

New concept of upgrade energy recovery systems within an operating desalination plant.



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**Abstract**

The Palmachim Desalination plant is one of the largest seawater reverse osmosis (SWRO) desalination plants in Israel with a capacity of 120,000 cubic meters per day ( $m^3/day$ ). Built by the Via Maris Desalination Ltd. consortium, the plant consists of six (6) parallel SWRO trains, each with a permeate production capacity of up to 20,000  $m^3/day$ . In addition its high-capacity SWRO trains, the Palmachim plant is unique because it was designed to be easily turned on, off or slowed down. Electricity tariffs in Israel are significantly higher during the day than at night with a cost ratio of up to six to one. The plant's flexibility allows the operators to minimize energy consumption during the day when the power cost is high by shutting down up to 85% of the plants capacity.

Each train has a dedicated high-pressure pump (HPP) equipped with an energy recovery turbine (ERTs) that rotates on the pump shaft. ERTs, also known as Pelton wheels, were standard equipment in SWRO plants designed and built in the 1990s and early 2000s. Very large ERTs, such as those in the Palmachim process, have two wheels (runners) which can be operated independently. The hydraulic efficiency of the ERTs at Palmachim is 88% and their net transfer energy recovery efficiencies (water to water) approach 76%.

Many plants originally equipped with ERTs have been retrofit with isobaric energy recovery devices (ERDs) to increase plant permeate production capacity and reduce power consumption. Isobaric ERDs are positive displacement devices that operate with energy transfer efficiencies as high as 98%. Each retrofit presents unique challenges. The Palmachim SWRO plant required an increase in production capacity, an improvement in energy consumption and a minimization of the capital costs for the expansion while maintaining high reliability and maximum operational flexibility.

The Palmachim owners decided to provide additional feed flow to the membranes with PX Pressure Exchanger ERDs and circulation pumps while continuing to operate the original HPPs, motors and ERTs without modification. This new hybrid energy recovery design requires that the ERTs, the HPP motors and the ERDs operate in balance at their best efficiency points and maintain the flexibility of starting and stopping on a daily basis. Other goals of the retrofit design were to minimize energy consumption and prevent overflowing, overloading or otherwise straining any of the system components.

The authors provide a detailed analysis comparing SWRO productivity, energy consumption, flexibility and reliability of the Palmachim plant before and after the retrofit.

### General information.

The Palmachim desalination plant is a BOO – Build, Own, Operate project for 25 years. The project was initiated by the Israeli government. The tender took place in 2002.

Shareholders:

- GES – 72%
- Tahal – 28%

The construction period for palmachim 1 was 2 years including commissioning.

Daily Production:

- Palmachim 1 – up to 110,000 m<sup>3</sup>/day (30 million m<sup>3</sup>/year) Completed and commissioned May 2007.
  - Palmachim 2 – up to 40,000 m<sup>3</sup>/day (45 million m<sup>3</sup>/year) Completed and commissioned April 2010.
  - Currently Total Daily Production up to 150,000 m<sup>3</sup>/day
- Water quality requirements Main features:

- 70 mg/l CL-
- 0.4 mg/l Boron

Unique desalination plant features:

- Easy start-up and shut-down procedures (1-1.5 hour for the entire plant)
- Production can be adjusted according to electrical tariff.
- First pass permeate is adjusted according to quality (split mode).
- Second pass recovery 97-98%



## I. INTRODUCTION

Reverse osmosis is a water desalination process used widely around the world. The osmotic pressure of a salt water solution is overcome with hydraulic pressure, forcing nearly pure water through a semi-permeable membrane and leaving concentrated reject behind. In seawater reverse osmosis (SWRO) systems, an operating pressure of 60 to 70 bar (870 to 1015 psi) is required. Even at these pressures, a maximum of approximately 50% of the available pure water can be extracted before the osmotic pressure becomes so high that additional extraction is not economically viable (1). The rejected concentrate leaves the process at nearly the membrane-feed pressure. Efficient recovery of the pressure energy from this stream is essential for making SWRO desalination economically viable.

