Desalination by renewable energy: A mini review of the recent patents

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Abstract

Recent patents on water desalination by using renewable energy technologies are critically reviewed with highlighting on environmental impacts and sustainable development. An overview of using wind, hydroelectric, wave and tidal, wind/solar, geothermal, and solar renewable energy technologies for desalinated water production are assessed. Solar energy is the mother of all other renewable energies; it does not pollute, it is free and available everywhere. Several patents have been invented systems and methods that collected and converted solar energy to electrical energy via solar energy which can be used for water desalination. Wind farm with wind-driven pressurizing devices is used to desalinate salt water by reverse osmosis. Geothermal has been used as an effective method for water desalination. It is highly recommended to provide seawater desalination powered by a renewable energy source in remote areas. On the other hand, sequentially staged of energy conversion steps operate at low efficiencies.

Keywords: desalination, economics, environmental concerns, renewable energy technology, sustainable development.

Available online at the Journal website: http://www.ache.org.rs/HI/

REVIEW PAPER

UDC 628.165:62:66:502.13

Hem. Ind. **71** (5) 451–460 (2017)

The water shortage has become even more of a major international concern. According to the last statistical data from World Health Organization (WHO), approximately more than two billion people worldwide live without water. By 2025, more than 4 billion people will be without fresh water. Thus, fresh water shortage is today's problem which affecting billions of people. As well, water treatment is needed, and desalination is the most efficient method for providing fresh water from brackish and/or seawater.

Desalination has been addressed in open literature since longtime ago by different researchers. Al-Rawajfeh *et al.* proposed and evaluated an evolved version of a multiple effect distiller (MED) system [1–3]. The aforementioned MED system was evolved to operate using solar energy under Jordanian conditions, and a computer program is proposed for the prediction of water amount that the MED system can produce at 10 different sites distributed all over the country, based on available solar radiation data and salinity of the feed water (TDS of 3000, 5000, 7000, and 10,000 mg/L).

Furthermore, Al-Rawajfeh *et al*. have modeled the CO_2 desorption rates in Multiple Effect (ME) distillers [4–7]. These simulations have not accounted for the deposition of alkaline scale and its effect on CO_2 desorption rates. Calcium carbonate and magnesium hydroxide were assumed to precipitate at negligible rates. Recently, Al-Rawajfeh [8] has developed a model to simulate the simultaneous desorption of CO_2 with the deposition of $CaCO_3$ and investigate their desorption–crystallization mutual effect in ME distillers. Then he simulated the desorption–crystallization of CO_2–$CaCO_3$ from evaporation of seawater in Multi-stage flash (MSF) distillers [9].

Cost is considered as one of the most critical side of any water desalination project. It is a worldwide challenge to find a cheap desalination process for the poor and remote regions. Such project has experienced an overall downward trend in overall costs, and technological advances will continue to bring costs down even further [10].

On the other side, the research trends increases in disciplines related to renewable energy according to a comprehensive analysis of the growth of research activity originating from Arab countries [11]. Therefore; using renewable energies to desalinate water is a matter of interest worldwide. This research will focus on recent patents and research in applications of renewable energy technologies for water desalination.

State of art

Grubert *et al*. [12] filled the gap that policy makers could not identify where desalination could make sense. He demonstrated a quantitative global analysis methodology for identifying suitable regions for solar-aided Seawater Reverse Osmosis desalination (SWRO) taking into consideration the potential of using the renewable resources, feed-water characteristics, and human populations. This work concludes that tropical

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Paper received: 8 March, 2016
Paper accepted: 17 June, 2016
https://doi.org/10.2298/HEMIND160308008A

and subtropical cities have the highest potential for economically sustainable solar-aided SWRO.

Geo-pressure of a subterranean formation has been used as the power source to desalinate produced water. This invention using the energy of the produced fluids from hydrocarbon wells to provide a steam of relatively fresh water [13].

Shields [14], in his patent, reduced desalination cost and negative environmental impact by using kinetic energy in ocean waves as a power source instead of pumps and motors. This design would reduce manufacturing costs and increase production rates.

