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Double-acting batch-RO system for desalination of brackish water with high efficiency and high recovery

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ABSTRACT

The batch-RO concept has been presented and demonstrated as a means of desalination that can approach the ideal minimum specific energy consumption, even as the recovery ratio is increased. It overcomes the configuration loss of conventional single or multi-stage constant flow processes, and it avoids the mixing of feed with re-circulated saline water inherent in closed-circuit desalination. A drawback of the batch system presented earlier, however, was the need to interrupt the output while the system was refilled between batches. In the new design presented here, the pressure exchange vessel is configured to be double-acting, such that one side is refilling while the other is pressuring. Thus, the output is maintained during refill, resulting in an increase in water output of about 25% compared to the earlier system, with membrane area remaining the same. The inconvenience of stopping and starting the feed pump is also avoided. A prototype of the double-acting system is under development and results will be presented at the conference, including specific energy consumption, recovery ratio, rejection fraction, and cycle time. The system is targeted for use in inland arid areas and may be powered by solar photovoltaic electricity.

Keywords: Brackish water; Reverse osmosis; High efficiency; High recovery; Solar

1. Introduction

Water resources play a vital role in sustainable development, affecting social, economic, and environmental factors. There are a number of linkages between water availability and global issues such as population growth, human health, food security, urbanization, and climate change. Water resources, and the related services they provide, must be carefully managed to maximize their potential and ensure fair and safe distribution.

By 2050, global water demand is predicted to increase by 55%, in close correlation to growing demands in irrigation, manufacturing, electricity generation, and domestic uses [1]. Irrigation, which accounts for the greatest usage of water by far (Fig. 1), is expected to increase alongside world population and rising food demand.

Water stress and water scarcity are pressing global issues. It has been predicted that, by 2025, half of the world's population will be living in water-stressed conditions and up to 1.8 billion in regions of absolute water scarcity [2]. Whereas 97.5% of the Earth's water is salty seawater; only 2.5% is present as freshwater; 1.74% is trapped in ice and snow making it inaccessible; and 0.75% is in the form of brackish groundwater, which can either be surface water or underground in salty aquifers [1]. In order to access sea- and brackish-water resources and provide safe water for human consumption, desalination technology is utilized. This study focuses on brackish water desalination.

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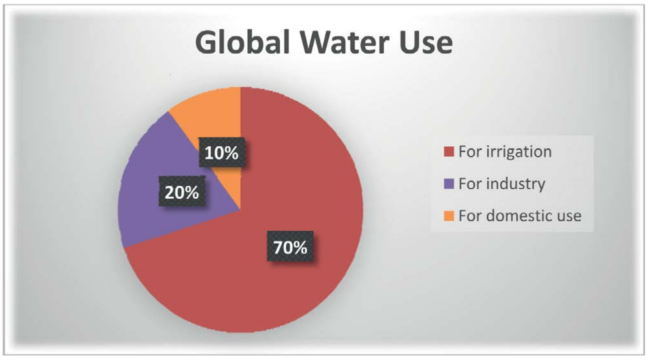

Fig. 1. Distribution of global water use (UN-WATER, 2013).

2. Brackish water desalination

The desalination market can be broken down according to feedwater type, with 58.9% using seawater, 21.2% brackish water and groundwater sources, and the remainder surface water and saline wastewater [3]. Energy consumption and total water costs determine the most suitable type of desalination plant to be implemented in a specific region and these are largely site-specific. Fig. 2 displays the average energy consumption and costs for various desalination technologies. The total water cost depends on the investment cost for the design, development, and manufacturing of the desalination plant.

Evidently, desalination of brackish water using reverse osmosis technology (BWRO) has the lowest energy consumption and thus produces the cheapest total water cost. This is because RO technology requires only electricity, whereas thermal desalination (MSF and MED) requires both electricity and heat, thus consuming higher energy in total. Therefore, RO technology is most suitable for rural areas of the developing world, as it provides a lower-cost solution to providing clean drinking water. Nonetheless, the installation and running costs of brackish water RO plants are still significant and prohibitive for many rural residents.

Two-thirds of total groundwater abstraction takes place in Asia, with India, China, Pakistan, Iran, and Bangladesh as the primary consumers. This groundwater is vital for the livelihood and food security of approximately 1.5 billion rural households in poorer regions of the world. The global groundwater abstraction rate has tripled over the past 50 y, and is predicted to continue to increase at an annual rate of 1%–2%. Groundwater resources contribute to approximately 50% of all drinking water, but the effects of climate change and urbanization are expected to negatively impact these vital reserves [4]. The need to conserve groundwater calls for the implementation of high recovery desalination systems, which will also minimize the discharge of brine to the environment.

3. Renewable energy for desalination

The World Bank has estimated that, on average, 5%–30% of the total operating cost of water and wastewater utilities is due to electricity costs. The global energy demand is predicted to increase by a third by 2030 and this is largely due to an increasing population. Renewables, in particular,

Process	Thermal energy kWh/m^3	Electrical energy kWh/m^3	Total energy kWh/m^3	Investment cost \$/m^3/d	Total water cost US\$/m^3
MSF	7.5–12	2.5–4	10–16	1200–2500	(0.8–1.5)[a]
MED	4–7	1.5–2	5.5–9	900–2000	0.7–1.2
SWRO	–	(3–4)[b]	3–4	900–2500	0.5–1.2
BWRO	–	0.5–2.5	0.5–2.5	300–1200	0.2–0.4

[a] Including subsidies (price of fuel).
[b] Including energy recovery system.