Membrane recovery rate is defined as the permeate flow rate divided by the membrane feed flow rate. A high recovery rate means a high process yield. However, in a desalination process, operation at high recovery results in higher average concentrate salinities in the membrane elements, higher osmotic pressures and higher membrane feed pressures compared to operation at low recovery. In addition, supersaturation of the concentrate at high recovery rates can result in scaling and high membrane flux can result in fouling. On the other hand, low recovery rate operation directly reduces process yield and can result in excess pretreatment and supply-pumping expenses. Permeate recovery rate optimization, therefore, is a critical exercise for RO process design and operation (2). Because energy consumption and related CO<sub>2</sub> emissions are by far the greatest environmental impact of a SWRO process, energy-efficient operation is important for minimizing greenhouse gas production.

The Palmachim Desalination plant was designed for maximum energy efficiency and operational flexibility. Comprised of large SWRO trains, it operates with high-pressure pumps and energy turbines that approach maximum achievable efficiencies. Although it has operated reliably and well, the demand for product water from the plant has increased since startup. In addition, the plant operators were interested in energy consumption reductions available with new desalination equipment technologies. For these reasons, a two-phase retrofit of the plant was undertaken.

The first phase of the retrofit will involve adding isobaric energy recovery devices (ERDs), additional membrane vessels and pretreatment capacity to the existing system, increasing train capacity from about 18,960 to 24,800 cubic meters of permeate per day (m<sup>3</sup>/day). The second phase of the retrofit will involve adding additional ERDs, vessels and pretreatment and the removal of the existing energy recovery turbines (ERTs) or Pelton turbines to increase train capacity to about 40,400 m<sup>3</sup>/day. These retrofit designs and their associated benefits are discussed below.

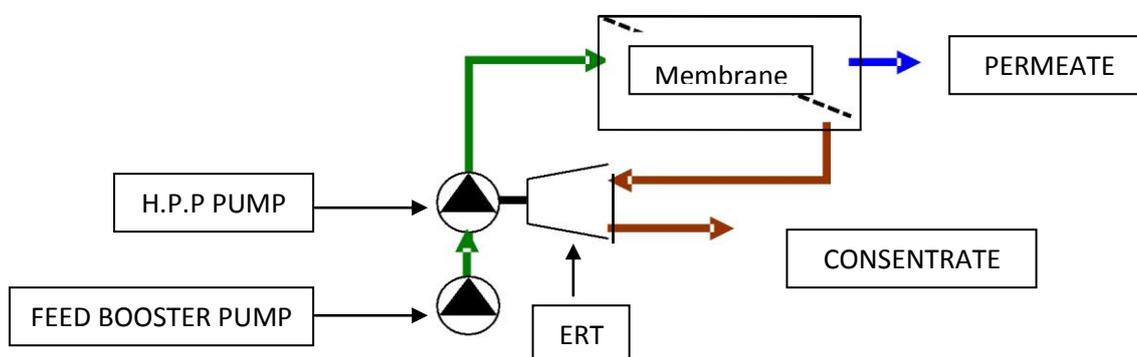
## II. ORIGINAL ERT PROCESS

The Palmachim Desalination plant is one of the largest SWRO desalination plants in Israel, originally design to produce 30 million cubic meters of permeate per year. Built by the Via Maris Desalination Ltd. consortium, the plant began operations in May 2007. Water produced by the plant enters the municipal supply for use in general domestic, industrial and agricultural applications.

### 2.1 Original SWRO Process Description

The plant is fed eastern Mediterranean seawater from an open intake. The feed water has a salinity of up to 42,000 mg/L total dissolved solids. The feed water temperature varies seasonally from 17 to 32 degrees Centigrade. Pretreatment consists of multi-media and cartridge filters.

