An Integrated Feed Pump – Recovery Turbine Reduces Energy Consumption and Capital Costs of Brackish Water RO Systems

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1.0 INTRODUCTION

Energy recovery devices (ERDs) in reverse osmosis (RO) systems recover hydraulic energy in the brine stream in order to do one of the following:

1. raise the pressure in the feed stream (hydraulic pressure boosters and turbochargers);
2. pump a side stream of feed water (pressure exchangers); or
3. reduce the load on the motor driving the high pressure (HP) feed pump (Pelton turbines and reverse running pumps).

All three approaches have achieved commercial success with hundreds of examples of each type in field service on seawater reverse osmosis (SWRO) systems.

From the forgoing, it is clear that ERDs are widely accepted in SWRO systems. However, a review of the literature shows very few ERDs installed in brackish water RO (BWRO) systems. This is especially disappointing as BWRO systems appear to greatly outnumber SWRO systems and have a vastly higher aggregate capacity.

2.0 ENERGY RECOVERY IN BWRO SYSTEMS

Why are ERDs apparently rare in BWRO and common in SWRO systems? To answer this question, let's examine and compare the hydraulic characteristics of BWRO and SWRO systems using several parameters. One parameter is the Energy Recovery Potential (ERP) defined by equation [1] as the ratio of the hydraulic energy available in the reject stream to the hydraulic energy in the feed stream:

$$\text{ERP} = (P_m - \Delta P_m - P_{ex}) \times \text{RR} / P_m \qquad [1]$$

where:

P_m = membrane feed pressure
ΔP_m = pressure loss in membrane array
P_{ex} = brine exhaust pressure (disposal pressure)
RR = reject ratio = Q_r / Q_f
Q_r = brine flow
Q_f = feed flow
(all flows are in gpm, pressures in psi and temperature in degrees F)

Chart 1 plots P_m, ΔP_m, RR and ERP as functions of feed TDS based on a generalized analysis of membrane performance. As the ERP decreases from about 58% for very high TDS feed to about 18% for low TDS feed, an ERD must contend with a diminishing amount of brine energy relative to the total energy input.

The Hydraulic Energy Density (HED) defined by equation [2] measures the available hydraulic energy in kW-hr per 1,000 gallons of brine:

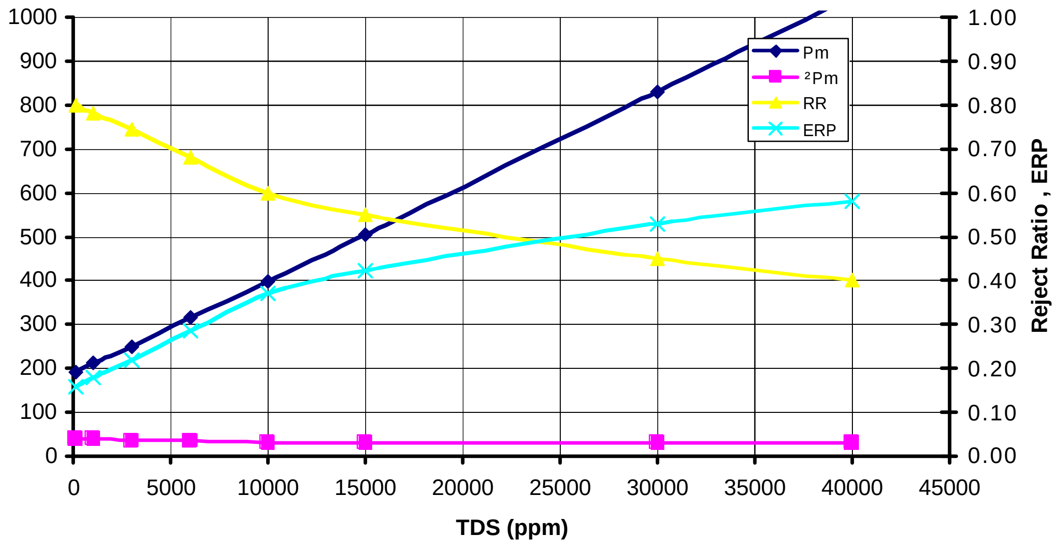
$$\text{HED} = 0.00721 \times \Delta P_r \qquad [2]$$

where:

ΔP_r = $P_r - P_{ex}$ (available brine pressure differential)
P_r = brine pressure

For example, 1,000 gallon of brine with an available pressure differential of 100 psi has an HED of 0.721 kW-hr or a little more than 4¢ worth of energy at 6¢/kW-hr electricity cost.

