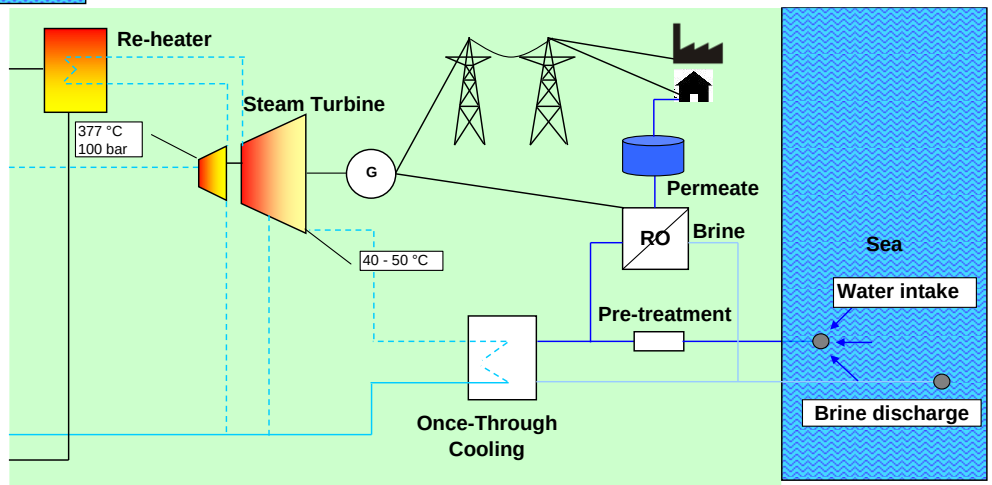
Electricity **Direct use of heat**

DESALINATION BY CSP

Most of the Countries with water scarcity have the highest solar radiation → **couple CSP to conventional desalination technologies**



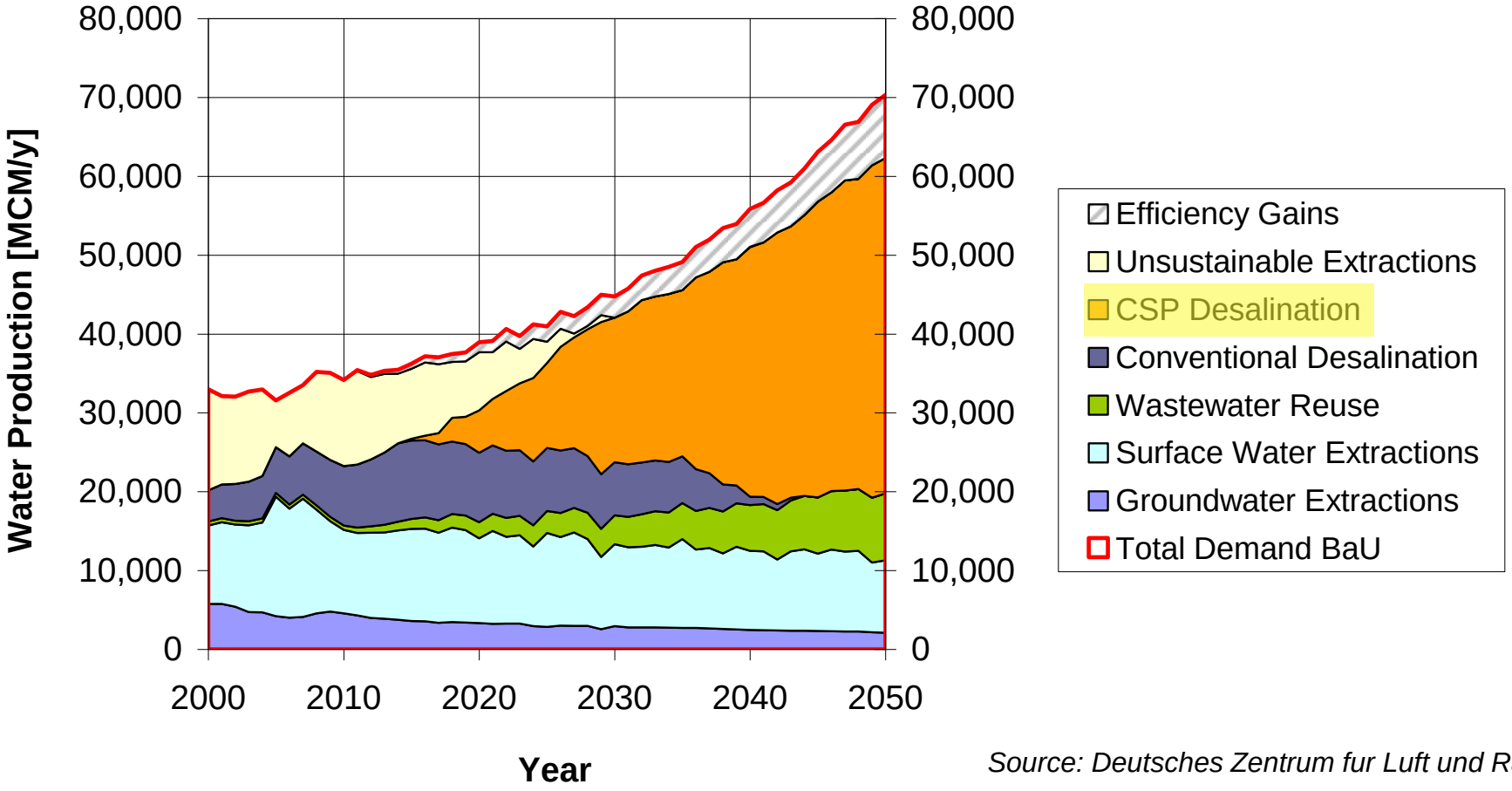
CSP-MED (using waste heat)