The SWRO portion of the plant consists of six (6) parallel trains, each with a dedicated feed booster pump, high-pressure pump and membrane array. Pressure is recovered from the membrane reject stream with energy ERTs mounted on the high-pressure pump shafts. Spent reject is returned back to the sea by gravity. A simplified schematic diagram of one SWRO train is given as Figure 1.



**Figure 1 – SWRO Train with Original ERT Design**

The SWRO trains normally operate at just under 16,000 m<sup>3</sup>/day but can produce up to 28,960 m<sup>3</sup>/day. The pumps produce 1,540 m<sup>3</sup>/hr at their best efficiency points and up to 1800 m<sup>3</sup>/hr. Their motors can take up to 1,980 kilowatts (kW) of power and deliver up to 1,920 kW of brake power. Very large ERTs, such as those in the Pamachim process, have two wheels (runners) which can be operated independently. Two wheels increase the capacity of the ERT. Each ERT turbine wheel can handle 375 to 475 m<sup>3</sup>/hr of reject flow. A photograph of an ERT is given as Figure 2 and figure 2A.



**Figure 2 – Palmachim Two-Runner ERT**



**Figure 2 A– Palmachim train include ERT+MOTOR+HPP**

The large size of the pumps and ERTs contribute to their high efficiency. Designed to be operated with feed booster pumps, the high-pressure pumps have relaxed (increased) net positive suction head requirements which allows them to be designed for additional efficiency. As a result, the high-pressure pumps operate at up to 87% and each ERT wheel operates at up to 88% efficiency. This compares favorably to smaller pumps and ERTs which typically operate at less than 84% efficiency. The net transfer efficiency or water to water energy recovery efficiency is the product of the pump and ERT efficiency. The net transfer efficiency in the original SWRO trains is just over 76% at the best efficiency point making whereas the net transfer efficiency of a more typically- sized SWRO train is less than 70%. Palmachim is one of the most efficient ERT-based SWRO processes in the world.

## 2.2 Original SWRO Process Operation

In addition to high efficiency, the SWRO trains are designed for flexible operation. The motors of the high-pressure feed-booster pumps are equipped with variable frequency drivers (VFDs) which can be used to vary the pressure at the pump outlets from 4 to 18 bar. This allows the output of the high-pressure pump outputs to be manipulated without large and expensive VFDs on their motors. The trains are easy to startup and shut down. The feed booster pumps partially pressurize the SWRO trains through the high-pressure pumps. This flow turns the turbines which result in additional pressurization (up to 40 Bar). The high-pressure pump motors are then engaged (using a soft starter). The result is a smooth, gradual pressurization achieved without a high-pressure control valve. Shutdown is similarly smooth.

Easy startups and shutdowns and variable operation give the plant's operators the flexibility to significantly adjust the plant's output and energy consumption. Electricity tariffs in Israel are significantly higher during the day than at night with a cost ratio of up to four to one. The plant's flexibility allows the operators to minimize energy consumption during the day when the power cost is high by shutting down up to 85% of the plant's capacity. In addition, the plant has proved to be highly reliable providing over 99% availability. For startup procedure note Figure 3.

