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Nuclear Desalination: A State-of-the-Art Review

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Abstract

Thermal desalination is an energy intensive process that satisfies its requirement from conventional fossil fuel sources. Current research efforts aim at finding alternatives for fossil fuels to power thermal desalination. Nuclear energy offers a feasible option for power cogeneration and production of fresh water due to the significant amount of recovered useful heat. The heat is exploited to produce steam and generate electricity on-site to power thermal and membrane desalination facilities. Large or small/medium nuclear reactors (SMR) can be used. This paper reviews the various aspects of nuclear desalination, the different nuclear reactors that have been coupled with desalination processes, and the hybrid desalination systems coupled with nuclear reactors. It also discusses the safety and public acceptance for the nuclear desalination practices as well as the latest economic studies and assessments for on –site nuclear desalination power plants. Ten main projects around the world are primarily operated as nuclear desalination plants. The major desalination processes coupled with nuclear SMRs are MSF, MED and RO. The cost of water production using nuclear desalination was estimated to range from 0.4 \$/m³ to 1.8 \$/m³ depending on the type of reactor and the desalination process used.

Keywords: Nuclear desalination, SMR in desalination, Nuclear power plant, techno-economic analysis, safety analysis.

Highlights

- ▣ The latest advances and technical features of nuclear desalination plants are reviewed
- ▣ Nuclear SMR reactors are promising for powering large scale desalination plants
- ▣ The hybrid nuclear systems offer a promising alternative for power cogeneration and fresh water production

- ▣ Techno-economic analysis of various nuclear desalination systems provide great potential
- ▣ The safety of nuclear desalination systems can be enhanced by reinforcing engineering design

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1. Introduction

The implementation of desalination technologies is becoming one of the practical solutions to meet the increase in fresh water demand in many regions around the world. Water desalination industry has been expanding dramatically since the 1950s. A significant increase in capacity observed in the gulf countries, Caribbean region and in southern California [1,2]. Conventional desalination technologies rely heavily on energy obtained from fossil fuels, which eventually leads to pollution and global warming. In principle, desalination processes are divided into two main categories: thermal and non-thermal processes (membrane processes) [3]. The main thermal processes include: multi stage flash (MSF), vapor compression (VC) and multi-effect distillation (MED), while reverse osmosis (RO), forward osmosis (FO) and electro-dialysis (ED) are classified among the membrane desalination processes [3–6]. The most commonly practiced processes are MSF and RO. In terms of global capacity, RO accounts for 63% and MSF accounts 23% [2].

A substantial reduction in the cost of the desalinated water has been achieved over the last decades. However, many factors still play a significant role in determining the cost of desalinated water. These factors include the type of technology used, plant size, geographical location, plant capacity, pretreatment requirements, quality of feed water and power cost. While considering the following factors: 1) the cost of energy, 2) sustainability of conventional energy sources, 3) the effect of fossil fuels on the environment and 4) the fluctuations of fossil fuel prices, it appears that there is a merit to find alternative energy sources to power desalination processes. Some desalination processes require thermal energy such as MSF and MED, while membrane technologies such as RO or forward osmosis (FO) for example require electricity. Hence, extensive research efforts are in progress to explore alternative energy sources in desalination such as solar, geothermal and nuclear energy [6].

Nuclear desalination appears to be a feasible and a promising option to power desalination plants at reasonable costs [7]. It is the production of fresh/drinkable water from seawater in a nuclear power plant. The amount of energy evolved can be utilized to power thermal desalination processes as well as running a cogeneration system to produce electricity [8–10]. The use of nuclear energy in desalination has been extensively studied by the International Atomic Energy Agency (IAEA) since the 1960s [11,12]. Since then, the IAEA have been actively leading surveys on the feasibility of integrating nuclear energy into desalination. Multiple IAEA reports were published [13–16].

The results showed several attractive features for nuclear desalination including the protection of environment by minimizing the greenhouse gas emissions, the eventual conservation of traditional energy sources (fossil fuels) and the economic feasibility in remote areas where fossil fuels are not available. The results also provided a general understanding for this technology and built more technical confidence in its implementation.

The number of studies concerned with nuclear desalination that have been reported in the literature is increasing. It is therefore the objective of this paper to provide a comprehensive overview of the most recent studies on the various aspects of nuclear desalination. It is also aimed at evaluating the current hybrid trends in desalination, and the future research activities. The assessment of economic impact and safety concerns is also presented in this context.

2. Nuclear Energy

Fossil fuels have been the dominant source of energy for the past 100 years in both industrialized and developed countries with a contribution of 81% [17]. However, there has been a change in energy consumption rate over the last 15 years with a heavy investment in renewable and sustainable energy sources [18]. For many countries, the energy supply security has been the main concern especially for those that import oil. This triggered several research efforts to find alternative cheap, stable and clean energy sources [19]. Nuclear power in particular received a considerable attention. The potential of less expensive nuclear fuel costs was the main motive in nuclear power plant constructions between 1970s and 1980s especially following the oil crisis in 1970s [18]. Many countries around the globe have nuclear power plants. Examples are Japan, Kazakhstan and in the Middle East [20]. As of 2016, a total of 441 nuclear reactors were operated in more than 30 countries with a total capacity of 382.9 GW(e) [(giga-watt (electrical)) [21]. Among these, 68 reactors are still under construction; 45 of which are in Asia alone, with a total capacity of 67.4 GW(e) [21]. Recent studies indicated that global nuclear power capacity will reach 511 GW (e) in 2030, compared to a capacity of around 370 GW(e) in 2009 [22]. This is triggered by the need to increase the required energy supply, expand fuel sources, minimize the dependence on non-renewable energy sources as well as the dependence on oil imports. These factors come in parallel with the several environmental concerns raised from the excessive use of fossil fuels as primary energy sources such as climate change, greenhouse effect and air pollution [23]. According to the IAEA's report in 2012, the global energy demand would increase by around one-

third by 2035 [24]. As per the World Energy Council assessments conducted in 2016, the identified Uranium resources have increased by around 70% over the last ten years, which would provide enough energy supply for more than 100 years based on the current consumption rates [18].

The generation of electricity from nuclear energy has been increasing over the past three decades with 14% of the total electricity generated in 2009 and around 18.9 % in 2016 [9,21,22]. Electricity generation using nuclear power depends on four major aspects: capital costs, operation & maintenance costs, fuel costs and back-end costs. These aspects are related to end-of-life plant decommissioning and disposal. Assessments and sensitivity analyses related to the electricity generation have been conducted and showed that the electricity generated through nuclear power is the lowest-cost electricity supply option in many markets due to the low fuel costs [25]. Fig. 1 and 2 below summarize the results of this study. The analyses reported the different fuels prices and electricity generation costs [25]. As can be clearly seen from figures 1&2, the electricity generated through nuclear power plants has achieved the lowest cost among the all the alternatives considered. The study also found that the cost of nuclear electricity is insensitive to the changes of nuclear fuel price.

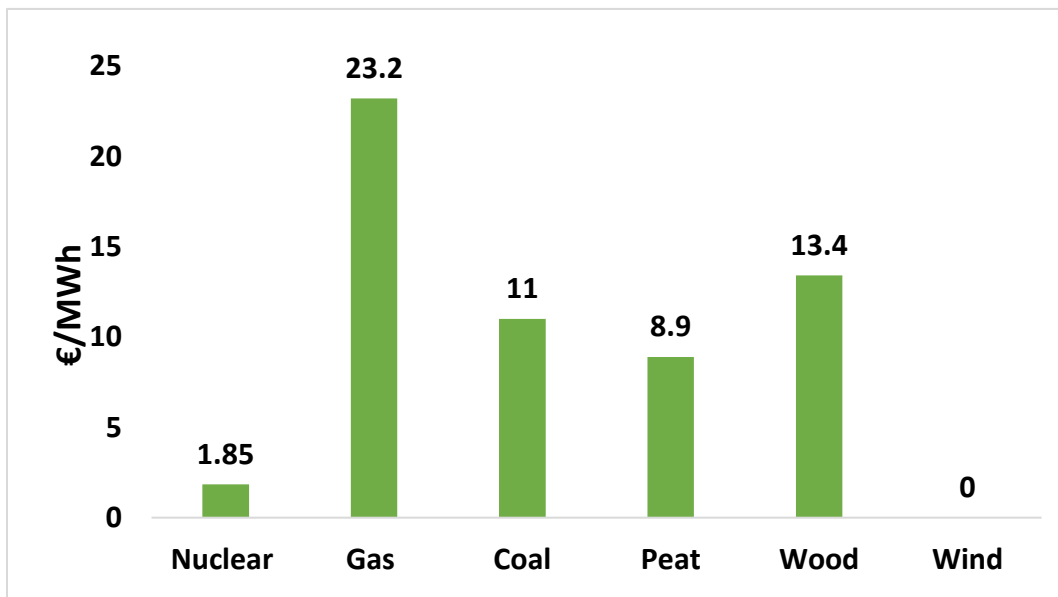


Fig. 1: Estimated cost of various fuel prices [25]

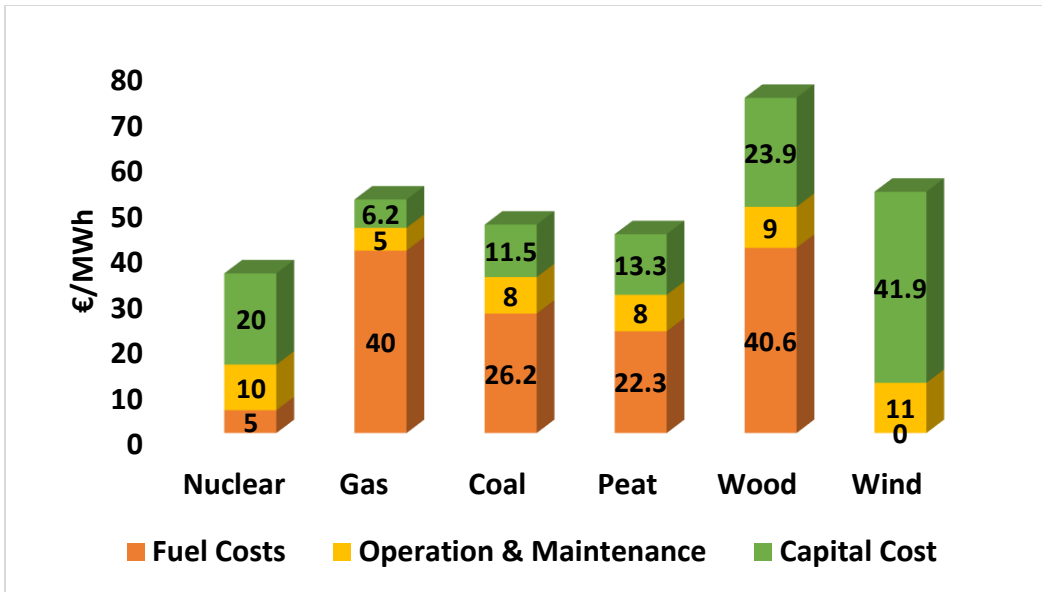


Fig. 2: Comparison of the estimated electricity generation costs [25]

Globally, and according the IAEA data, the nuclear power generation is expected to increase in the coming decades along with the applied policies toward the reduction in carbon dioxide emissions. In USA for example, the Environmental Protection Agency (EPA) aims at a reduction of 32% in greenhouse emissions by the year 2013, hence, suggesting the preservation of existing nuclear power plants [26]. China aims at increasing the production of energy from non-fossil sources by 20% in 2030, and by the end of 2017 china have constructed additional 37 nuclear facilities [27]. Fig. 3 shows the global nuclear electricity in TWh in the past decades and up to 2015. It can be clearly seen that, generally, there is an increase in global production. Based on these numbers, it is apparent that nuclear power has become a promising option for the production of clean energy.

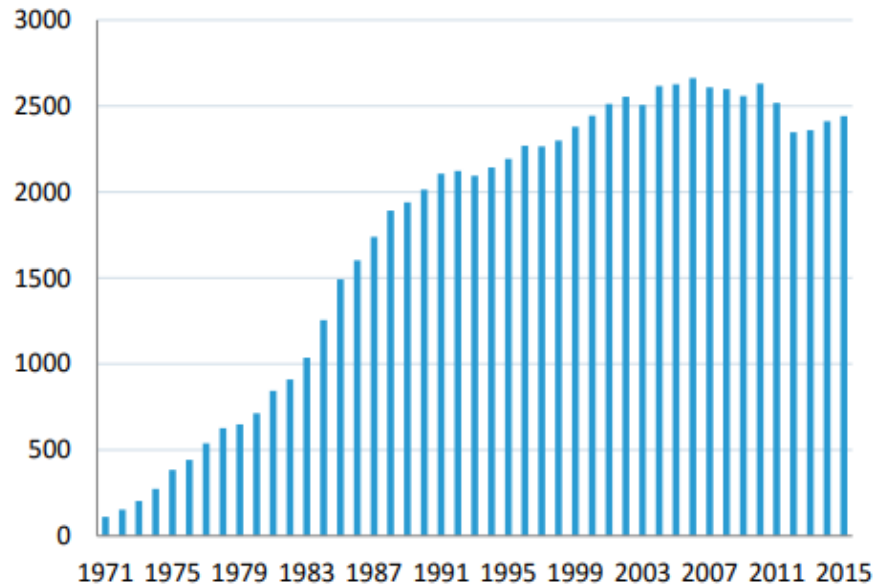


Fig. 3: World nuclear electricity production, TWh [18]

3. Nuclear Power Reactors

As of 2016, energy production from all of the operating nuclear power plants utilizes the process of nuclear fission [28]. During the nuclear fission, huge energy is released due to the split of the heavy atomic nuclei split apart in order to form lighter atomic nuclei. These atomic nuclei are characterized by their mass numbers, atomic numbers, and number of emitted neutrons as well as the γ -rays that are linked to the excitation of the primary nuclei. The role of nuclear reactors is to convert the resultant thermal energy into electricity [28,29]. Different nuclear reactor configurations are currently in use around the world. Based on their historic development, they are classified into generations. The following are the main types: pressurized water reactor (PWR), boiling water reactor (BWR), pressurized heavy water reactor (PHWR), gas-cooled reactor (GCR), advanced gas-cooled reactor (AGRs), light water (cooled) graphite (moderated) reactor (LWGR), fast breeder reactors (FBR), high temperature gas-cooled reactors (HTGRs) and liquid metal cooled fast reactor (LMFR) [30]. Fig. 4 below shows the different generations of nuclear reactors along with the time line developments [31]. Currently, there are around 441 nuclear reactors around the world. PWR reactors constitute around 68% , BWR reactors constitute for about 20%, PHWR reactors constitute around 6% and the rest is devoted to GCR, LWGR and FBR [7].