CSP-RO
(using electricity)

DESALINATION BY CSP

Potential in the Arabian peninsula…



Source: Deutsches Zentrum fur Luft und Raumfahrt

WIND POWERED DESALINATION

- Wind Powered Desalination is highly applicable to **locations with ample wind energy resources such as islands**
- Wind energy could be used to **power conventional seawater desalination**
- Wind turbines could either be connected in a **grid system** which provides power to a desalination system or individual wind turbines could be coupled **locally** to a desalination system

Wind Powered Desalination (Perth, Australia)
Emu Downs Wind Farm

SUSTAINABLE DESALINATION

SUSTAINABLE ENERGY

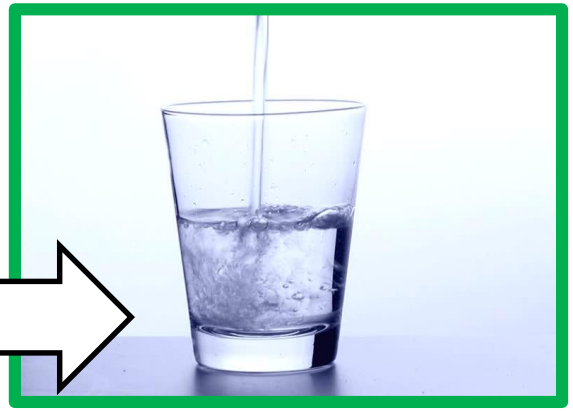
- Renewable energy (electricity, heat)
- **Recovered heat**

