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PURO: A unique RO-design for Brackish Groundwater treatment

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Abstract:

Depletion of fresh groundwater sources as the result of overdraft, salinization and pollution becomes a major problem in parts of the world. Desalination of brackish groundwater by membrane technology, e.g. reverse osmosis (RO), seems to be a promising solution to water scarcity problems. However, the energy consumption and concentrate disposal are considered as the main reasons for avoiding RO application. In order to overcome these drawbacks, the PURO concept, which consists of vertically-configured RO unit in an especially drilled well is designed, installed and is going to be tested. The installation operates without any chemical pretreatment and therefore, the concentrate can be injected into a deeper aquifer that contains water of similar concentration. To avoid chemical pretreatment, the system operates at lower recovery (50%) than conventional Brackish Groundwater Reverse Osmosis (BGWRO). Higher energy consumption, as the results of lowering the recovery, is avoided by using natural hydrostatic pressure at the depth that RO is installed and by extracting the permeate water only. PURO consumes about 39% less energy when compared to a conventional BGWRO installation of the same capacity. This article describes the PURO concept and discusses its advantages and disadvantages. It also provides a rough calculation of water cost for PURO and conventional BGWRO with emphasizing on the energy costs.

Keywords: PURO, reverse osmosis, energy, brackish groundwater

1 Introduction

Reliable access to fresh water is one of the fundamental pillars on which a society is built. However, only a tiny fraction of planet’s water is directly readily available as freshwater [1, 2]. The shortage of potable water, as consequence of population growth, current consumption patterns and climate changing, will be a major problem in the coming decades and will have the same social impact as that of increased energy prices [3-6].

Groundwater is by far the most abundant and readily available source of fresh water followed by lakes, reservoirs, rivers and wetlands [2]. When used for drinking water, fresh groundwater sources are preferred to other readily fresh water sources because of the absence of pathogens. However, regions with sustainable fresh groundwater resources are shrinking by the day, throughout the

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world. Salinization of groundwater due to intrusion of the saline boundary line, as the consequences of freshwater overdraft, makes the situation even worse. In countries such as The Netherlands, which are laying below the sea level, over 100 pumping stations are closed due to intruded brackish water and it is expected that over 20% of remaining wells suffer from salinization in coming years [7]. Artificial replenishment of groundwater by infiltration wells and infiltration through a dense network of ditches and canals [8], is used for years in The Netherlands as a solution for fresh water declination. Although the artificial groundwater recharge is an excellent alternative to natural refilling and is beneficial to environment, it has disadvantages such as considerable footprint and inapplicability of being used in the arid and semi-arid area due to high evaporation rate and operational cost.

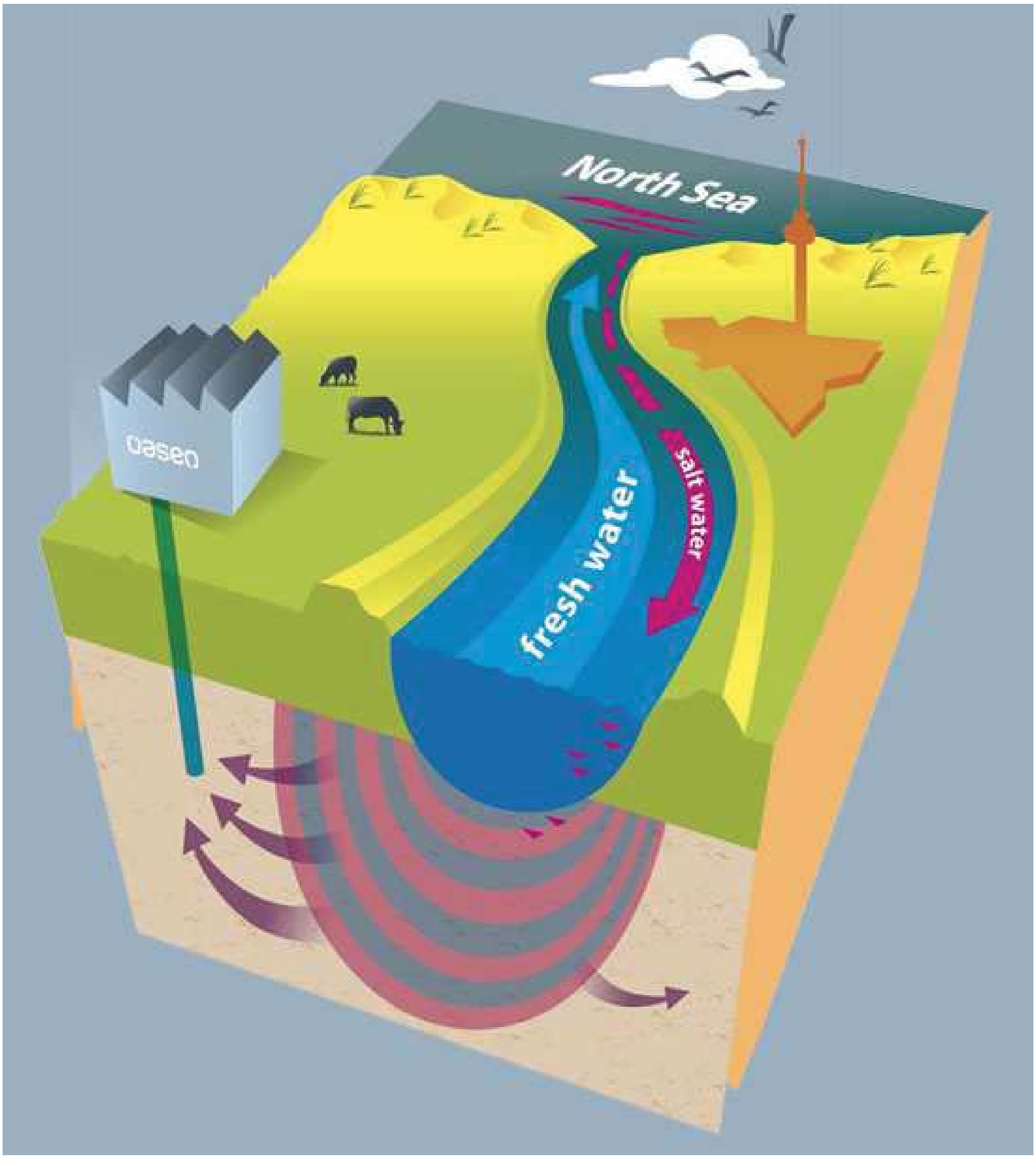

Figure 1: salt water intrusion as the result of climate changing (source of picture: Oasen Water company)