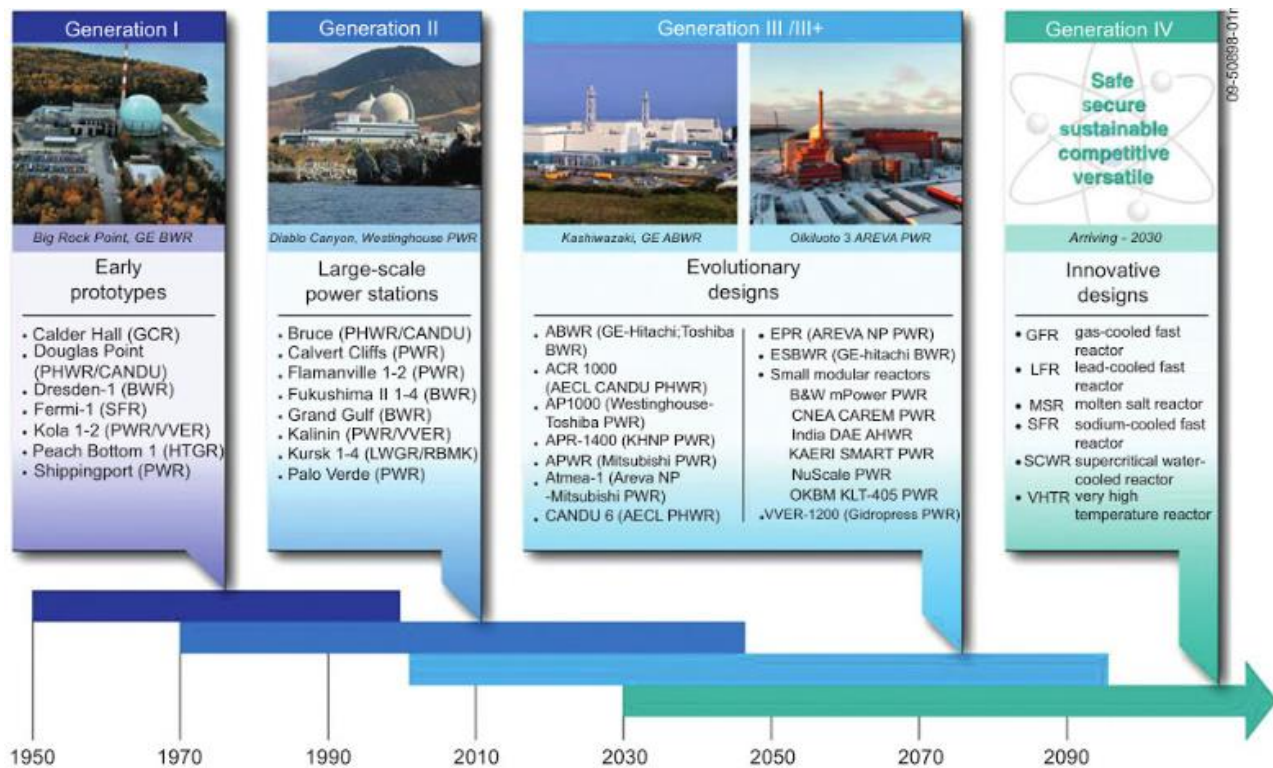


Fig. 4. Types and generations of nuclear reactors [31]

Many other reactor technologies and configurations are currently being developed due to the significant population growth. The small modular reactors (SMRs) and the fast neutron reactors are considered as the most promising technology for the near future [32]. SMRs are defined as advanced nuclear reactors that are able to produce electric power of up to about 300 MW(e) [32]. These reactors are considered most feasible because they can be fabricated then transported into the facility. They are characterized by the ease and speed of assembly, where such reactors can be moved and installed as per the facilities energy requirements. Huge investments in building and designing SMRs has been noted recently in many countries worldwide including USA, Russia, France, India, Japan, South Korea, Argentina, China and Italy [33].

Nuclear power is currently recognized as an energy source (both electrical and thermal) to seawater desalination, hydrogen production and many other applications. It is a reliable and efficient source of energy. As a global overview [34], there is a general agreement that utilizing nuclear power in desalination is practical and economically profitable. In the following sections, an overview for the desalination technologies is presented as well as the several nuclear reactors commonly used with desalination.

4. Desalination Technologies

Seawater desalination can be classified according to the source of energy used as thermal, mechanical, chemical and electrical [35]. In this section, an overview for the current desalination technologies in use will be presented with the focus on the sources of energy used. The following categories will be highlighted as per the latest available literature [20,35–38]:

- Thermal-based Technologies
- Membrane based Technologies

4.1 Thermal-based Technologies

In the thermal-based desalination, fresh water is produced via a phase change process, i.e., using evaporation and condensation to separate the salts from water [39]. These processes are therefore characterized by the huge amount of energy required as heat. The conventional thermal desalination technologies discussed in this context are: the multiple effect distillation (MED) and the multi stage flash (MSF) desalination [40].

4.1.1 Multi-Stage Flash (MSF)

Multi-Stage Flash (MSF) desalination was introduced in the early 1950s [41]. It is based on the principle of distillation through multi-stage chambers where the pressure is suddenly reduced at each successive stage [42]. MSF is an energy intensive process [42,43]. It has experienced dramatic improvements in the past decades that resulted in a massive increase of its use with around 60% of the global desalination and almost 80% of desalination in the Middle East region [40,44]. MSF is characterized by its high reliability, well established technology, ease of operation, and the low performance degradation over the years of utilization [44,45]. Previously, the MSF plants were mainly used in the Middle East due to the availability of fuel and the difficulties faced in the operation of reverse osmosis (RO) plants [44]. Most of the available commercial MSF installations are designed with 10–30 stages where the temperature drop attained is 2°C per stage [46,47]. The conventional MSF system consists of a brine heater where the feed water is admitted and heated, flashing stages where the pressure is reduced, hence, rapid evaporation or flashing, vacuum ejector, chemical addition pumps (to control scaling and inhibit corrosion) and, feed screens [48]. A schematic diagram for a conventional MSF process is shown in Fig. 5 [41].

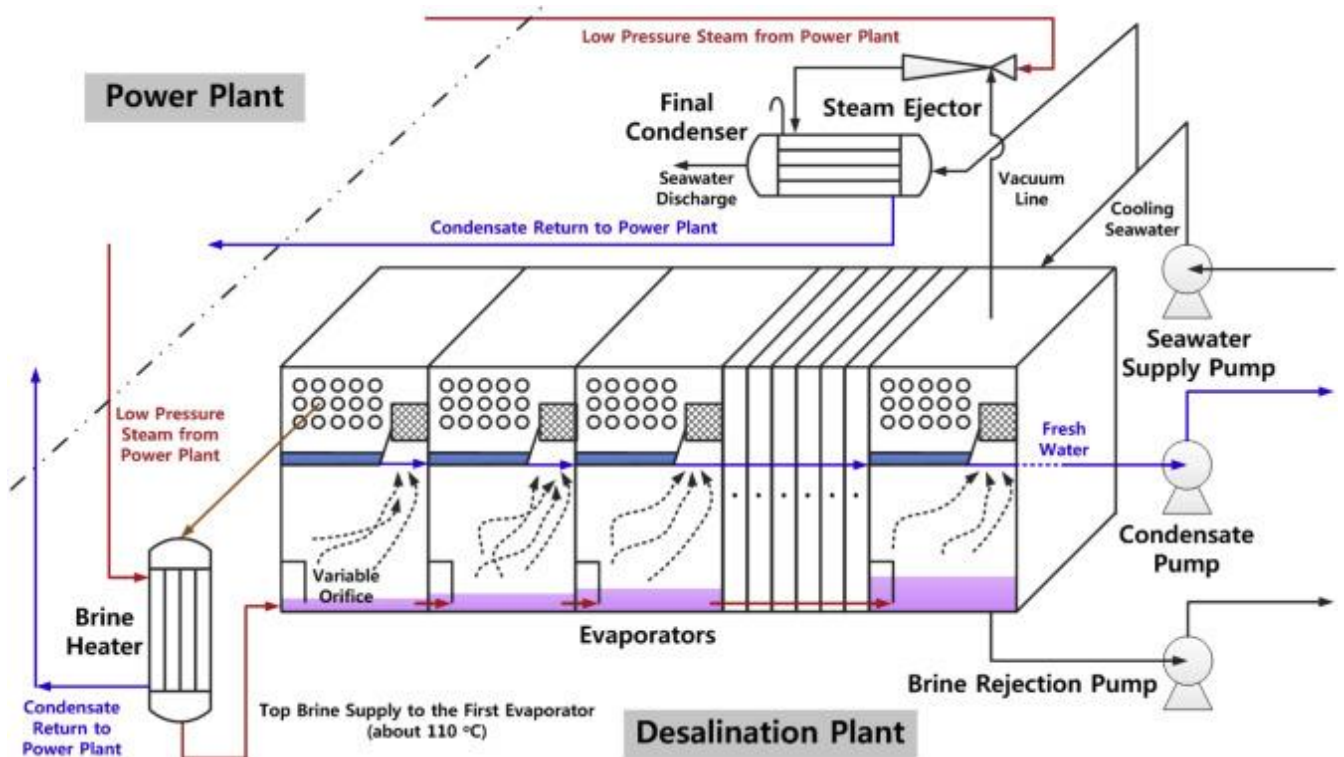


Fig. 5. A schematic diagram for a conventional MSF process [41].

Recent advances on MSF systems included the focus on two factors: 1) reducing the cost of MSF systems and, 2) integrating renewable energy sources. It appears that there is a significant decrease in the cost of water desalinated utilizing the MSF technology. Studies have shown that the cost of desalinated water via MSF have decreased by a factor of 10 since 1960 [44,49]. MSF systems where integrated with renewable energy sources such as solar collectors and geothermal source [50]. For example, a novel MSF process that used parabolic trough collectors (PTC) and a solar pond was recently described [51]. The integration of renewable energy sources in MSF was addresses in the literature; an example is the review of Abdelkareem et al. [6]. A mathematical model describing an MSF desalination unit with brine recirculation configuration coupled with nanofluid absorption solar collector as a heating source was studied [52]. Alsehli et al. [53] described a novel design for a solar powered multistage flash (MSF) desalination plant that uses a

group of solar collectors and a pair of thermal storage tanks. The brine was directly circulated through the solar collectors so that no heat exchanger and medium fluid are required [53]. The thermal performance of a high-capacity MSF desalination system was evaluated using three scale inhibitors including polymaleic, polyphosphonate and polycarboxylates, all of which were effective for both inhibiting alkaline scale formation and improving the top brine temperature [54]. The volatilization of boron in the MSF systems was also simulated [55]. The results showed that the boron concentrations reached in the simulated MSF process agree with the measured concentrations in the commercial MSF systems. Fouling dynamic models were developed to study the impact of calcium carbonate and magnesium hydroxide crystallization in the condenser tubes of a once-through desalination system [56].

4.1.2 Multiple Effect Distillation (MED)

Multiple Effect Distillation (MED) is among the oldest technologies practiced in desalination. MED system is composed of a number of preheaters, distillation units, and condensers [57]. In general, the evaporation process of sea water occurs at the surface of a tube bundles heated by the steam. The steam is condensing inside the tubes and the vapor generated in each effect is used in the subsequent effect. The steam experience a significant reduction at pressure and temperature [57]. MED plants are usually operated as a once-through system without a large quantity of brine re-circulating around the plant which in return reduces the plumbing requirement and the scale formation [46]. On the commercial scale, most of the MED plants are coupled thermal Vapor Compressors known as MED-TVC desalination. In this system, the evaporation in the first effect is driven through compressing part of the vapor at the last effect to the desired temperature either from a solar collector system or from a conventional boiler [40,47]. Some MED systems are coupled with the Mechanical vapor compression known as (MED/MVC) systems but not found in a wide scale in the industry [40,58].

Due to many operational problems such as scaling and the high capital/operating expenditures, the presence of the MED was limited compared to the MSF in the past decades [57,59], however, some studies showed that the MED processes may replace the MSF process in the near future because of the lower energy requirements [60–62]. MED technology have experienced several improvements during the past 10 years. These improvements include the significant increase in the capacity up to 22,700 m³/day, reduction in the tube scaling through proper design, and

improvement of the heat transfer with aluminum for surfaces [61,62]. Renewable energy sources were also investigated with MED such as direct solar energy, solar collectors, Photovoltaic thermal (PVT) collectors, solar ponds, and waste heat source [50]. A number of studies in the literature [63–65] have addressed solar MED processes in particular. For example, Sharaf et al. [63] compared solar power assisted MED-vapor compression (VC) systems. The results showed that the specific power consumption, solar field area and the thermo-economic cost could be reduced through reducing the compression ratio and increasing the number of evaporators. Hybrid MED plants as well as thermal-based desalination include other systems such as the vapor compression distillation (VC) were studied [66–69]. The results showed an increase in water production due to hybridization and vapor compression systems.

4.2 Membrane based technologies

Membrane based desalination is considered among the preferred processes for producing fresh water. This is due to several factors: it is efficient, easy to operate, with a high efficiency [70,71]. It is based on the use of semi-permeable membranes through which desalinated water can diffuse through (permeate) leaving the concentrated salt solution (retentate) behind under a driving force [70–72]. The main membrane-based desalination technologies that are currently in use are the following: reverse osmosis (RO), forward osmosis (FO), electro-dialysis (ED) nano-filtration (NF) and ultrafiltration [70]. Membrane desalination processes rely on electricity as the main source of energy. The membrane is defined as a thin porous film that allows the passage of water molecules and prevents the passage of other larger molecule such as salts, bacteria, metals and viruses as these cause biofouling [71]. Polymeric materials are usually used to fabricate the membranes. Examples of polymeric materials include acetate, cellulose, and nylon [71]. In the following section, the main membrane processes, reverse osmosis (RO), electrodialysis (ED) and membrane distillation (MD)) are discussed.

4.2.1 Reverse Osmosis

Reverse osmosis (RO) is a process that utilizes semi-permeable membranes to separate contaminants from feed water under the influence of osmotic pressure [72]. Generally, high pressures (50 – 80 bar) are required to overcome the osmotic pressure so that the water can pass through a unit area of membrane [72]. By far, RO is classified as the most energy efficient process

used for fresh water production with around 45% of the global desalination capacity [72]. Recent studies showed the suitability of RO systems for brackish water desalination purposes as they are capable of producing variety of water types; drinking water as well as agricultural water at a relatively lower cost [73,74]. The cost of water produced by membrane processes is usually around 1 USD/m³ depending on the source of energy. For example, if the membrane process is solar assisted, the cost reported is from 1-5 USD/m³ [51]. Current research efforts aim at evaluating the coupling of various renewable energy sources with RO to power the process [75]. Solar energy was investigated as a viable option to drive the pumps and/or produce electricity via the photovoltaic panels [47,75]. PVT collectors, wind energy can be also used as an energy source associated with the RO systems [50]. RO units driven by PV and thermal solar are currently available in many places with varied capacities that can go up to several hundred cubic meters per day [36]. Shalaby [76], provided a general design recommendation for a solar Rankine cycle (RC) powered RO systems. The thermodynamic cycle of a RO desalination membrane coupled with a thermal water pump was evaluated [77]. The performance of a photovoltaic/diesel/battery/reverse osmosis desalination hybrid energy system was optimized [78]. Wind was investigated as a possible renewable energy source to power RO desalination units [79–81]. The results showed that hybrid renewable energy system can decrease the cost of the system with enhanced reliability.

4.2.2 Electro-dialysis (ED)

Electro-dialysis (ED) is the transport of ions through a semi-permeable membrane under the driving force of potential difference [82]. ED has been used for brackish water desalination in different regions around the world [83]. The cation and anion exchange membranes are arranged in an alternating pattern in the ED cell. Cation exchange membranes allow only the passage of cations, whereas the anion exchange membranes allow the passage of anions. A schematic diagram for the process is show in Fig. 6 [82].