Chart 1 - Pm, DPm and RR vs Feed TDS



An even more telling parameter is the Specific Brine Energy (SBE) defined as the amount of hydraulic energy in the brine per 1,000 gallons of <u>permeate</u> or:

SBE = HED x (Q_r / Q_p) [3]

where:

Q_p = $Q_f - Q_r$ (permeate flow)

Chart 2 shows SBE varying from about 0.27 kW-hr for low TDS to about 10.9 kW-hr for high TDS. This means that the hydraulic brine energy for BWRO may be as little as 2.4% of that in SWRO per gallon of permeate. ERDs for BWRO clearly have a difficult challenge in harvesting the meager brine energy, which largely explains their general absence in BWRO systems.

The ultimate measure of an ERD is its ability to provide a financial return on investment (ROI) sufficient to justify its use. ROI is defined by equation [4] as:

ROI = Cost Saved / Total Cost [4]

where:

Cost Saved = energy cost savings <u>per year</u> minus maintenance costs <u>per year</u>
Total Cost = ERD cost + installation cost + training cost + spares cost – equipment cost savings

Total Cost includes offsetting equipment cost savings such as elimination of the brine control valve or reduced motor and feed pump size. For example, if Cost Saved is $6,000/year and Total Cost is $30,000, then the ROI is 0.20 or 20% per equation [4]. In this example, the ERD would pay for itself in about five (5) years ignoring costs of financing and inflation.

The manufacturer wishes for the end-user to accept a low ROI to maximize economic justification for purchase of an ERD. In contrast, the end-user seeks a high ROI with minimal risk. These interests appear to converge on the ERD warranty. The authors propose that the duration of the ERD warranty be used in conjunction with ROI to establish the Investment Safety Factor (ISF).

ISF = Warranty Period x ROI [5]

Implicit with the above is the requirement that the ERD warranty would commence from the time of commissioning, be comprehensive and may also involve having onsite spares sufficient to reduce potential downtime to a negligible level. An ISF of 1.0 or more indicates a safe investment. An ISF of, say, 1.5 would be a strong signal to seriously consider the ERD. An ISF of less than 1.0 suggests a careful financial and technical evaluation would be in order.

Chart 2 - Energy Savings vs Feed TDS

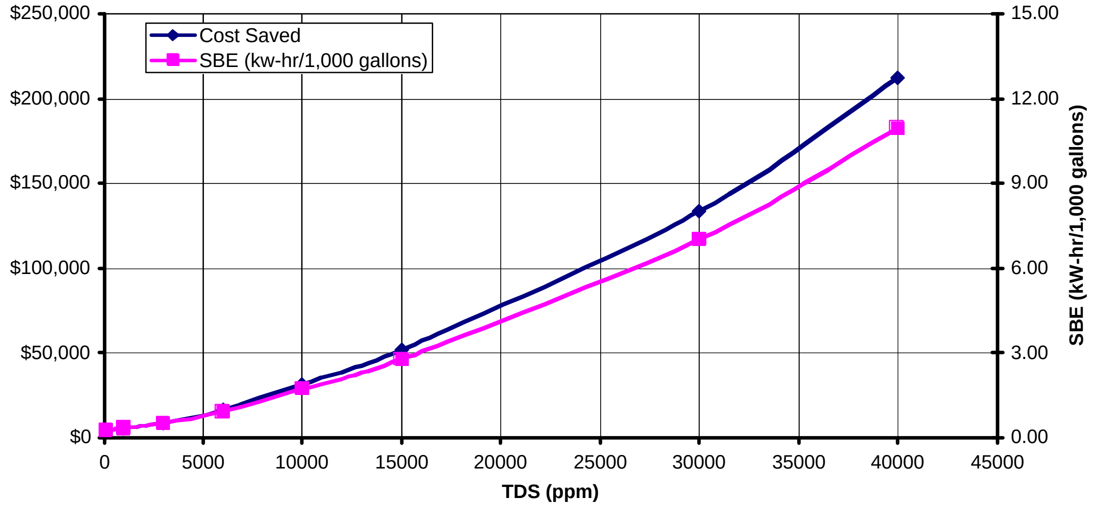


Chart 2 plots Cost Saved as a function of feed TDS assuming a nominal 1.0 mgd permeate output, 6¢/kW-hr power cost, and nominal ERD efficiencies. Other parameters are based on Chart 1. Note that the plot is similar to SBE. If ERD efficiency were constant with brine flow then the two curves would be identical.

