ASSESSMENT OF MOST PROMISING DEVELOPMENTS IN SOLAR DESALINATION

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Abstract. Indirect solar desalination systems consist of a conventional desalination unit coupled to a solar conversion system, unlike systems as solar stills that integrates in the same device the desalination and the energy conversion processes. They are among the most developed systems of renewable energy-powered desalination. Their most significant possibilities of development in the near future are assessed in this paper. Particular emphasis is given to the efficiency of such systems since their cost mainly depends on the maturity of the technology and the production scale, factors which may change in the future in favour of more efficient systems. Considerable research has to be conducted on the technologies that have never been coupled before as they could be reliable and cost-effective options.

Keywords: Solar desalination; reverse osmosis; multi-effect distillation; multistage flash distillation; membrane distillation

1. Introduction

The status of renewable energy desalination was reviewed in detail by the author [García-Rodríguez 2002; 2003; 2004]. The most mature technologies are solar distillation and reverse osmosis (RO) driven by wind

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power or solar photovoltaic systems. There are also systems with interesting potentials but scarce operational experience and there are even significant improvements which have never been implemented as section 3 points out. Particular emphasis is given to the efficiency of such systems since their cost mainly depends on the maturity of the technology and the production scale, factors which may change in the future in favour of more efficient systems. Within the above framework, this paper proposes the most promising developments of solar desalination, from the author's point of view, depending on the particular features of the plant location and fresh water demand.

2. The Present Status of Indirect Solar Desalination

Indirect solar desalination systems consist of a conventional desalination unit coupled to a solar conversion system, unlike systems as solar stills that integrates in the same device the desalination and the energy conversion processes. A brief summary of the present status of indirect solar desalination is presented in this section. Tables 1 and 2 show solar distillation plants, whereas tables 3 and 4 present desalination plants driven by solar heated thermodynamic power cycles: Table 3 reports desalination systems connected to conventional solar electricity generation plants – dual purpose solar plants- and table 4 shows other solar desalination plants based on Rankine or Stirling cycles. Finally, table 5 reports the pilot experiences on PV driven ED plants, and table 6 presents some of the PV-driven RO plants, the most frequently implemented technology.

TABLE 1. Solar distillation plants driven by salinity gradient solar ponds

Plant location	**Desalination process**	**m^3/d**	**Solar collector**
Margarita de Savoya,Italia[1]	MSF	50-60	Solar pond
El Paso, Texas[2]	MSF	19	Solar pond
Islands of Cape Verde[3]	Atlantis "Autoflash"	300	Solar pond
University of Ancona, Italy[4]	ME-TC	30	Solar pond
Near Dead Sea[5]	MED	3000	Solar pond
Tunez, laboratorie of thermie Industrielle [6]	MSF	$8.6 \cdot 10^{-3}$ m^3/h	Solar pond
[1]: Delyannis, 1987; [2]: Lu and Swift, 1998; [3]: Szacsvay *et al.* 1998; [4]: Caruso and Naviglio, 1999; [5]: European Commision, 1998; [6]: Safi, 1998.			

TABLE 2. Solar distillation plants

Plant location	**Desalination process**	**m^3/d**	**Solar collectors**
La Desired Island, French Caribean [1]	ME- 14 effects	40	Evacuated tube
Abu Dhabi, U.A.E. [2]	ME- 18 effects	120	Evacuated tube
Kuwait[3]	MSF autoregulated	100	Parabolic trough
La Paz, Méjico[3]	MSF-10 stages	10	Flat plate + Parabolic trough
Arabian Gulf[3]	ME	6000	Parabolic trough
Al-Ain, U.A.E. [4]	ME- 55 stages MSF- 75 stages	500	Parabolic trough
Takami Island, Japan[3]	ME- 16 effects	16	Flat plate
Berken, Alemania[5]	MSF	20	-
Lampedusa Island, Italy[6]	MSF	0.3	Low concentration
PSA, Almería, Spain[7]	ME- Heat pump	72	Parabolic trough
Gran Canaria, Spain[8]	MSF	10	Low concentration
Area of Hzag, Tunisia[9]	Distillation	0.1-0.35	Solar collector
Al Azhar University, Gaza[10]	MSF	0.2	Solar collector+ PV (auxiliary energy)
Safat, Kuwait[9]	MSF	10	Solar collector
[1]: Madani, 1990; [2]: El Nashar, 1985; [3]: Delyannis, 1987; [4]: Hanafi, 1991; [5]: Papadakis, 1996; [6]: Palma, 1991; [7]: Zarza Moya, 1991; [8]: Valverde Muela, 1982; [9]: European Comisión, 1998; [10]: Abu-Jabal et al., 2001			

