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## **Membrane technology at water-energy-raw materials nexus**

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Since the pioneering work of Sidney Loeb and Srinivasa Sourirajan in the late 1950's, who demonstrated the viability of asymmetric cellulose acetate membrane for seawater desalination via Reverse Osmosis (SWRO), membrane engineering has come a long way. Today, the majority of the 16,800 desalination plants operated worldwide - with global cumulative capacity of about 115 million m<sup>3</sup>/day – is based on SWRO technology, that dominates the desalination market [1]. Despite this enormous success, critical issues still remain open, i.e.: 1) adverse ecological and toxicological impacts of discharged hypersaline brine; 2) current SWRO energy consumption of 3-4 kWh per m<sup>3</sup> of desalted water at 50% recovery still far from the theoretical threshold (1.1 kWh/ m<sup>3</sup>).

Interestingly, under the impulse of emerging Circular and Green Economy paradigms, desalination brine is now conceived not merely as a problematic waste to dispose, but as an unconventional and potentially exploitable source of valuable minerals and energy. Seawater – composed by 3.3% of dissolved salts - consists of a storehouse of about 5·10<sup>16</sup> tons of minerals, and almost all elements in the periodic table can be found in seawater, although at ppm/ppb levels [2]. Moreover, Salinity Gradient Power generated by converting Gibbs energy of mixing for two solutions at different salinity into electrochemical energy is exponentially gaining attention: the theoretically extractable amount of energy by mixing 1 m<sup>3</sup> seawater (0.5 M NaCl) and 1 m<sup>3</sup> hypersaline brine (5 M NaCl) is about 4500 kJ, that is a 20-fold increase with respect to the energy amount generated by mixing seawater and river water (Blue Energy) [3].

In this framework, new membrane operations such as Photothermally-enhanced Membrane Distillation, Membrane Crystallization and Reverse Electrodialysis – going well beyond the traditional concept of molecular sieves – are attracting interest as integrated systems for applications at water-energy-raw materials nexus.

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[1] J. Eke, A. Yusuf, A. Giwa, A. Sodiq. *Desalination* 495 (2020) 114633

[2] <http://seafriends.co.nz/oceano/seawater.htm> (accessed on March 2021)

[3] R.A. Tufa et al. *Applied Energy* 225 (2018) 290-331

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