Energy-Water-Environment Nexus Underpinning Future Desalination Sustainability.

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Abstract:

Energy-water-environment nexus is very important to attain COP21 goal, maintaining environment temperature increase below 2^{o}C, but unfortunately two third share of CO_2 emission has already been used and the remaining will be exhausted by 2050. A number of technological developments in power and desalination sectors improved their efficiencies to save energy and carbon emission but still they are operating at 35% and 10% of their thermodynamic limits. Research in desalination processes contributing to fuel World population for their improved living standard and to reduce specific energy consumption and to protect environment. Recently developed highly efficient nature-inspired membranes (aquaporin & graphene) and trend in thermally driven cycle's hybridization could potentially lower then energy requirement for water purification. This paper presents a state of art review on energy, water and environment interconnection and future energy efficient desalination possibilities to save energy and protect environment.

Keywords: Desalination review, SWRO, Thermal desalination, Renewable desalination, Desalination performance, Sustainable desalination.

1. Introduction

Water and energy are closely interlinked and interdependent valuable resources that underpin economic growth and human prosperity. In every part of daily life cycle such as power generation, feedstock crops production and fossil fuel processing, water is ubiquitous source [1, 2]. Similarly, energy is vital to power water cycle that include, collection, treatment and distribution to end users. The mutual vulnerability of water and energy is amplifying due to rising demand as a consequence of exponential gross domestic product (GDP) growth, population bourgeoning and climate change [3].

The world's thermoelectric power generation sector strongly depends on the availability of water for processes heat rejection [4]. In 2010, world's total electricity generation capacity was 20 terawatt hour (TWh), 81% contributed by thermoelectric (fossil fuel and nuclear), 17% by hydropower and 2% by renewable energy sources as shown in Figure 1 [5]. In 2035, global electricity demand is expected to increase 70% to 34TWh as compared to 2010 consumption [6]. The findings show that the scale of water use for energy production is tremendous. In 2010, global freshwater withdrawals for energy production were 583 billion cubic meters (bcm), 15% of the world's total water withdrawals and it is expected to climb to 790 bcm in 2035, 35% higher than in 2010. Water withdrawals per unit of electricity generated are highest for fossil fuel operated steam power plants and nuclear power plants, at 75 000 - 450 000 liters per megawatt-hour (l/MWh). Combined-cycle gas turbines (CCGTs) plants are more efficient and generate less waste heat per unit of electricity production and therefore require less cooling water. Their water withdrawal and consumption are the lowest among thermal power plants, at 570 - 1100 l/MWh [7].

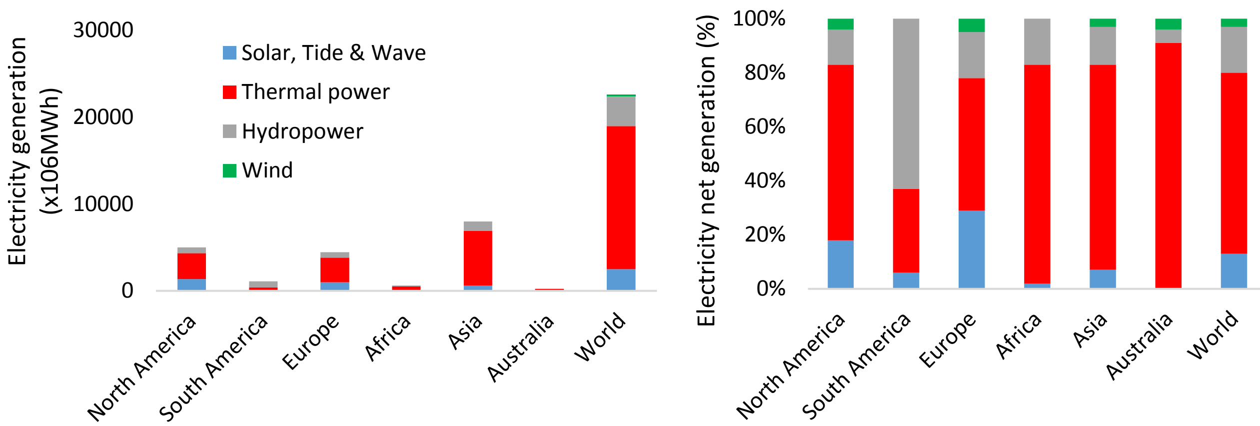

Figure 1: Net electricity generation in different parts of the World and percent share of different sources [5].

Global water demand is projected to increase more than 55% by 2050 mainly due to high GDP growth rate that will increase water demand for manufacturing, power generation and domestic sector use by 400%, 140% and 130% respectively. This current demand trend will push 40% of the World population below water scarcity level by 2050 [6]. Presently, more than 18,000 desalination plants in 150 countries producing roughly 38 billion m^3 per year as shown in Figure 2 [8-10]. It is projected to increase to 54 billion m^3 per year by 2030, 40% more compared to 2016 [11-13]. Desalination is the most energy-intensive water treatment process that consume 75.2 TWh per year, about 0.4% of global electricity [14]. The water cycle need energy during pumping and treatment processes [15, 16]. Pumping energy depends on distance, flow rate and friction. The desalination process energy depends on quality of the source water, the nature of any contamination, and the types of process employed [17, 18].

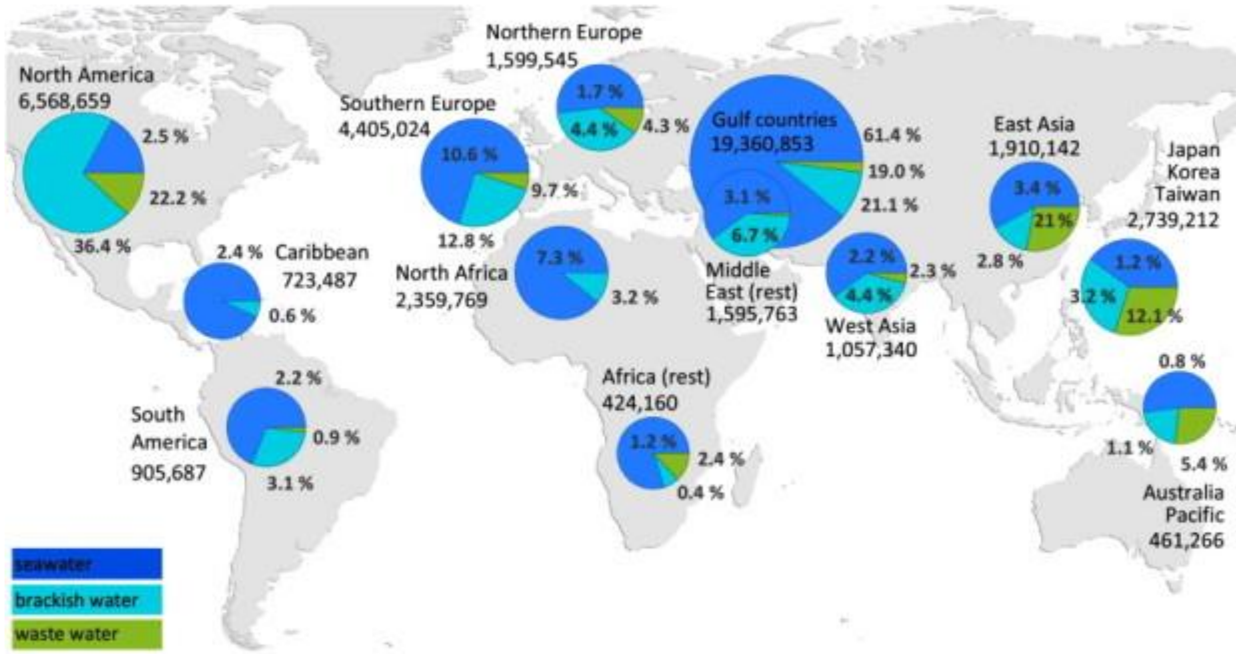

Figure 2: Desalination capacities installed in the World and percent share on the basis of feed water type [8-10].