Fig. 2. Energy consumption and water cost (average values) of commercial desalination processes (SWRO = seawater RO, BWRO = brackish water RO) [3].

are expected to increase in demand by 77%, which is greater than oil, coal, natural gas, or nuclear energy [1].

Desalination plants powered by renewable energy sources can provide a sustainable alternative for the production of freshwater. Communities that will benefit the most from desalination plants powered by renewable energy are those in rural areas, where there are limited financial resources and poor infrastructure for freshwater supply and electricity transmission. Using renewable energy that is locally available, such as solar and geothermal, can be a viable cost-effective solution [5].

There have been several small-scale renewable energy-powered desalination systems that have been successful in operation and have required minimal maintenance. With the increasing demand for desalinated water in energy-importing countries, such as India and China, there is a large market potential to provide desalination plants powered by renewable energy. This will lead to such countries being more water-secure, without the reliance on other nations for energy [6].

Currently, renewable-based desalination plants make up approximately 1% of the global desalination capacity and this is primarily focussed on the RO process, which encompasses 62% of such renewable-based systems. It is important that the technical feasibility and cost-effectiveness of any renewable desalination plant is appropriately assessed, to ensure it will be successful when implemented. Factors such as location, salinity of the feedwater, quality of the freshwater output, available renewable energy resources, plant capacity and size, population size, and the availability of grid electricity must all be evaluated to determine the most suitable type of desalination plant [7].

There are three major renewable energy resources that are currently utilized and these include; solar (photovoltaic and thermal), wind, and geothermal. The thermal energy resources are typically used in conjunction with thermal distillation desalination, whilst the wind and solar PV are usually paired with RO desalination. The most common renewable energy source is solar, which makes up 70% of the renewable energy desalination market [8].

4. Case study: Palestine

Sustainable implementation and management of groundwater desalination technology have to be considered in its geographical and political context. Groundwater resources frequently straddle international boundaries, and as resources become depleted the potential for conflict becomes

Year	Population (inhabitant)	Agriculture water demand	Domestic& industrial water demand	Total demand	Available resources	Gap
2000	1167359	91	55	146	109	**-37**
2005	1472333	92	100	192	131	**-61**
2010	1871144	88	125	213	137	**-76**
2015	2241206	86	152	238	145	**-93**
2020	2617823	80	182	262	155	**-107**

Source: PWA, CAPM (2000)
All figures in MCM/ year.

Fig. 3. Overall projection water demand in the Gaza Strip [12].

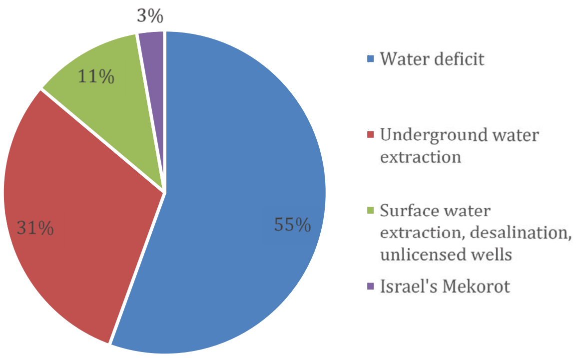

Fig. 4. Freshwater supply sources in the Gaza Strip [12].

Water Resource	Year				
	2000	2005	2010	2015	2020
Coastal aquifer**	55	92	100	119	148
Brackish groundwater	51	35	32	20	0
Wastewater re-use	0	23	34	48	63
Israel/ Mekerot	5	10	10	10	10
Desalination	**0**	**24**	**47**	**55**	**57**
Storm water recharge	3	4	5	6	7
Transfer from West Bank	0	0	0	0	0
Total	**114**	**188**	**228**	**258**	**285**

Source: PWA, (2000)
*** All figures in MCM/year*

Fig. 5. Water resources development in the Gaza Strip 2000–2020 [12].

heightened. This danger is very clearly illustrated in the case of Palestine and the Jordan river basin.

4.1. Palestine's looming water crisis

Water supply and sanitation in the Palestinian territories are characterized by severe shortages and poor quality. More than 20 y have passed since the Oslo Accord in which a water-sharing agreement was signed between the Palestinian Liberation Organisation and Israel. Since then, however, Israel has come to control the vast majority of Palestine's freshwater sources. This, coupled with an underdeveloped supply system, means that many Palestinians face serious water shortages (Fig. 3).

The problem is particularly severe in the Gaza Strip. While Gaza requires 180 million m^3/y, extraction from underground aquifers only provides 55 million m^3/y [9]. 5 million m^3/y is supplied from Israel's national water company Mekorot, resulting in a water crisis in the Gaza strip. There are over 6,000 unlicensed wells and a number of desalination units, resulting in an annual water deficit of 100 million m^3/y [9] (Fig. 4). Gazans are receiving less than half the water recommended by the World Health Organization to survive.

Israel has already doubled the amount of water sent to Gaza, but at least two additional large desalination plants will be needed to meet Gaza's needs [10] (Fig. 5).

Of the total 170 million m^3 used per year, 90 million m^3 is used for human consumption and 80 for agricultural use [11]. In 2013, 27% of households had water supplied on a daily basis, while 51.3% of households were supplied with water three to 4 d per week [12].

How Palestinians in Gaza rate their water:

- In 2013, 27% of households had water supplied on a daily basis [11], while 51.3% of households were supplied with water 3–4 d per week [13].
- Only 5.8% of Gaza Palestinians consider their water good enough to drink.