An alternative to replenishment of fresh groundwater by natural and artificial methods is the use of other water sources such as (partly) use of mostly deeper aquifer with brackish groundwater. That is especially interesting for the inland installation, coastal areas with seawater intrusion problems and landlocked countries. By utilizing brackish groundwater, the fresh groundwater remains intact and the risk of intrusion of brackish water on the fresh water decreases. The latter becomes more important considering the current trends of climate change. Increase of seawater level as the consequence of climate changing causes seawater intrusion and seepage of brackish water as the final result [9]. From the other side, due to climate changing, the replenishment of groundwater reduces especially in dry seasons due to lower precipitation. In addition, the brackish groundwater is theoretically free of xenobiotic substances when compared to fresh groundwater due to its age and the fact that it is not affected by human activities. These make the brackish water an important upcoming source of drinking water for future. However, the brackish groundwater is not directly consumable and extracted water should be treated.

Desalination technologies such as thermal and membrane desalination can be used for production of potable water from brackish water. However compare to thermal desalination, which is becoming more expensive because of rising energy prices, the membrane processes are becoming more attractive through cheaper material and system development. RO and nanofiltration are commonly used as the main techniques of producing potable water from the saline water.

2 Background

The design, configuration and geographical location of RO treatment plant depend on the application of produced water as well as the available water source in the region. Generally, seawater installations are used in coastal areas and brackish water installations by inland treatment plants. The pretreatment of seawater is more intensive than brackish water. Furthermore, the energy consumption in seawater installations is higher than brackish water due to higher osmotic pressure of the seawater. However, the inland treatment plants confront more severe legal issues concerning the concentrate disposal. Generally, concentrate disposal of brackish water into the seawater is not attractive due to high transportation cost. Below three examples of BGWRO configurations are mentioned that are currently used in The Netherlands: 1) a conventional BGWRO, 2) the fresh-keeper concept, and 3) the PURO concept.

2.1 Application of BGWRO in agriculture and horticulture

Agriculture, especially at the sites of highly intensive greenhouses, demands large amount of fresh water with the minimum salt content. Freshwater with minimum salt content is favorable to agriculture because firstly, it doesn’t damage the soil, it doesn’t stunt the plant growth, and it doesn’t harm the environment and secondly, it is used as the essence of production of plant food with determined type and concentration of nutrient for a specific type of crop. Precipitation is generally used as a source of water with low salt content. However, this is not enough to satisfy the water demands and it is only periodically available. In addition, it is foreseen that the natural precipitation in warm periods will decrease and evaporation rate will increase due to global warming leading to greater drought in warm seasons. On top of all, in some countries such as the Netherlands, the open reservoirs that are used for capture of precipitation have insufficient capacity to provide a reliable source during long summers. This urges the farmers to use the groundwater as additional water source. As discussed earlier the fresh groundwater is not sufficient and its refilling is forecasted to become limited due to global warming. Therefore, BGWRO becomes an attractive way of producing low concentrated water agricultural sections [7, 10]. Agriculture of several countries such as Spain (22%) [11], Australia (53%) [12], Israel and The Netherlands is partly depending on the desalinated brackish water.

Despite its popularity, the BGWRO is not appealing anymore for European greenhouse-holders due to legal issues concerning disposal limitations of the concentrate water. The disposal issue becomes more serious since the announcing of stricter regulations of European Union due to presence of xenobiotic substances such as antiscalants in the concentrate stream and uncertainty about the effects of disposal of concentrate into the ground. Therefore, investigation and finding of a solution for the concentrate disposal problem have drawn a lot of attention recently. Some of the researchers showed that there is a chance of short circuit between the concentrate wells after a couple of years [13]. Most of these studies lead to develop the Zero-Liquid Discharges (ZLD) systems such as pond evaporation and Eutectic Freeze Crystallization (EFC). However, application of ZLD systems is not economically attractive mainly due to a high energy consumption of these systems.

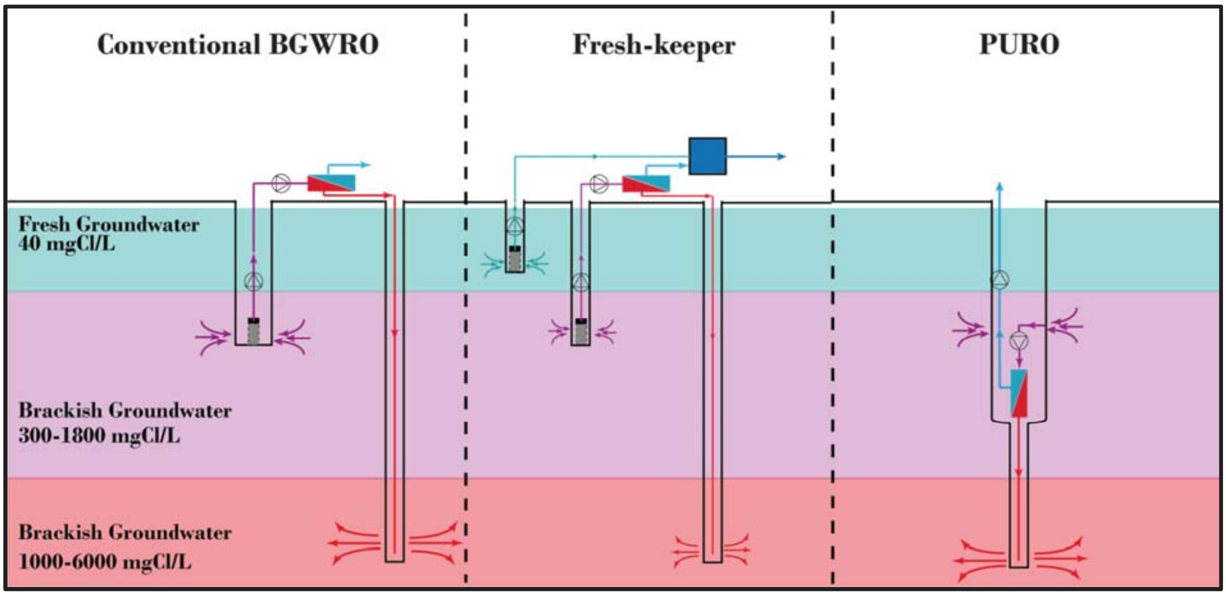

Figure 2: Three systems used in The Netherlands to treat the brackish groundwater with reverse osmosis. Fresh-keeper use partly freshwater and partly brackish water, while conventional systems and PURO work with brackish water. Fresh-keeper and PURO operate with a recovery of about 50% to avoid consumption of chemicals in pretreatment in order to have environmental-friendly disposal of concentrate. Fresh-keeper use the fresh well and PURO uses the RO-installation unit in depth to compensate for high energy consumption of BGWRO.