Fossil fuel operated energy intensive desalination processes are the major source of CO_2 emission. Presently, globally installed desalination capacities are contributing 76 million tons (Mt) of CO_2 per year and it is expected to grow to 218 million tons of CO_2 per year by 2040 [19, 20]. In 2019, global CO_2 emission is estimated to grow to 43.2 giga ton (Gt) per year, 20% higher than 2013 value of 36.1 Gt per year [21]. Two thirds share of the CO_2 emission for COP21 goal, maintaining environment temperature increase below 2^{o}C, has already been used and the remaining will be exhausted by 2050 [21-25].

Figure 3 summarized the percentage increase of World water withdrawals & consumption, population and CO_2 emission from 1900 to 2040. It can be seen that the CO_2 emission is over 1500% and it is expected to grow to 2200% by 2040 [26-32]. Similarly, water withdrawals and consumption also increased to over 1000% [33]. Increase in primary energy consumption is also plotted (1970 baseline at 100%) and it is expected to grow to 500% by 2040 [33-35].

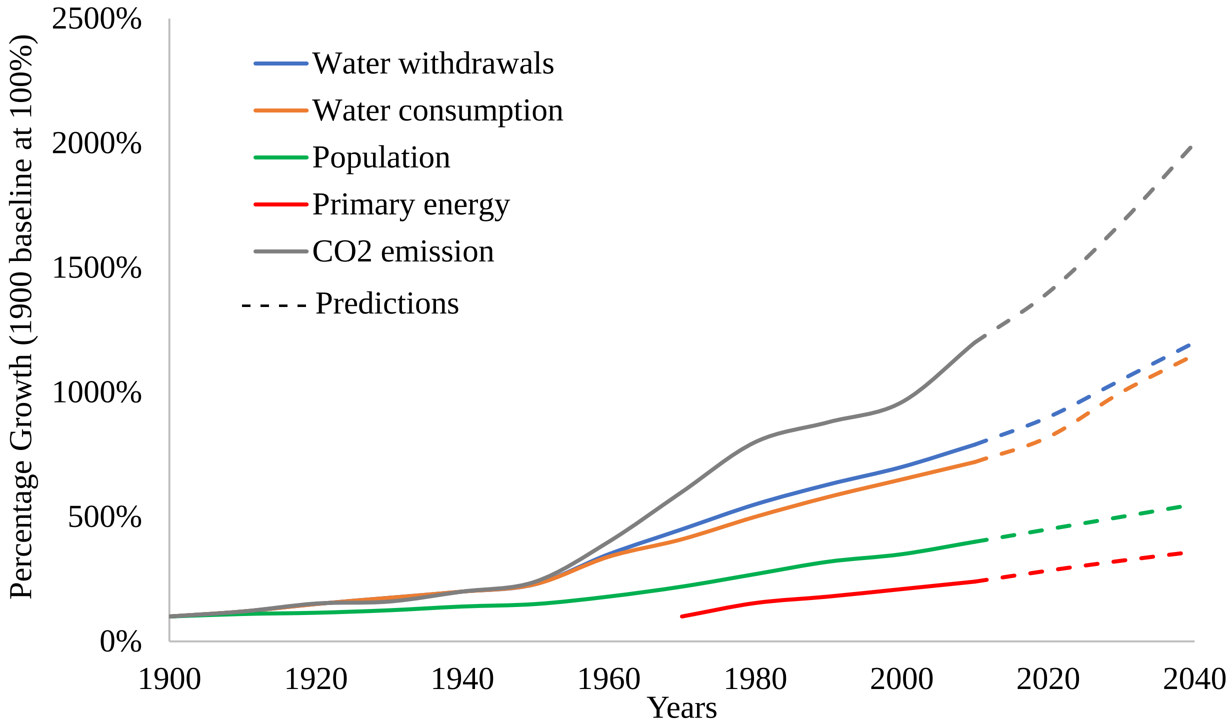

Figure 3: Water, population, primary energy and CO_2 emission percentage growth rate from 1900 to 2040. (Water, Population and CO_2 emission: 1900 baseline at 100% & Primary energy: 1970 baseline at 100%)

It can be seen that CO_2 emission growth rate is the highest and it is predicted to continue same trend. The efficiency improvement of two major sources, water and power, is important to control CO_2 emission to protect environment.

2. Water Treatment Processes & Energy Demand

The groundwater supplies are diminishing due to 2-3% annual increase in extraction rate [36-40]. More than 1.2 billion people live in physical water scarcity areas, the region having water availability less than 1,000 cubic meters per capita per year, that hamper the economic development and human health [41]. Risks to water resources lead to energy and environment risks. Conventional energy intensive water treatment processes increases pressure on designer and planners to develop an alternative energy efficient methods to fulfil future sustainable water supply demand for GDP growth rate. The level of water treatment depends on feed source and end user requirement. For drinking, extensive treatment is required to attain World health organization (WHO) drinking water standards. Amount of energy required to produce 1 m^3 of drinking water from various sources is presented in Figure 4 [42-45]. The energy requirement have direct impact on environment, the more efficient process mean less carbon emission. Surface water treatment is least energy intensive since most of time it is available near to the delivery point. Ground water treatment is energy intensive and most of energy is utilized by pumping process depending on water table depth. Brackish water treatment requires significant energy depending on composition and concentration of salt. Seawater treatment is not only highly energy intensive because of feed water quality but also impact environment in a number of ways such as (i) energy utilized by desalination processes increase environmental pollution, (ii) concentrated and hot brine can effect marine life, (iii) contamination of water aquifers due to pretreatment chemicals and corrosion materials and (iv) desalination processes can also cause noise pollution and vibration issues due to high pressure pumping [46]. The fresh water shortage can be partially (40% of 40% gap) addressed by mentioned measures such as water conservation, wastewater treatment and reuse. Closing the remaining gap (60% of 40%) through desalination processes, the only solution, would be extremely energy intensive and environment unfriendly [47].