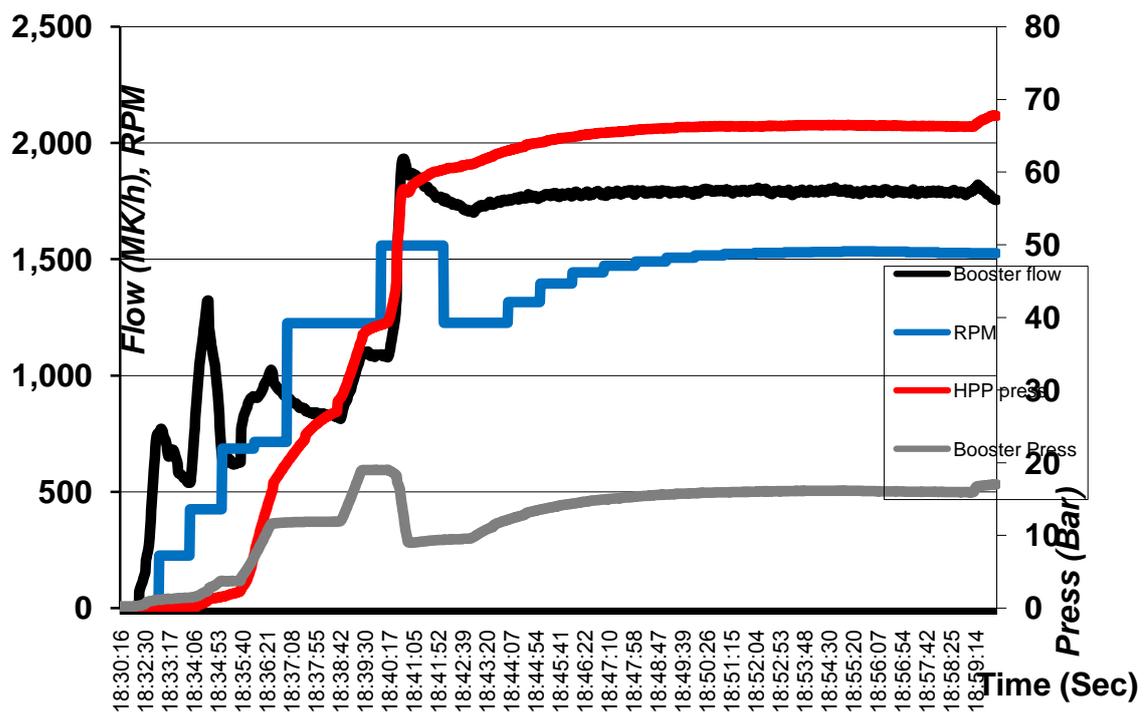


Figure 3- Start up procedure.

### III. HYBRID ERT-ERD EXPANSION RETROFIT

The demand for potable water in Israel has increased. The Palmachim plant sought a means to increase permeate production using its existing equipment without the undergoing a full expansion retrofit. In addition, the plant sought to maintain or

increase the operational flexibility it enjoyed with the original plant design. Therefore, the design team developed an innovative hybrid ERT-ERD retrofit scheme.

### 3.1 Hybrid Retrofit Process Design

The hybrid ERT -ERD retrofit design uses the original pumps, motors and ERTs. Additional membrane pressure vessels are added to the original vessels, increasing the maximum permeate production capacity to 1,100 m<sup>3</sup>/hr from less than 800 m<sup>3</sup>/hr. Additional membrane feed flow is provided by an array of energy recovery devices (ERDs), an associated circulation pump and additional low-pressure pretreated water. This increases the flow rate of concentrated reject from the membrane elements accordingly and the additional reject flow is the high-pressure supply to the ERDs. The ERDs transfer the pressure of the reject stream to pretreated feed water. This stream joins the high-pressure pump output to feed the membranes. A schematic diagram of the process is given in Figure 4 and Figure 4A.