Gaza also suffers from underdeveloped infrastructure, which causes leaks in pipes leading to a total of 77.3 million m^3/y in losses [13]. These leakages, as well as coastal ingression of seawater, have led to underground water contamination and increasing salinity levels. This is a problem that is not likely to be solved in the near future as successive wars have led to the destruction of water infrastructure and the absence of comprehensive development.

A recent report by the UN Conference on Trade and Development predicted:

"Gaza will be uninhabitable by 2020" [14].

4.2. Could desalination solve Gaza's water woes?

Many citizens now believe seawater desalination has become an essential solution. The problem lies not in technical feasibility, rather the high costs of such projects, as well as Israeli restrictions impeding developments and the fear that war or conflict may result in a plant being destroyed.

Fifteen years ago, a plan was put in place to develop Gaza's water infrastructure (Table 1); however, this was

Table 1
Development of desalination plant in Gaza Strip [16]

Stage	Capacity (million m^3/y)	Cost (€ million)
Stage 1 – 2015	13	10
Stage 2 – 2020	55	N/A
Stage 3	110	500

pushed back due to the existing political situation. This has prevented donors from investing in these projects and has forced the Palestinian Water Authority to find alternatives by establishing three desalination plants in Gaza for the production of 13 million m^3 annually, contributing to a small degree to fixing the problem [15]. The project will go undergo a number of expansions.

The costs of the project will be split between a number of European countries and the Islamic Development Bank [16]. Desalination is a practical and necessary solution to Gaza's water crisis. Further investment is expected especially for underground brackish as the coastal aquifer deteriorates further. Large-scale projects are out of the question; investors are dissuaded from investing in desalination projects which may soon be destroyed after completion. Desalinated water has become the only choice for drinking water for many Gazans. The water comes in the form of 120 small-scale desalination plants, distributed to households in private trucks [17]. According to Munther Sheblak, head of the Coastal Municipalities Water Utility "only 5% of Gaza's water is fit for human consumption" [17]. The water is highly contaminated (Table 2).

4.3. Gaza's energy problem

"In terms of water impacts, wind and solar PV are the most sustainable forms of power generation" [19].

Small-scale desalination units may seem like a suitable solution until the intensive cost of energy is considered. The Israeli embargo on the region is reducing electric power supply to 120 MW which is 65% of the total demand [19]. Thermal distillation has serious practical limitations, as it requires large quantities of thermal energy. However, RO desalination can be powered by the all-round-year solar energy over Gaza, which averages as 230 W/m^2 over the year (Fig. 6) [20].

The advancement in PV cells has led to efficiencies from 15% to 18% and lower production costs, such that they are becoming affordable even in poor regions. Furthermore, solar energy is well established in both the West Bank and Gaza Strip with 70% of households having installed solar domestic hot water [20].

4.4. Existing technologies

Alongside rising water demand (Fig. 7), the number of desalination plants in Gaza has been increasing for the past 15 y, especially unlicensed rigs (Fig. 8).

There are a number of companies that specialize in small-scale brackish water desalination in the West Bank. However, there are very limited few that function within the Gaza Strip.

Table 2
Gaza fresh water quality [18]

	Recommended limit	Recorded value
Nitrate	250–350 mg/L	50–70 mg/L
Chloride	250 mg/L	15,000 mg/L

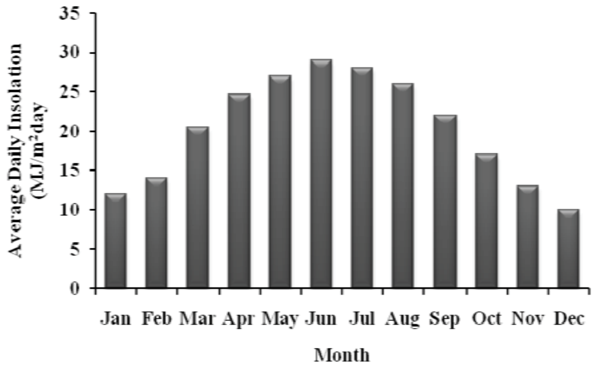

Fig. 6. Average daily solar radiation measured for Gaza (I. Khatib, 2010).

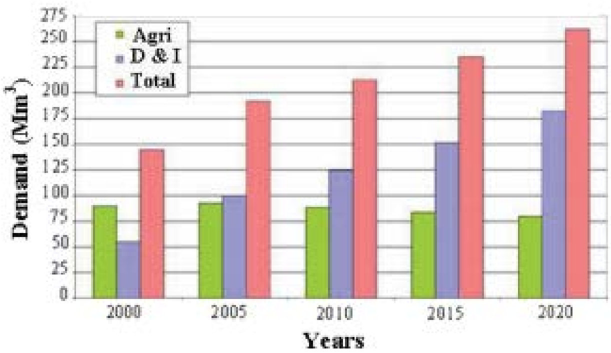

Fig. 7. Overall water demand in Gaza Strip [21].

4.5. Opportunity for investment

In 2014, international donors pledged $5.4 billion to help rebuild Gaza after the war [16]. The Union for the Mediterranean (UfM) presented a desalination facility project to the international community at a conference in Cairo in 2014. The Norwegian government has also funded the Comparative Study of Water Supply Options for the Gaza Strip (CSO-G) with support from the Palestinian Water Sector to come up with a water supply strategy [16].

NGO's such as UNESCO as well regional (EU) and national governments (Norway) are constantly seeking investments aimed at improving the standards of basic human needs in Gaza.