Cormier [15] found a solution for fresh water scarcity problem with a proposed desalination method. This invention desalinates seawater to produce fresh water by using recycled materials and solar energy. It is cost effective since it uses solar power and curbs pollution by using recycled 750 ml glass of wine bottles. The invention is summarized as follows; the seawater is collected at the seashore *via* a cone shaped pipe (diameter of 1 to 5 m) then it crosses a filter grid. Afterward, the contaminated water is transferred to a doughnut shaped reservoir. This reservoir is made of two different layers; the outer layer and the inner layer. A metallic reflector is placed under the wine bottles to reflect sunlight into wine bottles, so the water is evaporated. This evaporated water is condensed on the closed end. Finally, the condensed water from the evaporated water is collected by tubes with a diameter of 1 cm which attached to the outer layer of the reservoir.

High efficiency and a composite semipermeable membrane have been used in a forward osmosis membrane flow system [16]. The composite semipermeable membrane has the polyamide-based skin layer formed on the porous epoxy resin membrane, so a large amount of fluid moves in the semipermeable membrane in forward osmosis flow. Thus, an increased in efficiency is achieved. In addition to that forward osmosis membrane flow system has a high efficiency due to a large amount of moving fluid in the semipermeable membrane.

Braune [17] provided an apparatus and method to reduce the net energy used in desalinating water and to provide a feasible salinity gradient power plant. His proposed desalination plant preferably further consists of a solar power heater between the brine inlet of the salinity gradient power unit and the brine outlet of the desalination unit. As supplied feed is warmer; the power output from the salinity gradient power unit is higher.

Low grade heat sources and recovery of waste heat application is a matter of interest due to highly increase in energy costs and limitation of energy sources. On the other side, the cost of traditional desalination processes has increased by ten times over the past twenty years. Nirmalakhandan and Gude [18] proposed a new desalination process operates with low grade heat at a temperature range of around 40–50 °C. The desalination has a thermal energy storage system which enables waste heat and renewable energy sources to be used to drive the process with minimum dependence on fossil fuel.

A method and apparatus for dual purpose of cogeneration (coastal seawater desalination combined with power generation) is introduced by Germain and Barnett [19]. The energy requirements of the desalination plant is reduced either by capturing the heat vapor exhausted by the power generation system, or replacing a steam turbine generator’s condenser by the desalination plant’s heat exchanger. In the meanwhile the brine solution (treated by the desalination plant) is pumped from the substrata sea water table wells having low salt content brackish water.

Al-Garni *et al.* [20] suggested sustainable and environmentally friendly wind/solar desalination farm and park for providing drinking and irrigation water, electricity, and the other needs for a small community located near a body impregnated with salt.

Gordon [21] provides potable water, and/or water for industrial uses through a vessel has a water intake system, a reverse osmosis system, a concentrate discharge system which includes a plurality of concentrate discharge ports, a permeate transfer system, a power source, and a control system.

A series of independent float is used to desalinate cultivated field water as shown in Figure 1 [22]. This invention is a cheap and has low maintenance costs in agricultural field. In addition to use rugged units (no moving parts) can be fabricated of common plastics, and can be installed mechanically. The method based on taking up the saline water with a wick. Then, evaporate the water from the wick in desalinating relation

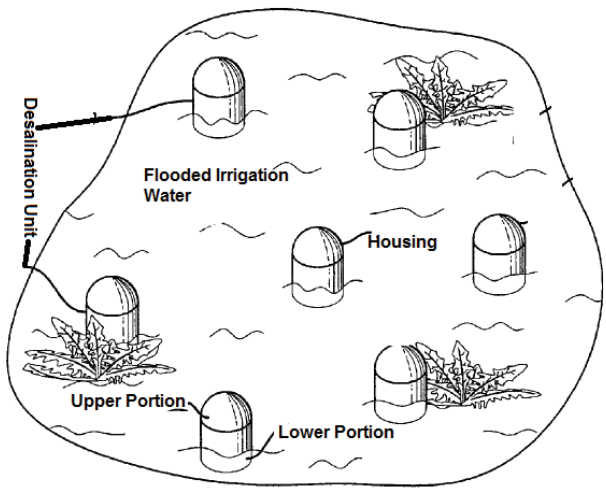

Figure 1. Schematic Viewof Coon’s Invention [22].

by using lenses and mirrors. The desalinated vapor is accumulated and the condensed water is returned to the field. The collected salt in a wick is removed and reconditioned at a remote site.

Klausner and Renwei [23] invented new process and apparatus called a division driven desalination fit low temperature and pressure operation. It is driven by forcing a low humidity air stream over the thin film of water. Then, liquid water is condensed out of the air/ /vapor mixture in a condenser using a diffusion tower. Moreover, the process may be driven by waste heat with low thermodynamic availability.