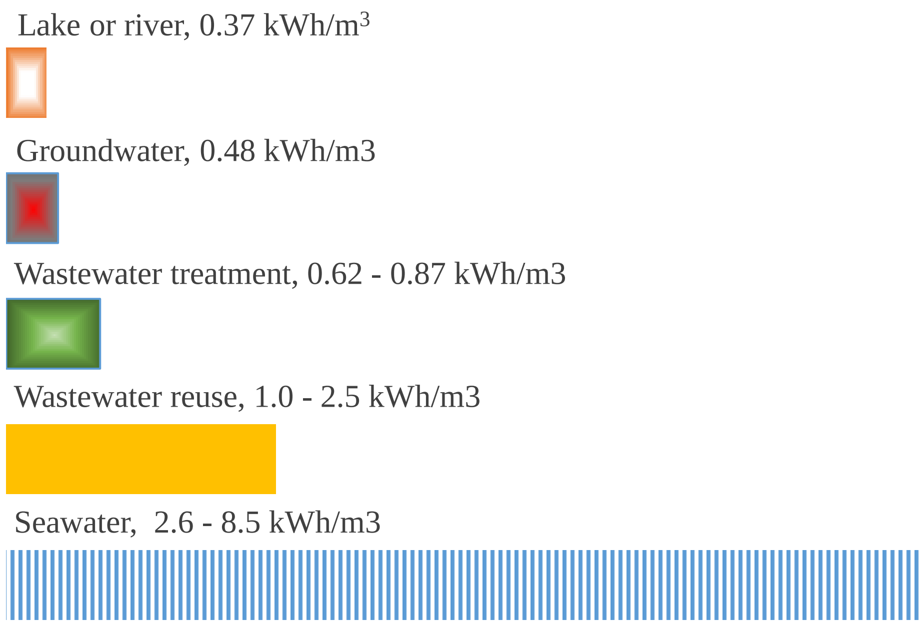

Figure 4: Typical amount of energy required for unit water production for different feed water quality [42-45].

3. World Desalination: Current Status, Energy Utilization & Environmental Impact

The commercial desalination technologies can be divided into two main categories: thermally driven (MSF, MED and AD) and membrane separation (RO) processes. In addition, there are different emerging technologies which are still under research and development (R&D), including forward osmosis (FO), membrane distillation (MD), capacitance deionization (CDI), gas hydrates (GH), freezing and humidification dehumidification (HDH). Moreover, supporting technologies include ultra/nano/ionic filtration (UF/NF/IF) [48-71]. Figure 5 shows World and Gulf Cooperation Council (GCC) countries desalination installed capacities and share of different technologies. It can be seen that in GCC countries, thermally driven desalination technologies are dominating due to operational limitations of RO at high turbidity of seawater. It is also shown that 59% of desalination technologies based on seawater desalination followed by brackish water 23%, river water 7%, waste water 5% and other sources 6% [72, 73].

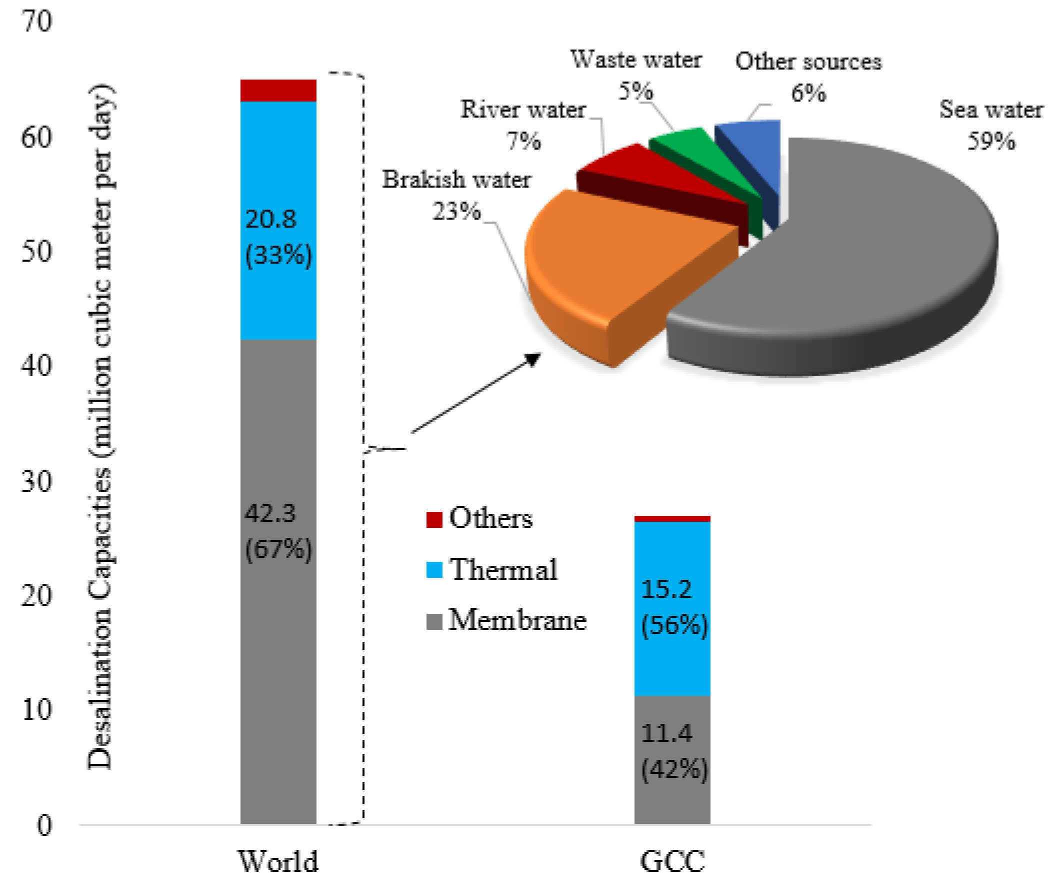

Figure 5: Total desalination installed capacities and share of different technologies in the World and in GCC countries [72, 73].

Recently, hybridization trends of desalination technologies such as MED-AD [74-79] , MSF-MED [80-93] and RO-MSF [94-106] is evolving to improve processes performance by overcoming conventional methods limitations. Thermally driven processes hybridization improve thermodynamic synergy and thermal system with membrane technologies improve fresh water recovery.

The desalination technologies capital expenditure (CAPEX) and operational expenditure (OPEX) depends on a number of parameters. Some technologies CAPEX are high due to land, engineering, unit purchase, transportation and installation etc. and others are leading in terms of high OPEX such as energy, maintenance, spares and labor but the overall water production cost is defined as $/m^3 [107]. Presently, the widely accepted parameter to evaluate the efficacy of practical desalination processes is the performance ratio (PR):- The equivalent heat of evaporation needed to produce one cubic meter of potable water to the actual kWh_{elec} or kWh_{ther} per cubic meter [108-110].

MSF Desalination

MSF technology was dominating from 1980s to 1990s due to robust operation and maximum availability during the time of the year. However, the recent technological developments in MED and RO processes took over the MSF installations worldwide, especially in the Gulf region [107]. Thermally driven MSF need both electrical and thermal energy and operates at top brine temperature (TBT) ranges from 90°C to 110°C [107, 111]. Increasing TBT enhance flashing and hence the performance ratio but it is limited by severe scaling and fouling problems at high temperature. Theoretically, they can have 4 to 40 number of stages but typically 18 to 25 number of stages are common with typical plant size from 50,000 to 70,000 m^3/day [107, 111, 112]. The typical thermal energy consumption for MSF varies from 191 MJ/m^3 to 290 MJ/m^3 that is equivalent to 15-25 kWh_{elec}/m^3 at 30% power plant efficiency [112, 113]. The electricity requirement for pumping energy ranges from 2.5 to 5.0 kWh_{elec}/m^3 therefor, overall equivalent electricity consumption is 20 to 30 kwh_{elec}/m^3 [112, 113]. In the Gulf countries, gain output ratio (GOR) varies from 8-10 and the typical PR ranges from 3.5-4.5 depending on steam temperature [112]. The variation in the water cost estimation presented in the literature can be attributed to inconsistent economic analysis methodology and fuel & material cost variation [114]. Water cost varies from 0.5$/$m^3$ at subsidized fuel cost of 5$/Barrel and 4$/m^3 for independent water and power project (IWPP) project with international fuel cost of 100$/Barrel [115]. The MSF brine discharge usually 7–15°C hotter and 15–20% more concentrated than the feed water that effect the marine environment [116]. Their CO_2 emission varies from 20-25kg/m^3 as a standalone operation to 14-16 kg/m^3 as a cogeneration operation with steam power plants [117, 118]. Although, there is a perception that MSF has no improvement margin as it is reached its maturity but latest patent [119] disclosed that an advanced MSF plant with combination of Nano-filtration technology allowing TBT to exceed 120°C to achieve highest performance of MSF plant [120].