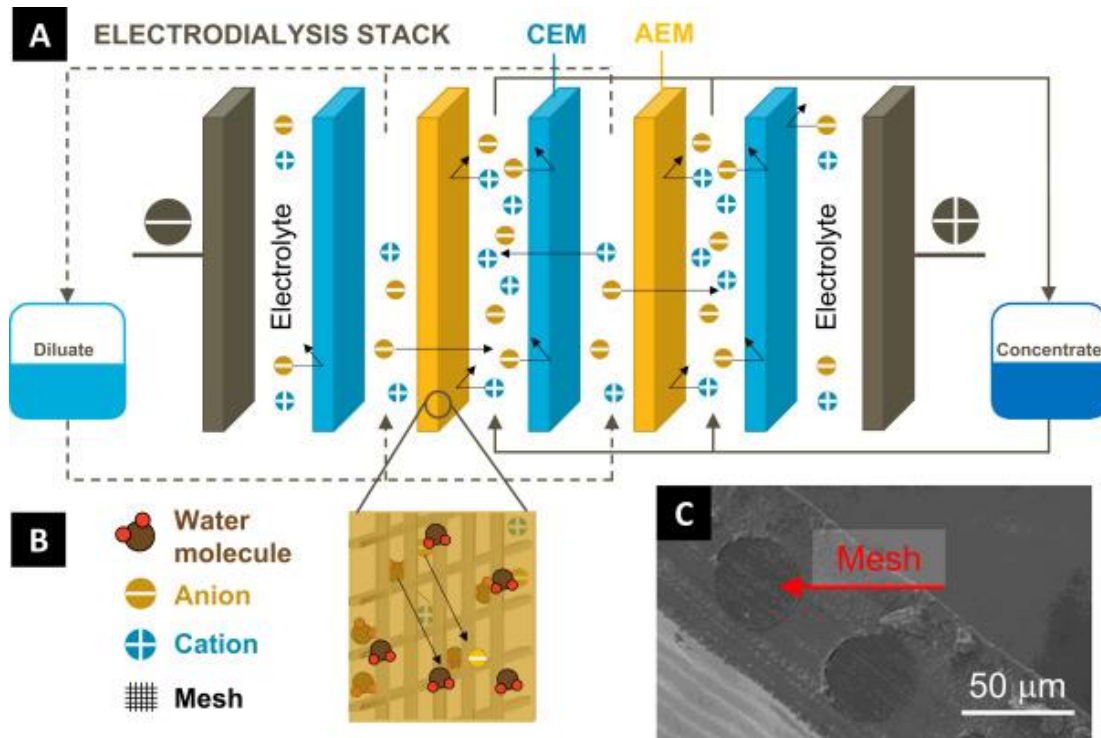


Fig. 6: Schematic diagram for the ED process [82].

This process removes the salt ions via applying a direct electric current (DC) where the saline feed water that contains salts are separated by moving towards the oppositely charged electrodes that are immersed in the electrolyte. Several studies were performed to investigate solar driven ED [84–88]. The results of these studies showed a promising cost reduction results.

4.2.3 Membrane distillation

Membrane Distillation (MD) is a thermally-driven process in which water molecules pass through a micro-porous hydrophobic membrane under vapor pressure difference [89]. Recent studies showed that MD possesses several advantages such as exploiting waste grade heat and producing high-quality water [90,91]. The improvement of the MD thermal efficiency was the subject of several studies in the literature [91–95]. Recent studies addressed the use of MD with thermal renewable sources such as solar and geothermal energy [96,97]. Banat et al. [96] explained the design and technical feasibility solar still integrated MD system for the production of potable water. Mericq et al. [97] presented a simulation study for different configurations of a solar-driven VMD system where solar ponds and solar collectors were used for the MD. The results indicated that the use of solar collectors could be promising as long as the water flux is maintained as high

as 142 L/m² h. Other studies have focused on producing drinking water via geothermal energy [98]. It indicated that a significant water cost (around 59%) can be achieved through the utilization of geothermal energy- driven vapor compression.

5. Aspects of Nuclear Desalination

Nuclear desalination is the process of producing fresh water using an on-site nuclear reactor [99]. Plant capacity and water quality are among the several factors that can significantly affect the energy demand in any desalination process [100]. The energy required to power desalination can be either thermal or electrical as previously stated in this context. Renewable sources such as geothermal and solar renewable energy sources can be used to drive MSF, RO and MED, however, they are integrated with smaller size plants [100]. Nuclear energy offers higher energy density compared to other conventional and renewable energy sources. With the continuous depletion of fossil fuels, continuous population growth, and the increase demand for fresh water, developing countries are currently in crucial need for the development of nuclear reactors. In developing countries, constructing large nuclear plants can impose a greater safety and economical risk due to the large space occupied by the plant. However, new technologies can solve some of these problems by building smaller size plants, produce hydrogen, generate electricity and produce fresh water by desalination on site [101]. For the past two decades, nuclear desalination have been officially recognized by IAEA as one of the most efficient and promising options for fresh water production and power generation [102]. Several research activities were initiated by the IAEA since the 1990's with nine state members [102]. They are called the coordinated research projects (CRP) and their aim is to investigate, assist improve and optimize nuclear desalination [102,103]. Additional objectives are to investigate the reliability, efficiency, cost analysis and safety of nuclear desalination. The studies offered sufficient data for future nuclear desalination systems and summarized the following substantial advantages for nuclear desalination processes [104]: 1) the possibility of harnessing useful amount of heat and invest it in thermal processes such as MED and MSF, 2) the development of an environmentally friend multi generation system, and 3) the reduction of the overall costs for the process along with the enhancement in plant efficiency. Globally speaking, the nuclear desalination systems fall into two major categories: nuclear desalination with power generation or, stand-alone nuclear desalination. In this section, a review for the various aspects and characteristics of nuclear desalination technologies is presented.

5.1 Types of nuclear reactors for desalination

The existing nuclear desalination plants around the world were established in the 1970's and they are located in Kazakhstan and in Japan [105]. Before the 1970's, research activities evaluated the possibility of nuclear desalination and showed its feasibility as well as its competency with other conventional energy sources [11,12,106,107]. In general, and according to the type of coolant used, there are two types of nuclear reactors that are used in desalination: light water reactors (LWR) and the heavy water reactors (HWR) [31]. LWR category also include boiling water reactors (BWR) and pressurized water reactors (PWR). Whereas, the HWR category include pressurized heavy water reactors (HPWR). There are other types such as the Liquid Metal Fast Breeder Reactor (LMFR) and high temperature gas cooled reactor (HTGR) [108]. In general, the water-cooled reactors are preferred because of the well-established technology. In the literature, Pressurized Water Reactor (PWR), Pressurized Heavy Water Reactor (PHWR), and Liquid Metal Fast Breeder Reactor (LMFR) are the most common nuclear reactors coupled with desalination processes [13,109].

The IAEA has classified the nuclear reactors based on their power output into three categories: "small" reactors if they have less than 300 MWe electrical output; medium if their electrical output is in between 300 and 700 MWe, and large reactors if their output is higher than 700 MWe [110]. The modern development of nuclear reactors for power generation is based on reactors from sizes 1100 to 1700 MWe [111]. The adoption of large scale reactors in desalination is currently feasible but several factors have to be evaluated first before operation such as safety and stability [105].

In theory, all types of nuclear reactors have the capability of providing the required energy for desalination processes [102]. However, the recent developments focused on investigating generation III nuclear reactors such as the AP1000 [112,113]. Alonso et al. [111] evaluated and compared the performance of two PWR nuclear reactors: one large reactor (called AP1000) versus a medium size reactor (called IRIS) combined with the following desalination processes: MSF, MED and RO. The results are summarized in Table 1. This study concluded the following: 1) water can be produced with the cogeneration of useful electricity and, 2) the use of the small reactor (IRIS) appeared to be more feasible due to cost

and versatility. The cost analysis will be discussed in subsequent sections of this paper. However, it is worth mentioning in here that generation III nuclear reactors suffer from a major drawback, i.e. the heavy development investment [114].

Table 1. PWR nuclear reactor coupled with various desalination processes [111]

Reactor type and desalination process	Net electricity produced (MW)	Net water production (m³/day)
AP1000 RO	957.25	1,100,000
AP1000 MSF	1568.83	1,000,000
AP1000 MED	1919.75	1,040,000
IRIS RO	1188.80	1,040,000
IRIS MSF	1028.08	1,000,000
IRIS MED	1348.50	1,100,000
IRIS MSF-RO	1180.80	1,040,000
IRIS ED-RO	1389.00	1,100,000

Dardour et al. [115] evaluated the performance of two nuclear reactors for desalination: gas turbine-modular helium cooled reactor (GT-MHR) and the pebble bed modular reactor (PBMR) reactor. The results showed that these two reactors are suitable for desalination, in particular when coupled with MED. Khalid et al. [116] performed a thermodynamic analysis for a gas turbine-modular helium reactor (GT-MHR) coupled with reverse osmosis (RO) process. The study assessed the amount of waste heat utilized in generating electricity and concluded that utilizing this heat has increased the exergy efficiency by 10%. Ahmed et al. [117] reviewed the small/medium (or modular) nuclear reactors (SMRs) in large scale desalination. The review compared the following nuclear reactors: pressurized water reactors (PWR), gas cooled reactors (GCR), heavy water reactors (HWR), boiling water reactors (BWR), and liquid metal fast breeder reactors (LMFBR) in terms of their technical features. The review addressed several advantages for SMR reactors in desalination including moderate space occupied, ease of construction into modules and in a short time, and their suitability for remote areas.

The status of the early established nuclear desalination processes around the world is summarized in Table 2 [117,118]. As shown in the table, the use of nuclear heating reactors (NHR) was proposed in China. Other countries such as Canada, India and Pakistan are considering the PHWR

reactors. Overall, it can be noticed that the commercial types of nuclear reactors coupled with desalination are the PWR, PHWR, and LMFR respectively.

In 2015, the use of NHR-200 (200 MWt) was examined in China to be applied by 2030 [26]. It was aimed to couple this reactor with an MED process to produce steam. The assessment showed a decrease in electricity costs however, the use of this novel technology can increase the design costs. The use of pressurized heavy water reactor (PHWR-220) reactor for desalination in India was also investigated [119]. The reactor PHWR-220 (220 MWe) is currently under commissioning with 14 units operating. Other types of nuclear reactors include the liquid metal fast reactor (LMFR) such as the one used in Kazakhstan and the advanced pressurized nuclear reactor (APR 1400) that is intended to be built in United Arab Emirates (UAE) by Korea power corporation [120].

Table 2: Status of the early established nuclear-desalination plants [117,118]

Reactor Type	Location	Desalination process	Status
PWR	Japan (Ohi, Genaki, Ikata)	MED, MSF, RO	In service for more than 125 years
	Korea and Argentina	MED and RO	Under design
BWR	Japan	MSF	Testing in the 1980s, dismantled in 1999
NHR	China	MED	Under design
LMFR	Kazakhstan	MED, MSF	Was in service till 1999
HTGR	South Africa, France, Netherlands	MED, MSF, RO	Under consideration
PHWR	India, Canada and Pakistan	MED, MSF, RO	Under design

5.2 Coupling desalination processes with nuclear reactors

The flowchart for a desalination process coupled with a nuclear power plant is shown in Fig. 7 [121]. The figure includes an MED and an RO as an illustration. It is an on-site nuclear-desalination system. The purpose is to generate electricity (to power RO) as well as utilizing the waste heat to produce steam that will be fed into the MED unit. In order to design a nuclear desalination process, the following steps should be performed: 1) proper modeling for the reactor-

desalination systems, 2) careful evaluation for the nuclear plant safety and, the 3) technical outcomes from the desalination process itself.

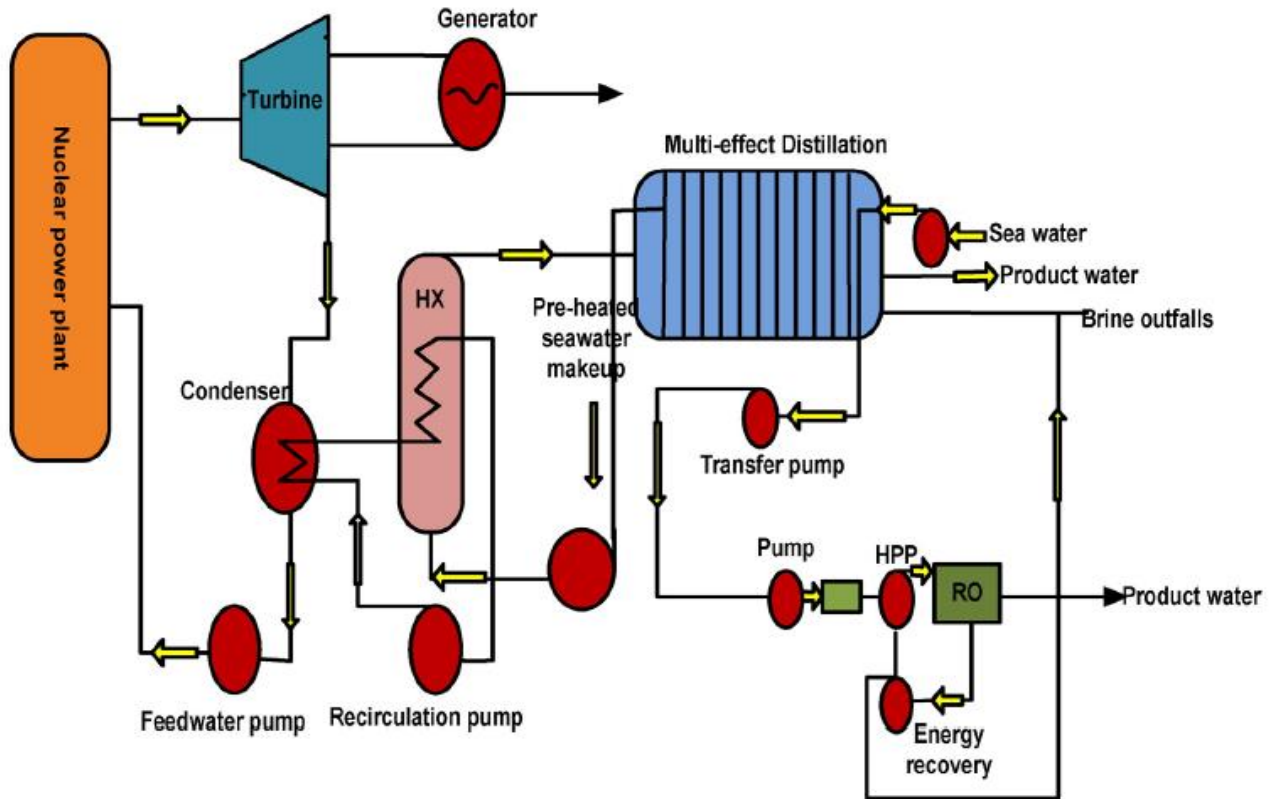


Fig. 7. A schematic diagram for a nuclear desalination process [121]. HX: Heat Exchanger, and HPP: High Pressure Pump.