Geothermal

Geothermal has been used as an effective method for water desalination. Lakic [24] discovered a method to desalinate the water from a large body of salty water by lowering a geothermal generator deep into a pre-drilled well bore below the Earth's surface. Sarria showed up a method for using deep underground concentric tubes to heat liquids and generating electricity and/or desalinized seawater [25]. Marshall disclosed a system to produce a thermal energy source by direct a flow from a recovered superheated fluid from deep-ocean hydrothermal vents to the surface. This thermal energy source is used to generate electricity or desalinate water [26]. Another method for water desalination has been imposed from at or near the sea surface by means of the deep sea fluids produced by the thermal vents formed at the scattering ridge zones of the earth's oceans due to the internal energy of a more or less surficial hot magma [27].

Shnell [28] discussed a geothermal system comprising: at least one production well, at least one injection well, and at least one geothermal energy generator (at a depth of at least 2 km) coupled to the at least one production well and the at least one injection well. The production well has a top and bottom where the injection well is designed at appropriate length to access geothermal heat from one or more areas under the floor. The energy generator is used to convert the energy from one form (geothermal energy) to another.

Pflanz [29] used a combination of fluctuating renewable energy and energy storage devices. This aimed to eliminate the using of fossil and nuclear power plants in the future. The system consists of a long-term energy storage device (underground heat energy reservoir) and a short-term storage device.

A novel water desalination system using geothermal energy includes a plurality of stepped evaporation trays has been investigated by Al-Garni and Abdelrahman [30]. A block diagram of a water desalination system using geothermal energy according to this invention is shown in Figure 2. Salt water flows into the uppermost tray and cascades to each successively lower tray to overflow from the lowermost tray when all trays are full. Two sloped glass panels pass solar energy there through to heat the water. Condensation collects on the inner panel and runs down the panel to collect in a trough at the lower edge. The desalinated water then flows to a collection tank. Additional heat energy is provided by a working fluid that is pumped to subterranean levels where significant geothermal heat is produced. The heated air is then circulated around the evaporation trays to enhance evaporation. Solar cells and wind energy may be used to cover the required energy for the operation of the system. In addition, Mirrors and functionally graded material further increase the efficiency of this system.

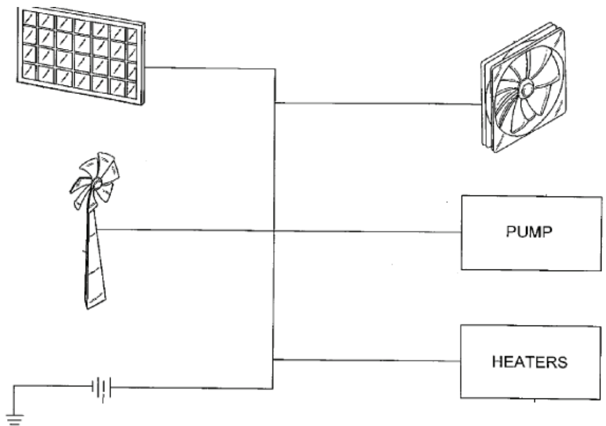

Figure 2. A block diagram of a water desalination system using geothermal energy [30].

Hydroelectric

Hydroelectric power production used a huge amount of mechanical and electrical engineering to supply the required power which emits greenhouse gasses to environment [31]. On the other hand, the XCL power producer is constructed with zero emissions as well as its lower maintenance costs. XCL power producer creates an acceleration of energy production. It produces 45,000 V at 300 A every 4 min for a 14-years cycle.

Solar energy

Solar energy is the mother of all other renewable energies; it does not pollute, free, and available everywhere. Several patents have been invented systems and methods that collected and converted solar energy to electrical energy via solar energy which can be used for water desalination [32–37]. A new system arrangement, as shown in Figure 3, has been invented by Abdeen [32] to improve the heat and mass transfer inside the desalination chamber. Briefly, the fine water droplets are injected to the desalination chamber by an air atomizer. The contact time between the droplets and the surrounding air is increased by ejection the hot saline water vertically upward. The solar energy is used to preheat the surrounding air side by side an auxiliary