MED Desalination

MED has been used in process industries for a long time but it was failed in desalination industry to compete with MSF due to the scaling problem and the larger CAPEX and OPEX in the past [108, 114]. Recently, technological development of MED, low temperature operation with TVC, solved this problem and as a consequence, MED started to gain ground to compete MSF [108, 114]. In last decades, 2000-2008, MED trend showed steady but year 2009 showed sharp increase in its market in terms of contracted capacities in the Gulf. Experts believe that MED may reinforce its major share in desalination market in the future due to its greater compatibility with solar thermal desalination and hybridization with other thermally driven cycles such as adsorption cycle (AD) [107, 112]. Similar to MSF, MED plants require both electrical and thermal energy but their specific energy requirement is lower than MSF because they operate at lower top brine temperature typically below 70°C [121]. The thermal energy requirement for MED operation varies from 145MJ/m^3 to 230MJ/m^3 depending on TBT that is equivalent to 12-19 kWh_{elec}/m^3 based on 30% power plant efficiency [112, 113]. Operational pumping require 2.0-2.5 kWh_{elec}/m^3 and overall equivalent electricity consumption ranges from 15-22 kWh_{elec}/m^3 [112]. Typically, MED operate at a GOR of 10-16 but in Gulf region it varies from 8-12 due to sever feed water quality [112].

MED CAPEX are higher than MSF but OPEX are lower and total production cost reported as \$0.7/m^3 to \$0.8/m^3 [122, 123]. In terms of CO_2 emissions, MED is also ranked lower than 12-19kg/m^3 as a standalone operation to 8-9 kg/m^3 as a cogeneration operation with steam power plants [117, 118]. Recently, the Saline Water Desalination Research Institute (SWDRI) of SWCC and the Water Re-use Promotion Center (WRPC) of Japan together with Sasakura Engineering Co. Ltd. have conducted promising research to hybridize nanofiltration (NF) membranes as a pre-treatment with MED to increase TBT from 65°C up to 125°C. At TBT 125, MED-TVC can have 24 number of recoveries and GOR can be increased to 20, doubling the water production as compared to conventional MED with GOR 9-10 [124-128].

SWRO Processes

RO processes are dominating in brackish water treatment market and they showed increasing trend for seawater desalination from 2.0 Mm^3/day to 3.5 Mm^3/day from 2005 to 2008 and it is expected to be strengthen in future due to highly efficient aquaporin and graphene membrane development [129, 130]. In last decades, RO processes improved tremendously due to pressure recovery devices and NF integrated pre-treatment processes [131]. RO processes only required electricity for desalination and the energy consumption is depend on recovery ratio and total dissolved solids (TDS) in the feed since the osmotic pressure is related to total dissolved solids (TDS). For severe feed water conditions such as high turbidity, high algae concentration, high temperature and high TDS, the RO cost will be higher than thermally driven processes because of extensive pre-treatment process requirement [132]. At start, in 1970s, SWRO processes were highly energy intensive with specific energy consumption of 20 kWh_{elec}/m^3 [133]. Present technological development reduced energy consumption to many fold. Today's SWRO processes required from 3-8 kWh_{elec}/m^3 (55 to 82 bar pump pressure) for seawater and 1.5-2.5 kWh_{elec}/m^3 for brackish water from large to medium size of plants [112, 134-137]. For small size, it can be as high as 15 kWh_{elec}/m^3 (17 to 27 bar pump pressure) [112]. Kinetic® energy recovery system achieved lowest specific energy consumption level of SWRO at 2.00 kWh/m^3 with most efficient energy recovery devices at many locations, Sal Island-Cape Verde 1000 m^3/d SWRO plant is one of the example [138]. Since RO specific energy consumption is the lowest among all desalination technologies, it cause lowest CO2 emission, 2.79kg/m^3 in steam cycle operation and 1.75kg/m^3 in combined CCGT power plants [117, 118]. This variation in CO_2 emission is due to difference in overall system efficiency. Since CCGT power plants efficiency is higher so SWRO connected with CCGT have less emission contribution. On the other hand, thermal power plants efficiency is lower so desalination cycle connected with single thermal power plant have higher contribution in CO_2 emission. RO water production cost varies from 0.45-0.66 US\$/m^3 for large size plants, 0.48-1.62 US\$/m^3 for medium and 0.7-1.72 US\$/m^3 for small size plant [139]. In RO processes, brine is rejected at ambient temperature, no thermal pollution as in thermal technologies. However, the chemicals added for the pretreatment add toxic brine pollution to marine environment and cause RO membrane cartridge fouling [140-156]. Currently, spiral wound membranes are introduced to provide greater filtration surface area within the same volume. They offer high salts rejection, low-energy requirement and high-productivity up to 47.5 m^3/d [157-159]. Hybrid RO membrane inter-stage design also called internally staged design is introduced in which different membranes are packed in same pressure vessel to get operational and maintenance advantages and 5% to 8% of capital costs savings as reported by the manufactures [160-165].

3.1- Cogeneration Systems

The world's trend in water desalination industry has been moved towards the efficient cogeneration concept where both power (electricity) and potable water are produced simultaneously. Combined water and energy production has several benefits namely; (i) process low grade waste heat can be re-utilized for desalination that reduce specific energy and hence CO_2 emissions, (ii) process cooling water demand can be reduced, (iii) the cost of desalinated water and power decreases and (iv) the integrated system is more efficient than the stand-alone operation. However, the disadvantages of cogeneration system includes: (i) complex operation and (ii) sessional variation in water and power demand difficult to handle. Demand variability can be managed, but when the two demands are not aligned, the system runs below maximum efficiency. This problem can be solved using MED/MSF-RO hybrid systems [131].