2.2 Fresh-keeper

While it is economically prudent to maximize the recovery, the concentrate disposal problem of BGWRO can be solved by lowering the recovery as consequence of avoiding of chemical pretreatment such as avoiding of antiscalants, albeit at the expense of higher energy consumption. The higher energy consumption is required to extract more brackish water to have constant water production. Blending of permeate of RO with a freshwater from top aquifer is a way of compensation of energy requirements compare to full BGWRO. This concept is called Fresh-keeper. Fresh-keeper installations, which are used for producing potable water or blending the feed water of conventional treatment plant, exist of two or three filters at different depth. Each of these filters is located in a separate well to prevent mixing of water during extraction or disposal. Water of top filter (fresh water filter) blends with the permeate water of middle filter, which is produced by Brackish Groundwater Reverse Osmosis (BGWRO). The top filter is used to compensate the energy requirements of RO installation. The aim of second filter is to lower the fresh groundwater extraction. The third filter is used for disposal of concentrate stream of RO installation in deeper layer of the aquifer, preferably under an impermeable clay layer to prevent short circuit with top layers. In the new design of the Fresh-keeper, all three filters are located in the same well in order to lower the investment cost. Separation materials are used to prevent mixing of different layers at the well.

2.3 PURO Concept

PURO is an alternative way of producing fresh water by using RO-membrane at low recovery. The main advantage of PURO is its lower energy consumption compare with the Fresh-keeper and the conventional BGWRO. A difference of PURO with Fresh-keeper concept is that PURO use only brackish water, which lead to preservation of freshwater sources. However, the main difference of PURO with Fresh-keeper and conventional BGWRO is that PURO treats the brackish water deep in the ground. In the PURO concept, the RO-installation is placed inside the well at depth of 100 meters. The concept benefits from the available hydrostatic water pressure at this depth and the fact that only permeate extracted from the well, which consequently lead to significant decrease in energy cost and a solution to concentrate disposal of BGWRO membranes. In the following section, the PURO concept will be described in more details.

Table 1: rough comparison of Conventional BGWRO with Fresh-keeper and PURO on utilization of fresh water sources, energy consumption and concentrate disposal

Concept	Conventional BGWRO		Fresh-keeper	PURO
	R=80%	R=50%		
Using of freshwater	+	+	-	+
Energy consumption	+	-	-/+	+
Concentrate disposal	-	+	+	+

3 PURO: Design and specific futures

The PURO (Put-RO) concept or in well (Put) installed RO consists of PURO well and RO unit. After passing through the cartridge filters, the brackish ground water will be treated by RO elements with total recovery of 50%. The permeate of installation is pumped to the surface to be mixed with the drinking water of local pumping station during the pilot study and the concentrate, without any xenobiotic substances, is disposed to the deeper aquifers. A schematic view of PURO concept is illustrated in Figure 3.

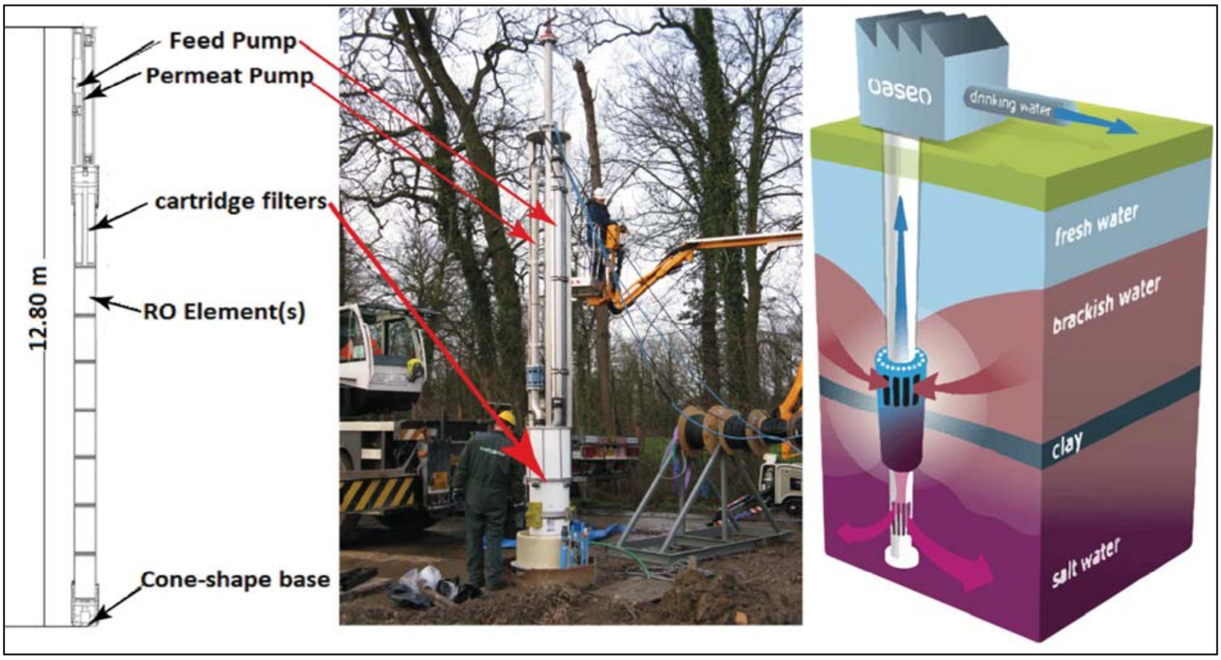

Figure 3: Schematic view of PURO inside the ground (right), actual placing of RO unit inside the PURO well (middle). The schematic view and positioning of important component of RO unit (left). Feed and permeate pumps are installed on top of the cartridge filters.