5. Aston University's solution

In order to address the aforementioned global issues of water scarcity, poverty, and potential conflict, a brackish groundwater desalination system was built and tested in

No.	Plant Name	Governorate	Source of row water	Design capacity M³/day	Quantity sold M³/day	Brine discharge	TDS (Mg/L)
1	Al methali		brackish well	96	96	irrigated gardens	51
2	Al khayria1		municipal water	12	12	Municipal network	22
3	Al karama	North	municipal water	20	10	NA	NA
4	Al gadir		municipal water	30	20	Municipal network	100
5	Yaffa		brackish well	96	40	Municipal network	NA
6	Al ain safi		brackish well	90	40	irrigated gardens	65
7	Al Ain		brackish well	40	30	Municipal network	46
8	Al khayria2		municipal water	12	12	Municipal network	78
9	Al khayria3		municipal water	12	12	Municipal network	187
10	Salsabil		brackish well	20	10	irrigated gardens	205
11	Sehaa		municipal water	10	6	Municipal network	51
12	Al janoub		brackish well	60	40	Wadi Gaza	183
13	Al kemma	Gaza	municipal water	12	12	Municipal network	35
14	Al fardaws		brackish well	100	60	Municipal network	60
15	Al sahib		brackish well	100	40	Municipal network	57
16	Al sabra		brackish well	20	10	Municipal network	83
17	Akwa		brackish well	1200	120-80	Municipal network	260
18	Al khayria4		municipal water	12	12	Municipal network	76
19	Al khawthar		brackish well	40	20	Municipal network	75
20	Al shalal		municipal water	12	12	Municipal network	40
21	Al khayria5		brackish well	12	12	irrigated gardens	NA
22	Al furat	Middle	brackish well	50	20	Wadi Gaza	120
23	Al westa		brackish well	12	12	irrigated gardens	185
24	Zamzum	Rafah	brackish well	20	10	Municipal network	37
25	Al furat		municipal water	20	10	Municipal network	42

Source: Ismail, M., (2003)

Fig. 8. Commercial RO private desalination plants in the local market [10].

2015 by a team of M.Eng students at Aston University, UK. This system was designed to operate with high recovery, utilizing energy from a solar photovoltaic array simulator. It was able to reach a recovery ratio of 70%, with specific energy consumptions below 1 kWh/m³. Exceptional performance and efficiency were achieved by means of a non-conventional batch arrangement to provide high energy and water recovery. Nonetheless, in its current form, the system must be operated manually by at least two operators, thus requiring high labor costs if implemented for mainstream use [22].

It was determined from this project that a more compact, fully automated system, with a higher recovery ratio, can be developed through careful design and implementation. This work is currently being conducted by another team at Aston University, to provide a more commercial product that can be marketed for mass production, in regions suffering from water scarcity.

5.1. Aim and objectives

The Mark 2 system that is currently under development is being designed as a practical solution for use in arid regions throughout the world, to successfully tackle the issue of water scarcity where saline groundwater is available. The objectives of this development are as follows:

- Estimated daily output (dependent on weather conditions and input water quality): 1 m³ of water per day, which is enough to support at least 20 people for their daily water requirements (50 L/person).
- Operate with low energy consumption (less than 0.25 kW) to provide rural villages with a cost-effective and feasible solution to produce fresh water.
- Operate with a high recovery ratio of 70%–80%; this minimizes brine management problems.
- Ensure the system is compact in size, with a reduced footprint.
- A fully automated system, thus eliminating the requirement of a constant operator when the desalination system is in use. This also minimizes the maintenance required.
- The desalination plant must successfully remove any biological and chemical contaminants to ensure the water output is at a quality level recommended by WHO, along with a reduced salinity of less than 500 ppm.

5.2. Design overview and rationale

To successfully design a desalination product for use in such rural regions, it is important to consider a number