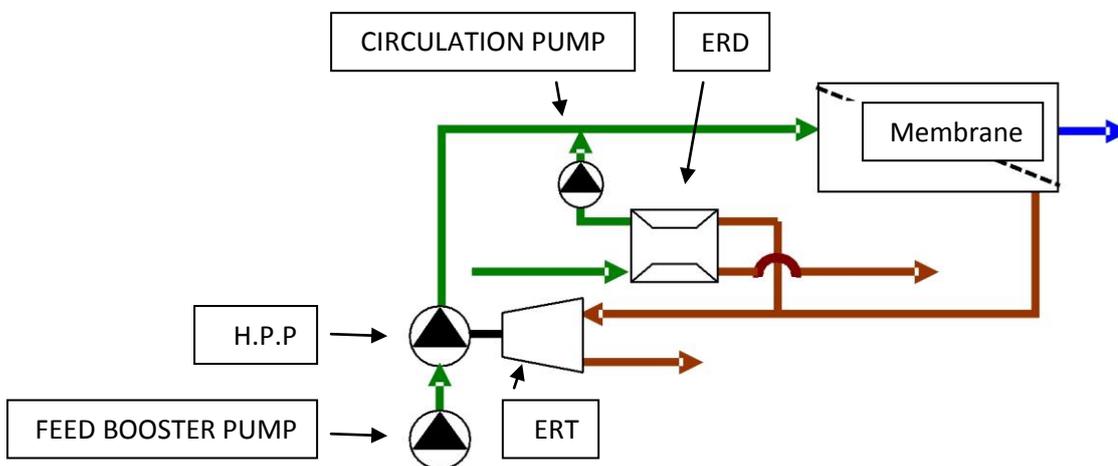
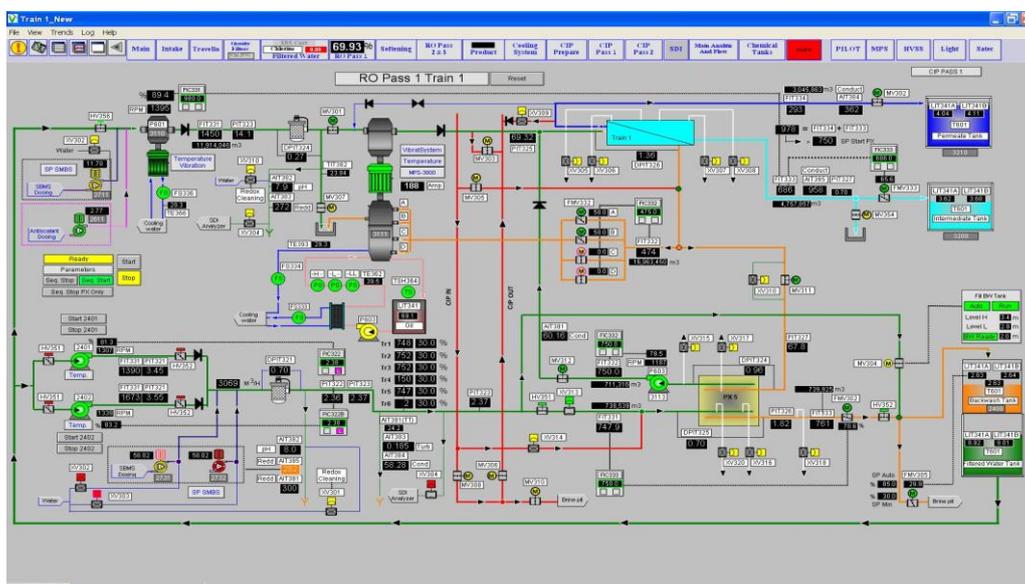


Figure 4 – 4A SWRO Train after Hybrid Retrofit,



For ERDs, each SWRO train will be equipped with arrays of 14 PX's model PX-260 Pressure Exchanger devices. These are positive displacement isobaric devices in which pressure transfer occurs through direct contact between the high-pressure membrane reject and pressurized seawater. They operate at up to 98% pressure-transfer efficiency. Each PX-260 unit has a capacity of 41 to 59 m<sup>3</sup>/hr, providing a flow range of plus or minus 18% from the mid-flow rate or up to 31% turndown capacity from maximum flow. This flow range is greater than that of the ERTs which can be turned up or down 15% from their mid-flow rate when considering a "normal" operation conditions using all inlet valves of the turbine (considering working in efficient points). The capacity of each ERD array is up to 826 m<sup>3</sup>/hr. Therefore, they supplement the original membrane feed flow by up to 50%. This increases the SWRO train capacity to a maximum of nearly 26,000 m<sup>3</sup>/day. The footprint of the PX devices and circulation pumps is about 25 square meters. The ERD arrays are located above the existing piping system next to the HPP, on a "lifted balcony" and the installation requires minimal new civil work. Additional high-pressure piping is added to connect the ERDs and circulation pumps to the new membrane elements. Low-pressure pretreated water will be piped to the ERDs from the pretreatment system. The ERDs do not require or benefit from boosted feed pressure. Because of that the feed booster system remains dedicated to the high-pressure pumps and is not affected by the retrofit.