3.1 PURO well

The geology at the pilot location exists of semi-impermeable layer of clay and peat to a depth of 15m below the surface. Underneath is a sandy aquifer, which contains fresh water, to a depth of 26m and is separated by a major semi-impermeable layer of clay (26-40m) from the second aquifer. At greater depths, down to about 100 meter, an alteration of (fine) sands and poorly developed impermeable clay layers is found. The boundary between fresh and brackish water is found at about 60 meters. The intake of RO unit is located at the depth of about 60-70m in the second aquifer. The injection filter of the concentrate is located at a depth of 175-200 m. At this depth, the salinity of the groundwater is about 1000-1500 mg/l.

The PURO well is drilled by airlifting/reverse circulation method. The diameter of the well decreases from 900mm (top part) to 500mm (lower part) at a depth of 125m. The casing or borehole of upper part, which contains the well intake filter and RO unit, is made of a high pressure PVC casing with a diameter of 630mm.The lower borehole, which meant to infiltrate the concentrate, has a reduced diameter of 200 mm, in a well diameter of 500mm.

The annular space between the well wall and borehole is filled with sieved sandy filter material (0.8-1.25 mm) at the intake and injection filter level. The natural semi-impermeable clay layers are restored with special bentonite clay, preventing a shortcut of water flow between the high salinity deeper aquifers and the less salty aquifer at the intake. The constriction at the transition part of the well is used for positioning of RO unit. Two observation wells equipped with measuring devices are drilled respectively at distance of 28m and 68m from PURO well to provide information on effects of concentrate on the deeper layers.

3.2 RO unit

The RO unit composed of five spiral-wound cartridge filters, a feed pump, a permeate pump, seven RO elements inside a pressure vessel and measurement tools. The unit weighs about 1500kg at non-operational mode. This will be reduced during the operation mode due to Arachnids law injection of concentrate that cause the water pressure to rise about one bar [14]. The counter pressure will be increased in the case of clogging of the filter at the concentrate site. Positioning and removal of the installation unit in the PVC pipe can be done with an 8cm stainless steel permeate pipe that works as a hanger at the top and eight wheels mounted around the pressure vessel for easy sliding of installation. Since the replacing-frequency of cartridge filters is higher than RO elements, five cartridge filters are included to prevent frequent hoisting of the unit from the well. The cartridge filters will be replaced every two years, during cleaning and well rehabilitation.

3.2.1 RO membranes modules

8-inch modules are the current industrial standard and most popular elements of spiral wound modules of RO [15, 16] The chosen criterion for design of RO elements is that an element should be as large as possible to obtain maximal production yet small enough to be handled and installed by a single individual [15]. Recently, large-diameter RO elements such as 16inch (406mm) and 18inch (457mm) have started to emerge in the market.

In PURO project, well diameter was the decisive parameter for designing the size of RO-elements. Also using of one pressure vessel with big elements instead of smaller elements and plenty pressure vessels, was cost effective and more practical during installation and maintenance. The laboratory experiment by Bartel *et al.* [17] and pilot study by Ng and Ong [18] showed a reduction of costs by the increase of module diameter due to a reduction of system footprint, number of housing, piping interconnection and seals between the modules. Ng and Ong [18] reported no significant improvement of performance in larger modules, but a reduction of about 20-25% in infrastructure, auxiliary parts and pipes costs. Bartel *et al.* calculated the operating costs for different module diameters and three different water sources: seawater (TDS 38000), brackish ground water (TDS 2200) and effluent water (TDS 920). A major cost reduction was achieved by increasing of diameter from 8-inch to 16-inch in all three types of water. A further diameter increase did not result in substantial cost reduction. The largest life cycle cost saving in their experiment was determined for the brackish groundwater and lowest for the seawater [17].

3.2.2 Permeate water in PURO

The RO-unit operates with a recovery of about 50% and a permeate production of 25m^3/h. After analyzing the primarily results, the recovery will be increased to evaluate its effects on production, fouling and energy saving.

3.2.3 Concentrate disposal in PURO

PURO and other low-recovery BGWRO installation have the advantage that they produce a concentrate stream free of xenobiotic substances. The brackish groundwater is generally anaerobe, which works chemically and biologically in advantage of membrane fouling. Besides, the brackish groundwater is barely affected by human activities. Therefore, the brackish groundwater provides a feed water source with almost constant quality for reverse osmosis unit. The common tend is then to dive the BGWRO with highest possible recovery for lowest production costs. However, the high operation recovery causes the membrane scaling and therefore antiscalants are used. Such as other materials in the feed antiscalants are also rejected by the membrane and appears in the concentrate stream. This is become an issue since the effect of the antiscalant on deeper ground layers is not yet fully known. One way to avoid this problem is to lower the recovery of the RO in such an extent that no antiscalant is required. In this way, a concentrate with constant and predetermined quality will be discharged to the deeper aquifer that has higher salt concentrations than concentrate stream. To produce the same amount of water with low-recovery installation, higher amount of brackish groundwater should be extracted, which can be translated into higher energy requirement. In contrary to other low-recovery BGWRO, PURO operates at low-recovery and with low energy consumption at the same time. In the following part, the costs of PURO are compared with a conventional BGWRO-system with emphasizing on the energy cost.

4 Cost comparison of PURO with Conventional BGWRO

For comparing the production cost of PURO with a conventional BGWRO installation, an installation with similar properties such as quality of feed water, plant capacity, site conditions, qualified labor and plant life amortization is chosen. The estimated costs in this article are based on the method mentioned in the “Desalting handbook for planners”[16]. However, it should be mentioned that the low capacity of the treatment plant cases high sensitivity of the calculation to small changes. The costs and numbers mentioned in the following parts are only used for clarification of the difference of PURO with conventional treatment plant with use of most realistic values.

4.1 Designing criteria

Description of conventional concept: The conventional BGWRO consists of an extraction well, RO unit, disposal well and appendages. The conventional BGWRO is designed with recovery of 50% to prevent adding of chemicals. The permeate production will be used for green houses without any special post-treatment.

The conventional BGWRO unit is designed in two stages with four pressure vessels in the first stage and two pressure vessels in the second stage (2:1) within each pressure vessel six elements. The modules that are used are popular eight inch membranes.