5.2.1 Coupling nuclear with thermal desalination technologies: multi-stage flash distillation (MSF) and multiple effect distillation (MED)

Fig. 8 shows the coupling the MSF thermal process with a nuclear power plant [111]. The principle of MSF is previously explained in this context. Using the on-site nuclear power plant, it would be possible to have a cogeneration system and generate electricity. In addition, the waste heat is utilized to heat seawater. This configuration has the capability of improving the system economics, hence, reducing the costs.

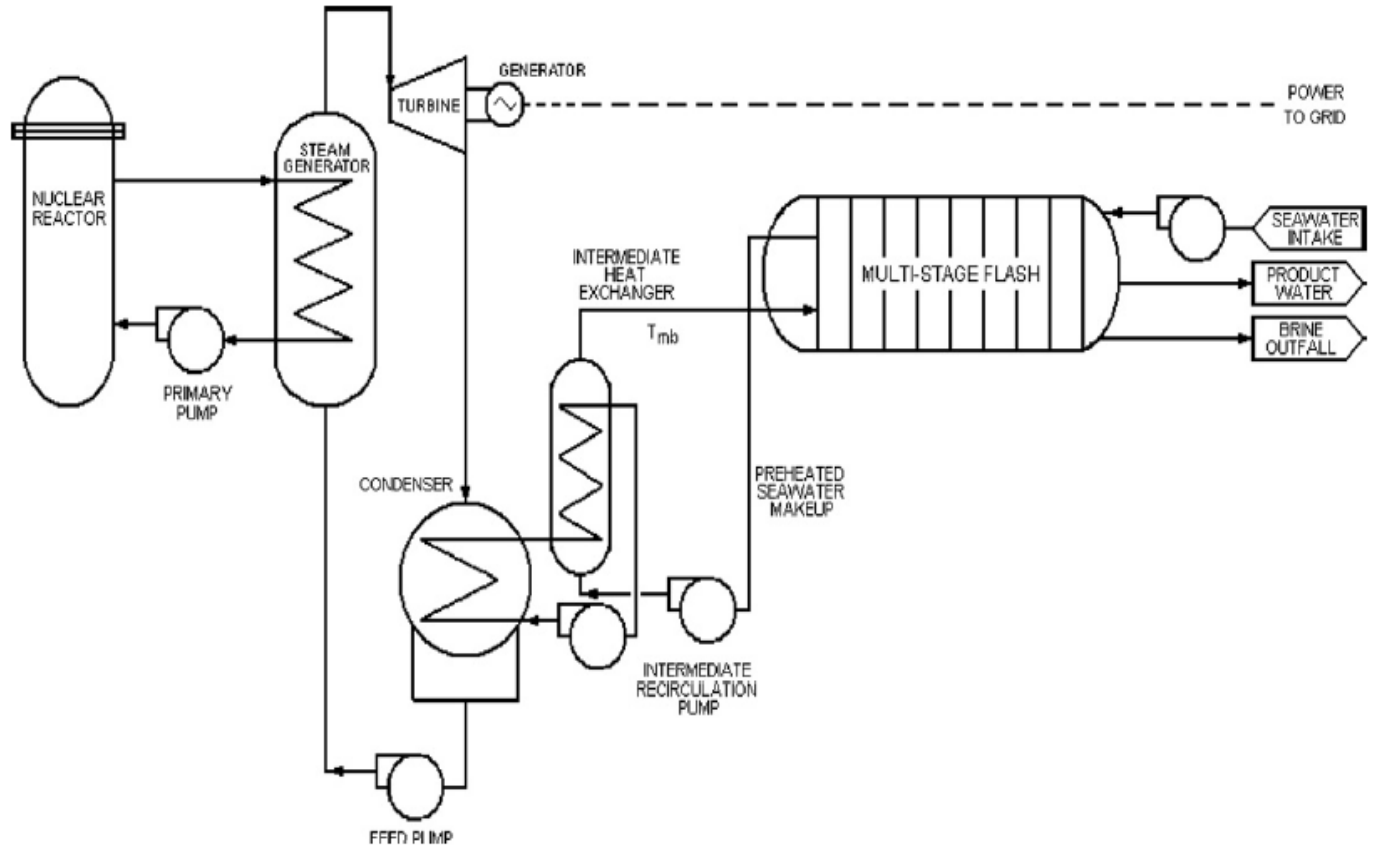


Fig. 8. Coupling the MSF thermal process with a nuclear power plant [111].

The flowsheet for multiple effect distillation (MED) coupled with a nuclear power plant is shown in Fig. 9 [32,111]. The principle of the MED desalination process is previously explained in this context. The MED unit can be seen as a series of adjacent spaces where surrounded by a heat sources at one side and a heat sink at the opposite side. As steam is flowing from one effect to another it exchanges heat with sweater. Eventually, more water will be evaporated and the brine will be more concentrated by the end of the series. A power cogeneration system is supplied in the nuclear plant to generate electricity. Both MSF and MED are more expensive and more energy demanding, however, they are used because they produce the highest water quality as opposed to membrane technologies such as RO [32,111,122].

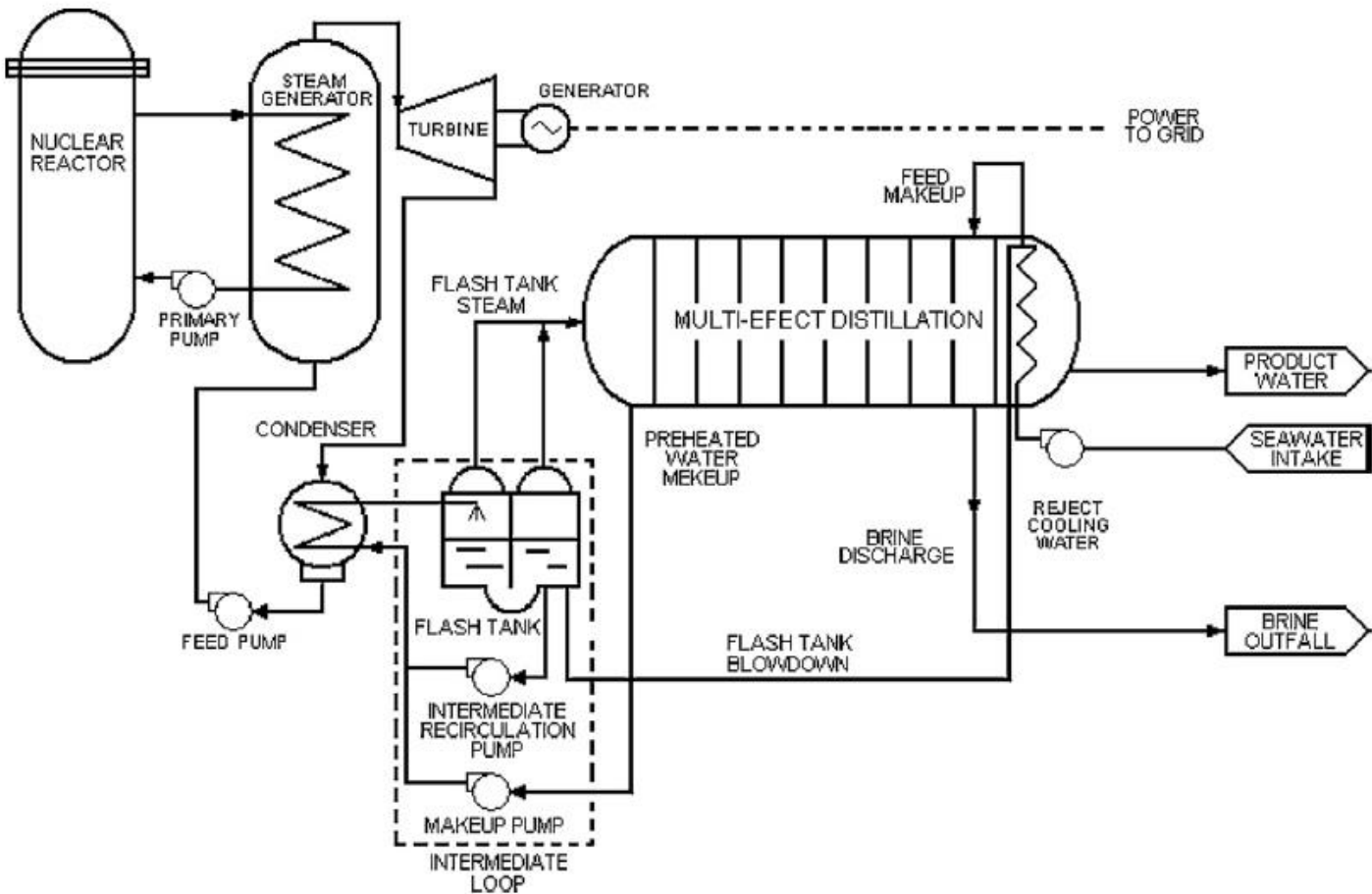


Fig. 9. Coupling the MED thermal process with a nuclear power plant [111].

5.2.2 Coupling with RO

Reverse osmosis (RO) is currently being considered as the most economical technology for desalination [123]. As explained in section 4.2, it is based on applying a high pressure that can reach 70 bars depending on water source. This pressure is exerted at one side of the membrane to overcome the osmotic pressure of seawater and force it to pass through the membrane, hence, obtain fresh water [72]. RO can be used to treat waste water, seawater, brackish water and oily water once properly treated [124]. Coupling RO with any power plant is feasible and done to generate electricity required to run the RO units. Electricity is utilized to power the pumps and plant utilities. Fig 10 shows a typical nuclear power plant coupled with RO. The nuclear reactor is used to

generate steam, in which is passed in an expander (turbine) to generate the electricity required to operate the pumps in the RO desalination plant.

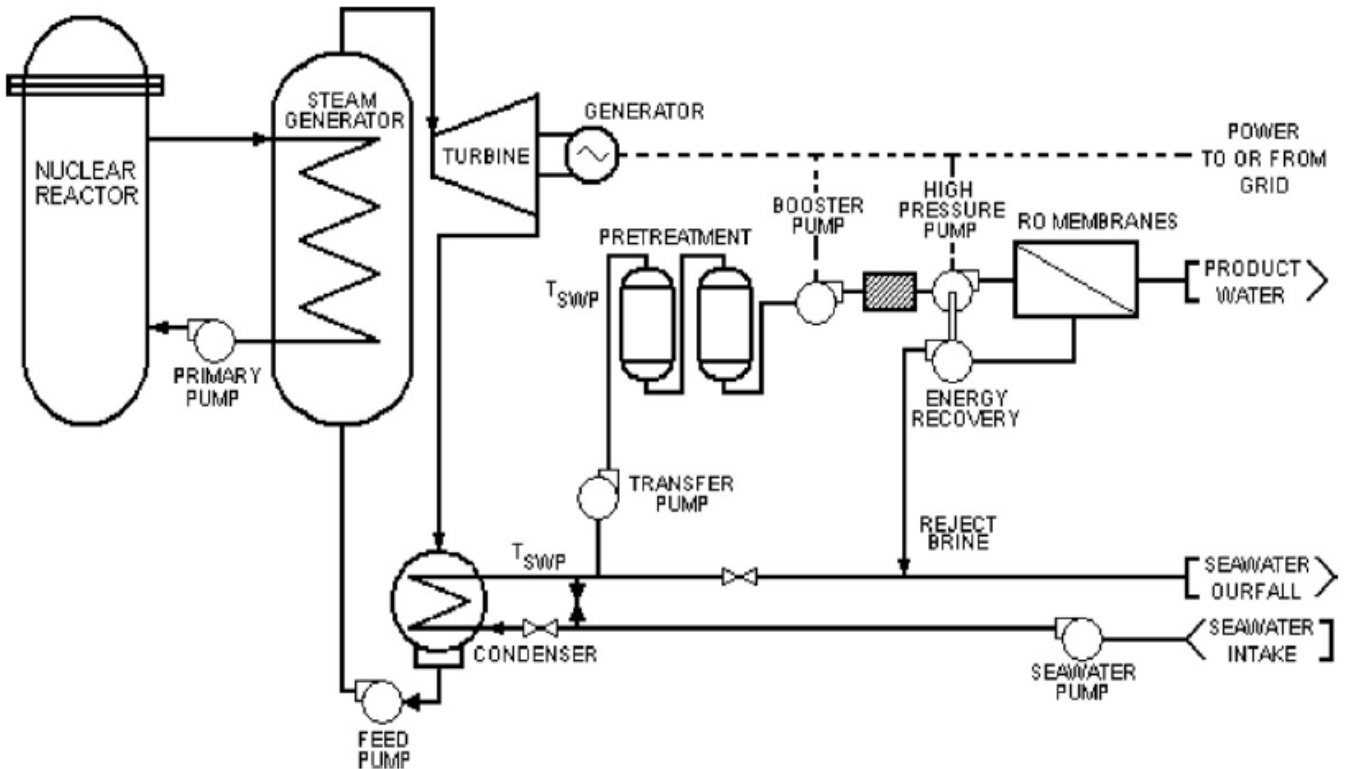


Fig. 10. Nuclear desalination coupling with RO [111].

Based on the previous discussion and literature, it is evident that the main desalination processes that have been coupled with nuclear reactors for fresh water production are: 1) multi stage flash distillation (MSF), 2) multi effect distillation process (MED) and, 3) reverse osmosis (RO). Each desalination process requires a certain nuclear reactor configuration based on the type of energy required. Table 3 below shows the capacity of some desalination plants at different locations around the world including Japan, Kazakhstan and India with electrical power capacity exceeding 1000 MW as well as the method of desalination used. It can be clearly seen that PWR reactors are the most commonly used with MSF, MED and RO.

Table 3. Global nuclear desalination capacities [13,125]

Plant name	Location	Gross power [MW(e)]	Capacity [m³/d]	Energy/Desalination
Shevchenko	Aktau, Kazakhstan	150	80,000–145,000	LMFR/MED, MSF (Hybrid will be discussed in section 6)
Ikata-1,2	Ehime, Japan	566	2000	PWR/MSF
Ikata-3	Ehime, Japan	890	2000	PWR/RO
Ohi-1,2	Fukui, Japan	2 × 1175	3900	PWR/MSF
Ohi-3,4	Fukui, Japan	1 × 1180	2600	PWR/RO
Genkai-4	Fukuoka, Japan	1180	1000	PWR/RO
Genkai-3,4	Fukuoka, Japan	2 × 1180	1000	PWR/MED
Takahama-3,4	Fukui, Japan	2 × 870	1000	PWR/RO
NDDP	Kalpakkam, India	170	6300	PHWR/Hyb. MSF-RO (Hybrid will be discussed in section 6)
LTE	Trombay, India	40 [MW(t)]	30	PHWR/LTE (Low temperature evaporation desalination)
Diablo Canyon	San Luis Obispo, USA	2 × 1100	2180	PWR/RO

5.3 Small modular reactors (SMRs) in desalination

According to the IAEA reports, there is an increasing interest in the investment of SMR in desalination. IAEA anticipates that by 2030, there will be 96 installations around the world [126]. SMR possess several advantages including the occupation of smaller area, more economical and safer in operation, less time in construction, hence, reduced cost [32]. They are currently in

operation in various locations around the world. The main types are: 1) Light water-cooled SMRs (integral or iPWRs). Examples are: the KLT-40 in Russia, SMART in Korea, IRIS in USA and CAREM in Argentina, 2) Heavy water-cooled SMRs such as the PHWR 220 in India and, 3) High-temperature gas-cooled reactors such as the HTR-10 in China and the GTHTR300 in Japan [32,127].