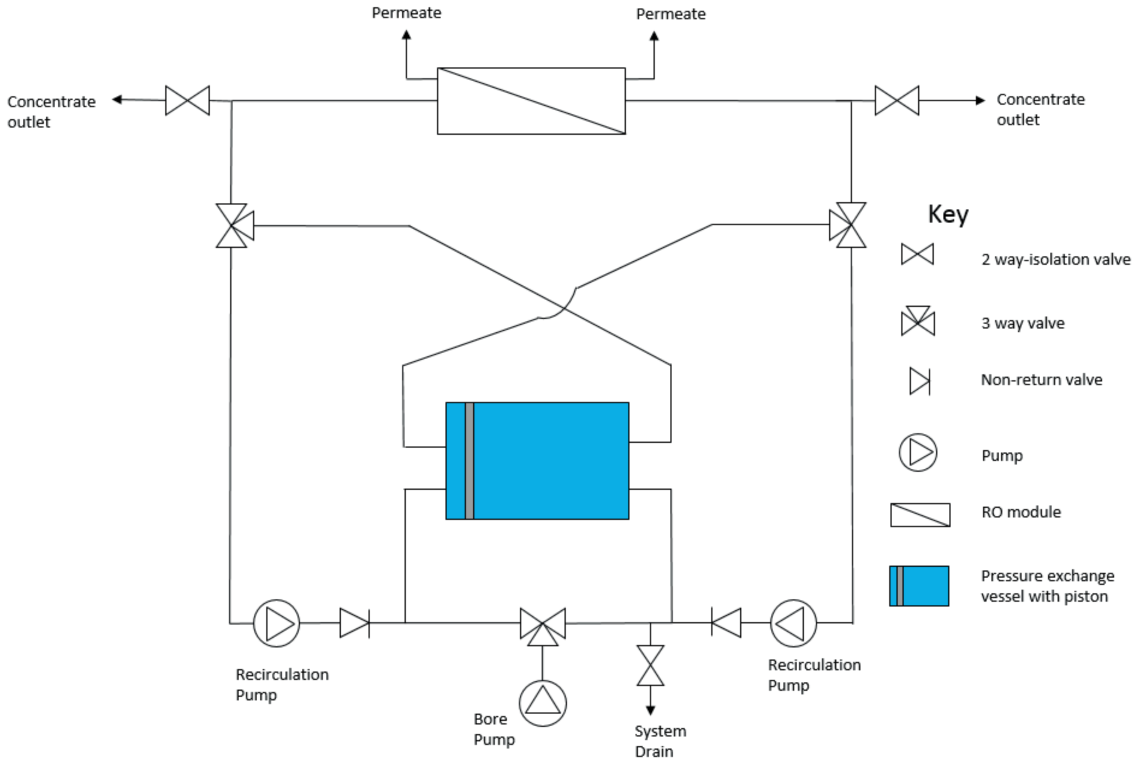

Fig. 9. Overall concept schematic.

of factors, including; energy supply, energy consumption, maintenance, overall cost, and water distribution. These factors were all considered to ensure the final product is feasible for the selected market regions. The following section describes the overall concept and functionality of the Mark 2 system. The main difference in comparison to Mark 1, is the capacity to operate without interruption, as the pressure exchange vessel works in a double-acting mode: one side is refilling while the other side is pressuring. This avoids the need to halt the pump between stages of operation and will lead to greater efficiency and output.

5.3. Concept of operation

Fig. 9 shows the concept schematic, detailing the components and how they function as a system.

Fig. 9 shows the design of the overall system. The system will be made up of:

- 2 × automated 2-way isolation valves
- 3 × automated 3-way valves
- 2 × non-return valves
- 1 × manual drain valve
- 2 × recirculation pumps
- 1 × bore pump
- 1 × GRP pressure vessel (with R.O. membrane inside)
- 1 × GRP pressure vessel (with a piston inside)

5.4. Sequence of operation

The proposed desalination plant is set to operate in a 4-stage sequence that will be repeated continuously throughout the day, until the system is switched off or until the water demand is satisfied. Figs. 10–13 display the sequence as follows.

5.4.1. Stage 1: pressurization (first time)

During startup (initial pressurization), the bore pump will be switched on, and the flow of feed water will push the piston toward the far end of the pressure vessel. This will result in the water on the other side of the piston, within the vessel, becoming pressurized and go through the RO membrane. This water will then split into two flows; the treated permeate will come out of the end port. Whereas, the reject concentrate will be re-circulated back into the pressure exchange vessel. Recirculation of the flow of the concentrated brine back into the pressure exchange vessel enables the reject to pass through the RO module several times for enhanced recovery. During this stage, the feed water does not mix with the pressurized water, therefore resulting in the gradual increase of the salt concentration within the pressure exchange vessel, pipework, and RO module; thus raising the osmotic pressure and the work needed to counteract this, for the next batch of water.

Note that the recirculation flow rate should exceed several fold the feedflow rate, to ensure homogeneity within the loop, and to provide a rapid cross-flow that minimizes concentration polarization.

5.4.2. Stage 2: purge (first time)

In order to reduce the osmotic pressure of the concentrated brine accumulated within the system, a purge