Table 2: Some design criteria, which are used for cost estimation of two scenarios

Description	Unit		
Design case	-	Conventional BGWRO	PURO
Feed Flow (Q_f)	m^3/h	50	50
Recovery	%	50	50
Plant Capacity	m^3/h	25	25
Pass configuration	-	1	1
Stages configuration in each pass	-	2	1
Number of pressure vessel (Stage 1)	-	4	1
Number of pressure vessel (Stage 2)	-	2	0
Number of element in pressure vessel	-	6	7
Diameter of each element	Inches	8	16
Total number of elements used	-	36	7
Membrane Area	-	1472	1122
Amortization period	Years	30	30

Feed water: The feed water quality at the extraction point of PURO is summarized at Table 3. The same water composition is used for conventional BWRO installation.

Plant capacity: Generally by increasing the plant capacity, the cost per unit products will be reduced, despite higher initial investment costs. Therefore, both study cases are operated with the same recovery (50%) and plant capacity (25m^3/h) to nullify the effects of these factors on the costs

Table 3: Feed water quality at extraction location, Ridderkerk the Netherlands

pH	7.1	-	
Qf	50	m3/h	
Component	Concentration [mg/l]	Component	Concentration [mg/l]
Ca	169	CO3	0.26
Mg	34.3	HCO3	280
Na	89.1	SO4	1.6
K	0	Cl	380.15
NH4	3.39	F	0
Ba	0.15	NO3	0
Sr	0		
B	0		
SiO2	25		
TDS	981.35		

Site conditions: The site conditions are associated with availability of feed water intake, brine disposal and pretreatment facilities. The site conditions are assumed to be the same for both installations, since both installations are newly designed. It has been assumed that construction of specific building is not necessary and will be an available site condition. However, the foot print of PURO is limited to only a recognition part on the ground, while the ground installation requires a bigger footprint. The site conditions will work in advantages of PURO in terms of costs by increasing the capacity.

Qualified labor: Availability of qualified operators, engineers and management personnel will results in shorter plant downtime and therefore, higher plant availability and production capacity. It has been assumed that the operators of the same qualifications are operating both systems.

Plant life and amortization: Increasing of the plant life time reduces the product capital costs. An amortization period of 30 years is used for calculation of costs for both systems.

4.2 Factors affecting the costs

The unit production cost is a function of process capacity, site characteristics and design future [19]. A summary of the cost elements for desalination processes is shown in Figure 4, which is based on the approach of Watson *et al.*[16]. The unit cost of the water is estimated dividing the sum of the annual capital repayment and annual operation and maintenance by the volume of water produced during one year.

The annual fixed charges (annual capital charges) composed of annual depreciating costs and annual non-depreciating costs. The non-depreciating costs consist of the land cost and working capital. The latter is a percentage of annual operation and maintenance. The depreciating costs are composed of direct capital costs and indirect capital costs, which the latter is calculated as a percentage of direct capital costs. Indirect capital costs and non-depreciating costs together amount to slightly more than 40% of total fixed costs. Consequently, the direct capital cost is the baseline of calculation of fixed charges. Paragraph 4.2.1 and 4.2.3 respectively describes the assumptions, which are done for calculation of direct capital costs and annual costs. The percentage that are used for calculation of indirect capital costs are mentioned in paragraph 4.2.2.

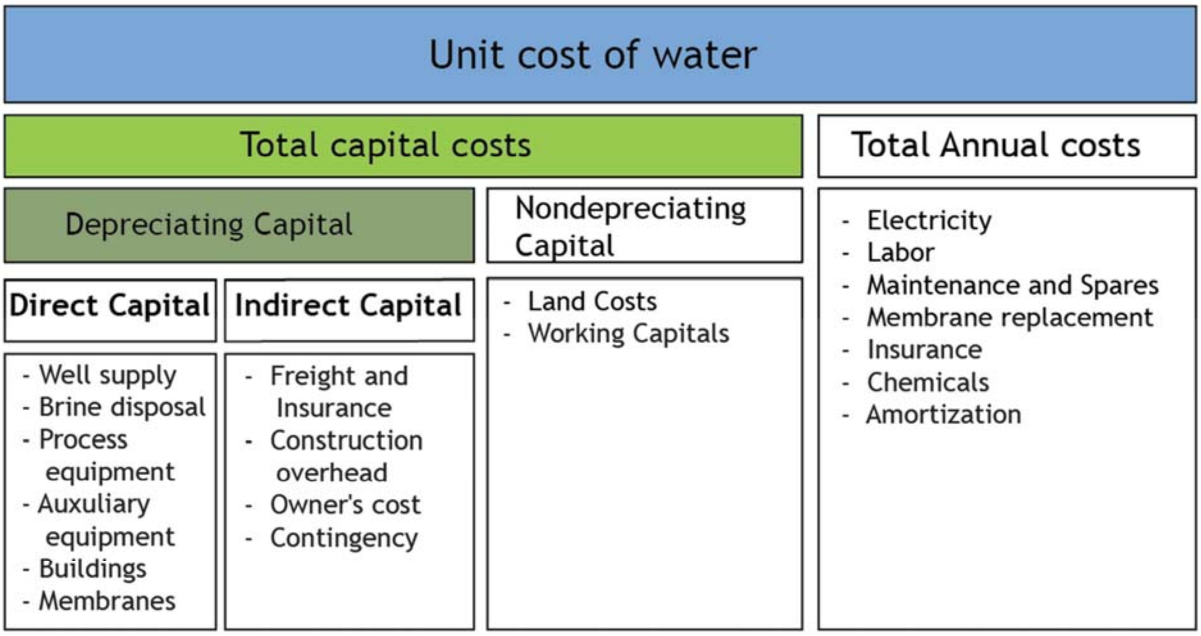

Figure 4: elements of costs analysis for membrane process

4.2.1 Direct capital costs

Direct capital costs include the purchase cost of major and auxiliary equipment and construction cost. It is assumed that the membrane cost is about 17€/m^2. The PURO is designed with one feed pump for RO unit and one well pump for transporting the permeate water. The conventional BWRO installation is designed with one well pump for extraction of feed water and one feed pump for RO. The finished costs of the well(s), including the casting, were based on the actual projects. No auxiliary equipment and building costs are considered for these calculations.