TABLE 3. Dual purpose solar plants

Plant location	**Desalination Process**	**Solar Collector**
Kuwait[1]	MSF (25 m^3/d)- OI (20 m^3/d)	Conventional solar power plant
PSA, Almería, Spain[2]	(72 m^3/d)	Conventional solar power plant
[1]: Delyannis, 1987; [2]: Zarza Moya, 1995		

TABLE 4. Desalination plants driven by solar-heated thermodynamic cycles

Plant location	**Desalination process**	**m^3/d**	**Solar collector**
Yanbu, (Saudi Arabia)[1]	Freezing	-	point-focusing collectors
Los Baños, California, USA[2]	OI	-	Solar pond
El Paso, Texas, USA[3]	OI	-	Solar pond
Cadarache, France[4]	OI (brackish water)	15	Flat plate collector (3 kW)
El Hamrawin, Egypt[4]	OI (brackish water)	54	Flat plate collector (10 kW)
[1]: Luft, 1982; [2]: Engdal, 1987; [3]: Lu et al., 2000; [4]: Libert and Laurel, 1981;			

TABLE 5. PV-driven ED systems

Plant location	**Desalination process**	**Plant capacity**
Thar desert, India[1]	ED- brackish water	0.120 m^3/h
Ohsima island, Nagasaki[2]	ED- sea water	10 m^3/d
Fukue city, Nagasaki, Japan[3]	ED- brackish water	8.33 m^3/h
Spencer Valley, New Mexico[4]	ED- brackish water	2.8 m^3/d
[1]: Adiga *et al.*, 1987; [2] : Kuroda et al., 1987; [3]: Ishimaru, 1994; [4]: Maurel, 1991.		

3. Most Significant Possible Developments

Section 2 pointed out the different status of maturity of the indirect solar desalination systems implemented. Some of them only require minor improvements on control systems in order to fit the solar energy resource or more extensive operational experience. Nevertheless, some other interesting technologies have been scarcely implemented.

Towards the maximum exploitation of natural resources, the most significant development should offer considerable decrease in specific solar energy consumption or high increase in desalination process recovery. Both of them result in much lower specific solar energy consumption and therefore, much lower specific investment cost of the solar system. Nevertheless the complexity of the system should be taken into account, unless it was designed for a developed area or for medium to high capacity range. For instance, in principle hybrid processes are not suitable for small capacity systems or remote locations since they may increase the complexity of the maintenance and the scale economy may be not favourable.

TABLE 6. Some reverse osmosis plants driven by photovoltaic cells, adapted from García-Rodríguez (2003)

Plant location	**Salt concentration**	**Plant capacity**	**PV system**
Cituis West, Jawa, Indonesia[1]	BW	1.5 m^3/h	25 kWp
Concepción del Oro, Mexico[2]	BW	1.5 m^3/d	2.5 kW peak
Doha, Qatar [1]	SW	5.7 m^3/d	11.2 kWp
Eritrea[3]	-	3 m^3/d	2.4 kWp
Florida St. Lucie Inlet State Park, USA[1]	SW	2x0.3 m^3/d	2.7 kWp + diesel generator
Hassi-Khebi, Argelie [1,4]	BW (3.2 g/l)	0.95 m^3/h	2.59 kWp
Heelat ar Rakah camp of Ministry of Water Resources, Oman[5]	BW	5 m^3/d (5 h/d operation)	3250 kWp
INETI, Lisboa, Portugal[6]	BW (about 5000 ppm.)	0.1-0.5 m^3/día	-
Jedd ah, Saudi Arabia [1,2]	42800 ppm.	3.2 m^3/d	8 kW peak
Lampedusa island, Italy[1]	SW	3+2 m^3/h	100 kWp
Lipari island, Italy[1]	SW	2 m^3/h	63 kWp
North of Jawa, Indonesia[2]	BW	12 m^3/d	25.5 kW peak
North west of Sicily, Italy[1]	SW	-	9.8 kWp + 30 kW diesel generator
Perth, Australia[1]	BW	0.5-0.1 m^3/h	1.2 kWp
Pozo Izquierdo- ITC, Gran Canaria, Spain[8]	SW	3 m^3/d	4.8 kWp
Red Sea, Egypt [1,7]	BW (4.4 g/l)	50 m^3/d	19.84 kW peak (pump) 0.64 kW peak (control)
Thar desert, India [1]	BW	1 m^3/d	0.45 kWp
University of Almería, Almería, Spain[1,9]	BW	2.5 m^3/h	23.5 kWp
Vancouver, Canada[1]	SW	0.5-1 m^3/d	4.8 kWp
Wanoo Roadhouse, Australia[1]	BW	-	6 kWp