### 3.2 Hybrid Retrofit Plant Operation

Startup with the hybrid retrofit SWRO process begins as was done before the retrofit, i.e start the booster pump, deliver all flow to the Pelton turbine, rotate the main shaft and increase pressure up to 40 Bar and then started the HPP.

Only after the HPP works and desalinated water are being produced than the ERD system is started up.

Low-pressure feed water is supply to the ERDs (low pressure loop). Next the ERD circulation pump is started up in parallel to throttle the flow to the turbine by shutting down two turbine nozzles (High pressure loop). The circulation pump being control by a VFD allows maintaining adequate flows through the ERT system.

After one inlet valve per ERT wheel is shut down the electric motor will supply the required power to the high-pressure pumps. The procedure is simple to execute and provides a smooth startup as achieved with the original design. Shutdown is the same procedure in reverse.

This procedure allows the plant operators to shut down the ERD system whenever require and move back to ERT mode by pressing a button. This capability increase the availability of the system and allow maintaining the system without the need to shut down the whole train.

In the retrofited Palmachim plant, membrane recovery can be adjusted by changing the feed booster pump speed, or by changing the speed of the ERD circulation pump. This gives the plant operators the flexibility to change the plant operation according to needs (water conditions change or the cost of power changes). However, there are some practical limits to recovery variation as shown in table 1.

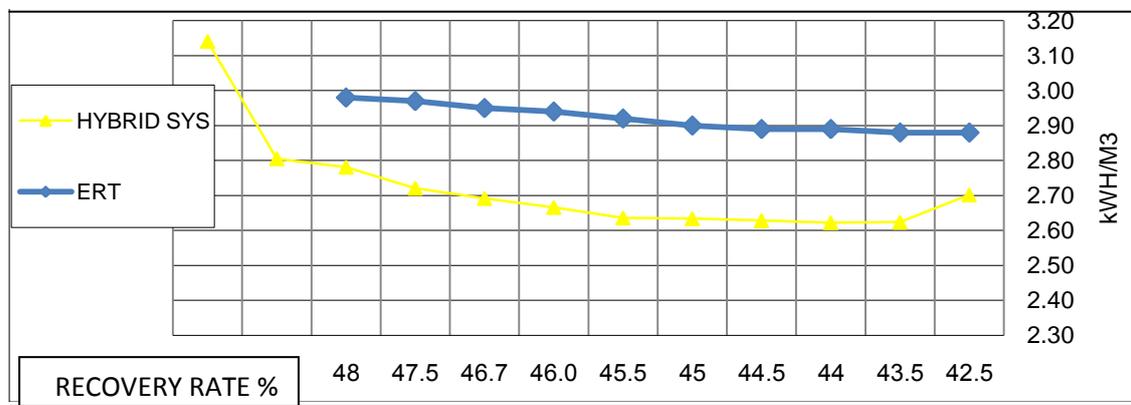
Permeate flow m <sup>3</sup> /h	Min % recovery	Max % recovery	Limiting factor low recovery	Limiting factor High recovery
950	42.2	49.0	Max flow allow to ERT & Turbine	Min flow allow to ERD & Turbine
1000	42.0	49.0	Main motor capabilities	Min flow allow to ERD & Max working Pressure to the membranes
1050	44.5	47	Max flow allow to ERT & Turbine & Main motor capabilities	Main motor capabilities

**Table 1: limiting factors for different recovery rates.**

Membranes are TORAY 820 C Seawater Temperature 29C.  
 Min flow to ERT 415 m<sup>3</sup>/h (One runner). Max flow to ERT 475 m<sup>3</sup>/h (One runner).  
 Min flow to ERD 574 m<sup>3</sup>/h. Max flow to ERD 826 m<sup>3</sup>/h.  
 Max power output of the motor 1950 Kw/h.