Table 4 presents a summary for the SMR reactors in use around the world up to 2015 and their coolant type [127].

Table 4: SMR reactors currently in use around the world up to 2015 [127].

Light water-cooled SMRs (iPWRs)	Heavy water-cooled SMRs	Liquid metal-cooled fast reactors	High-temperature gas-cooled reactors
KLT-40 (Russia) SMART (Korea) CAREM-25 (Argentina) IRIS (USA) NuScale (USA) MPower (USA) ACP 100 (China) VBER-300 (Russia) ABV-6M (Russia) Flexblue (France) DMS (Japan) IMR (Japan)	PHWR 220 (India) EC-6/CANDU-6 (Canada) PFBR-500 (India) AHWR300-LEU (India)	4S (Japan) PFBR-500 (India) Hyperion (USA) PRISM (USA) SVBR (Russia)	CEFR (China) HTR-10 (China) HTR-PM (China) GTHTR300 (Japan) PBMR (South Africa) HTMR 100 (South Africa) EM2 (USA) SC-HTGR (USA) Xe-100 (USA) GT-MHR (Russia) MHR-T/100 (Russia)

6. Continuing nuclear desalination projects around the world

There are ten main projects around the world that were launched to perform study and optimization for nuclear reactors coupled with desalination [13,31,107]. These projects are INVAP in Argentina, CANDESAL in Canada, INET in China, NPPA in Egypt, BARC in India, KAERI in the republic of Korea, CNESTEN in Morocco, OPPE, OKBM, JSC in Malaya, Energetica in Russia and CNSTN in Tunisia. Each project details are summarized in Table 5.

Table 5: Nuclear desalination projects around the world

Project Name	Location	Comments	Reference
INVAP	Argentina	INVAP developed a simulation spreadsheet called DENSU to model desalination plants based on MSF/MED/RO and provide data for safety assessment.	[128]
CANDESAL	Canada	CANDU nuclear power generation using a PWR reactor and RO desalination. Achieved an increase of 20–40% in water production efficiency.	[129]
INET	China	Nuclear heating reactor NHR of 200 MW coupled with MED desalination. Two types of MED processes investigated: low temperature horizontal tube MED with 120000 m ³ /day capacity, and high temperature stack MED of 160000 m ³ /day capacity.	[130,131]
NPPA	Egypt	A request submitted in 1997 by the Nuclear Power Plants Authority (NPPA) to investigate PWR reactors and process conditions such as feed water temperature and pressure on RO membrane as well as their effect as a function of time for a fresh water production capacity of 140 000 m ³ /day.	[132]
BARC	India	MSF and RO, with PHWR. Up to 425 m ³ /day from MSF and 90 m ³ /day from RO.	[133,134]
KAERI	Republic of Korea	SMART PWR reactor coupled with MSF and RO, 40000 ton of water /day and MED–TVC process coupled with SMART	[135,136]
CNESTEN	Morocco	Study and optimization for two sites in Morocco The studies were economically evaluated using DEEP for MED and RO coupled with NHR. Up to 600 MW electric power.	[137]

IPPE, OKBM	Russia	Development of modular fast reactors with lead-bismuth as a coolant as well as part of the research and development program to evaluate 20 test facilities. Study the coupling configurations of SMR nuclear reactors with various desalination plants. The project aims at providing an economical study, feasibility and optimization for nuclear desalination plants.	[138]
BATAN	Indonesia	An assessment for SMR PWR reactors of 100 MWe is performed in Bangka Island to be coupled with desalination. The results showed feasibility and safety of the proposed project.	[139]
CNSTN/ TUNDESAL	Tunisia	This project aimed at studying the coupling, feasibility and optimization of nuclear reactors and cogeneration mode using PWR AP-600, the gas cooled reactors and the high temperature reactors using two desalination processes; MED and RO. This is part of an agreement between the National Centre for Nuclear Sciences and Technologies (CNSTN) /Tunisia and the International Atomic Energy Agency. This agreement is known as the TUNDESAL project.	[109,131]

In addition, there is the EURODESAL project in southern Europe where scientists and engineers are evaluating the technical, safety and economic feasibility of nuclear power for MED-RO desalination using 600 MWe PWR (AP600) nuclear reactor [140,141]. More countries are currently considering nuclear power plants including Veitnam, Albania, Algeria, Chile, Croatia, DR Congo, Peru, Sri Lanka, Thailand , Uganda, Uruguay, and Zambia [142]. However, Vietnam for example had to cancel its plans at present due to economic reasons. Generally, the results of these projects are to be used with future plans in coupling these desalination processes with nuclear reactors. It is however necessary to consider several aspects including safety of operation

to avoid fresh water contamination with radioactive substances, and economics of the process. The process design should include barriers between the reactor and the desalination. In the Middle East in particular, several countries are interested in nuclear desalination to satisfy their water needs including Kuwait, United Arab Emirates (UAE) and Saudi Arabia. Desalination in these countries have become a major concern hence, several studies were triggered to evaluate the feasibility of this option using computational methods [13,32,143]. The studies concluded that these countries might be ideal options to carry on with nuclear desalination. Additional number of nuclear power plants are under construction around the world as shown in Fig. 11 below [144].

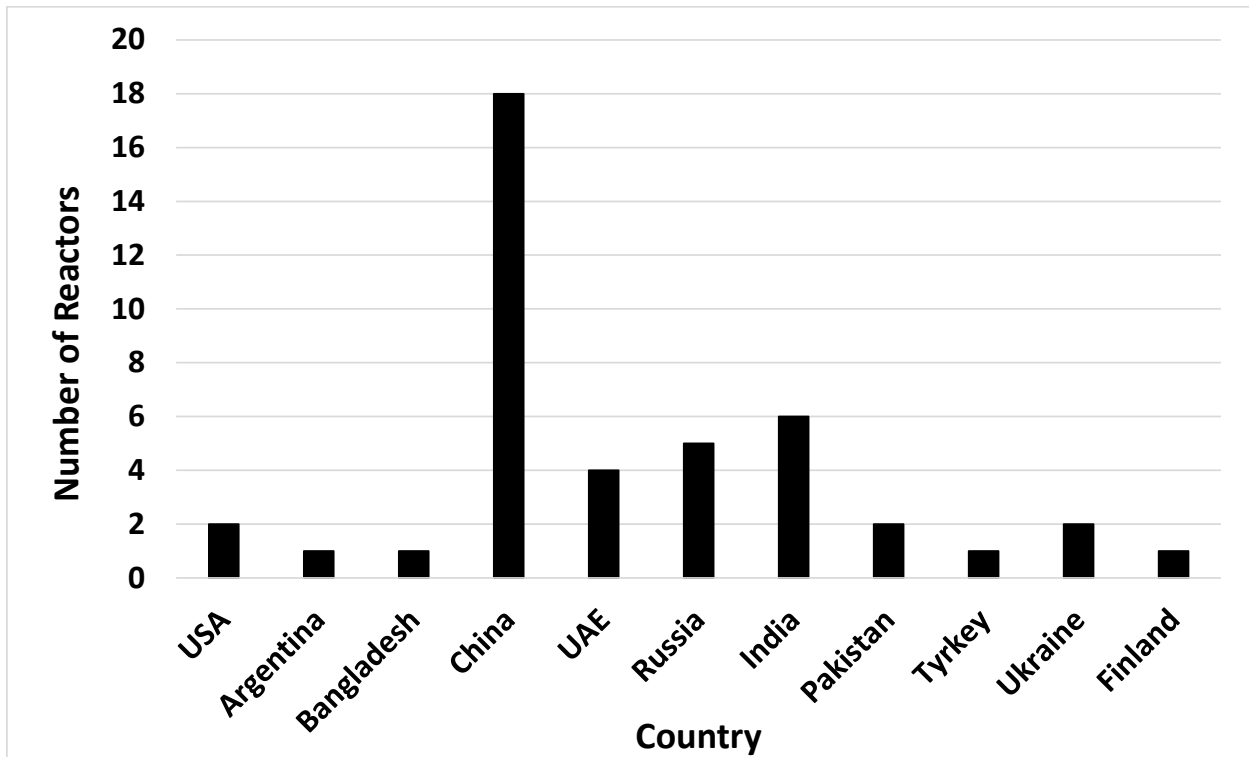


Fig. 11: Nuclear reactors that are under construction as of April 2018 (adapted from [144])

6. Hybrid nuclear desalination trends

Both MSF and MED are more energy demanding than RO, however, they produce better water quality. Hence, several combination trends were reported in the literature to investigate a nuclear reactor with one type or more of these desalination processes. For example, Wu et al. [122] investigated a hybrid system coupling the PWR reactor NHR-200 with MED and RO to improve the economy and efficiency of the desalination process. The study evaluated two systems: 1) PWR

NHR-200, with low-temperature MED+RO and 2) PWR NHR-200 with low-temperature MED+MED/vapor compression (VC). The study concluded that the major part of electricity could be obtained from the NHR reactor with additional few megawatts supplied from the grid with fresh water production and less cost than MED or MSF standalone processes.

The aspects and thermos-economics analyses of hybrid nuclear desalination systems such as nuclear-RO-MED and nuclear RO-MSF) were addressed in several studies [145–150]. The studies concluded the economic feasibility of hybrid nuclear desalination as a viable option to minimize the cost and obtain higher quality water. Famous examples of hybrid nuclear desalination plants around the world are the NDDP plant in Kalpakkam, India that uses PHWR with MSF-RO with a 6300 m³/day capacity, the Shevchenko in Aktau, Kazakhstan with a capacity up to 145,000 m³/day and uses LMFR and MED-MSF hybrid process, as well as Karachi Nuclear Power Plant (KANUPP) RO-MED plant [13,150]. Nuclear power plants were coupled with hybrid MSF-RO and MED-RO [111,116,122,147]. A schematic diagram for a typical hybrid MED-RO process is shown in Fig. 12 [111].

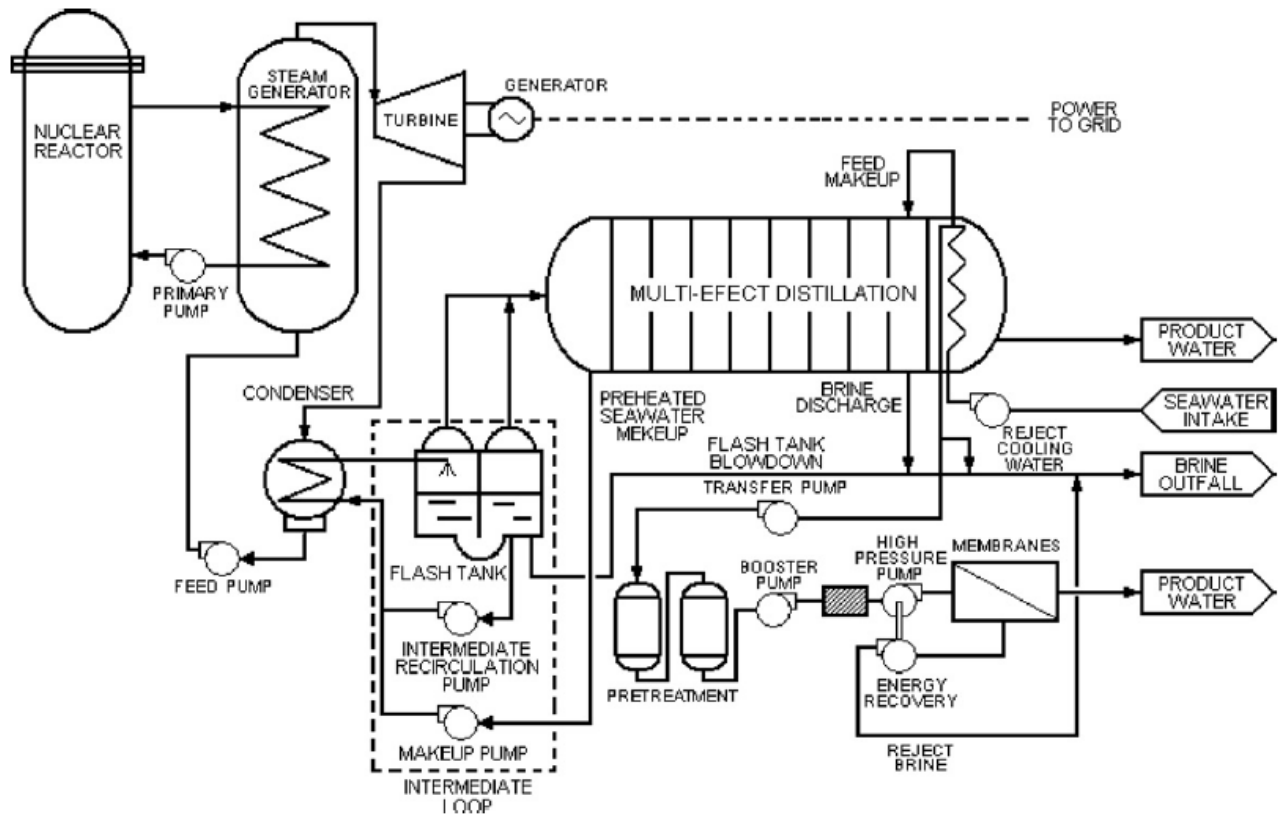


Fig 12. Nuclear desalination hybrid processes MED-RO [111].

The coupling of RO-MSF in a nuclear power plant was discussed and evaluated [151]. The results showed that the hybrid RO-MSF system offered the following advantages: 1) optimum performance in between the two processes, 2) a lower demand in energy, 3) lower cost for the hybrid process, 4) enhanced water quality and 5) more efficient performance in operation. MED combined with a thermal vapor compression process and RO was studied and a computational model was developed [152]. The results showed that the best exergetic performance is in the MED-RO system. Overall, the literature shows that the combination of two desalination processes with a nuclear power plant offers the optimum advantages from the two systems that would result in a better water quality as well as savings in energy and cost.

7. Recent research and development activities in nuclear desalination

Extensive research and development activities are in progress to investigate nuclear reactors for water desalination. The primary objectives of these activities are to increase the efficiency and lower the cost. The studies also focused on improving the design and performance of nuclear reactors to eliminate any possibility of contamination by the radioactive materials and hydrazine from the primary reactor coolant. The radioactive materials could be solid, liquid, and gaseous radioactive wastes and include depleted uranium, fission products, tritium and iodine. The main research activities are discussed in the following paragraphs.

Park and Kim [153] proposed integrating VHTR (a Very High Temperature Reactor) with FO system. In order to thermodynamically analyze this integration system, in their study, UNISIM program and the OLI property package were used. It was found that the gain output ratio (GOR) for the FO–VHTR system was in the range of 9.0 and 13.8, which is significantly higher than the GOR for MSF and MED. The rate of heat utilization and water production was also notably higher for the same VHTR capacity. For instance, FO-VHTR system produced five times more water than MSF–VHTR system for the same VHTR capacity. Nevertheless, the produced water is more likely to be contaminated with tritium. Tritium emitted low energy beta particle that are unable to penetrate human skin, hence, it is not harmful with external exposure. It is only harmful when absorbed by the body [154]. The water produced from FO–VHTR is most likely will be ingested, consequently, the behavior of tritium was investigated and analyzed [155]. A sensitivity analysis was also carried out using the behavior of Tritium Analytic Code (BOTANIC) to detect the efficient practices to decrease tritium concentration in the produced water.