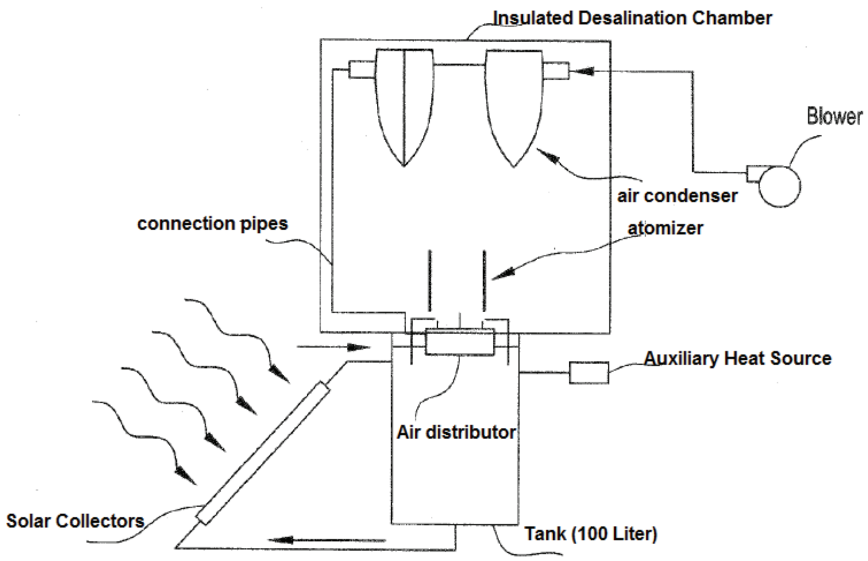

Figure 3. Abdeen's Desalination System [32].

heat source. Then, the salt water is pulling into the atomizer by using a pumped air. The results show that this system costs about US$ 500 and the estimated liter cost of the desalinated water is 0.2 US$/L, based on 500 operating man hours at a fare of $ 5/h and an average of 13 m^3 desalinated water production.

The main disadvantages of the solar energy that it is fluctuated source. On the other hand, the water usage is continuous. Therefore; Mueller *et al.* [33] investigated the possibility of switching between day and night operations. In order to keep the solar liquid available all the time the following process has been done. During the day, the solar liquid receives the energy form the solar thermal power. Some of this solar liquid is withdraw as a heating medium while the rest part is stored in a storage device for later use. During the night, the stored solar liquid is withdrawn as a heating medium. The model in nighttime and daytime operation is shown in Figure 4.

Water has been generated from atmospheric air by an atmospheric potable water generator apparatus [34]. Atmospheric air is heated by solar energy in a condensing air chamber, and then the air is cooled by wind. After that, water is condensed on a cooling surface. This invention does not need an additional external power source or form of refrigerant solutions, since it depends on renewable energy to function. Another method and apparatus has been disclosed to desalinate salt water and generate electricity using solar energy [35]. Large compound magnifying lens is used to vaporize the internal fluid (a heating grid containing fluid, *e.g.*, salt water). Then, the vapor from the grid system is transmitted to a steam turbine where the generated electricity will charge a battery. At that point the accu-

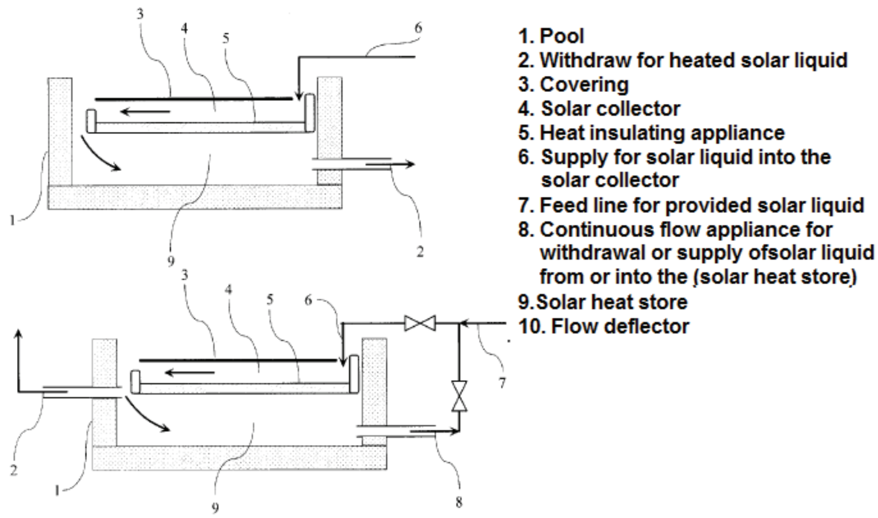

Figure 4. Mueller et al. model during nighttime and daytime [33].

mulated vapor from the steam turbine is cooled at the condenser in which fresh water is provided from the condensate. The remaining fluid (from the condenser) is driven back into a storage reservoir waiting to be conducted into the heating grid. This method is shown in Figure 5.