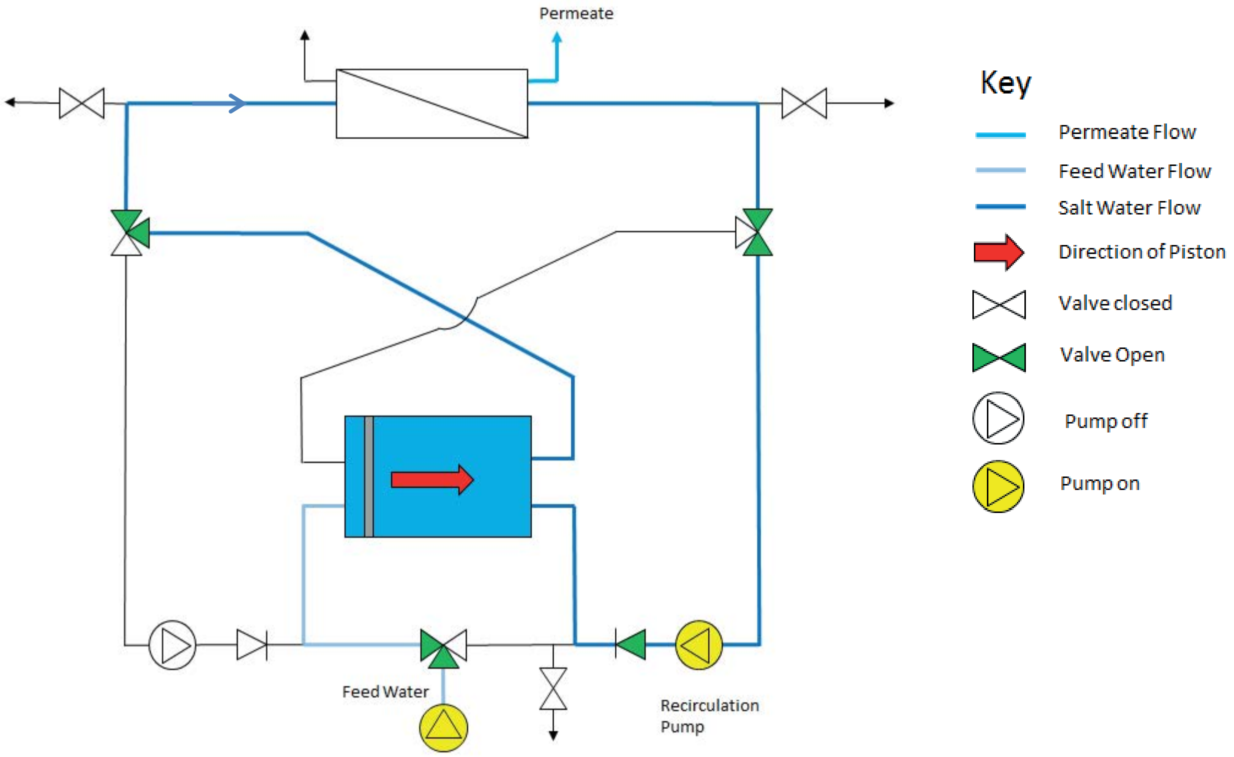

Fig. 10. Stage 1; pressurization (first time).

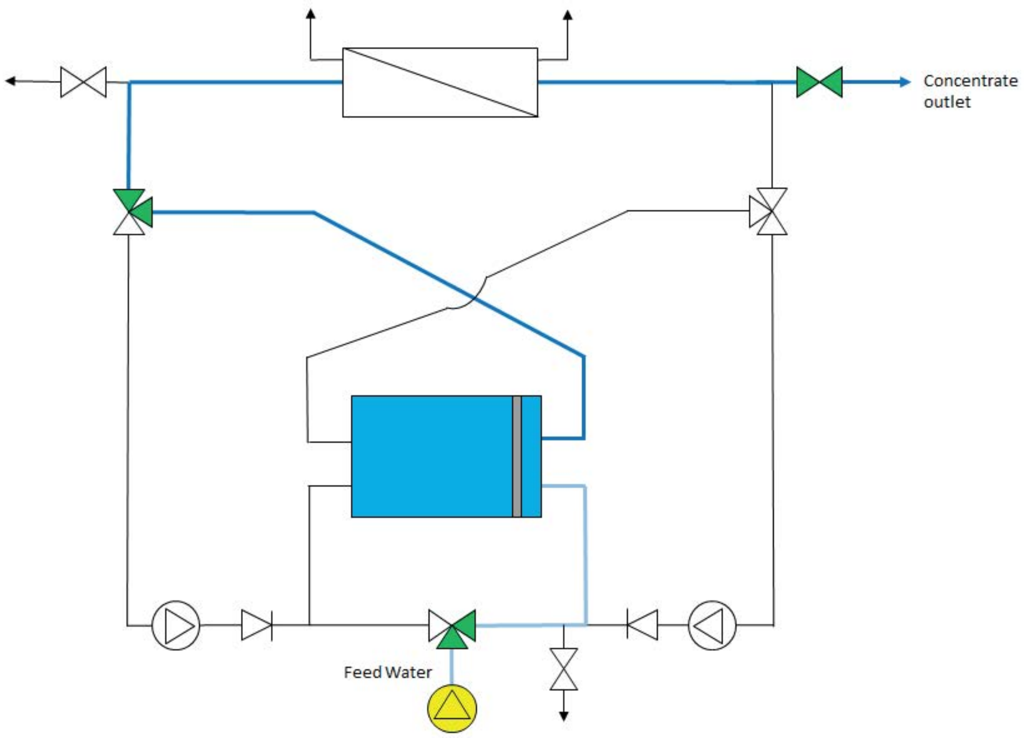

Fig. 11. Stage 2; purge (first time).

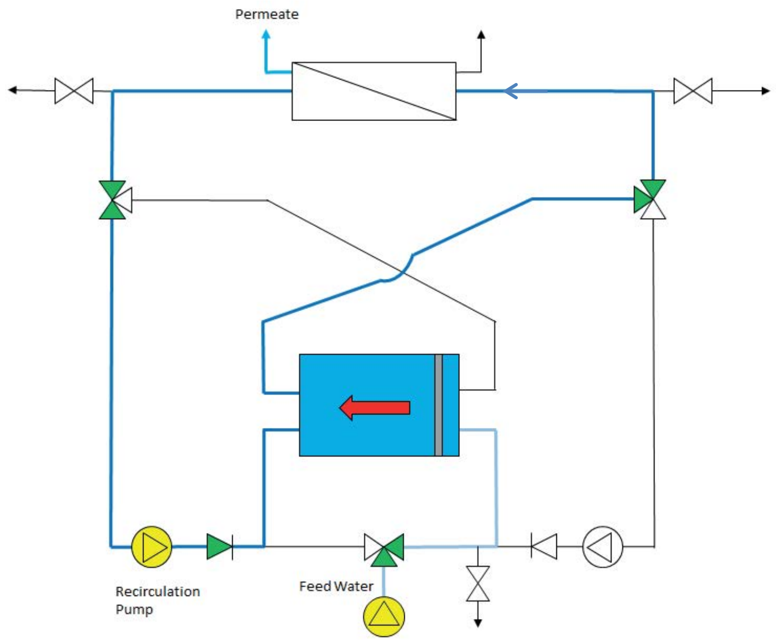

Fig. 12. Stage 3; pressurization (second time).