It is anticipated that powering desalination facilities will consume about 10% of the thermal power produced by the nuclear reactor [156]. Lee et al. [157] proposed replacing the steam in Rankine cycle with super critical carbon dioxide Brayton cycle. A comparative analysis was also conducted for different alternatives to determine the preferable choice with respect to power generation and desalination capacity. The analysis was used to identify the optimum operating conditions [158]. Khalid et al. [116] proposed a new configuration for coupling RO with gas turbine modular helium reactor (GTMHR) and analyzed it thermodynamically. Several parameters were considered in the analysis such as the power cycle compression ratio, the inlet temperature of the turbine, waste heat recovery ratio, and the inlet temperature of the preheated seawater feed. The effect of these parameters on the overall exergy efficiency of the RO-GT-MHR process was evaluated. The exergy efficiency of the electrical power generation, the electrical power generation without the work output of the turbine and the RO unit were calculated. The study showed that the proposed RO-GT-MHR coupling is beneficial as indicated by the overall exergy efficiency of the proposed process of about 41.0%. The study also revealed that the exergy efficiency of the electrical power generation was increased by 10.3%.

Several studies have been conducted on optimizing the coupling between the nuclear reactors and desalination units. Two important aspects have to be taken in consideration before the coupling: the safety and the site of the reactor [131]. For instance, in thermal desalination processes such as MSF and MED, the coupling is very strong between the reactor side the desalination side. Hence, any fluctuation of any side of the operation will have a tense impact on the other side [128]. However, in the case of RO process, the coupling is very simple and notably weak [151]. Thus, the fluctuations of the desalination capacity will not lead to significant impact on the reactor operation [159]. EURODESAL [141] is an example of an international project that investigates the potential impacts of the coupling between nuclear reactor and desalination processes on the safety of the reactors. EURODESAL inspected the safety and technical and economic feasibility of various coupling schemes as previously mentioned in section 6. For instance, it examined the probability and effects of numerous fluctuations such as the loss of the MED unit and the loss of RO electrical load on the safety of the reactor.

Several steam extraction options for the usage in water desalination units were analyzed using System-integrated Modular Advanced Reactor (SMART) [160]. This was performed by analyzing

exergy and thermo-economy analyses for each extraction option. Both MSF and MED were considered and several gain output ratio (GORs) and desalination unit capacities were investigated for each extraction option. It was found that using a GOR value of 15 produced the highest amount of water and the production cost of MSF is lower than that of MED.

Heat pipes were used in both solar desalination [161,162] and nuclear desalination [163,164]. In the latter, they replace the shell and tube heat exchangers. Heat pipes have several advantages over shell and tube heat exchangers. They do not require pumps to operate and they provide an excellent indicator for operation problems through the temperature difference between their hot and cold parts. They also lower the risk of radioactive contamination of the water produced and decrease the fouling potential. Hence, heat pipes improve both the economic feasibility and the safety of the desalination process.

Another way to improve the feasibility and the productivity of nuclear desalination plants is by recovering the heat effectively and preheating the seawater feed [165]. Khamis and El-Emam [148] presented a nuclear desalination pilot plant using ultrafiltration (UF)-RO integrated with low temperature evaporation (LTE). In this pilot plant the feed for the RO unit is preheated by mixing the treated water from the UF unit and outlet hot stream from the LTE condenser. The preheating temperature depends of the mixing proportions. The effect of temperature of the inlet stream for RO unit on the productivity and heat recovery ratio was demonstrated using the seawater RO unit powered through Bhabha Atomic Research Centre (BARC).

The nuclear desalination cost is affected by many parameters such as the capital cost, labor, infrastructure energy and fuel costs, discount rate, construction time, life time, performance ratio and energy police instruments. Kavvadias and Khamis [24] conducted a sensitivity analysis for the main parameters to examine the interactions between them and to evaluate the uncertainty for different nuclear desalination alternative scenarios. The water cost was estimated in the analysis using Monte-Carlo simulation integrated with AEA's Desalination Economic Evaluation (DEEP) software package. DEEP has been used extensively to assess nuclear desalination systems. It performs the techno-economics analysis for desalination processes coupled with various energy sources [166]. The analysis is usually conducted for an individual desalination process such as RO, MSF and MED, or for hybrid desalination systems such as RO/MSF and RO/MED. DEEP was

used to analyze the economical characteristics and the sensitivity of the key parameters that influence the energy and water costs for two nuclear thermal desalination systems intended for UAE. These systems are small-sized nuclear heat-only plant (SNHP) and cogeneration large-sized nuclear power plant (LNPP) [156]. DEEP was also utilized to conduct a techno-economic analysis for SMR integrated with different desalination systems across Middle East and North Africa (MENA) region [32]. The analysis was performed for two SMRs coupled with various individual desalination processes such as RO, MSF and MED, and several hybrid desalination systems such as RO/MSF and RO/MED. In addition to DEEP, there are several simulation tools that are used by researchers for the purpose of technical and economic analyses of nuclear desalination systems. The most common tools are DE-TOP (desalination thermodynamic optimization program) [121], APROS (advanced process simulator) [167] and SEMER (Système d'Evaluation et de Modélisation Economique de Réacteurs) [109].

8. Environmental Impacts of Nuclear Desalination

The co-location of desalination plants and nuclear facilities inevitably raises some concerns related to the environmental impacts of nuclear desalination. Although the literature presents several studies on the environmental impacts of seawater desalination [168–172], environmental monitoring data specific to nuclear desalination is limited [125]. The key environmental impacts associated with nuclear desalination are outlined in this section.

8.1 Marine impacts

The marine impacts are mainly attributed to seawater intake and brine disposal from the nuclear desalination facilities. In the context of seawater intake for nuclear desalination, direct intake systems (open or surface intakes) are typically employed. This is because the indirect intake systems such as beach well intakes, horizontal collector wells, and horizontal directional drilling (HDD) systems are unable to provide sufficient quantity of feed water required for the nuclear desalination plants [173]. The use of direct intake systems along with the integral components such as pumps, filters, and screens impose serious threats to the aquatic life. The marine environment is a rich and complex ecosystem consisting of a variety of organisms such as phytoplankton, fishes, and invertebrates [174,175]. The direct intake of seawater into the nuclear desalination facilities can result in impingement and entrainment of these organisms within the intake systems [174].

Marine organisms that are large in size, such as fishes and crabs, are particularly susceptible to impingement. They are trapped against the intake screens due to the suction forces created by the flowing water. Impingement may cause immediate death or can significantly reduce the survival rates due to starvation, exhaustion, suffocation, or serious sustained injuries [125]. Entrainment, on the other hand, mainly affects the smaller organisms (such as fish eggs, larvae, seagrass, and plankton) that are able to penetrate through the intake screens but are killed within the processing equipment of the desalination plant [125]. In comparison with fossil fuel co-located desalination plants, nuclear desalination plants are expected to exhibit higher impingement and entrainment rates owing to higher water intakes rates [176]. In addition, the magnitude and probability of impingement and entrainment depends on the intake location, the biological productivity within the intake zone, intake velocity, incoming water quality (temperature and dissolved oxygen), the anatomy of the marine organisms, and the design and operation of the intake system [177].

Any desalination process produces brine with a higher level salinity than that of the feed. The high salinity of the brine combined with unfavorable temperature and pH values, caused by preheating as well as chemical pretreatment of the incoming seawater, can produce undesirable marine impacts [125,178]. Owing to its high salinity level, the disposal of brine from nuclear desalination facilities can significantly affect the marine organisms that are sensitive to salinity alterations and variations in their natural habitat. Generic studies on brine disposal into the sea have indicated negative marine impacts. For instance, studies have shown low tolerance of *Posidonia oceanica* meadows to salinity increments introduced by brine disposal into the sea [179–182]. In particular, RO brine has been reported to cause deterioration of *Posidonia oceanica* meadows, increase in epiphyte load and nitrogen content in the leaves, increase in frequencies of necrosis marks, disruption of the carbon balance, and decrease in glutamine synthetase activity [181]. Elevated salinity due to RO brine disposal has also been reported to inhibit the survival and growth of *Posidonia australis* [183]. Frank et al. [184] studied the short term effects of RO brine on benthic heterotrophic microbial communities. Brine discharge with salinity 5% above the ambient was observed to reduce the benthic bacteria abundance and alter their metabolic activity. Brine disposal has also been observed to cause a reduction in fish populations, plankton, and coral die-off in the Red Sea [185,186]. An increase in salt concentration due to brine disposal can also limit the dissolved oxygen supply [125], promote stratification of receiving water bodies, and interrupt the photosynthesis process [187]. All these factors combine can create serious marine impacts.

The effect of brine temperature and pH on the aquatic life is also an important consideration. Brine temperature exceeding 20 °C has been reported to significantly reduce the survival rate of *Scapharca subcrenata* [188]. High brine temperature can also decrease the dissolved oxygen level which can affect the metabolism rate of the faunal inhabitants and alter the physiological and behavioral responses in organisms [187]. Brine with low pH can affect the calcification rates in oysters, mussels, and coral reefs [125,189,190]. This can hinder the mechanisms involved in the formation of protective shells of these species. Chemical constituents of brine such as chlorine, heavy metals, corrosion products, coagulants, and antiscalants can also create adverse marine impacts. For example, desalination brine discharges that include chemicals such as iron hydroxide and polyphosphates have been reported to induce physiological and compositional changes in the microbial communities [191].

Considerable attention is required in order to mitigate the marine impacts of nuclear desalination. Impingement and entrainment can be reduced by employing indirect intake systems, if practicable. Favorable design features of the indirect intake systems, such as the presence of porous rocks and sand between the intake arrangements and the sea, result in low suction forces and provide barriers for the marine organisms. As a consequence, the entrainment and impingement rates are considerably lower in comparison with the direct intake systems [125]. The use of indirect intake systems, however, is only limited to small scale nuclear desalination plants. Nuclear desalination plants with small capacities can be converted from once-through cooling to closed-loop cooling utilizing cooling towers. This will decrease the seawater intake volume and, consequently, reduce the entrainment and impingement rate. Impingement and entrainment can also be reduced by conducting a comprehensive hydrological study in order to locate the intake systems in areas of low biological activity (outside the littoral zones). Proprietary barrier technologies and collection systems can also be used as measures to reduce the entrainment and impingement. Physical barrier measures include the use of wedgewire screens, fine mesh screens, barrier nets, and aquatic filter barriers [192]. For instance, fine mesh screens can reduce the entrainment rates by more than 80% [125] and collection systems such as Ristroph travelling screens can decrease the fish impingement death rate by 70-80% [125,176]. Alternative mitigation methods involve the use of fish diversion systems such as angled screens, modular inclined screens to enhance the diversion of fishes away from the intake systems [125]. Also, behavior deterrent devices can be employed in order to

provide repulsive stimuli for the marine organisms. These involve devices such as velocity caps, acoustic barriers, strobe lights, and air bubble curtains [192].

The intake velocity is of immense importance when considering the rate of entrainment and impingement. Low intake velocity is preferred in order to allow the marine organisms to swim against the intake currents and can be achieved by using physical barriers such as barrier nets and aquatic filter barriers [125,192]. As another measure, entrainment and impingement can be reduced by intermittent operation of the intake systems. During spawning or periods of high biological activity, the intake of seawater into the nuclear desalination plant can be reduced or stopped [193]. However, this solution is highly limited since it requires an alternative water source for the nuclear desalination plant.

Marine impacts due to brine disposal can be eliminated by finding effective means of utilizing the brine, for example, for salt production. This will prevent the need for brine disposal and, consequently, eliminate the associated adverse marine impacts. If disposal cannot be eliminated, subsurface disposal should be practiced. Also, discharge to open oceans with high energy waters can be considered in order to promote mixing with the ambient. Mixing can be further enhanced by using diffusers at the exit of the discharge pipes [194]. In addition, marine impacts can be reduced by diluting the brine with the plant cooling water prior to discharge [125].

8.2 Coastal impacts

The coastal impacts of nuclear desalination are related to construction and land use [195]. Like any desalination facility, construction of a nuclear desalination facility involves the use of heavy machinery which results in noise and visual disturbances, thereby, disturbing the natural habitat and the environment [125]. The construction activities can result in discharge of construction chemicals such as oils, greases, and other wastes into the sea. In addition, and compared to other co-located desalination facilities, smaller construction site area requirement gives an advantage to the nuclear desalination option [195]. In general, nuclear power generation requires less operational land in comparison with the other power generation technologies such as wind, solar thermal, and geothermal due to the enormous amount of energy produced. Nuclear power plants require 0.75 acres/MW of operational land. This is far lower than the operational land requirement of 5.4, 6.75, and 1.7 acres/MW for wind, solar thermal, and geothermal power generation

technologies [196]. Besides better land use, nuclear power plants require lower specific use of materials, such as concrete and steel, for construction. For example, in comparison with wind power plants, the nuclear option requires five to ten times less steel and concrete per MW of electrical power generation capacity [195,197]. Again, this gives nuclear desalination an advantage over other co-located facilities.

Nuclear desalination as well other desalination facilities can create adverse coastal impacts by generation of noise. Typically, noise is generated from sources such as high pressure pumps in RO and steam ejectors, turbines, and cooling systems within the nuclear power plant [125]. The adverse effects of noise, however, can be minimized by conducting suitable and sufficient noise assessment and the use of acoustical barriers.

Construction of new nuclear desalination facilities can result in visual disturbances to the scenery of the coastal areas. However, the visual impacts tend to be smaller when compared to other co-located desalination facilities due to lower land use requirement. In case of co-locating the desalination facility to an existing nuclear plant, the visual impacts have been reported to be insignificant [125,195].

8.3 Atmospheric impacts

In desalination plants, adverse impacts on the atmosphere are caused by the employed energy source. Nuclear desalination plants, in this context, produce the lowest impacts on the atmosphere in comparison with other desalination facilities [195]. For instance, Weisser [198] compared the life-cycle greenhouse gas emissions from selected energy technologies. The results, as depicted in Fig. 13, show that atmospheric impacts of nuclear power are comparable to those from wind and hydropower and are much smaller compared to the other energy sources.