Moreover, Penciu [36] disclosed systems and methods that include solar collectors, transporting and transferring mechanisms, and multiple thermodynamics engines. The concentrated solar energy is transported and transferred directly into closed-cycle thermodynamic heat engine/engines without heating the engine/engines outside surface which protect the collectors. The efficiency has been maximized through using multiple engines. Furthermore, Almogy *et al.* [38] discussed systems, methods, and apparatus using a concentrating solar energy collector to produce electricity and/or heat.

Prueitt [37] invented a novel system operates optimally in areas of abundant sunshine. The seawater or brackish water is desalinated economically. Mainly, his invention focused on pumping the boiler feed liquid by a novel motor less feed pump. In brief, a pressurized vapor from a solar powered boiler drives an expander that generates output motive force. The motive force is pressurized to give pressurized seawater or brackish water using pump. Then, a reverse osmosis unit receives the pressurized seawater to produce fresh water and pressurized brine. After that, a hydraulic motor receives the pressurized brine and gives an augmenting motive force to the pump. A heat recuperator transfers heat from expander exhaust gas to boiler feed liquid.

Browe [39] invented a comparatively inexpensive system that collect the renewable energy and transfer it into an electrical charge. The electrical charge is transmitted to one or more storage batteries, for later use, which provide auxiliary power for one or more desired uses. This invention may provide reverse osmosis purified drinking water and electrical power to run computers, cell phones, appliances etc.

Hrayshat and Al-Rawajfeh proposed a solar desalination system using a multiple effect distiller (MED), Figure 6 [3]. It consists of two components: the solar thermal subunit and the desalination subunit. The solar thermal subunit consists of 16 solar modules (vacuum tubular). Distilled water is circulated through the collectors at atmospheric pressure as a heat carrier medium. Maximum working temperature of the collectors is above 350 °C. The steam generated in the solar collectors as a steam water mixture goes to the desalination subunit. The water production at 10 different Jordanian sites is predicted. The results show that in the selected sites about 63% of the daily amount of water produced during a 1-year cycle occurs during April to September.

A multi stage and multi effect desalination device using solar heat is invented by Kwak *et al*. and shown in Figure 7. This invention solved the economic problem due to star ability and cost-effectiveness *versus* an amount of fresh water output [40]. A multi-stage vapor generator generates vapor by heating sea water inside thereof according to a temperature of inflowing high temperature water and a multiple evaporator composed of a plurality of evaporator groups that desalinate sea water by using vapor generated in the multi stage vapor generator as heat source as well as constructing a condenser that condenses vapor discharged from the multiple evaporator, thereby not directly dis-

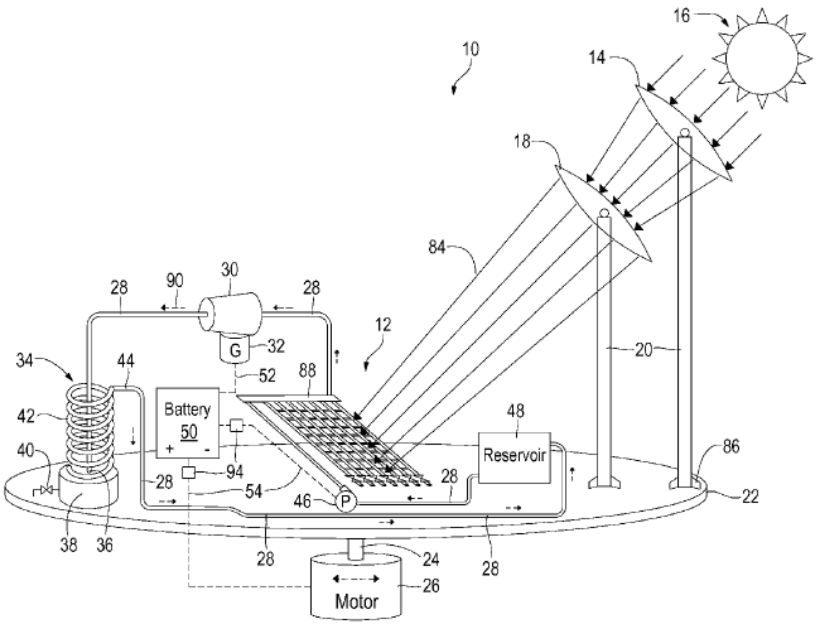

Figure 5. Perspective view of Griggs model [35].