BW, Brackish water; SW, Sea water.

[1]: European Commision (1998); [2]: Delyannis (1987); [3]: Thomson and Infield (2003); [4]: Kehal (1991); [5]: Al Suleimani and Nair (2000); [6]: Joyce et al. (2001); [7]: Maurel (1991); [8]: Herold and Neskakis (2001); [9]: Andújar Peral et al. (1991)

To gain maximum availability of desalination equipment on stand alone system, the annual mean of hours in operation has to be maximized by proper selection of the solar system and by optimizing the balance of solar system area and operation temperature, and energy storage and desalination plant capacities. If conventional energy backup is available, the solar fraction should be increased to achieve the minimum product cost of solar-driven operational mode.

The following subsections focus on different desalination technologies and point out the most significant improvements that every technology offers.

3.1. REVERSE OSMOSIS DESALINATION

Renewable energy-driven reverse osmosis (RO) normally consists of solar photovoltaic (PV) fields or wind turbines coupled to the RO plant which consumes the produced electricity. Solar RO desalination consists of either, solar photovoltaic fields or solar thermal-driven power cycles as section 2 reported – tables 3-4 -. The energy storage in such systems, if any, normally consists in batteries, although the use of batteries has several disadvantages: maintenance, limited lifetime and toxic wastes. If the RO system is designed for matching the available energy - batteries are not required -, the control of the process has to be carefully designed and tested. There are two possibilities:

- the design arrangement of the system consists of a set of desalination units in parallel working at nominal conditions which can be connected or disconnected.
- the desalination unit is able to match the energy input by suitable changes of working conditions. Simulations of such systems have to take into account that equipment does not operate in nominal conditions, in order to avoid estimations over actual experimental results. Fluctuations in operational conditions may result in damage to the equipment, experimental research on the influence on membrane behaviour of fluctuations in operational parameters is being carried out – pressure, volume, pH, conductivity, concentration of salts, temperature and recovery – [Gomez Gotor et al, 2003][de la Nuez Pestana et al., 2004]-.

On the other hand, energy recovery systems do not usually exist in RO plants powered by renewable energy which results in lower efficiency than that of conventional energy plants. Thomson et al (2002) described an energy recovery device, the Clark pump, specially designed for renewable energy applications to RO desalination, reporting a main energy consumption of 3.5 kWh/m^3.

The most suitable systems for driving solar stand-alone RO plants are salinity gradient solar ponds, dish/Stirling and photovoltaic systems. PV and dish/Stirling systems have the advantage of modularity whereas cost of solar ponds increases considerably in small capacity range. Trieb et al, (1997) presented a case study for solar electricity production comparison and reported specific investment cost of a 5 MW solar pond around one fourth of that of photovoltaic systems, while the cost of dish/Stirling systems are 20% lower. The resulting electricity cost reported for solar ponds are about one ninth of that of photovoltaic systems. Besides that, both, dish/Stirling and photovoltaic technologies permit less than a half of annual full load operational hours than solar ponds permit. On the other hand, some disadvantages of dish-Stirling systems and solar ponds should be taken into account such as their requirements of fresh water or the difficult stabilization of the salt gradient within the solar pond in windy areas.