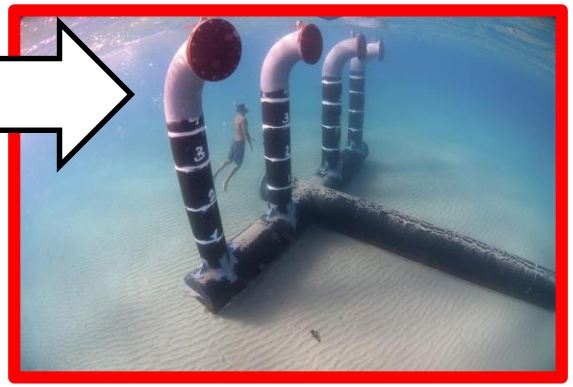
SALTWATER

Thermal
or
Membrane

SEPARATION UNIT

FRESHWATER





BRINE

SUSTAINABLE THERMAL DESALINATION

MEDECINS SANS FRONTIERES
MEDICI SENZA FRONTIERE

and

seed grants

Solar energy source

Heat from solar concentrators in developed countries

OR

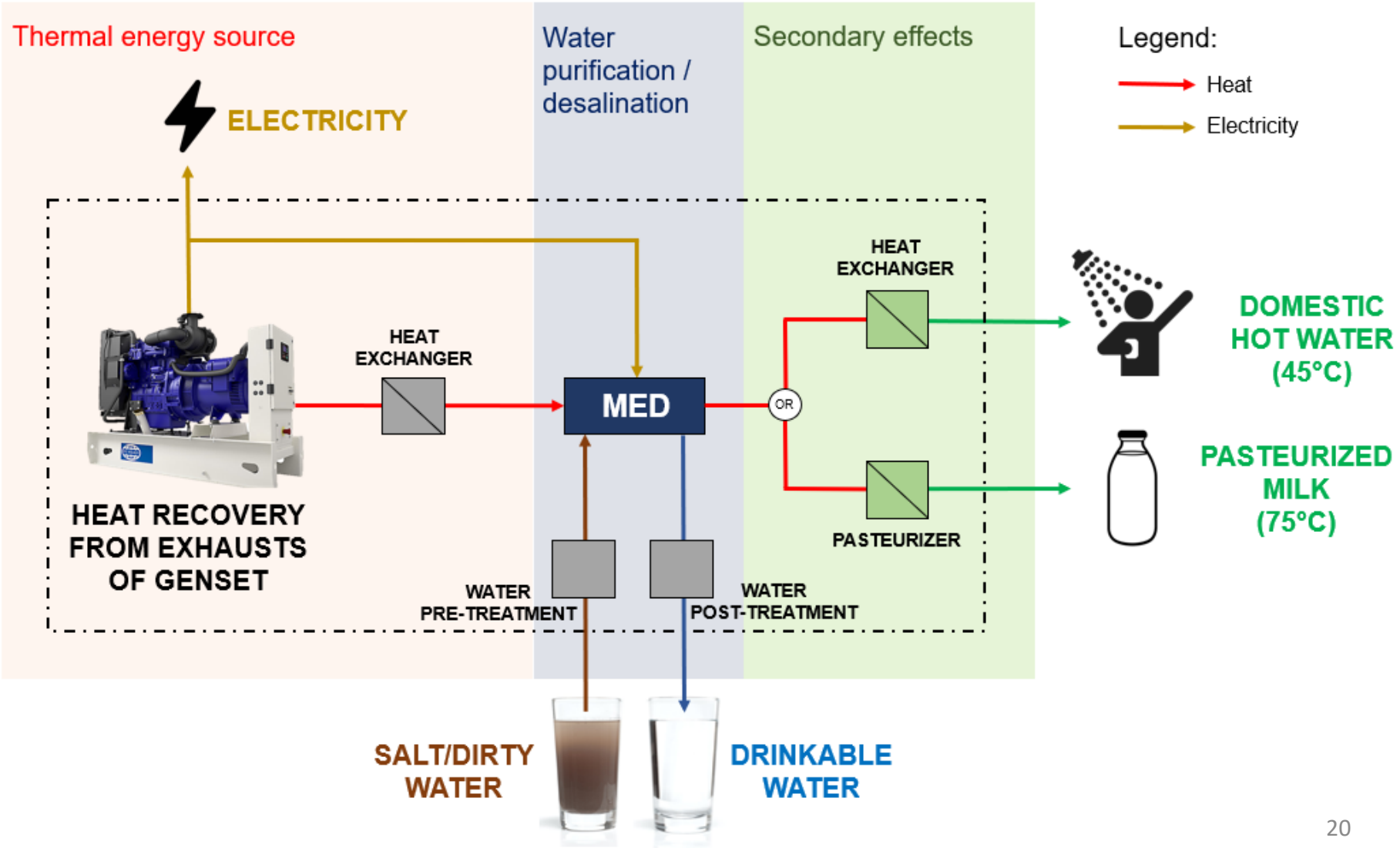
Waste heat recovery

Heat from exhaust gas of gensets in remote areas of developing countries

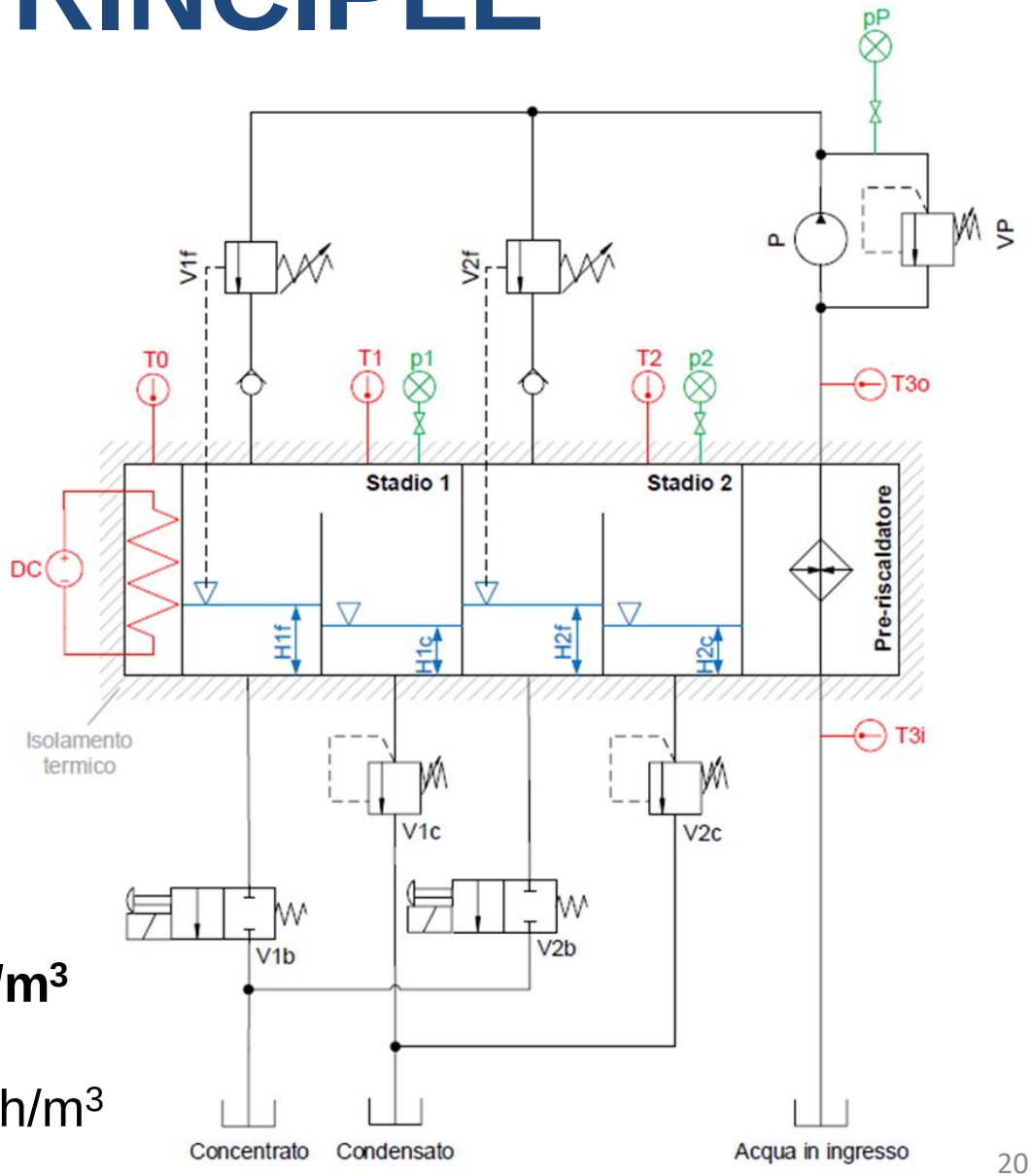
Water desalination

Proof of Concept (2 stages): **100 L/day**
Next step: **pilot plant** in collaboration with MSF

PLANT SCHEMATICS



WORKING PRINCIPLE



Productivity:

- Current version **720 kWh/m³**
  100 L per day (3 kW)
- Upscaled version 350 kWh/m³

THE STORY OF OUR MED

https://www.youtube.com/watch?v=YTnlaRC4sfw

TAKE-HOME MESSAGES

- **Freshwater scarcity is a global issue** that is expected to rise in the next decades. **Water efficiency** and **non-conventional freshwater resources** could mitigate it
- Traditional, large-scale **desalination** methods are chemically and energetically intensive, relatively expensive, and not suitable for most of the world. **Reverse Osmosis** is the dominant large-scale technology. **Thermal processes** are convenient where high salinity/biofouling is an issue
- Less than 1% of all desalination is based on **renewable energy**, mainly solar PV. Main developments focus on **solar thermal** but also other technology, e.g. wave or wind
- Focus should be also dedicated to **small-scale desalination**, to provide freshwater in remote areas

Thanks for your attention!

Email: matteo.fasano@polito.it

ACKNOWLEDGEMENTS

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www.polito.it/small

http://cleanwater.polito.it/