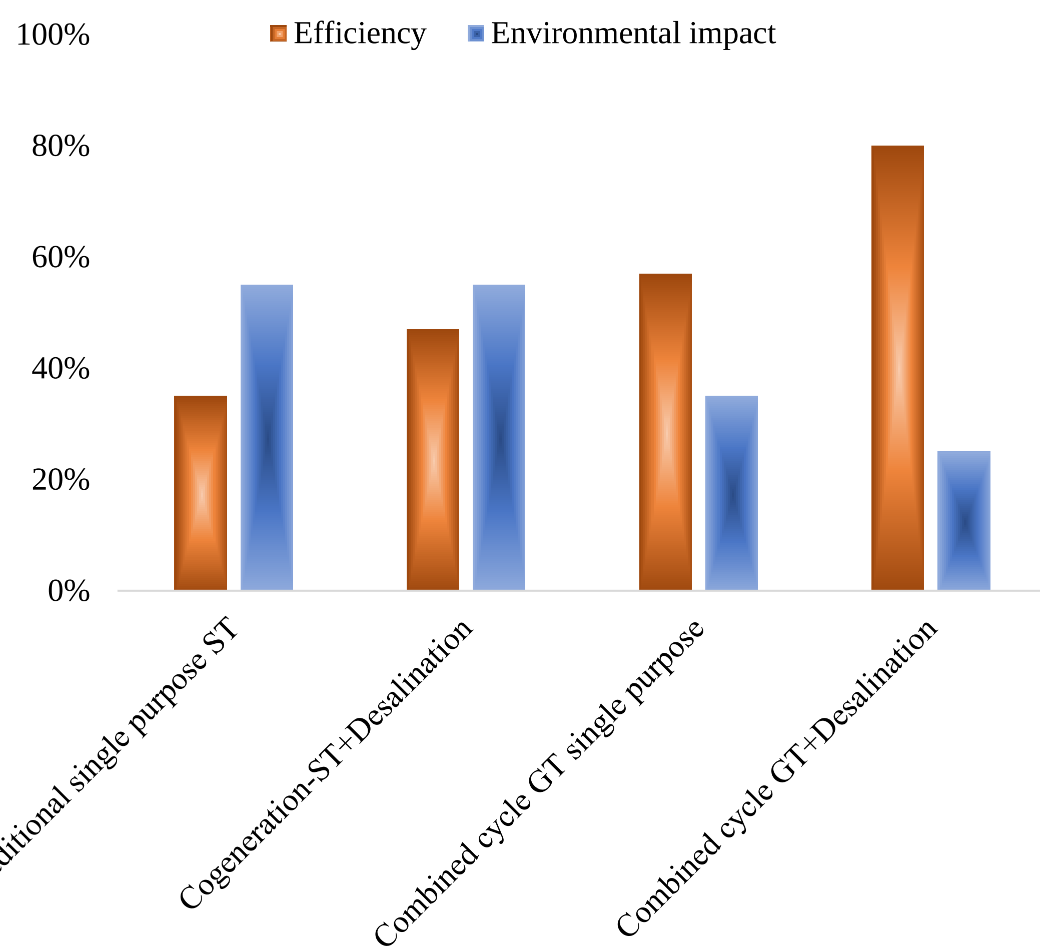

Figure 6: Single purpose and cogeneration process impact on overall plant efficiency and environment [131].

Figure 6 shows the overall system efficiency and environmental impact of different configuration of power and desalination systems. Single purpose plants are less efficient and hence high environmental impact. In multi-purposed plants, working fluid exergy can be utilized more efficiently due to cascading arrangement of processes that improve overall system performance and reduce environmental impact. It can be seen that combined CCGT power and desalination plant can achieve 80% overall efficiency and 25% environmental impact as compared to 57% efficiency and 35% environmental impact of single purpose CCGT power plant. This improvement in overall efficiency and reduction in environmental impact is due to excellent thermodynamic synergy of cascading arrangement of thermally driven systems. Similar improved trend has been observed when single purpose steam power plant combined with desalination cycle. This shows, higher the overall system efficiency, lower the environmental impact [131].

3.2- Desalination Technologies Comparison

As it is mentioned earlier, desalination processes CAPEX and OPEX depends on many parameters such as; plant capacity, design, material and feed water quality. It is noticed that feed concentration doesn't effect thermally driven processes energy consumption but it influence membrane systems energy consumption. It is also reported that thermally driven systems require higher energy compared with membrane processes. Table 1 summaries the important parameters of most common desalination technologies and a case study of Jubail CCGT and desalination plant is also presented in table 2 to highlight the rejected brine impact on marine environment in terms of concentration and temperature [48].

Table 1: Summary of operational and performance parameters of different desalination processes.

Parameters	**MED**	**MED-TVC**	**MSF**	**SWRO**	**MD**	**Hybrid *MED+AD**
Typical size and capital cost 107, 123, 132, 155, 175, 166-194, 203, 204						
Typical plant size (x1000m^3/day)	5-15	50 - 100	50-70	Up to 128	24	50 - 100
Unit capital cost (\$/m^3/day)	2000	1860	1598	1313	1131	2200
Energy consumption, water cost & technology trend 107, 122, 123, 132, 139, 155, 175, 166-198, 200-202, 205-208, 212-214						
Operating Temperature (^oC)	65 - 70	65 - 70	90 - 110	Ambient	60 - 90	65 - 70
Thermal Energy (MJ_{ther}/m^3)	145 - 230	180 - 290	190-282	NA	360	108 – 144
Thermal Energy (KWh_{ther}/m^3)	40 - 65	50 - 80	53 - 70	NA	100	30 - 40

Electric Energy (kWh_{elec}/m^3)	2.0-2.5	2.0-2.5	2.5-5.0	4.0-6.0	1.5-3.65	3.38
Performance Ratio (PR)	Up to 10	Up to 16	Up to 10	NA	Up to 5	Up to 20
GOR	9-10	12-14	8-14	NA		20 - 22
Cost of water ($\$/m^3$)	0.52-1.01	1.12-1.50	0.56-1.75	0.26-0.54	1.17-2.0	<0.48
Technology growth trend	High	High	Moderate	High	R&D	R&D
Environmental impact and water quality 42, 107, 113, 116-118, 199, 213						
Environmental impact	Discharge is 10–15°C hotter than ambient, TDS increase of 15–20%	Discharge is 10–15°C hotter than ambient, TDS increase of 15–20%	Discharge is 10–15°C hotter than ambient, TDS increase of 15–20%	Brine discharge at ambient temperature, TDS increase of 50–80%	Discharge is 10–15°C hotter than ambient, TDS increase of 15–20%	Discharge is 10–15°C hotter than ambient, TDS increase of 20–30%
CO_2 emission (kg/m^3)	7.0 – 17.6	7.0 – 17.6	15.6 – 25.0	1.7 – 2.8	7.0 – 17.6	5.0 – 10.0
CO2 abatement ($\$/m^3$)	0.18 – 0.35	0.18 – 0.35	0.31 – 0.50	-	0.18 – 0.35	0.18 – 0.35
Recovery rate (%)	15-50%	15-50%	15-50%	30-50%	60-80%	60-80%
Product water (ppm)	<10	<10	<10	<500	<10	<10
Others factors 209-211						
Ton of seawater required per ton of water production	5-8	5-8	8-10	2-4	5-8	4-5
Footprint $M^2/m^3/hr$	6.5-7.0	4.5-5.0	4.5-5.0	3.5-5.5		4.5-5.0
Shut-down for maintenance	1/every 2-year	1/every 2-year	1/every 2-year	>4/year		1/every 2-year
Availability	96-98%	96-98%	96-98%	92-96%		96-98%
Plant life (years)	15-25	15-25	25-40	10-15		15-25
*MEDAD hybrid cycle values are estimated on the basis of $10m^3$/day pilot installed in KAUST, Saudi Arabia [78]						

Table 2: Jubail CCGT and desalination plant brine impact on parameters of marine environment [48].