3.0 PRESENT APPLICATIONS

Interstage pressure boosting has long been recognized as a way to achieve flux balance among the brine stages, to improve 2nd stage production and to reduce 1st stage feed pressure. The Turbochargers (TC) replaces an interstage boost pump while eliminating the associated energy consumption. Please refer to Figure 1. First mention of this concept was made in 1992[1].

A TC consists of an integral turbine driving a pump solely energized by the brine. Good examples are at Marco Island, Florida[2], and Brownsville, Texas[3].

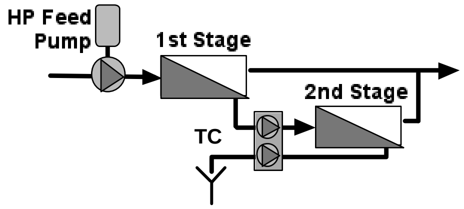


Fig 1 – Turbocharged interstage boosting

The TC pressure boost, ΔP_b, equals:

$$\Delta P_b = N_{eff} \times RR \times \Delta P_r \qquad [6]$$

where

N_{eff} = hydraulic transfer efficiency

In the case of interstage boosting, RR in equation 6 is set to the ratio of 2nd stage brine flow to interstage flow. N_{eff} may be regarded as essentially constant for a given TC therefore the boost is largely determined by RR and ΔP_r, both of which can vary in response to changes in feed TDS, feed temperature and membrane fouling. Hence, the amount of interstage boost may often be higher or lower than desired creating a system that may be impossible to control.

Other than interstage pressure boost, there appears to be only a handful of BWRO ERD installations such as a work exchanger at Key Largo, Florida[4] and scattered applications of power recovery turbines such as at Arlington,Virginia[5] and the Yuma RO desalter. The vast majority of BWRO systems appear to use no energy recovery.

Based on the forgoing, the main limiting factor in applying energy recovery is not technical but rather simply an absence of ERDs that display a good ISF and have good controllability.

4.0 THE LP-HEMI

The Low Pressure Hydraulic Energy Management Integration (LP-HEMI™) was developed to recover brine energy while providing a favorable ROI and ISF in typical BWRO installations. Figure 2 illustrates the general features,

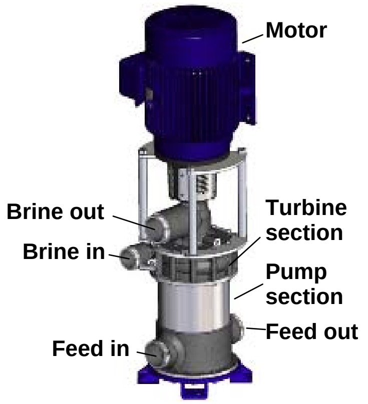


Fig 2 – LP-HEMI – vertical configuration

Figure 3 indicates the approximate brine flow and pressure regimes where the LP-HEMI can display an ROI of 33% or better ("excellent") or between 25% and 33% ("good") based on $0.06/kW-hr electrical cost. Often a much better ROI can be demonstrated than indicated, however, site-specific conditions must be considered for each application.

It should be noted that other manufacturers have offered integrated pumps and turbines such as Afton Pump however these are mostly aimed at SWRO applications. The key challenge addressed by the LP-HEMI is to display a reduced capital cost combined with good efficiency both as a HP feed pump and recovery turbine.

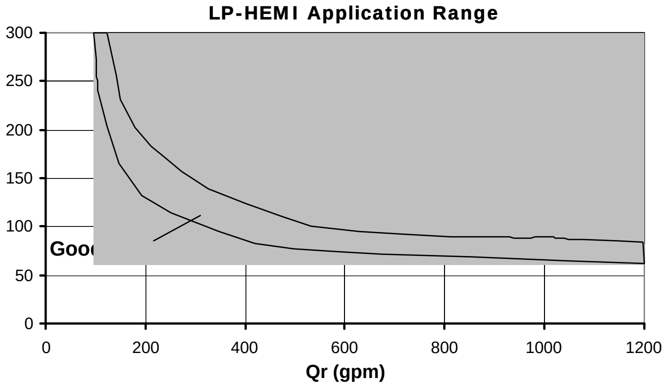


Figure 3 – Approximate HEMI hydraulic coverage

4.1 System Configurations

Figure 4 depicts a typical BWRO system (may be single or multi-staged) with the LP HEMI recovering brine hydraulic energy to reduce feed pump power consumption. This configuration would be appropriate for retrofits of existing systems or for new systems that do not use interstage pressure boosting.