With regard to efficiency, the thermal performance of commercial photovoltaic systems is around 10% on stand alone system. Nevertheless, solar dish/Stirling systems achieve more than 20% of thermal performance with the same features of modularity and distributed systems than PV ones. Solar electricity generation with paraboloidal dishes has lower costs than photovoltaic systems [Mills, 2004]. The experience on RO systems able to match the variability of the solar resources without batteries above mentioned is applicable to dish-Stirling collectors. In spite of the perspectives of dish-Stirling/RO technology it has not been implemented yet.

Other technologies for solar desalination are the distributed systems based on solar organic Rankine cycles driven by parabolic trough collectors. Such a technology, with evaporation temperature about 250-300ºC, is able to achieve thermal performances around 16% or more, even with heat rejection at temperature high enough to provide additional uses [Delgado Torres, 2004] – Toluene: 16%, boiling temperature, 300ºC; maximum temperature, 400ºC, condensation temperature, 113ºC, turbine efficiency, 75%.

Low temperature organic Rankine cycles have been mainly developed for geothermal energy systems. The thermal performance of electricity production with static solar collectors is of the same order as solar photovoltaic systems and the temperature of the heat rejection is not high enough to be valuable. High and medium temperature solar organic Rankine cycles permit the consumption of electricity by a reverse osmosis system and thermal energy by a distillation process, absorption chillers or other processes. Both possibilities, high and medium temperature solar systems, have been implemented – see tables 3-4 -, but only medium temperature plants based on parabolic trough solar collectors are suitable for distributed production of fresh water within a range of medium to low desalination capacities. None of such systems have been implemented. Mechanical and thermal powers delivered by such systems are able to supply basic needs such as electricity, water desalination, cooling and heating, etc.

Except for very small systems for water irrigation pumping, low to medium temperature solar-heated cycles for small or medium-size systems have not been deeply analysed or developed and very few implementations exist. With regard to desalination, only two designs of solar heat engine-driven RO were performed. All of them use commercial low temperature solar collectors and operate with top cycle temperature around 70ºC [Maurel, 1991; Libert and Laurel, 1981][Manolakos *et al.*, 2004]. The experimental research literature related to distributed power plants of medium temperature solar technologies (parabolic trough) or low temperature (stationary collectors) solar technology is also very scarce: In the early 1980´s, a 150 kWe organic Rankine cycle plant powered by parabolic trough solar collectors was demonstrated. Hassani and Price (2001) reported that the operation problems of this plant precluded further development of such systems. Nevertheless they carried out aa assessment of the technology taking into account the current significant improvements in both, solar and organic Rankine cycle technologies. Saitoh and Hoshi (2002) reported tests on a small electricity generation prototype with 7.6 kW in summer weather conditions, in a system powered by conventional compound parabolic solar concentrators.

3.2. MULTI-EFFECT AND MULTISTAGE FLASH DISTILLATION

Multi-effect and multistage flash processes are considered together in this section because their common features are more important than their differences, regarding their coupling to solar technologies.

There are three different possibilities of reducing the specific consumption of a desalination process: to lower the solar energy requirement of the main energy consumption or the auxiliary energy, or increase the recovery of the desalination process with similar thermal power consumption.

The selection of the solar thermal technology in a solar desalination system with conventional energy as backup should take into account the efficiency of the solar technology with reasonable solar fraction, thermal storage size and costs. With regard to stand alone system, for a given annual demand of fresh water, maximizing the possible annual mean of operation hours normally leads to the most economic solution since it requires the minimum nominal capacity of the desalination plant. In that sense, salinity gradient solar ponds are the best solar technology if the system capacity is not too small since they permit 4316 annual full load hours [Trieb, et al., 1997]. For systems with energy backup, medium temperature technology –parabolic trough collectors- are the most efficient. Among the solar thermal static collectors, compound parabolic concentrators showed to be superior in an assessment performed within Spanish climatic conditions of Plataforma Solar de Almería (CIEMAT) at Almería, Spain. Salinity gradient solar ponds, parabolic trough and compound parabolic concentrators, and evacuate tube and flat plate solar collectors were successfully connected to multi-stage and multi-effect distillation plants – see tables 1 and 2 -. In every case study, the top brine temperature on a multistage flash distillation as well as the number of effects on a multi-effect distillation should be carefully selected according to the solar technology selected in order to minimise the product costs.