Parameters	Sampling Zones			
	Intake bay	**Open sea**	**Outfall mixing bay**	**Recovery zone (1km)**
Sea surface temperature (ºC)				
Winter	17.90±0.85	17.80±1.06	27.30±2.47	20.50±4.95
Spring	24.42±5.10	24.00±4.09	33.08±4.06	25.91±5.59
Summer	30.25±0.35	30.75±1.06	37.25±0.35	34.38±3.71
Fall	27.00±1.41	27.00±1.41	34.50±0.75	30.00±2.82
Conductivity (ms/cm)				
Winter	57.28±4.70	57.58±5.90	67.33±1.23	60.15±6.15
Spring	58.83±1.33	59.56±3.11	65.55±2.65	61.21±1.62
Summer	63.85±1.77	63.73±1.66	69.53±2.65	68.58±3.57
Fall	61.15±1.49	61.60±0.00	67.40±4.53	64.43±1.66
PH				
Winter	8.36±0.00	8.38±0.02	8.39±0.02	8.39±0.00
Spring	8.29±0.06	8.31±0.06	8.32±0.05	8.31±0.05
Summer	8.34±0.06	8.35±0.06	8.34±0.04	8.34±0.06
Fall	8.60±0.22	8.61±0.21	8.63±0.24	8.67±0.17
Dissolved Oxygen (mg/L)				
Winter	6.88±0.56	6.98±0.41	6.36±0.61	6.65±0.00
Spring	6.66±0.52	6.85±0.79	6.18±0.49	6.27±0.54
Summer	5.24±0.68	5.46±0.27	5.34±0.44	5.17±0.29
Fall	5.22±1.09	4.89±0.69	4.86±0.45	5.17±0.00

It can be seen that conventional desalination processes have severe environmental impact in terms of seawater temperature, PH and concentration increase. The reject increase seawater temperature increase from 3-4°C and concentration up to 50% at outfall bay.

The differences in specific energy consumption, as presented in Table 1, can be attributed to many factors such as (i) difference in fuel cost, (ii) site specific cogeneration plant efficiency and (ii) methods of calculation. The method of calculation has major impact on specific energy consumption and PR calculation. The conventional definition of PR have misconception due to different grade of energies (thermal and electric) incorporating in calculation directly and treating them similar since they have same units as Watt. The PR definition must be based on primary energy (pe), not on derived energies, to compare different desalination processes at same level. The improved PR definition is proposed as discussed in following sections.

4. Re-Defining the Performance Ratio

Conventionally, the method of PR calculation is based on derived energies such as thermal and electricity without distinguishing the grade/quality of energy as presented in Equation 1. Since derived energies are involved their generation efficiencies, so considering these derived energies directly in PR calculation may gave distorted view of practical PR. For meaningful comparison of different desalination processes, PR must be defined on primary energy basis. The accurate conversion of derived energy to the primary energy input at cogeneration plants is the key for having an equitable platform for comparing the efficacy of all desalination methods and input fuel cost apportionment. The derived energies can be converted to primary energy by considering their conversion efficiencies i.e. boiler for steam and power plant for electricity.

$$PR = \left(\frac{\begin{array}{c} Equivalent\ heat\ of\ evaporation \\ of\ distillate\ production \end{array}}{Energy\ input} \right) \cong \frac{2326 \left\{ \frac{kJ}{kg} \right\}}{3.6\ x \left[\left\{ \frac{kWh_{elec}}{m^3} \right\} + \left\{ \frac{kWh_{ther}}{m^3} \right\} + \left\{ \frac{kWh_{Renewable}}{m^3} \right\} \right]} \tag{1}$$

In view of the imbalanced exergy destruction in cogeneration processes, researchers [215] proposed to convert all derived energies to primary energy using appropriate conversion factors to calculate universal performance ratio (UPR) as presented in Equation 2. The proposed revised UPR gives a fair platform for cross-comparison of all desalination technologies without any distortions from the ad-hoc conversion efficiencies.

$$UPR \cong \frac{2326 \left\{ \frac{kJ}{kg} \right\}}{3.6\ x \left[\left\{ \frac{kWh_{elec}}{m^3} \right\} CF1 + \left\{ \frac{kWh_{ther}}{m^3} \right\} CF2 + \left\{ \frac{kWh_{Renewable}}{m^3} \right\} CF3 \right]}$$
$$CF = conversion\ factor$$
$$1 = electrical, 2 = thermal\ and\ 3 = renewable \tag{2}$$

A cogeneration plant analysis [215] showed that the average exergy consumed by gas turbine cycle (GT) amounts to 73.17% of the total fuel exergy at input, whilst product gases containing remaining 26.83% of exergy are supplied to heat recovery steam generator (HRSG) to produce high temperature and pressure steam at the expense of minor exergy loss due to exhausted of flue gas. Steam turbines (HP, MP and LP turbines) consuming about 23.43% of total fuel exergy and only the remaining 3.4% of total fuel exergy input is consumed by the MED for potable water production. Based on these conversion factors, the derived energies are converted into primary energy to calculate UPR as presented in Table 3. Despite the seemingly high values of UPRs, all desalination methods available hitherto are operated far remote from the ideal or thermodynamic limit (TL) of 0.78 kWh_{pe} /m^3. Presently, these desalting processes are operating from 10-15% of TL where the UPR at TL is 828. These lower value of conventional desalination technologies shows that these are not sustainable for future water supplies. For future sustainable desalination, conventional processes need to improve for higher efficiency or need to investigate alternate energy sources such as renewable energy sources. High efficiency desalination processes integrated with renewable energy sources can be best choice for future water supplies.

Table 3: Summary of derived energies, conversion factors, primary energy and UPR of different desalination processes [215].

Desalination technology	Electrical energy consumption	Thermal energy consumption	Conversion factor for electricity	Conversion factor for thermal energy	Primary energy	UPR	UPR percentage of TL (UPR at TL=828)
	(kWh_{elec})	(kWh_{ther})	(57.2%) CF1= 0.572	(3.4%) CF2= 29.4	(kWh_{pe})		
SWRO	3.5	NA			6.11	105.74	12.8%
MED	2.3	71.7	0.572	29.4	4.02+2.43 =6.45	100.17	12.1%
MSF	3.0	80.6			5.24+2.74 =7.98	80.97	9.8%

$* TL = \frac{2326\ kJ/kg}{2.8\ kJ/kg} = 828, \quad \left[\frac{0.78\ kWh}{m^2} = \frac{2.8\ kJ}{kg}\right]$

5. Desalination with Renewable Energy: An Alternate Choice?

Conventional fossil fuel driven desalination technologies will have large environmental impacts by 2050 in terms of volume of brine rejection and environmental emissions. With current trend, brine rejection will increase to 240 km^3 and emission will be approximately 400 million tons of carbon equivalents per year [216-218]. Coupling the desalination technologies with renewable energy sources have potential to supply sustainable fresh water for future demand. The three major benefits that World will reap by renewable desalination processes are (i) environmental sustainability, (ii) future fresh water sustainability and (iii) energy sustainability [216]. Currently, 131 renewable-powered desalination plants producing only 1% of the world's desalinated water. In renewable energy utilization, solar photovoltaic (PV) is leading with 43% followed by solar thermal 27%, wind 20% and hybrid 10% [219, 220]. The only drawback with PV utilization is the availability and area required for installation. As a rule of thumb, to operate a small RO plant of capacity 1 m^3 /day (with a total specific energy consumption of 8 kWh/m^3), PV installation require 26.5-28 m^2 area based on electricity rating of 110-120 kWh/m^2 .year. PV-SWRO have advantages of continuous operation if they are integrate with cogeneration plants grid. Since solar energy is intermittent, so PV can supply power to cogeneration plants grid at day time and at night SWRO will be operated by tapping power from cogeneration plants grid. In 2015, Advanced Water

Technology (AWT), Saudi Arabia started installation of World largest PV-SWRO plant at Al-Khafji. This $130m project is expected to be completed by 2017 and it will produce 60,000m3/day. Typical costs for renewable energy operated desalination processes ranges from 2.0-32.0$/m-depending on size of plant, technology and renewable energy potential. Figure 7 illustrates the development stage, typical capacity and cost of different desalination technologies based on different renewable energy sources [221, 222].