Table 4: Values that are used for calculation of Direct Capital costs

Parameters	Unit	Value in Literature	Reference	Applied	value
				PURO	Conventional BGWRO
Membrane diameter	Inch			16	8
Membrane elements	€/m^2		[19]	17	17
Pressure vessel	€/PV	950-2000	[20]	21000	1000
Purchase costs of pumps	€	Differs	[21, 22]	16500	16400

4.2.2 Indirect capital costs

Indirect capital costs are generally expressed as percentages of the total direct capital costs. Freight and insurance, construction overhead, owner's costs and contingency costs are considered to be respectively 5%, 15%, 10% and 10% of total direct capital costs [16, 19].

4.2.3 Annual operating costs

The expenses incurred after plant commissioning and during actual operation such as labor, energy, chemicals and spare parts are included in the annual operating costs. Generally, due to automation, a very small team of engineer(s) and operator(s) are working in RO treatment plant. Since the scenarios mentioned here are too small, it has been assumed that units can operate fully automatic. The replacement rate for membranes used with high salinity is reported to be around 20% and for water with low salinity is reported to be around 5% [16]. A yearly RO-membrane replacement of 13% (Brackish water) is assumed for both cases. The cost of repairs and spare parts is mentioned to be less than 2% of total capital costs on annual basis in the literature. This is estimated to be around 1% for our study cases. Insurance is about 0.5% of total capital costs. As discussed earlier, no antiscalant will be added and it's assumed that there is no need of chemical cleaning during two years. For the chemical cleaning, the PURO installation has to be lifted from the well. The maintenance cost of PURO well is, therefore, estimated to be about 10 times higher than conventional well mainly due to lifting of installation.

The amortization or fixed charges are accounts for annual interest payments for direct and indirect costs. It is obtained from multiplication of these costs with the amortization factor (Equation 1). In Equation 1 "i" and "n" respectively denotes the annual interest rate and the amortization period and assumed to be 6.0% and 30 years.

$$a = \frac{i \times (1+i)^n}{(1+i)^n - 1}$$ **Equation 1**

Table 5: Parameters that is used to estimate the annual water costs

Parameters	Unit	Value in Literature	Reference	Applied value	
				PURO	Ground-level
Electricity	€/kWh	Differs		0.098	0.098
Repairs and spares	% total capital	1%-2%	[16, 19]	1%	1%
Membrane replacement	%/Year	3-20	[16, 19, 23]	13%	13%
Insurance	% of total capital	0.5%	[16, 19]	0.5%	0.5%
Annual interest rate	%	5-10%	[16, 19]	6.0%	6.0%
Water extraction costs	€/m^3	0.19		0	0
Well maintenance	€	Practical Value		10000	1000
Well rehabilitation	€	Practical Value		2500	3000

5 Results and discussion

A unit production cost of respectively 0.34€/m^3 and 0.35 €/m^3 for conventional BGWRO and PURO is estimated. The estimated costs are lower than cost ranges that are mentioned in the literatures [24-28] because no water extraction taxes, no pretreatment and no post-treatment costs are considered in both situations. The post treatment is assumed not to be necessary because the produced water is not used as potable water and the distance between treatment plant and end user is not bigger than 200 meters. The permeate water of PURO aims blending water of existing treatment plant and permeate of conventional BGWRO is used as the main substance of preparing plant foods. Considering the quality of feed water, recovery of the system and new European regulations for concentrate disposal no pretreatment is applied.

The calculations are performed without considering the water extraction taxes due to spatial and temporal diversity of taxes worldwide. Generally, in The Netherlands, the central and provincial government impose separated (respectively 0.16€ and 0.01-0.03€ [29]) levies on groundwater extraction. However, since beginning of 2013, only the provincial taxes have to be paid, and governmental taxes are abolished. Since the level of provincial taxes, for current situation, is low compare to other cost elements, they are neglected for water cost calculation. However, for countries that levy charges on groundwater or for the situation that the groundwater taxes law in The Netherlands become effective again, PURO has the advantage of extraction only half of water (when recovery is 50%) to the surface. This means paying half of the water taxes with current regulations.

Figure 5 compares the important elements of water cost of PURO with conventional BGWRO on a yearly basis. As Figure 5 shows, the membrane replacement cost of conventional BGWRO is slightly higher than PURO since the membrane area (Table 2) of conventional design is slightly higher but the replacement frequency (Table 5) of both designs is the same. According to Figure 5, the capital and operational charges of PURO on a yearly basis are higher than conventional BGWRO. Considering all the cost differences results in about 0.01€/m^3, which is mentioned earlier.