In Table 1 the maximum achievable recovery rate (when the high flow points are considered), is mainly dominated by the membrane performance. High flow membranes that require lower pressure will allow the modified train to move off the boundaries mentioned, i.e. to increase recovery and reduce energy consumption further more. Production is limited by the capacities of these ERD & ERT. It should be noted, however, that a range of 42 to 50% recovery is relatively wide and sufficient for all of the plant’s operating requirements.

The SWRO specific energy consumption is the power consumed by the feed booster, high-pressure pump and circulation pump divided by the permeate flow rate. In the Palmachim plant, the estimated specific energy consumed by the original ERT SWRO process in the production of 790 m<sup>3</sup>/hr of permeate as a function of recovery rate is illustrated with the Blue (upper) data set in Figure 5. This is compared with the expected energy consumption by the hybrid process as a function of recovery rate illustrated with the blue (lower) data set in Figure 5.



**Figure 5 –SWRO Specific Energy Consumption ERT VS Hybrid system as measured in Palmachim.**

The specific energy consumption of the hybrid process is lower than that of the original process because of the higher efficiency of the ERDs. At recovery rates of 47% and up the savings by the Hybrid design get smaller in compare to the ERT design. This phenomenon occurs because in high recovery rates there is a need to minimize the flow through the ERD system while there is still a requirement for power from the Turbine. This shifts the energy recovery duty from the ERDs to the less efficient ERT and increasing the specific energy consumption.

### 3.3 Improved Process Performance

Design	Max Permeate Capacity m <sup>3</sup> /day	Max H.P.P motor power kw	Specific energy kWh/m <sup>3</sup>	CO2 Emission (g/m <sup>3</sup> )
Original design	18,960	1540	2.91	286
Hybrid retrofit	25,680	1920	2.7	265
Full retrofit (include new motor and 65 % more membrane area)	40,400	3000	2.38	233

**Table 2 – Retrofit SWRO System Performance.**

A comparison of the performance of a single SWRO train at 45% recovery before and after retrofit is shown in Table 2.

45% recovery is estimated to be the optimum recovery rate for the plant. Also shown in Table 2 are performance figures for a full retrofit to be discussed in the following section. In the comparison, the same high-pressure pump flow rate was assumed in all cases.

The data in Table 2 show that the hybrid retrofit increases permeate production by up to 35%. It also shows that specific energy consumption after the hybrid retrofit was estimated to reduce by about 8% from the original design. The actual reduction ranges from 7% to 11% at recovery rates between 42 and 49%. The estimated specific CO<sub>2</sub> emissions will reduce in proportion to the specific energy reductions. Not quantified in the analysis are the greenhouse gas emissions saved by expanding the plant within its current footprint rather than constructing new civil works, see pictures of the retrofit as figure 6 and 6A.