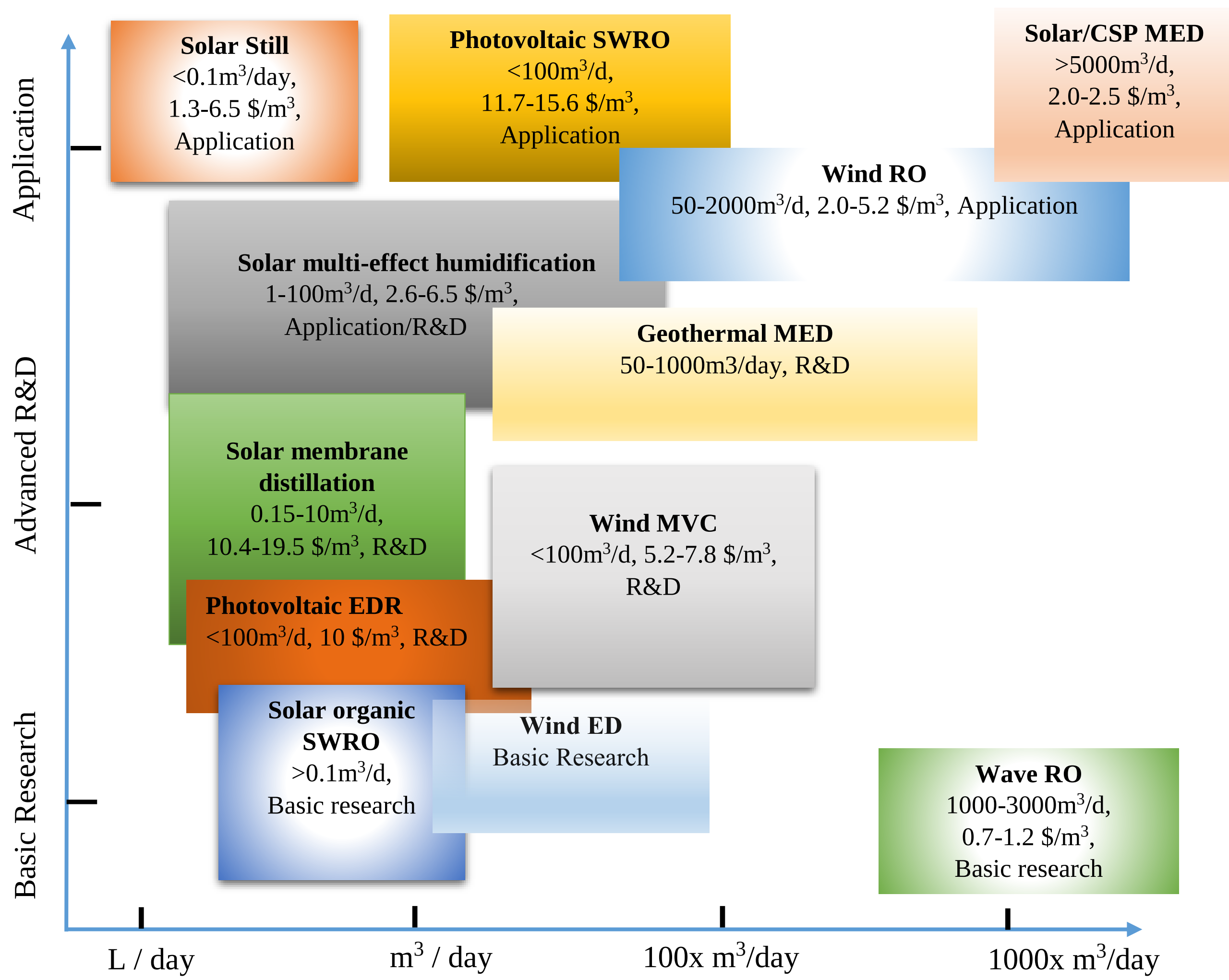

Figure 7: Renewable energy operated desalination technologies status: Capacity, production cost & technology trend.

The examples of commissioned renewable energy operated desalination plants are; (i) wind energy operated RO Kwinana desalination Plant in south of Perth in Australia. Total 48 number of turbines producing 80MW to operate RO consuming 26MW. This wind operated RO was opened in April 2007 and was the first of its kind in Australia [223], (ii) low temperature thermal desalination cycle operating with ocean thermocline energy has been implemented in Hawaii (USA) and Karavatti (India) to supply water to remote Islands [224-226], (iii) IBM currently working on membrane distillation (MD) operated with CPV heat. Their results shows that high concentration photoVoltaic thermal (HCPVT) system can achieve 90°C to operate MD with production capacity of 30-40 liter water per square meter of receiver area per day [227]. Similarly, there are many other RO plants operated by wind energy as summarized in Table 4 [228].

Table 4: Wing energy operated RO plants in the World [228]

Plant location	Commissioning year	Capacity (m3/day)	Wing turbine capacity (MW)
De Planier, France	1983	12	4
Fuerteventura Island	1995	56	225
Therasia island, Greece	1997	19.2	15
Crest, UK	2003	12	2.5

6. Future Energy and Environment Sustainability Roadmap

The conventional desalination technologies are not decent solution for sustainable future water supplies as they are operating at very low efficiency, 10-15% of their thermodynamic limit. To achieve the goal of COP21, desalination processes need to improve their efficiencies up to 25-30% of thermodynamic limit. Scientists are developing new materials for RO processes to increase flux and improved processes (hybridization) of thermally driven MED/MSF technologies for high efficiency.

6.1- RO Processes Future Roadmap:

Presently, membrane processes consume 3-5kWh/m^3 but the drive to achieve future sustainable water supply goal demands membranes with high flux, selectivity, fouling resistance and stability with minimum cost and manufacturing defects. The variety of efficient materials have been proposed to improve the performance of conventional ceramic and polymeric based membrane [229, 230] such as: (i) catalytic nanoparticle coated ceramic membranes, (ii) zeolitic, (iii) inorganic–organic hybrid nanocomposite membranes and (iv) bio-inspired membranes that includes protein– polymer hybrid biomimetic membranes, isoporous block copolymer membranes and aligned nanotube membranes. In terms of performance and commercialization, bio-inspired membranes are highest in performance but farthest (5-10 years) from commercial reality. However, nanocomposite membranes are commercially available with significant performance improvement [231]. These innovative materials will not only help to save energy but also to protect environment to achieve sustainable desalination goal.

Aquaporin membranes were proposed by Agre et al. and they won a Nobel Prize for this discovery in 1993 [232]. Aquaporins are the protein channels that control water flux across biological membranes and transfer water molecules at rates of 2–8 x10^9 molecules per second. RO membrane with 75% coverage of aquaporins increase permeability to 2.5x10^{-11} m Pa^{-1} s^{-1}, an order of magnitude higher than commercial seawater RO membranes [233]. Presently, aquaporin-based membranes are not commercially available due to material unavailability and technological limitation to produce large protein area but it shows the potential for incorporation of biological aquaporins into pressure-driven RO membranes in the future [234]. Further research is needed in future to optimize the formation of biological structures in terms of selectivity, robustness, material cost, scalability and specific energy consumption of RO processes, less than 2kWh/m^2.