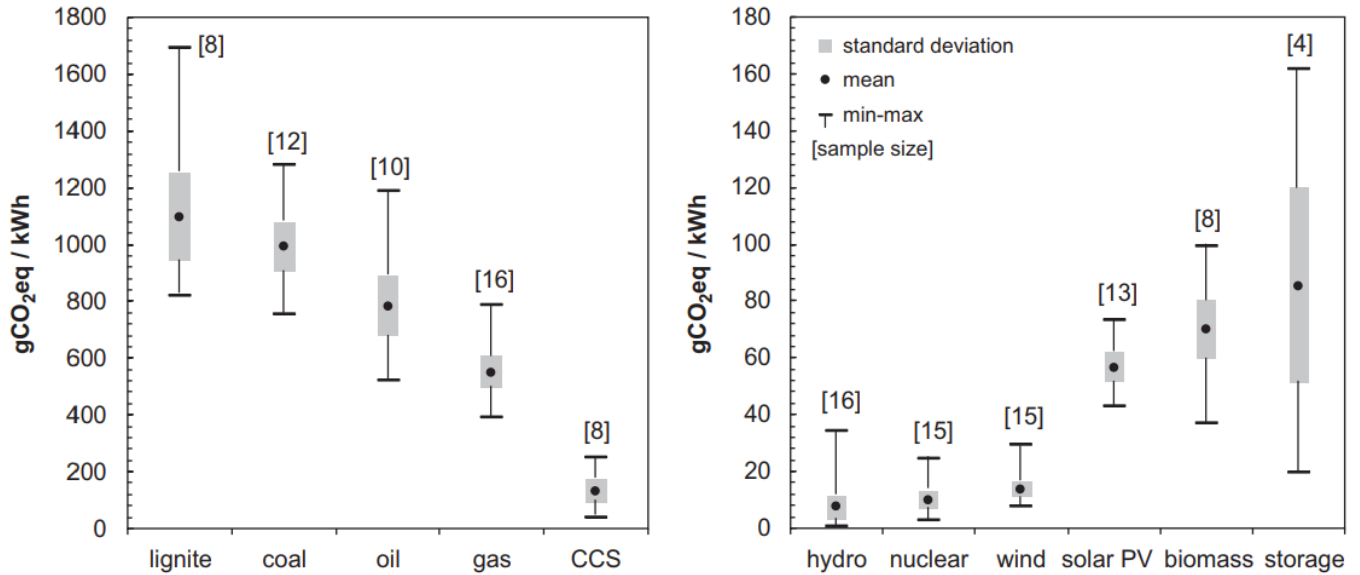


Fig. 13. Greenhouse gas emission from different energy sources (adopted from [198])

Using the data presented in Fig. 13 and assuming an efficient RO process with an energy consumption of 2.5 kWh/m³ [125], nuclear desalination can release approximately 10 to 60 gCO₂-eq into the atmosphere for every 1 m³ of desalinated water. This is by far lower than the greenhouse gas emissions of 1000-2000 gCO₂-eq and 1900-3200 gCO₂-eq per m³ of water produced from RO powered by natural gas and coal, respectively. Besides greenhouse gas emission, radioactive releases into the atmosphere is also an important consideration. Studies have shown that nuclear power plants release 100 times less radioactive material into the atmosphere compared to a coal power plants of comparative capacity [125,199]. Coal typically contains 1-4 ppm of radioactive materials [125,200] which are released into the atmosphere in large quantities owing to the large quantities of coal used in the power plants.

9. Economics of Nuclear Desalination

The Desalination Economic Evaluation Program (DEEP), a computer software developed by the IAEA, is often employed to evaluate the performance and economics of nuclear desalination plants. The software allows analysis with different plant styles (steam, gas, combined cycle, and heat only plants), fuels (nuclear, oil, and coal), and desalination techniques (MSF, MED, and RO). Although the software is not intended to accurately calculate the cost of electricity or water production, but it allows the comparison between design alternatives and identification of the

lowest cost alternative for the production of electricity or potable water in a given location [201]. Details of the latest version of the software can be found elsewhere [202].

A number of studies have focused on the economics of nuclear desalination. In general, nuclear desalination has been reported to be economically attractive and competitive with fossil fuel based alternatives mainly due to low fuel cycle cost involved in the former process. For instance, Faibish and Ettouney [203] conducted detailed economic analysis of four co-located plants of MSF (capacity: 348,000 m³/day) coupled to (i) pressurized water nuclear power plant (PWR) with back pressure steam turbines, (ii) pressurized heavy water nuclear power plant (PHWR) with back pressure steam turbines, (iii) heating nuclear reactor (HR), and (iv) oil/gas fossil fuel power plant (SSOG) with back pressure steam turbines. Results indicated that the nuclear power plant options (both PWR and PHWR) produced the lowest specific product water cost of around 0.79 \$/m³. The cost was significantly lower than the product water cost for the fossil fuel power plant (1.21 \$/m³).

Nuclear desalination has been reported as a viable and economical option in different regions of the world. For example, Gowin and Konish [102] performed economic evaluation of nuclear desalination in three broad regions: (1) southern Europe, (2) southeast Asia, the Red Sea region and the North African region, and, (3) the Arabian Gulf. A number of fossil and nuclear energy sources coupled to MSF, MED, and RO desalination processes were considered. The study concluded that nuclear desalination is economically feasible and cost competitive with the fossil fuel desalination option. Further details on the economics of nuclear desalination in these three regions were presented by IAEA [201]. The desalination cost was found to be between 0.40 \$/m³ to 1.90 \$/m³ depending on the desalination process, its capacity, energy source, region, and economic conditions. The results concluded that the nuclear option for desalination (using RO or MED) was better than the fossil fuel option under economic conditions favoring nuclear energy. Also, under economic conditions favoring fossil energy, costs from nuclear and fossil fuel desalination options were found to be comparable. However, the competitiveness of nuclear desalination may be compromised if the capital costs of nuclear plants increase by about 15-20% with fossil fuel cost to be 25 \$/boe (barrel of oil equivalent) or lower [204]. Results also showed that the costs of water production with small nuclear reactors dedicated to heat production were

higher than the costs associated with larger dual-purpose (dedicated to production to both water and electricity) nuclear reactors.

Nuclear desalination has been reported as an economical option for China. Wu and Zhang [122] evaluated the cost of water production in China for nuclear heating reactor (NHR) coupled with hybrid RO and low-temperature multi-effect distillation (LTMED) desalination system and hybrid LTMED and MED/VC system. Each hybrid system had a total production capacity of 162,000 m³/day. The costs of potable water produced with the hybrid coupling scheme (NHR+RO+LTMED) were estimated to be 0.538 \$/m³ and 0.77 \$/m³, respectively. In case of hybrid coupling scheme (NHR+MED/VC+LTMED), the costs were found to be 0.73 \$/m³ and 0.77 \$/m³, respectively. In another study related to China, Wu [205] studied the economics of nuclear desalination utilizing NHR coupled with LT-THE-MED (low temperature multi-effect distillation with horizontal tube evaporators) and HT-VTE-MED (high temperature, multi-effect distillation with vertical tube evaporators). Water production costs were estimated to be 0.72 \$/m³ and 0.76 \$/m³ for coupling of NHR with HT-VTE-MED (capacity: 170,000 m³/day) and LT-THE-MED (capacity: 120,000 m³/day) processes, respectively. Similarly, Tian et al. [206] conducted an economic study of HT-VTE-MED desalination process in China (capacity: 160,000 m³/day) coupled with NHR. Nuclear desalination was again found to be economically feasible and competitive with a pure water production cost of 0.54 \$/m³. Weihua et al. [207] evaluated the costs of NHR coupled with MED-TVC or VTE-MED and hybrid RO+MED processes in China. The production capacities were 107,500 m³/day, 160,000 m³/day, and 250,000 m³/day, respectively. The product water cost was found to be 0.90 \$/m³ for MED-TVC, 0.80 \$/m³ for VTE-MED, and 0.50 \$/m³ for hybrid RO+MED coupling scheme.

Ghurbal and Ashour [208] studied the economic competitiveness of nuclear desalination in Libya for two selected sites: the Tripoli site (Site I) and the Sirt site (Site II). Their results showed that the cost of pure water production using nuclear-assisted MSF, MED, and RO processes ranged from 0.87 \$/m³ to 1.78 \$/m³. Nisan and Dardour [109] compared the desalination costs for four nuclear reactors and two fossil fuel sources (gas turbine combined cycle and simple gas or oil fired boiler) coupled with MED and RO systems. The results were specific to Tunisia. The simple gas or oil fired boiler option was found to be the most expensive. Also, the results showed that the four nuclear options exhibited lower desalination costs compared to the gas turbine combined cycle

option provided that the gas prices remained above 150 \$/toe (metric tons oil equivalent). Similarly, economic studies specific to Muria Peninsula showed that the water cost was about 0.885 \$/m³ and 0.788 \$/m³ for PWR coupled with MED and RO plants, respectively [209]. The production capacity was 2750 m³/day.

In Argentina, a CAREM plant (a small reactor developed by Investigaciones Aplicadas Sociedad del Estado and the Comisión Nacional de Energía Atómica) coupled to an RO system has been reported to be economical and technically feasible. With a capacity of 12,000 m³/day, the cost of pure water production was estimated to be 0.67 \$/m³ [146,210]. Recently, an economic study was conducted for nuclear desalination at Karachi Nuclear Power Plant (KANUPP) in Pakistan [150]. For a production capacity of 22,000 m³/day, the water production cost was estimated to be 1.0, 1.57, and 1.25 \$/m³ for the nuclear power plant coupled with MED, MSF, and hybrid RO+MED.

The economics of nuclear desalination in the Middle East and North Africa (MENA) region have also been investigated. For example, Jung et al. [156] compared the economics of MED-TVC desalination system coupled with dedicated small-sized nuclear heat-only plant (SNHP) and large-sized nuclear power plant (LNPP) in the United Arab Emirates. For an equal desalination capacity of 178,451 m³/day, the results indicated that SNHP coupled with MED-TVC was economically more attractive than LNPP coupled with MED-TVC. The water production costs were 1.142 \$/m³ and 1.224 \$/m³ for the SNHP/MED-TVC and LNPP/MED-TVC systems, respectively. Khan et al. [32] conducted an economic evaluation for the coupling of small modular nuclear reactors (CAREM and SMART) with MSF, MED, RO, and hybrid desalination systems in the MENA region. For a production capacity of 10,000 m³/day, water production costs were estimated to be 1.50, 1.81, 1.88, 2.36 \$/m³ for CAREM reactor coupled with RO, MED, RO+MED, and MSF, respectively. In case of SMART reactor, the water productions costs were 0.81, 1.07, and 1.53 \$/m³ when coupled with RO, RO+MED, and RO+MSF, respectively, each with 40,000 m³/day capacity. A summary of economic studies on nuclear desalination is presented in Table 6.

Table 6: Summary of product water cost from nuclear desalination

Nuclear reactor type	Location	Desalination process	Power (MW)	Water production capacity (m ³ /day)	Water cost (\$/m ³)	Currency reference year	Interest rate (%)	Reference
Pressurized heavy water nuclear (PHWR)	Southern Europe	MED	676 MWe	120,000	0.56	1999	8	[102,201]
	Southern Europe	RO	676 MWe	120,000	0.47	1999	8	[102,201]
	Southeast Asia, Red Sea region and North African region	MED	676 MWe	120,000	0.66	1999	8	[201]
	Southeast Asia, Red Sea region and North African region	MSF	676 MWe	120,000	1.20	1999	8	[201]
	Southeast Asia, Red Sea region and North African region	RO	676 MWe	120,000	0.68	1999	8	[201]
	Arabian Gulf	MED	676 MWe	120,000	0.65	1999	8	[201]
	Arabian Gulf	MSF	676 MWe	120,000	1.19	1999	8	[201]
	Arabian Gulf	RO	676 MWe	120,000	0.74	1999	8	[201]
	-	MSF	-	348,000	0.79	2003	3	[203]
Pressurized water nuclear power plant (PWR)	Southern Europe	MED	600 MWe	120,000	0.73	1999	8	[102,201]
	Southern Europe	RO	600 MWe	120,000	0.53	1999	8	[102,201]
	Southeast Asia, Red Sea region and North African region	MED	600 MWe	120,000	0.84	1999	8	[201]
	Southeast Asia, Red Sea region and North African region	MSF	600 MWe	120,000	1.61	1999	8	[201]
	Southeast Asia, Red Sea region and North African region	RO	600 MWe	120,000	0.77	1999	8	[201]
	Arabian Gulf	MED	600 MWe	120,000	0.83	1999	8	[201]
	Arabian Gulf	MSF	600 MWe	120,000	1.59	1999	8	[201]
	Arabian Gulf	RO	600 MWe	120,000	0.83	1999	8	[201]
	-	MSF	-	348,000	0.79	2003	3	[203]
	Tunisia	MED	951 MWe	39,703	0.71	2006	5	[109]
	Tunisia	RO	951 MWe	43,676	0.50	2006	5	[109]
	Muria Peninsula	MSF	1000 MWe	2,750	1.35	2009	5	[209]
	Muria Peninsula	MED	1000 MWe	2,750	0.89	2009	5	[209]
Muria Peninsula	RO	1000 MWe	2,750	0.79	2009	5	[209]	
Nuclear heating reactor (NHR)	China	Hybrid LTMED + RO	200 MWt	162,000	0.538 (RO) 0.77 (LTMED)	2003	8	[122]
	China	Hybrid LTMED + MED/VC	200 MWt	162,000	0.73 (MED/VC) 0.77 (LTMED)	2003	8	[122]
	China	HT-VTE-MED	200 MWt	170,000	0.72	2006	5.85	[205]
	China	LT-THE-MED	200 MWt	120,000	0.76	2006	5.85	[205]
	China	HT-VTE-MED	200 MWt	160,000	0.54	2005	8	[206]
	China	MED-TVC	200 MWt	107,500	0.90	2012	-	[207]
	China	VTE-MED	200 MWt	160,000	0.80	2012	-	[207]
	China	Hybrid RO+MED	200 MWt	250,000	0.50	2012	-	[207]
	Libya (Tripoli and Sirt)	MSF	200 MWt	250,000 (Tripoli) 40,000 (Sirt)	1.37 (Tripoli) 1.42 (Sirt)	2002	7.5	[208]
	Libya (Tripoli)	MED	200 MWt	250,000	0.89	2002	7.5	[208]
SMART	Libya (Tripoli and Sirt)	MSF	200 MWe	250,000 (Tripoli) 40,000 (Sirt)	1.52 (Tripoli) 1.78 (Sirt)	2002	7.5	[208]
	Libya (Tripoli and Sirt)	MED	200 MWe	250,000 (Tripoli) 40,000 (Sirt)	1.20 (Tripoli) 1.13 (Sirt)	2002	7.5	[208]

	Libya (Tripoli and Sirt)	RO	200 MWe	250,000 (Tripoli) 40,000 (Sirt)	0.83 (Tripoli) 1.02 (Sirt)	2002	7.5	[208]
	Kingdom of Saudi Arabia	RO	330 MWt	40,000	0.81	2016	-	[32]
	Kingdom of Saudi Arabia	RO+MED	330 MWt	40,000	1.07	2016	-	[32]
	Kingdom of Saudi Arabia	RO+MSF	330 MWt	40,000	1.53	2016	-	[32]
AP-600	Tunisia	MED	610 MWe	39,703	0.76	2006	5	[109]
	Tunisia	RO	610 MWe	43,676	0.52	2006	5	[109]
Gas Turbine Modular Helium Reactor (GT-MHR)	Tunisia	MED	286 MWe	39,703	0.51	2006	5	[109]
Pebble bed modular reactor (PBMR)	Tunisia	MED	115 MWe	39,703	0.74	2006	5	[109]
Canada Deuterium Uranium (CANDU)	Pakistan	MED	137 MWe	22,000	1.0	2017	-	[150]
	Pakistan	MSF	137 MWe	22,000	1.57	2017	-	[150]
	Pakistan	RO+MED	137 MWe	22,000	1.25	2017	-	[150]
CAREM	Argentina	RO	-	12,000	0.67	-	-	[146,210]
	Kingdom of Saudi Arabia	RO	110 MWt	10,000	1.50	2016	-	[32]
	Kingdom of Saudi Arabia	MED	110 MWt	10,000	1.81	2016	-	[32]
	Kingdom of Saudi Arabia	RO+MED	110 MWt	10,000	1.88	2016	-	[32]
	Kingdom of Saudi Arabia	MSF	110 MWt	10,000	2.36	2016	-	[32]
Small-sized nuclear heat-only plant (SNHP)	United Arab Emirates	MED-TVC	400 MWt	178,451	1.14	2013	5	[156]
Large-sized nuclear power plant (LNPP)/ APR-1400 (Advanced Power Reactor)	United Arab Emirates	MED-TVC	4000 MWt	178,451	1.22	2013	5	[156]

10. Safety of nuclear desalination and public acceptance

Public acceptance is still one of the main issues of nuclear energy in general and therefore, of nuclear desalination. This is usually impacted negatively, in particular, when there is an immense nuclear accident such as Chernobyl and Fukushima nuclear disasters. For instance, the Fukushima accident elevated safety concerns related to nuclear power and significantly affected nuclear policies not only in Japan but in many countries [144]. Several countries learned from the Fukushima accident and reviewed their energy policies, revised their future energy mix, modified their plans regarding nuclear energy and stopped or postponed the building of new nuclear reactors

[211]. Examples of these countries are Germany, Switzerland, Italy, Korea, Belgium, France, Sweden and United States of America [212–214].