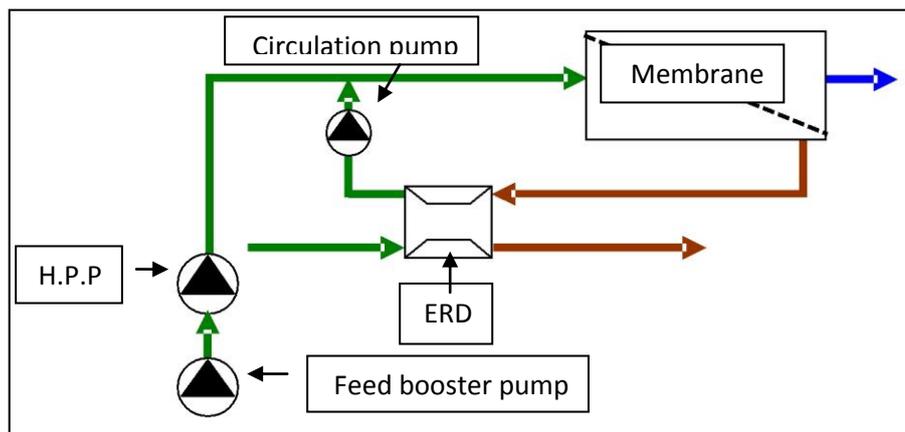
**Figure 6 ERD during installation.**



**Figure 6A ERD "Second floor" above H.P piping.**

#### IV. FULL EXPANSION RETROFIT

While the hybrid retrofit meets the design goal of increasing production and decreasing specific energy consumption with minimal modification of the existing system, a greater production increase and energy savings can be achieved with a full retrofit. In a full retrofit of an ERT-based SWRO process, the turbines are removed altogether. The resulting process, which is a standard isobaric ERD design (3), is illustrated in Figure 7.



**Figure 7 – SWRO Train After Full Retrofit.**

A full retrofit makes use of the original high-pressure pump, however, the motor must either be of sufficient size to handle the full load of the pump without assistance from the turbines or be replaced with a larger motor.; In the Palmachim plant a second motor will be coupled to the main motor instead of the turbine to provide 3 MW/h to the H.P.P. Sufficient new ERD (total of 38 per train), and second circulation pump of the same type will be installed together with supplemental membranes, pretreatment capacity and post-treatment capacity.

Although the high-pressure pump flow rate is the same in the full retrofit as in the original design, the membrane feed flow is increased by about 130% or by a factor of 2.3 compared to the original design. Production can be comfortably increased by factor of 2.2 compared to normal operation of the original design or to a daily output rate of 40,400 m<sup>3</sup> per train or 88 million m<sup>3</sup> per year for the plant. A full retrofit saves significant energy compared to the original design because the additional membrane feed flow requires very little additional energy input. As illustrated in Table 1, a full retrofit is estimated to reduce specific energy consumption by 18%.

#### V. ENVIRONMENTAL SUSTAINABILITY

SWRO process retrofits offer the opportunity to increase permeate production with minimal new equipment and construction. High-efficiency isobaric ERDs are available with sufficiently small footprints to be integrated into existing process layouts. As illustrated by the Palmachim retrofit, even large, energy-efficient plants operating with state-of-the-art ERTs can reduce energy consumption on a per-unit-

permeate basis by nearly 20% by retrofitting with isobaric ERDs. The potential benefits of retrofitting less- efficient, medium-sized plants are even greater. For these reasons, retrofits are an environmentally favorable alternative to constructing new plants.

As discussed, another aspect of the Palmachim plant design that is important for managing energy consumption is flexibility. Both the hybrid and full retrofit designs have equal or greater flow ranges compared to the original ERT design. This flexibility is primarily used in Palmachim to minimize production during peak periods and maximize it during non-peak periods. However, the process recovery rate can also be adjusted in response to changing feed water or membrane conditions. For example, recovery can be reduced to lower membrane feed pressure and energy consumption by the high-pressure pumps. Alternately, recovery can be increased to minimize seawater intake and pretreatment requirements.

## **VI. CONCLUSIONS**

An SWRO process retrofit involves replacing some or all of the ERT capacity with isobaric energy recovery devices ERDs. SWRO processes retrofits offer the opportunity to increase permeate production with minimal new equipment and construction and reduce energy consumption per unit of permeate produced. Therefore, when feasible, retrofits are generally an environmentally favorable alternative to constructing new plants. The Palmachim plant plans to implement their retrofit in two phases starting with adding ERDs to the original plant design, followed by adding additional ERDs and removing the original ERTs. Specific energy consumption and CO<sub>2</sub> emissions reductions from the original plant design of 8% and 18% for the two phases, respectively, are expected. In addition, the retrofit designs increase operational flexibility.

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