6.2- Thermal Processes Future Roadmap:

Thermally driven processes MSF/MED have lower performance because of their processes limitations. In MED processes, top brine temperature (TBT) is limited at 70 ^oC due to soft scaling components such as magnesium (Mg^{++}), calcium (Ca^{++}), and sulfate (SO_4^{-2}) ions in the feed that contribute in system degradation at high TBT typically more than 70^oC. As a solution, researchers found that these scaling agents can be suppressed by pre-treating the feed through nano filtration (NF) or anti-scalant dosing and TBT can be raised to 130^oC [126, 235]. The last stage operating temperature limitations, 40^oC, can be overcome by adsorption cycle hybridization that can operate below ambient conditions typically as low as 10^oC [75-79, 236]. This tri-hybrid desalination cycle, NF+MED+AD, can operate from heat source temperature 130^oC to last stage temperature 10^oC with more than 20 number of effects and hence the UPR=250, over 20% of TL. The other hybrid combinations such as NF+RO+MSF, NF+MSF+MED were also proposed for higher performance and maximum thermodynamic synergy [95, 96]. In terms of robustness and commercialization, all individual technologies (NF, MED, MSF & AD) are well proven and readily available in the market. Today, thermally driven technologies are available on the shelf to achieve COP21 goal for sustainable water supplies.

Figure 8 shows the conventional desalination technologies performance from last three decades. It also shows that high performance membranes may need 5-10 years to achieve sustainable desalination goal but thermally driven desalination technologies are readily available

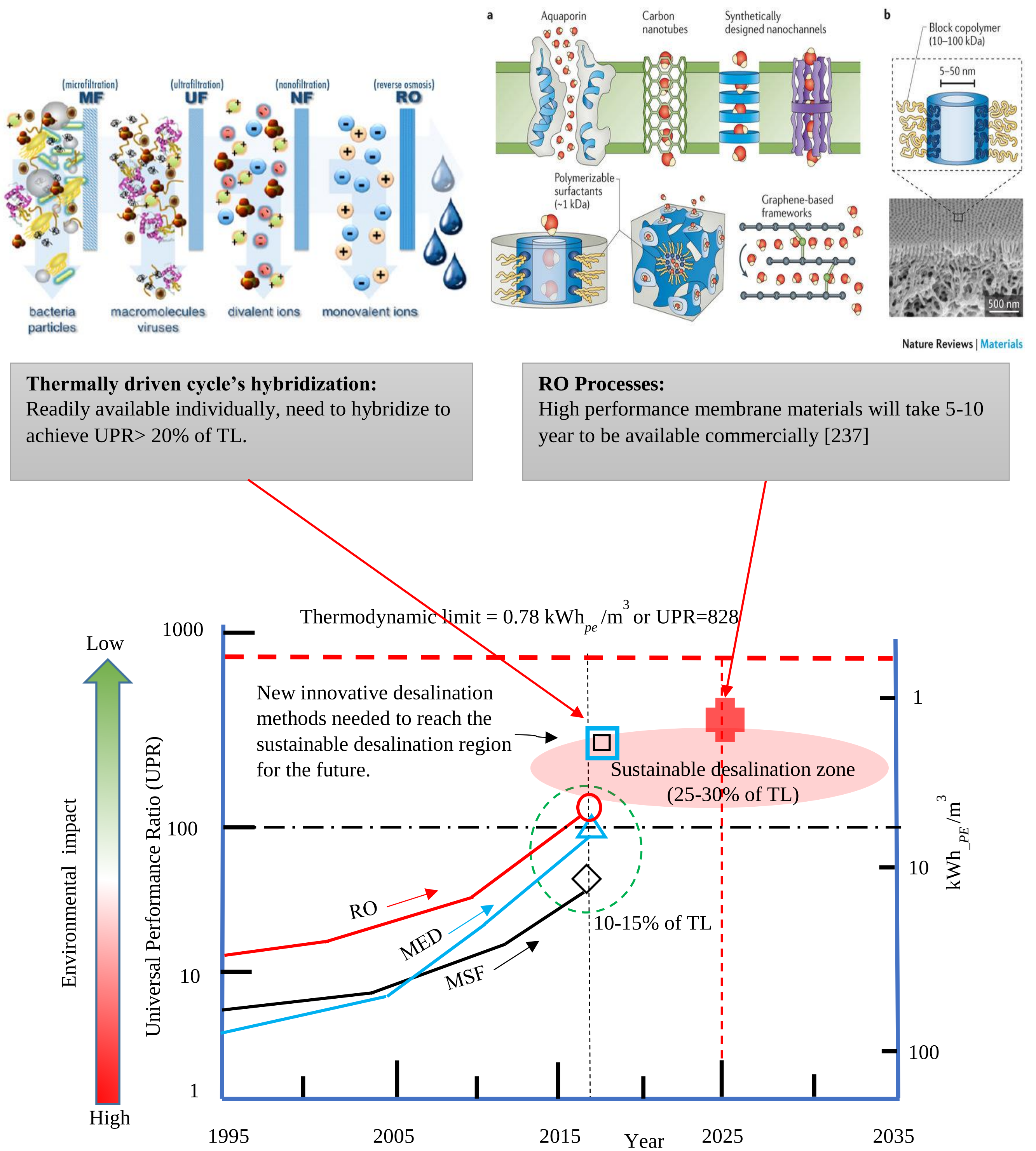

Figure 8: Desalination technologies roadmap for future sustainability.

Conclusions

In 2010, 15% of global fresh water was consumed for power generation that was produced by desalination processes at an expense of 75.4TWh energy and 76 million ton of carbon emission. The current energy intensive desalination processes, with 10-15% efficiency, are not sustainable for future water supplies. For future sustainability, innovative membrane materials are proposed but they need 5-10 years intensive research to produce commercially. On the other hand, thermally driven desalination technologies hybridization can achieve 20-25% of efficiency, close to sustainable production zone, in 1-2 year experience. These innovative solutions will help to save energy and protect environment. Further research is needed to develop more innovative sustainable desalination solutions to achieve COP21 goal.

Nomenclature

GDP	Gross domestic product
CCGT	combined-cycle gas turbine
MWh	Megawatt hour
TWh	Terawatt hour
Mt	Million ton
Gt	Giga ton
WHO	World health organization
RO	Reverse osmosis
SWRO	Seawater reverse osmosis
MED	Multi effect desalination
TVC	Thermal vapor compressor
MSF	Multi stage flash
MD	Membrane distillation
FO	Forward osmosis
HDH	Humidification dehumidification
AD	adsorption desalination
UF	Ultra filtration
NF	Nano filtration
IF	Ionic filtration
CAPEX	Capital expenditure
OPEX	Operational expenditure
TBT	Top brine temperature
MJ	Mega joule
IWPP	Independent water and power plant
PR	Performance ratio
GOR	Gain output ratio
SWCC	Saline water conversion cooperation
Mm^3	Million cubic meter
GT	Gas turbine
HP-ST	High-pressure steam turbine
HRSG	Heat-recovery steam generator
LP-ST	Low-pressure steam turbine
MP-ST	Medium-pressure steam turbine

PPM	Parts per missions
PE/Pe	Primary energy
TL	Thermodynamic limit
CF	Conversion factor
PV	Photovoltaic

Subscripts

Ther	Thermal
Elec	Electrical
Pe/PE	Primary

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