Figure 5 shows the LP-HEMI providing interstage pressure boosting. Typically, the boost pressure would be controlled by a signal to the LP-HEMI VFD and the brine flow would be regulated by the turbine variable area nozzle in response to a control signal from the 2nd stage permeate flow meter. If there is a potential for excess brine energy, a line-regen VFD may be justifiable to recover that energy in the form of electrical power (discussed below). A key feature of the LP-HEMI is the ability to provide precise control of the level of interstage boost while simultaneously recovering available brine hydraulic energy.

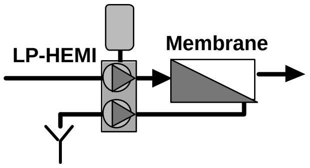


Figure 4 – HEMI as feed pump and recovery turbine

Figure 6 illustrates a modified LP-HEMI functioning as a energy recovery turbine converting brine energy into electrical energy through a line-regen VFD. A similar concept was proposed based on use of a Pelton turbine[6]. Note that in this example, two brine streams are feeding the unit. The ability to recover energy from two trains with one unit greatly improves the ROI. Each brine stream can be independently regulated for flow and pressure via the LP-HEMI's variable area turbine nozzles. This configuration is appropriate for existing SWRO systems where minimal equipment and operating changes are desired.

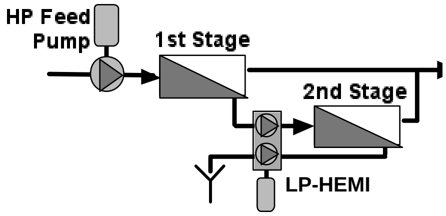


Figure 5 – LP-HEMI as interstage booste

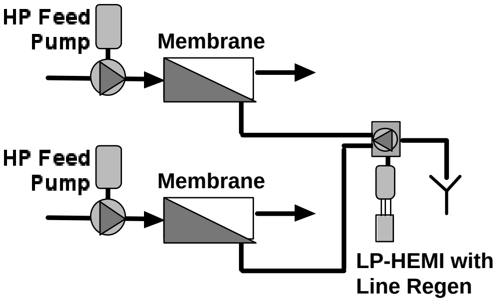


Figure 6 – HEMI for power recovery

4.2 Development Status

Figure 7 shows a LP-HEMI on a test stand with torque meter and test motor. Note the unit is installed horizontally to facilitate testing. The unit under test is a model LP-HEMI-160 rated for a feed flow up to 700 gpm and a brine flow up to 400 gpm at pressures up to 300 psig. Test procedures and instrumentation generally comply with relevant sections of the ASME PCT 9.2-1990 and Hydraulic Institute HI 1.6 test codes for centrifugal pumps testing.

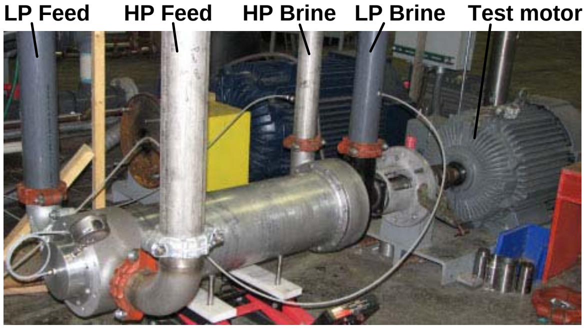


Figure 7 – LP-HEMI-160 on test stand

Measured parameters include feed flow and pressure differential, brine flow and pressure differential, shaft speed, input torque from the motor, water temperature and thrust bearing pressure. A data acquisition system collects, corrects, normalizes, displays and saves all measured parameters.

4.3 Variable Frequency Drives (VFDs)

VFDs are nearly ubiquitous on BWRO systems due to their ability to vary feed pump speed to meet a wide range of feed pressures without energy-wasting pressure throttling. Likewise, the LP-HEMI is typically supplied with a VFD to maximize energy efficiency.

A modification to the VFD, called a line regenerative VFD allows the LP-HEMI motor (which is a standard inverter-rated TEFC motor) to act as an induction generator. A VFD with Line Regeneration converts the excess mechanical energy from an overhauling load into useable electrical energy. Line regeneration is especially useful for systems where the load could be overhauling for protracted periods – or even continuously. Figure 8 illustrates a typical line regenerative VFD package.