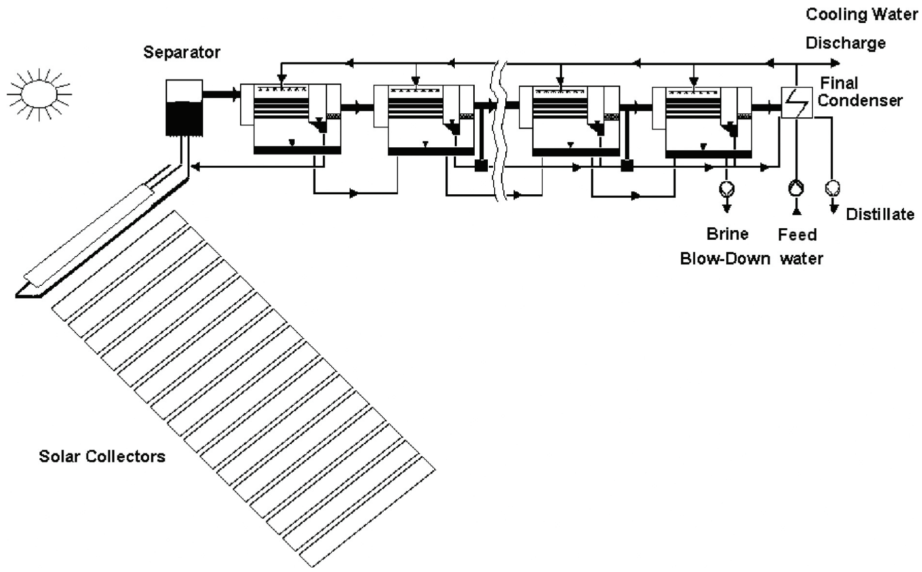

Figure 6. Schematic diagram of the solar MED system [3].

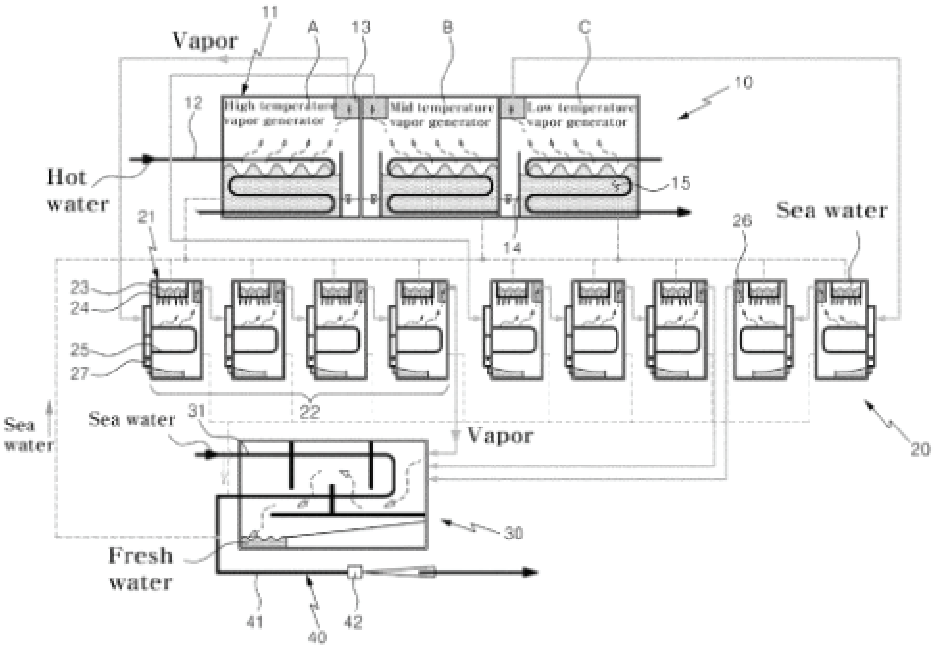

Figure 7. Three-stage vapor generators of an evaporative desalination device of multi stage and multi effect using solar heat [40].

charging waste heat but reusing in multi-effects and multi stages.