The most efficient solar thermal technology and desalination process should be selected in order to decrease the solar energy requirement of the main energy consumption. An additional possibility is to recover the heat rejected by means of coupling other processes in order to achieve a decrease in the energy consumption of the process as a whole. Even a slight reduction of the auxiliary energy consumption is important because it does not require thermal energy, but electricity. Since both multi-effect and multistage flash distillation require a significant part of the auxiliary consumption for pumping the mass flow rate only required as coolant, special attention should be paid to that stream.

In order to maximise the efficiency of a multistage flash (MSF) process we could either increase the top brine temperature or decrease the minimum temperature. Both cases were analysed as follows:

- The minimum temperature is limited by the necessary heat rejection from the system to the ambient. Coupling to an absorption heat pump would allow cooling of the desalination process below ambient temperature, although the low pressure required and the high specific volume of the vapour in the last stages have to be considered. Even though these aspects could make it inadvisable to lower the minimum brine temperature below the values normally used, the coupling of the absorption heat pump (AHP) avoids the discharge of the cooling seawater, thus reducing the auxiliary energy required. Moreover, the main effect of coupling such a heat pump is the recovery of the heat otherwise rejected. Then, the main heat input of the desalination unit is reduced, although the temperature required for driving the heat pump is higher than that of the thermal energy delivered by it. This fact does not represent a disadvantage if solar parabolic through collectors drive the process. There is no experience of AHP/MSF although it is a promising technology for medium to large capacity solar desalination with conventional energy backup.

- The top brine temperature is limited by the feedwater pretreatment. Even more than 120ºC can be achieved with nanofiltration pretreatment [Hassan, 1998], which results in considerable increasing of the performance ratio of the process. Since the auxiliary energy consumption on a multistage flash process is high, it would be an important drawback to increase it even more.

3.2.1. *Coupling a solar-driven double-effect absorption heat pump to a multi-effect of multistage distillation unit*

There was an experience of multi-effect distillation process at the Plataforma Solar de Almería (CIEMAT), Spain, with the coupling of an AHP in order to recover the heat rejected on the end condenser. A prototype of LiBr-water double effect absorption heat pump (DEAHP) was coupled to an existing 3 m^3/h multi-effect distillation unit, SOL-14 plant [Zarza Moya, 1995]. The operation temperatures of the 14-effect remained unchanged but two heat exchangers were incorporated to preheat the feedwater with product and brine outlet streams. The viability of the system was shown and performance ratio around 20 was measured, although different improvement was identified to improve the reliability of the system. A second prototype has been recently coupled to the SOL-14 plant, which is expected to prove the reliability of such coupling obtaining twice performance ratio than that of the SOL-14 plant.

The DEAHP coupled to SOL-14 plant consumes about 108 kJ of thermal energy at 180ºC per kg of distilled water. This is less than one half of the thermal energy required at 70ºC in the multi-effect distillation unit. Let us compare the case study of solar desalination based on SOL-14 plant. Three main possibilities have to be taken into account: a) Medium temperature solar collectors - parabolic trough ones (PTC) - as heat source of a DEAHP coupled to the MED unit. b) Medium temperature solar collectors as direct source of the multi-effect unit. The solar field and the MED plant are connected by a steam generator. c) Low temperature solar collectors (LTC) connected to the multieffect distillation unit.

Table 7 shows the main energy consumption of the desalination system considered, both, the MED unit and the MED unit coupled to the DEAHP (DEAHP-MED).

3.2.2. *Using nanofiltration pretreatment on solar-driven multi-efect distillation*

The use of nanofiltration pretreatment on solar-driven multi-effect or multistage distillation has not been implemented yet. In principle, an increase in the top operation temperature would permit performance ratios around 20 on multi-effect distillation. An organic Rankine cycle with parabolic trough collectors would drive the nanofiltration system and use heat rejection to drive the thermal process with low solar energy consumption. Such systems have interesting perspectives but have never been implemented. Analysis performed on candidate working fluids suggest that only multi-effect distillation process coupled to nanofiltration exhibit interesting perspectives since multistage flash distillation requires quite high temperatures of the heat input in order to achieve significant increase in the performance ratio. None of such solar systems have been implemented.