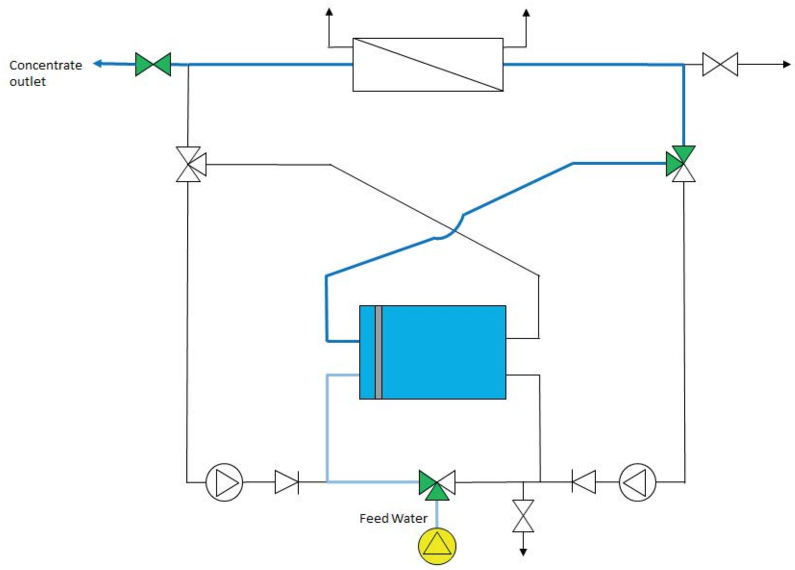

Fig. 13. Stage 4; purge (second time).

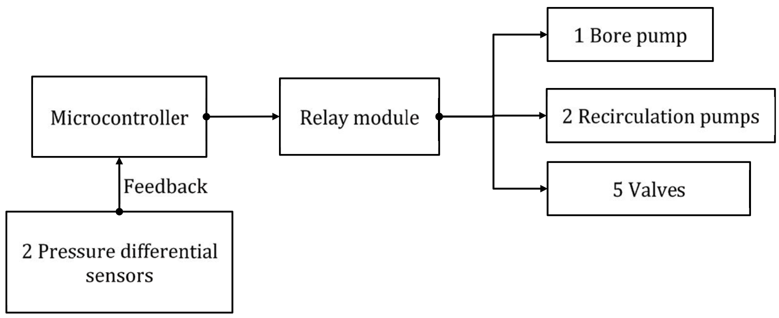

Fig. 14. Electric control of the system, using Arduino.

stage is required. During this stage, the system will not be under pressure, as the piston within the pressure exchange vessel will be under a hydraulic lock. The bore pump will be used to draw feed water of lower salt concentration to purge the system to remove any built-up salt concentrations out of the pipework and RO module.

5.4.3. Stage 3: pressurization (second time)

Unlike the Aston University Mark 1 system, where a refill stage was required to reset the position of the piston inside the pressure exchange vessel, to treat the feedwater that was added to the system in stage 1, this stage has been replaced by another pressurization stage. The new design has negated the need for re-priming the system, as it allows the piston to work in reverse. By allowing the piston to work in reverse, the overall capacity of freshwater that the system can produce per day is increased.

5.4.4. Stage 4: purge (second time)

In essence, the second pressurization stage works under the same principles as the first pressurization stage. Therefore a second purge stage is required to remove the build-up of brine rejects within the system. Note that during the second pressurization stage, the direction of cross-flow is reversed with respect to the first pressurization stage. This continual reversal is expected to reduce the tendency for precipitation of foulants on the membrane to occur.

5.5. Avoidance of batteries

The proposed desalination system will avoid the use of batteries, as they are found to have many undesirable disadvantages for the intended target markets. Batteries are typically found to be very expensive, especially for higher quality ones that would be used for energy-intensive applications such as desalination. In Germany, there are cases where a battery storage system for off-grid PV systems could at least £10,000 to the cost of a project. Furthermore, batteries are usually made up of hazardous materials that affect the environment during manufacture, use, and disposal. Batteries also have a limited lifetime, thus adding to maintenance costs for when they need replacing. It is also found that batteries can be wasteful, as 20% of all the energy put into them is wasted due to influences in the charge/discharge cycle [23].

6. Design implementation

Once the overall concept was finalized, the design specification was set and a detailed implementation process ensured the correct components and materials were selected for the successful operation of the desalination plant.

6.1. Design specification

The expected specifications of this machine are:

Rated output	2.2 L/min
Estimated daily output (dependent on weather conditions and input water quality)	1 m^3/d
Input salinity (TDS)	1,000–5,000 ppm
Output salinity	<500 ppm
PV array peak rating	250 W
PV array size	1.7 m^2
Machine dimensions (m)	2 long × 0.5 wide × 1 high
Recovery rate	70%–80%

6.2. Bill of materials

The components of the desalination plant consisted of specialist parts, that require importation from specific suppliers, and general components that can be locally sourced. These are displayed in Tables 3 and 4.

6.2.1. Specialist components

Table 3
Specialist components

Item	Quantity	Total Cost
4″ RO Membrane module	1	£185
4″ Pressure vessel	2	£360
Electrical controls	Various	£90
Recirculation pump	2	£195
Special valves	5	£220
PV panel (250 W)	1	£290
Borehole pump	1	£1,280
	Total	£2,620

6.2.2. Commonly available components, locally sourced

Table 4
Commonly available components

Item	Quantity	Total cost
Framework and painting (local construction)	30 m	£200
Pre-treatment filters	2	£200
Pipework and fittings (standard PVC components)	Various	£240
Instrumentation pressure gauges and flowmeters)	Various	£60
	Total	£700

6.3. RO module and membrane

The RO module that was selected as the 4″ End Port Pressure Vessel (4E350N.1) from Phoenix Vessel Technology Ltd., (Gloucester, UK) as it had a suitable pressure rating of 24.2 bar and working temperature of 0°C–45°C.