Walker *et al*. carried out apparatus and system of a solar still countercurrent flow [41]. This system includes a solar collector located adjacent to a condenser, the condenser located at an angle with respect to the condenser. The solar distillation system further includes a 2nd effect and an insulated portion located between the condenser and the 2nd effect. The solar collector, the condenser, the insulated portion, and the 2nd effect function to desalinate and purify saltwater or brackish water flowing through the solar distillation system.

Another application of desalination by solar energy is the desalination greenhouse which is a solar distillation device that doubles as an insulated greenhouse [42]. The desalinated water produced is very high quality, inexpensive, and could be used for any purpose (high value boiler and industry demineralized water, potable, agriculture and any combination of the above). The structure is an insulated greenhouse where heat producing infrared radiation is captured in forced air conduits, passes through evaporation pads to be humidified to saturation, then over a crop and through heat exchangers carrying cold water from the evaporation cooler to cause its condensation of the moisture laden air that passed over the crop. It uses inexpensive materials and renewable energy for power. Thus, the capital cost of desalination is significantly reduced. The desalination greenhouse of this invention also provides a number of flexible operation controls to produce crops rapidly in a desert environment using brackish water.

A desalination plant powered by renewable energy, which comprises of a pre-filtration assembly, an assembly for reverse osmosis water desalination, and means of purifying the desalinated water (Figure 8) [43]. The electric power is generated from a renewable source. It is subdivided into sectors dedicated to the electric power supply respectively of the pre-filtration assembly, of the first reverse osmosis subassembly and of an auxiliary electric power supply assembly.

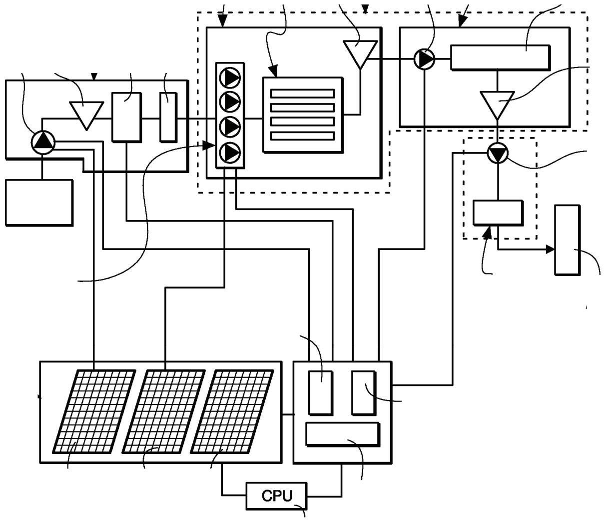

Figure 8. Schematic diagram of a desalination plant powered by renewable energy [43].

Wind energy

Wind farm with wind-driven pressurizing devices is used to desalinate salt water by reverse osmosis (constant pressure and variable flow) [44]. Borden and Smith investigated a structure for converting wind energy to mechanical energy then store and convert to hydrogen fuel by using a vessel having wind towers or turbines [45].

Siegfriedsen's invention [46] uses most of the available kinematic energy of a wind power plant directly for driving pump units. The plant consists of a tower, a gondola, a rotor, and at least one pressure pump that feed a raw water-treating reverse osmosis plant.

Wave and tidal energy

Pumping by wave and tidal energy depends on the depth of the fluid and the length of the pump cylinder. Hill [47] depends on a float for the lift of a ballast weighted piston and the ballast weighted piston, when descending, provides the means of creating pressure on the water entrapped in the cylinder, thus causing a pumping action. Several applications have been suggested for this invention. Some of them are; pump the ocean water over obstructions, creation of hydro-electric power, desalination of sea water, seafood farming, land reclamation from the sea, oil and contaminant reclamation [47].

Throughout the years, none of the proposed hydrokinetic devices have been used the full energy provided by the waves. Therefore, Raftery [48] optimized energy extraction output from hydrokinetic devices by optimizing the devices functionality which applies real time adjustments in response to real time changes in wave characteristics. This optimization controls the depth of the housing to produce wave shoaling/storm avoidance, as well as to perform continuous phase control and load control for the purpose of matching the devices response frequency to the incident wave's frequency.