There are several different techniques that can provide line regeneration but the basic principle is the same; the drive is provided with extra regenerating transistors in the converter/rectifier stage. If the motor is spinning faster than the output frequency would dictate, a "generator effect" takes over and the energy flows back from the motor into the drive; the transistors in the regenerative system then convert this into an AC wave form which can in turn flow back into the supply.

The whole operation is completely automatic and the system regulates itself with no user intervention being required. A correctly sized regenerative controller will allow 100% motor overhauling torque indefinitely.

Regenerative controllers can be supplied as separate units (one unit can supply more than one drive) or are sometimes built into the main body of the VFD. Regenerative Controllers are usually used in conjunction with an AC reactor, which has the effect of improving the waveform of the current fed back onto the supply line.

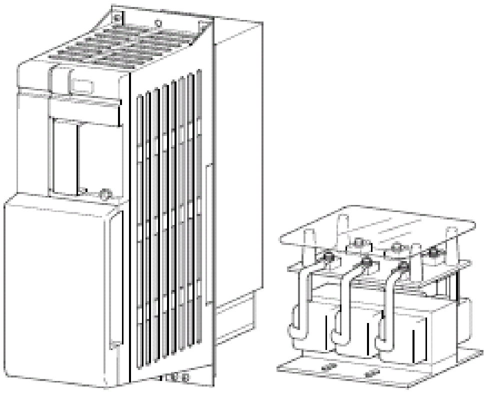


Figure 8 – Mitsubishi RV-CV Regeneration unit and line reactor

In a typical RO system, a control signal such as 4-20 mA indicates the desired pressure. The VFD sets the LP-HEMI rotor speed accordingly. If the turbine tries to spin the rotor faster than the VFD frequency setting (i.e. overhauling), the line regenerative VFD automatically extracts power from the motor (thus creating a drag on the rotor hence reducing the speed to the set speed). The extracted power is converted by the regenerative VFD into the proper voltage and is synchronized with the electrical supply.

The VFD and motor of the LP-HEMI can provide additional capacity to handle unexpected feed conditions or membrane performance. This may be viewed as an insurance policy in that if unexpected membrane or feed conditions occur, the LP-HEMI will have reserve capacity to accommodate accordingly.

A line regenerative VFD is useful for interstage pressure applications when the available brine energy exceeds the need by the LP-HEMI to generate the desired interstage boost. Another application is where the LP-HEMI is used purely as a electrical generator that is entirely energized by brine energy as illustrated in Figure 6 and further discussed below.

5.0 CASE STUDIES

The following case studies are based on customer data and membrane projections from several membrane suppliers. The ISF calculation will be based on a 3-year warranty commencing from the time of commissioning per the anticipated LP-HEMI warranty. Electricity costs shall be $0.06/kW-hr for all case studies.

5.1 – Pure Water System

The customer currently uses two HP feed pumps operating in parallel each equipped with a 75 hp motor (total power is 150 hp). Feed flow is 600 gpm and recovery is 75%. Feed is essentially tap water. The permeate is used in industrial processes that require high-purity water. Please refer to Table 1 and Figure 4 (P_m is HP pump inlet pressure).

Temp	**Q_f**	**Q_r**	**P_m**	**P_r**	**P_{ex}**	**ERP**	**SBE**
70 F	600	150	243	200	5	0.200	0.469

Table 1

The LP-HEMI-160 replaces the dual-pump package with a single five-stage pump section and integral energy recovery turbine driven by a 100 hp motor (the unit pictured in Fig 7 is a production prototype for this application). The incremental cost is estimated at $4,000. The LP-HEMI reduces energy consumption by about 28 kW that yields a $14,700 annual savings.

The ROI is about 300% per year yielding an ISF of 9.0 suggesting a very safe investment with an excellent financial return. This application is good for the OEM due to the simplification of the pumping package and good for the end-user due to low energy consumption and likely reduced maintenance requirements.

5.2 – Low Pressure BWRO Systems with Interstage Pressure Boost

This case addresses a large 2-stage system with a permeate production of 10,700 m3/day (2.8 mgd) and recovery of 75%. The membrane array is 52 x 26 with 7 elements/vessel. Projected performance is per ROSA v6.1 with BW-30-400 membranes. Feed TDS is about 650 ppm. Subscripts 1 and 2 in Table 2 refer to the 1st and 2nd stages respectively. The suffix “int” refers to interstage conditions. Please refer to Figure 5.