The 4″ LCHR-4040 DOW FILMTEC membrane was used in this system, which is a polyamide thin-film composite membrane suitable for treating brackish water with a maximum SDI of 5. It was chosen due to its high efficiency and performance characteristics, as it is able to produce high purity water at a low total system cost.

6.4. Pressure exchange vessel and piston

The pressure exchange vessel was identical to the RO module (Product Code: 4E350N.1), as it was able to operate at a high-pressure rating and house a 4″ piston. A cylindrical, high-density polyethylene (HDPE) piston was used to isolate the volume of saline water undergoing reverse osmosis from the water being utilized to drive the process. The piston length determines the recovery ratio of the system and this was carefully evaluated and custom-designed to achieve a recovery in the range 70%–80%.

6.5. Pumps and valves

There are three pumps used in this system and these include:

- 1× bore pump
- 2× recirculation pump

The bore pump used is the positive displacement Grundfos SQF 0.6–2.3″ submersible pump. Unlike a centrifugal pump, where the flow varies with changing pressure, a positive displacement pump has a constant flow with changing pressure. Furthermore, a positive displacement pump creates a negative pressure at the inlet port, for brackish groundwater applications and this is essential, as it allows for a dry pump to prime on its own. Whereas centrifugal type pumps require the liquid to be inside in order to create a pressure differential; due to this, a dry centrifugal pump will not prime on its own. Positive displacement type pumps have a high head when compared to centrifugal type pumps, which make them very suitable for drawing water from a deep bore [24,25]. Another major advantage of using a positive displacement pump is the type of power source that the system will be using. Since the proposed RO desalination plant will be powered using a solar PV panel, it is likely to experience power fluctuations. The positive displacement pump with this type of power source will vary the pressure whilst maintaining a constant flow of feedwater.

The selected recirculation pump was a 230 V Flomasta Central Heating pump and this was due to the fact it is able to operate at a maximum flow rate of 3.5 m^3/h with a maximum head delivery of 5 m. It operates within a temperature range of –10°C to +95°C, which is ideal for an application that will be implemented in arid, hot regions.

The 3-way T-port actuated ball valve with auto-return, from solenoid valves, was chosen as it allows the system to be fully automated and operates at a low voltage of 9–24 V. It can effectively function with a water temperature of up to 100°C and at a maximum pressure of 16 bar. The 3-way valve is also designed in accordance with IP 65 coding, which ensures it is dust and water jet resistant.

The 2-way actuated ball valve with auto-return, from RS Components, also operates at a low voltage of 12 V DC, making it ideal for this system, as it requires a low power consumption to operate effectively.

6.6. Pipework

¾ inch Imperial PVC pipe was selected as it is designed to operate at a maximum pressure of 15 bar and has been calculated to produce a low-pressure drop of ≈50 Pa/m of pipe [26]. The PVC pipe is also resistant to corrosion from saline water, thus is ideal for use in treating brackish water with a high salinity [27]. 90° elbow joints were used to connect two perpendicular PVC pipes at 90° and T-joints were used to connect three PVC pipes in conjunction. Straight union joints were implemented into the design to allow the pipework to be easily assembled/disassembled from any valves, pumps, and vessels if maintenance is required.

6.7. Pre-filters

A Parker M19R10A-RS 10 micron polypropylene wound depth cartridge filter was used to treat the feedwater before it enters the system. This is to remove any debris from the water that will affect the performance of the desalination plant when in use.

6.8. Electronics

An electronic control system was developed, consisting of:

- Microcontroller programmed to switch on/off the pumps and valves during pressurization and purge stages (Fig. 14).
- Pressure differential sensors feedback to the microcontroller whether to switch off the bore pump when the pressure vessel is over pressurized.
- Relay module allows for the microcontroller to control the on/off state of the pumps and valves, which operates at higher voltages than what the microcontroller can handle.
- Bore pump provides the saline feed water to be processed by the system.
- Recirculation pumps recirculate the concentrate leaving the reverse osmosis module during the pressurization stage.
- An electrically actuated valve allows the machine to be operated automatically.

6.9. Framework

The simplistic aluminum framework of dimensions 2.2 m length, 1.5 m height, and 0.63 m (with extra 0.3 m for added stability) in width were constructed as a platform for the test rig components. The frame was manufactured from hollow aluminum struts, 1.1/4 inch in size, cut to size, and assembled using an array of brackets, nuts, and bolts. This means the frame can be de-assembled, allowing for smaller packaging, cheaper and easier transport as well as being adaptable and mobile for various locations.

7. Conclusion

A new batch-mode RO desalination system has been designed and is being built, requiring only readily available off-the-shelf components. The main components used are two standard RO pressure vessels, one of which serves to house the RO membrane, while the other functions as a pressure exchange vessel containing a free piston. The free-piston is driven by feed water pumped against one side, transmitting pressure to the batch of saline water on the other side. Recirculation pumps maintain the batch of water at an almost homogenous concentration, while the gradually increasing pressure drives water through the RO membrane included in the recirculation loop. Once the piston reaches one end of the vessel, the operation is reversed by means of valves, and the piston moves in the opposite sense so that the former feedwater becomes a second pressurized batch. This double-acting arrangement is expected to allow non-stop pump operation and increase output by at least 25%.

A solar-powered, small-scale desalination system is resilient and appropriate for an area of conflict like Palestine, where large plants could be destroyed and electricity supplies disrupted. The ease of construction of the system described here – together with its high recovery, modest energy consumption, and potential to use renewable energy sources such as solar – are expected to ensure its suitability for many arid regions including the Middle East and North Africa and the Indian subcontinent.

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