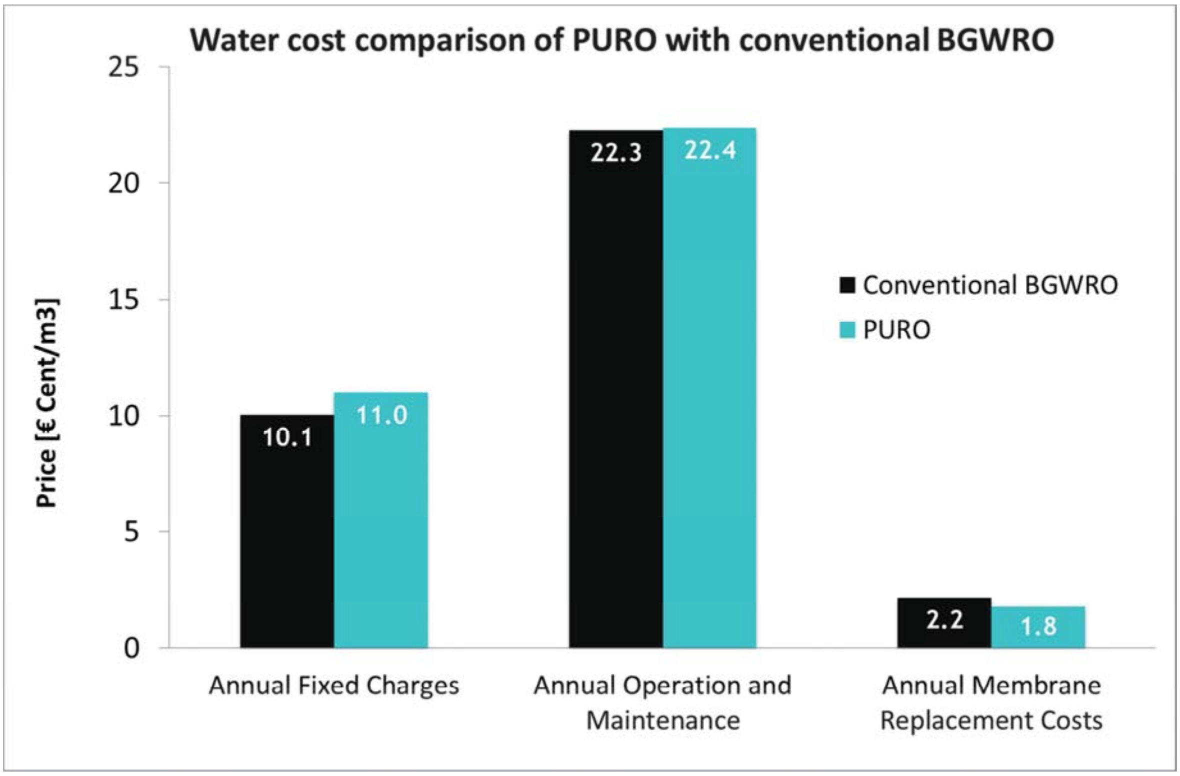

Figure 5: Cost comparison of PURO with a conventional BWRO installation. The fixed costs for PURO are higher than conventional BGWRO, while the annual operation and maintenance of conventional BWRO is higher than PURO project.

5.1 Annual fixed charges

From the items considered for capital costs only plumbing cost of PURO is lower than conventional BGWRO due to fewer numbers of connections with a bigger size in PURO. Construction of well(s) is a major factor of direct capital cost in both scenarios. Despite the construction of two separate wells in BGWRO (Figure 7), the cost of well construction in PURO is slightly higher than conventional BGWRO due to complexity of PURO well and lake of experience in constructing of such wells. Considering the capital costs, manufacturing of a unique pressure vessel for PURO to work properly in the brackish water environment and endure the weight of RO installation is one of the major investment cost for PURO when compare to conventional BGWRO. The cost of such a pressure vessel was about two times higher than all pressure vessels used for conventional BGWRO.

5.2 Annual operation and maintenance

Comparison of annual operation and maintains costs shows that the total operation and maintenance costs are comparable for both cases (Figure 5). A breakdown of operation and maintenance block (Figure 5) is depicted in Figure 6. The main differences in annual operation and maintenance costs appear in power utilizations and in the well and RO-unit maintenance. The sum of maintenance and rehabilitation cost of PURO are higher than conventional BGWRO, which are mainly caused due to hoisting cost of PURO for inspection and maintenance. However, this ratio will be decreased in PURO when the plant capacity increases, for instance by using more PURO wells.

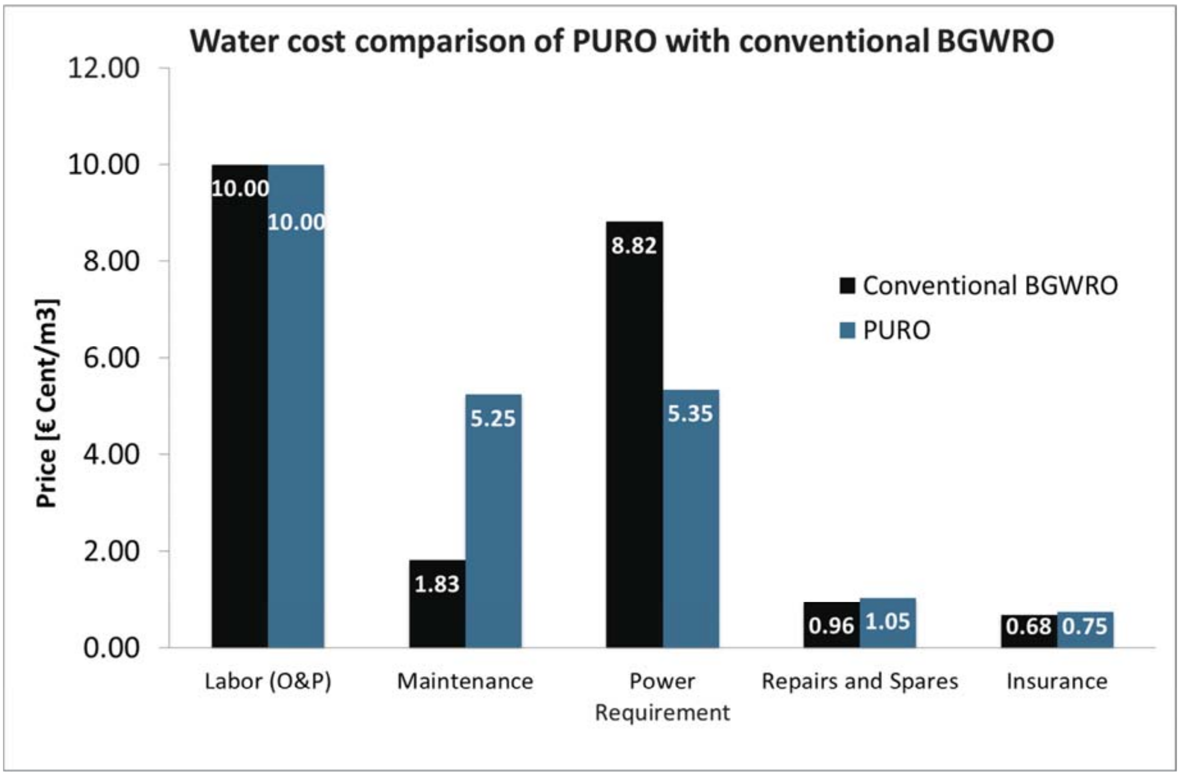

Figure 6: Annual operation and maintenance costs comparison

Figure 6 shows that lower energy consumption is the main advantage of PURO. PURO consumes about 39% less energy compare to conventional BGWRO of the same capacity (Figure 7), which is mainly due to more efficient use of available hydrostatic pressure.

In conventional BGWRO, the hydrostatic pressure is mainly spent to transport the feed water to surface. At the surface, the water pressure is almost zero and has to be pressurized through the RO-unit (in this case with 9.70 bars) to be able to produce permeate water. From the total feed pressure about 1.5 bars will be lost due to resistance of different instruments and the remaining will be lost through the concentrate, unless Energy Recovery Devices (ERD) are used at the concentrate end. However, application of Energy Recovery Devices (ERD) is not common in BGWRO because of relatively low feed pressure and low flow rate of the membrane concentrate stream [30, 31] when it compares to seawater RO, which are usually equipped with ERD. Besides, the successful application of ERDs in brackish water installation is not yet proved and requires more details analysis of entire RO system.