Accidents in a nuclear reactor or in the fuel production plant lead to plant destruction and massive releases of radioactive materials outside the plant location. These radioactive materials have harmful influences on the environment and human health. Safety culture plays a crucial role in accidents prevention and any deficiency in that culture typically caused a safety issue [215]. Despite the fact that nuclear power in desalination is a proven effective technology in producing fresh water, however, there are always safety concerns that need to be considered in the design of the desalination plant. In order to monitor the nuclear desalination process, the following should be examined: 1) the amount of thermal energy produced per module during the operation and after the shutdown process, 2) proper cooling down of the reactor to avoid any core meltdown, 3) radiation, to prevent any accidental release of radioactive contamination into fresh water [204].

There is a general agreement that the use of (SMR) rather than large reactors is an advisable alternative and that is mainly due to their considerable safety enhancement [216,217]. The thermal energy generated by SMRs during operation and after shutdown is significantly lower compared to other types of reactors [144]. Hence, their cooling after shutdowns or accidents is easier, which eventually, lowers the possibility of the core meltdown and the release of radioactive materials. Therefore, researchers recommended the use of a small modular reactors with desalination as a safer approach [156]. SMART reactors (the Korean system-integrated modular advanced reactor SMR) were proposed with enhanced design features for desalination purposes [218]. SMART reactors use passive systems. More specifically, they offer a passive residual system for heat removal that functions upon demand along with a cooling system to ensure safe shutdowns. The SMR design is based on eliminating large size tubing and preventing the radiation release using the preceding passive and closed-loop residual heat removal system. While several countries are currently interested in nuclear energy, the SMRs are considered due to several advantages but most importantly, their safety [144]. Other efforts in the literature aimed at reducing the amount of tritium concentration to prevent contamination with fresh water. Tritium is defined as a radioactive hydrogen isotope that occurs during the operation of a nuclear reactor. Khamis et al. [148] proposed the heat pipe technology to eliminate chances of mixing in between contaminated water and fresh water during a desalination process. The technology is explained in Fig. 14 [148].

Irradiation corrosion often imposes a risk of mixing in between heat exchange streams either in the evaporator (where steam flows in the tubes and exchanges heat with seawater), or in the condenser, where heat is exchanged in between the contaminated seawater and the produced fresh water. When heat pipes are integrated into the system, a physical barrier exists in between contaminated streams and fresh water product as shown in Fig 14, hence, eliminating the risk of contamination.

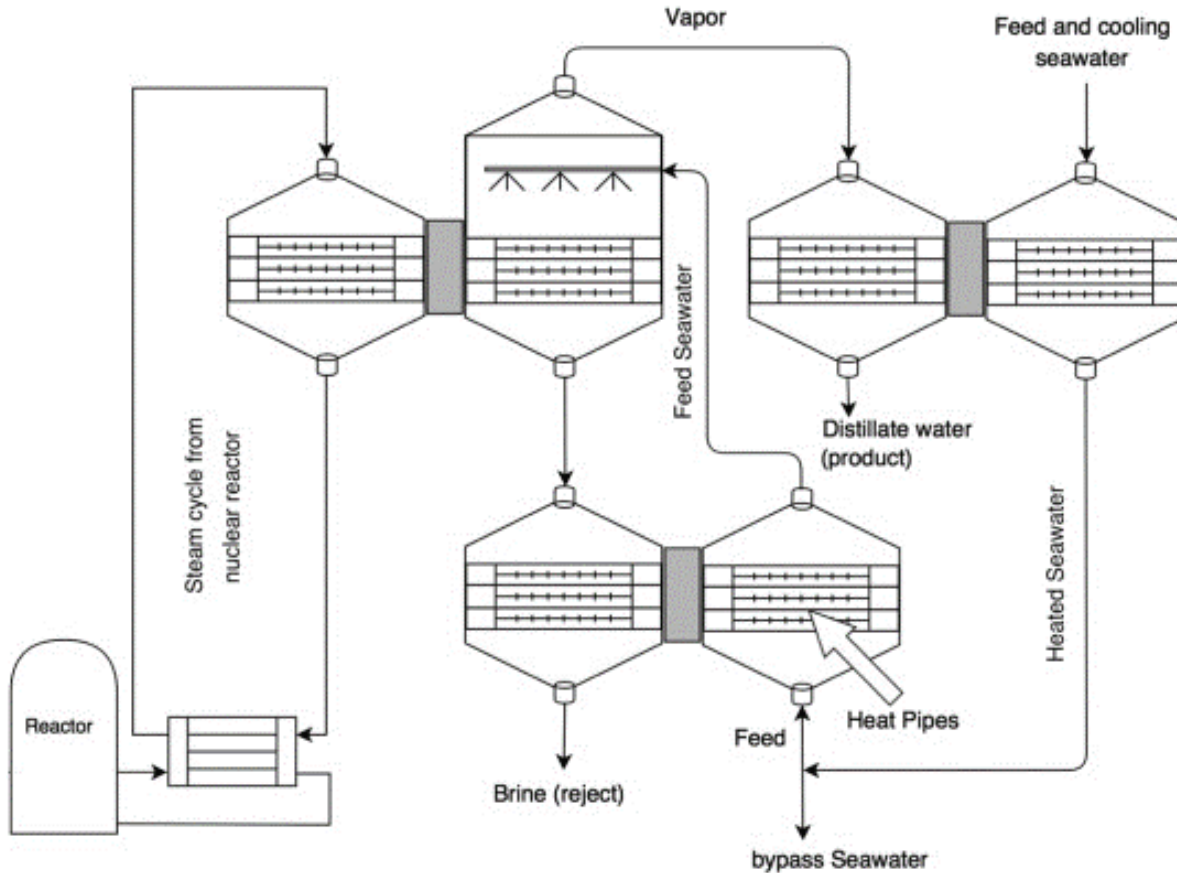


Fig 14. Heat piping system for a nuclear desalination plant [148]

New designs based on off-shore nuclear power plants (ONPP) concepts were also discussed in the literature as shown in Fig. 15 [219]. The ONPP design offer several safety features including 1) a new emergency passive containment cooling system and 2) a new emergency passive reactor-vessel cooling system. This makes the ONPP suitable and well prepared for tsunamis and earthquakes.

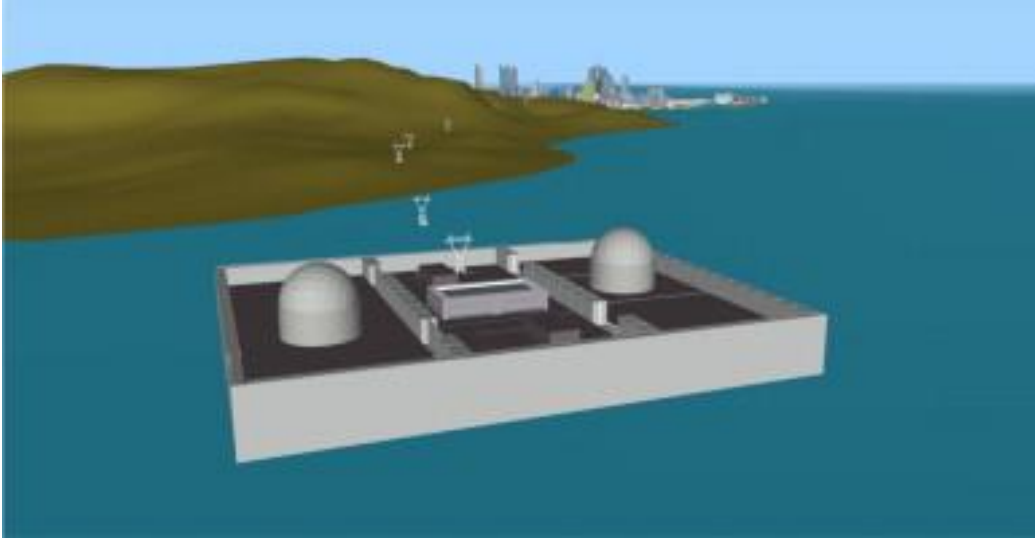


Fig. 15: Offshore nuclear power plant (ONPP) [219]

The as-low-as-reasonably-achievable (ALARA) approach is proposed by researchers in nuclear reactor design to enhance safety [220]. It is basically based at the account of operators to do their best at ensuring minimum doses to human beings. The defence in depth (DiP) strategy is also adapted [221]. It is composed of various safety levels starting from the conservative design and high quality construction, through proper control and surveillance systems to offsite emergency response.

Over all, it seems that the major safety concerns in the nuclear desalination plant are related to the nuclear reactor operation itself and the coupling of desalination with nuclear power. The latter is concerned with the contamination of fresh water by radioactive materials. Careful design and assessments for the barriers in between plant streams should be performed for on-site nuclear desalination facilities. A reasonable result would be that the use of SMRs as opposed to other reactors is the safest option especially for “newcomer” countries that are still considering nuclear desalination. The safety precautions for any nuclear power plant facility is based on the following elements: design, operation and quality assurance, in addition to governmental regulation. If a thermal coupling of nuclear power plant with desalination is to be conducted, such as MSF and MED then, the design should consider several cooling intermediate loops that are maintained at a certain pressure. This will eliminate the possibility of contamination by radioactive material and carryover to the fresh water stream. RO on the other hand, relies on electricity. However, thermal

energy is still produced during the nuclear power plant operation. This energy is discharged through the condenser cooling system that operate under vacuum. Therefore, any failure during the condenser operation would result in a leakage into the condenser and not into the feed stream. The design of nuclear RO desalination considers the separation in between electricity production and the RO plant, where RO can obtain electricity from a separate steam generator. This design configuration ensures that there is no physical path for radioactive material carryover in the process. Careful water resources assessment should be performed on a regular basis for tritium, which is a naturally occurring radionuclide. In this regard, the IAEA is currently leading in safety assessment activities. Recently, in 2017, the IAEA steered three projects for integrated safety assessment of research reactors (INSARR) in several countries including Jamaica, Norway, Poland and Turkey [222,223].

Conclusions

This paper provided a comprehensive review for the various aspects of nuclear desalination processes including the different nuclear reactors used, the hybrid trends, safety and environmental analyses, and economic assessments for on –site nuclear desalination power plants. It was evident that the development of various nuclear reactors is increasing significantly while small size modular reactors (SMRs) are receiving a considerable attention. This is due to the several advantages they offer over large reactors, including the moderate space for installation, the shorter time for construction, the economical construction as they have less capital cost, and safe operation. Hence, they appear to be a more attractive especially for newcomer countries. This review also revealed the role of the International Atomic Energy Agency (IAEA) in leading research activities, directing, and assisting in the nuclear desalination projects around the world including developing countries. The following conclusions can be also drwan:

- The purity of water, safety, possible contamination, and type of desalination process should be carefully studied before coupling nuclear reactors with any desalination process.
- The techno-economic assessments performed in the literature revealed the feasibility and the competitiveness of nuclear desalination as opposed to conventional desalination techniques relying on fossil fuels.

- Research on hybrid nuclear desalination facilities showed the several advantages offered by the hybrid systems where a low pressure steam can be produced when waste heat in nuclear reactors is utilized. This can be directed to a thermal process (MSF or MED). Electricity on the other hand can be generated to drive the necessary pumping system in RO or membrane processes. The optimum features from the participating desalination technologies can be obtained.
- The use of SMRs as opposed to other larger reactors appears as the safest option especially for “newcomer” countries that still do not possess experience in nuclear power plants facilities. The uncertainty about the economics of large reactors is another risk factor. However, the safety precautions should be strictly followed in design (e.g. offshore design that allows the travel of heat for a distance or the integration of heat pipes) during operation and quality assurance.
- Environmental assessments for nuclear desalination plants showed that they produce the lowest impacts on the atmosphere in comparison with other desalination facilities, and they are comparable to wind and hydropower.
- Future research trends are focusing on the use of SMRs in desalination as the most promising alternative. Their feasibility and cost-competitive features were often reported in the literature. This triggered the interest of several countries worldwide in nuclear desalination, such as Saudi Arabia, UAE, Algeria, Chile, Croatia, Peru, Sri Lanka, Thailand and Uganda. The IAEA have been recognizing nuclear seawater desalination as a promising technology. However, these activities are still limited because of safety concerns. Therefore, future research activities are directed into detailed design studies that address crucial engineering concerns such as several intermediate circuits to ensure the protection of produced water.

Nomenclature

AGR	Advanced gas-cooled reactor
APROS	Advanced process simulator
BWR	Boiling water reactor
DEEP	Desalination Economic Evaluation Program

DE-TOP	Desalination thermodynamic optimization program
ED	Electro-dialysis
FBR	Fast breeder reactors
FO	Forward osmosis
GCR	Gas-cooled reactor
GT-MHR	Gas turbine-modular helium reactor
GW(e)	giga-watt (electrical)
HTGR	High temperature gas-cooled reactors
HWR	Heavy water reactors
IAEA	International Atomic Energy Agency
LMFBR	Liquid metal fast breeder reactors
LMFR	Liquid metal cooled fast reactor
LWGR	Light water (cooled) graphite (moderated) reactor
LWR	Light water reactors
MD	Membrane distillation
MED	Multiple effect distillation (MED)
MHR	Modular helium reactor
MSF	Multi stage flash (MSF)
MVC	Mechanical vapor compression
NF	Nano-filtration
NHR	Nuclear heating reactors
NPPA	Nuclear Power Plants Authority
PHWR	Pressurized heavy water reactor
PVT	Photovoltaic thermal process
PWR	Pressurized water reactor
RO	Reverse osmosis
SEMER	Système d'Evaluation et de Modélisation Economique de Réacteurs
SMART	System-integrated Modular Advanced Reactor

SMR	Small modular reactors
TVC	Thermal vapor compressors
VHTR	Very high temperature reactor

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