TABLE 7. Thermodynamic assessment of three different solar desalination systems based on solar thermal collectors and a MED unit (PTC: parabolic trough collectors, LTC: temperature solar collectors)

Desalination system	**Main energy consumption, kJ/kg**	**Solar desalination system**	**Solar energy consumption(*), kJ/kg**
DEAHP-MED	108 (at 180ºC)	PTC-DEAHP-MED	142
MED	240 (at 70ºC)	PTC-MED	315
MED	240 (at 70ºC)	LTC-MED	545-1600 333-369(**)
(*) Efficiency of solar collectors at 800 W/m^2 (solar irradiance) (**) If evacuated absorber tubes are used			

3.2.3. *Coupling a membrane distillation system to a solar-driven multi-effect or multistage flash distillation units*

Coupling a membrane distillation process to recover part of the heat rejected by the warm blowdown also increases the recovery of the hybrid desalination process as a whole, with a negligible increase in auxiliary energy. Since the heat consumption of the membrane distillation process does not reduce the performance ratio of the multi-effect process, the economy of the process should be favourable. A precise assessment is not possible since costs of the membrane distillation process are not precisely defined in the literature, and also because the extrapolation or experimental results to different conditions are also difficult [Alklaibi and Lior, 2004].

The different possibilities of hybridation mult-stage flash and multi-effect distillation should be analysed and implemented. A deeper analysis is required in order to assess the limit of possible performance ratio of the hybrid system as a whole and the specific product costs.

3.3. MEMBRANE DISTILLATION

The coupling of a membrane distillation system to a solar-driven multi-effect or multistage flash distillation units in order to increase the overall performance ratio was discussed in section 3.2. Other hybrid desalination processes also have interesting potentials. Reverse osmosis desalination driven by solar-assisted power cycles provides the electricity consumption of the RO plant as well as the low grade thermal energy consumption of the membrane distillation process in order to distil the blowdown of the RO plant. To the author's knowledge, none of these hybrid desalination processes have ever been implemented.

In stand-alone solar desalination systems, the connection of a salinity gradient solar pond to a membrane distillation process has never been implemented. It could however be one of the most economic systems since a given membrane distillation system is able to operate at varying top brine temperature provided by the solar pond during the year. This fact guaranties the continuous and troublefree operation of the desalination system along the year, according to solar pond behaviour – see Al-Jamal and Khashan (1998) -. Only a slight decrease in the performance ratio should be exhibited in winter since the decreasing ambient temperature partially overcomes the decreasing temperature of the heat storage zone.

If a conventional thermal input is available as energy backup, an absorption heat pump provides a higher exergetic performance for the fossil fuel since the temperature of the required heat input is higher than that of the membrane distillation process. The coupling of a heat pump would also lower the temperature of the coolant below ambient temperature, thus increasing the performance of the membrane distillation process.

4. Conclusions

The main conclusions about future development of solar-powered desalination come from the assessment presented above:

- If the water demand in the near future is not predictable, modular systems are the best option. First of all reverse osmosis should be considered, although membrane distillation could soon be an economic option.

- If conventional energy is available as energy backup and the fresh water demand is not small, multi-effect or multistage flash distillation processes should be considered as important as reverse osmosis.
- If a stand-alone system is projected, firstly the use of salinity gradient solar ponds should be compared with reverse osmosis powered by dish/Stirling systems as the best options. Solar pond-powered desalination cost mainly depends on plant capacity since small solar ponds are much less cost effective than large ones. Solar ponds also permit the highest annual operation hours. The coupling of the solar pond to a membrane distillation process permits continuous operation during the year, although membrane distillation is not a mature technology. Other reasonable processes are multistage flash distillation, multi-effect distillation or reverse osmosis. Multi-effect and multistage flash distillation require careful analysis of the optimum number of effect and top brine temperature, respectively.
- If thermal energy is available as backup, organic Rankine cycles driven by parabolic trough collectors coupled to reverse osmosis are superior to conventional solar distillation processes. Nevertheless high efficiency thermal processes have to be considered, parabolic trough collectors coupled to:
    - multi-effect distillation driven by a double-effect absorption heat pump;
    - multi-effect distillation with nanofiltration pretreatment by means of organic Rankine cycles;
    - hybrid processes membrane distillation/multistage flash or membrane distillation/multi-effect distillation.

Considerable research has to be conducted on the technologies that have never been implemented before as they could be reliable and cost-effective options.

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