In contrary to conventional BGWRO, the hydrostatic pressure in the PURO will be spent to drive the RO-unit. The hydrostatic pressure available at the PURO site ($88mH_2O$) provides major parts (80%) of the operating pressure ($110mH_2O$) and the remaining is provided by the installed feed pump (20%).

The extraction pump in PURO transport only permeate to the surface, but do not benefits from the hydrostatic pressure anymore since permeate is pressure-less. The energy consumption of extraction pump in PURO seems to be higher than BGWRO. That is mainly due to that fact that the permeate has no pressure in PURO and extraction pump in conventional BGWRO benefits from the available hydrostatic pressure at the site (50mH_2O).

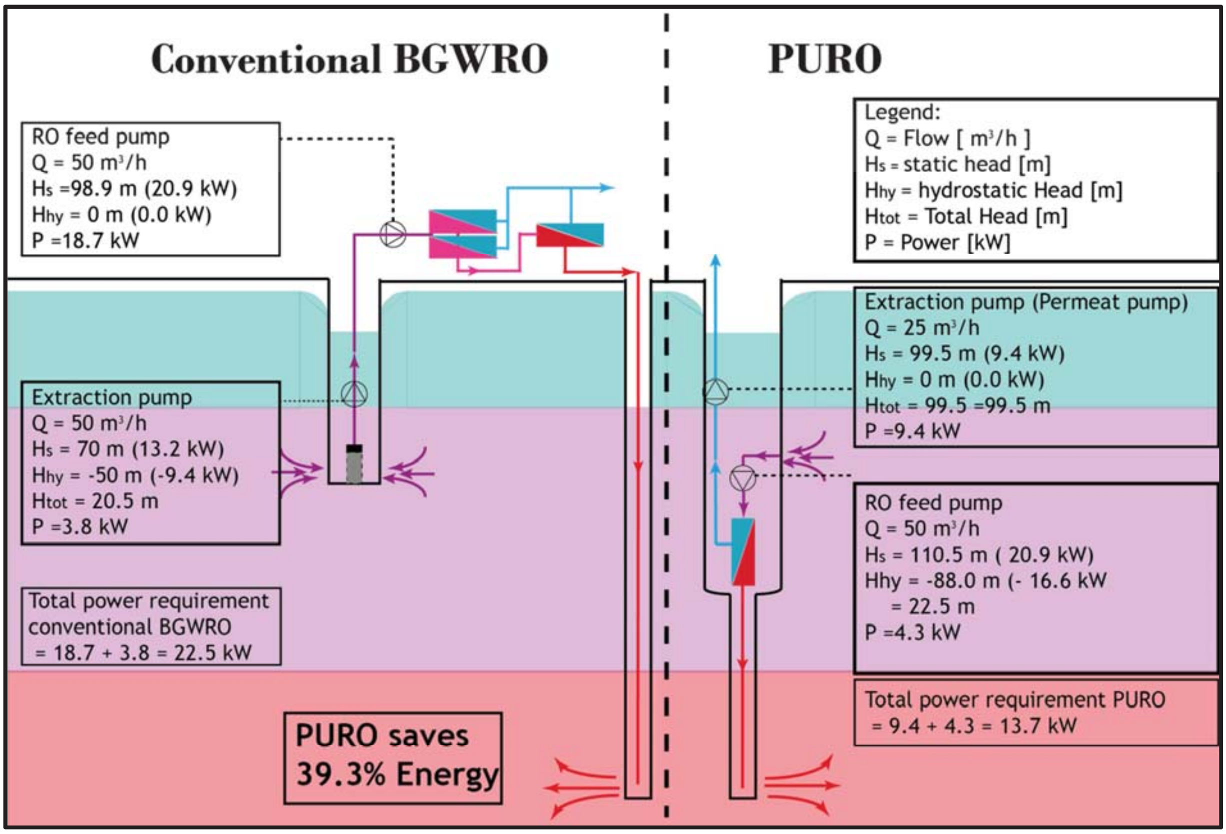

Figure 7: Energy consumption for PURO (right) and conventional BGWRO (left). Energy consumption in PURO is lower than conventional BGWRO and that is the main advantage of PURO when no chemical pretreatment is desired.

In The Netherlands, man applied Optiflux [32, 33] for treatment of brackish groundwater instead of the conventional BGWRO such as described above. In Optiflux concept, the pressure vessel is equipped with a watertight connector in the middle that allows the concentrate to flow back and leave the pressure vessel from both ends and therefore, the pressure vessel acts as two separate pressure vessel with half of elements in each section. An Optiflux pressure vessel containing six elements, for instance, functions as two separate pressure vessels of three elements. In this way the feed pressure required will be reduced duo to reduction of hydraulic losses without extra investment for more pressure vessels. However, even with the application of Optiflux instead of conventional BGWRO, PURO has about 28% advantages in terms of energy consumption.

6 Conclusion

Brackish groundwater is becoming an important source of water for inland RO- installation partly due to the climate changing, overdraft and contamination of fresh groundwater resources. When applying RO for treatment of brackish groundwater, the disposal of contaminated concentrate stream can be prevented by avoiding of chemicals pretreatment of feed water and direct application of feed water to RO system. However, to prevent scaling of membrane modules, the operation recovery should be reduced. Therefore, more water should be extracted to have the same production capacity. As the consequence of more water extraction, more energy will be required. PURO is a solution to this higher energy consumption of RO systems operating at low recovery. PURO owes its lower energy consumption mainly to an efficient use of available hydrostatic pressure.

Since PURO operates inside the well, a good analysis of the location and feed water, a proper well construction and a good monitoring are essential for PURO. The extra equipment that is required for proper functioning of PURO results in extra investment cost of PURO. Furthermore, the maintenance of PURO is difficult and costly due to limited accessibility of PURO. Despite the higher investment and maintenance cost, the water cost by PURO is comparable with conventional BGWRO. Although the production cost of PURO seems to be the same as conventional BGWRO, it is a big step toward more energy and environmental friendly desalination of groundwater with RO. It is expected that in the future, the investment and maintenance costs for the PURO installation decrease due to increased experience in making such installations. Also, application of PURO with higher capacity will reduce the maintenance cost of PURO.

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