Taylor and Taylor in their invention presented a method of providing and storing energy and water by using a renewable energy integrated with power plant [49]. The system breakdown is shown in Figure 9. This system has a cross-flow wind turbine with an airfoil stator. The airfoil stator generates electrical and mechanical power in response to wind energy. There are solar cells that are mounted on the airfoil stator which generate electrical power. This electrical power may be used in local electrical devices. Furthermore, the electrical power is used to supply a source of purified drinking water and store the purified drinking water in a tank in the airfoil stator.

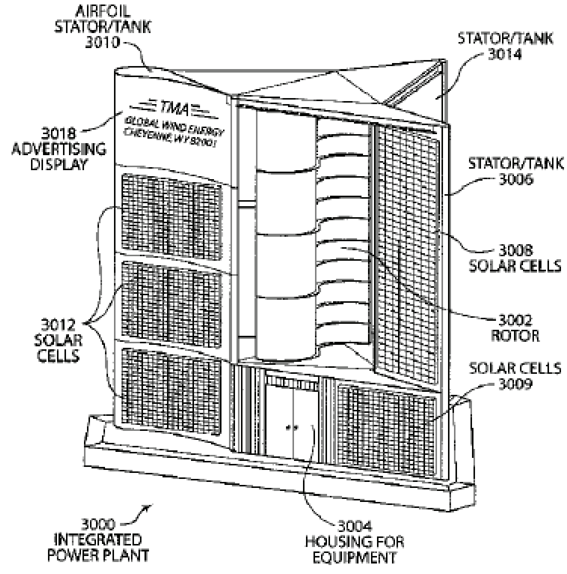

Figure 9. Taylor and Taylor System [49].

It is highly recommended to provide seawater desalination powered by a renewable energy source in remote areas. On the other hand, sequentially staged of energy conversion steps is operated at low efficiencies. Some proposals have been done to use the waves power to drive an evaporator–condenser cycle for desalination [50,51], while another has been investigated to drive a DC generator which then drives a high pressure pump which desalinate seawater through reverse osmosis [52]. Another proposal uses tidal energy to drive a high pressure [53]. In particular, it is desired to provide an impulse-type "wave motor" design that is leveraged to generate high output fluid pressures suitable for desalination by reverse osmosis and other uses [54]. This gives a wave energy conversion device a high efficiency and maintains efficient operation despite tidal variations.

Chen [55] invented a system that utilizes tidal energy. This system can perform seawater desalination, power generation, and utilizing energy from tides, wind, and the sun.

CONCLUSION

It is a fact that fossil fuel is finite and produces greenhouse gases. Therefore, other technologies are urgently required such as renewable energy technologies. Therefore, in this research the relevant wind, hydroelectric, wave and tidal, wind/solar, geothermal, and solar technologies for exploiting the future energy for the friendly environment are reviewed.

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IZVOD

DESALINACIJA KORIŠĆENJEM IZVORA OBNOVLJIVE ENERGIJE: KRATAK PREGLED NEDAVNIH PATENATA

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(Pregledni rad)

U ovom preglednom radu data je kritička analiza najnovijih patenata za desalinaciju vode primenom tehnologija koje koriste obnovljive izvore energije. Posebno je izvršen osvrt na njihov uticaj na životnu sredinu i održivi razvoj. Procenjene su tehnologije korišćenja obnovljivih izvora energije za proizvodnju destilovane vode kao što su energija vetra, energija vode, talasa, plime, hidroelektrična, geotermalna i solarna energija. Solarna energija je majka svih ostalih obnovljivih izvora energija; ona ne zagađuje, slobodna je i dostupna svuda. Nekoliko patenata je izumelo sisteme i metode koje sakupljaju i pretvaraju solarnu energiju u električnu energiju, gde se deo solarne energije može koristiti za desalinizaciju vode. Vetropark sa vetropotisnim uređajima može se koristi za desalinizaciju slane vode pomoću reverzne osmoze. Geotermalna energija se koristi kao vrlo efikasna metoda za desalinizaciju vode. Preporučuje se da se obezbedi desalinacija morske vode korišćenjem obnovljivih izvora energije iz udaljenih područja. S druge strane, sekvencijalno izvedeni koraci za korišćenje obnovljivih izvora energije daju nisku efikasnost.

Ključne reči: • Desalinacija • Održivi razvoj • Ekonomija • Tehnologije obnovljive energije