Temp	**Q_{f1}**	**Q_{int}**	**Q_{r2}**	**P_{m1}**	**P_{r1}**	**ΔP_{int}**	**P_{m2}**	**P_{r2}**	**P_{ex}**
54 F	2615	1330	656	241	206	65	267	232	5
79 F	2615	1330	656	136	123	46	149	122	5

Table 2

A LP-HEMI-320 can provide the indicated interstage pressure boost (note ΔP_{int} is somewhat higher than the pressure difference between the 1st stage concentrate pressure and the 2nd stage feed per the projection recommendations). At 79 F, the LP-HEMI will require about 5 kW of electrical power. At 54 F, the LP-HEMI will generate about 7 kW when equipped with a regenerative VFD. Therefore, on average, the LP-HEMI will generate about 1 kW of electrical output while providing the entire amount of interstage pressure boosting.

Note that if a standard turbocharger were used in the above system (see Figure 1), then ΔP_{int} would be insufficient during warm feed operation and would be excessive during cold feed operation.

If interstage boosting were to be provided by a centrifugal pump and VFD package, the average energy input would be about 23 kW based on a 75% feed pump and 92% motor efficiencies. The net advantage of the LP-HEMI would be 24 kW. The annual energy cost saving from the LP-HEMI would be $12,600/year.

The ROI is based on the incremental cost of the LP-HEMI relative to a conventional interstage booster pump package. The incremental cost is estimated to be about $14,000 taking into account the extra brine piping and the elimination of the HP brine control valve for the LP-HEMI. The LP-HEMI ROI is estimated at about 90% and an ISF of 2.7.

5.3 - Retrofit of an Existing System

This case examines the economics of retrofitting a LP-HEMI to an existing system with hydraulic characteristics given in Table 3. The existing pump and motor have an efficiency of 75% and 94% respectively yielding an electrical input power is 182 kW. Please refer to Figure 4.

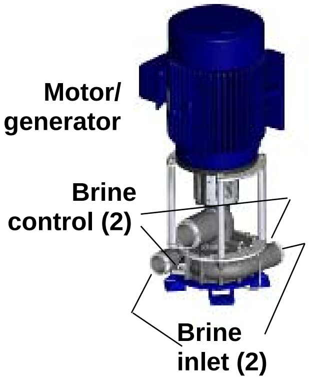


Figure 9 – Power recovery configuration

Q_f	Q_r	P_{suc}	P_m	P_r	P_{ex}	ERP	SBE
1850	460	30	196	160	5	0.197	0.370

Table 3

A LP-HEMI-480 reduces the input power to 144 kW through a combination of slightly higher pump efficiency and (mostly) from the power recovery turbine. The savings of 38 kW yields a $20,000 annual savings for an ROI of 33% and ISF of 1.0 based on preliminary equipment pricing. This ROI analysis makes a pessimistic assumption that the replaced feed pump and motor have no salvage/surplus value.

5.4 – Retrofit with Minimal Disturbance to Existing System

In this case, the customer desires to reduce energy costs but does not wish to significantly modify the existing equipment or operating procedures. The system contains two (2) trains, each with the following characteristics. Please refer to Table 4 and Figures 6 and 9.

Q_f	Q_r	P_{suc}	P_m	P_r	P_{ex}	ERP	SBE
925	232	30	175	150	5	0.208	0.350

Table 4

Given the imperative for minimal disturbance of existing equipment and plant operation, a LP-HEMI configured as a turbine-motor/generator package would be preferred. This package simply turns brine hydraulic energy into electricity with no connections to the RO systems other than brine piping and electrical wiring. To minimize equipment and installation costs, the turbine section is equipped with two (2) turbine nozzles allowing one LP-HEMI to serve both trains. Each turbine nozzle section has adjustable flow and pressure thus each train can operate at its own optimal recovery and pressure.

The LP-HEMI installation saves about 22 kW or $11,500 annually. The ROI is expected to be better than 33% and an ISF greater than 1.0.

6.0 CONCLUSIONS

This paper has examined difficult BWRO energy recovery applications involving brine pressure differentials as low as 117 psi as well as retrofitting ERDs to existing BWRO systems. The analysis suggests that an ROI of better than 30% and an ISF greater than 1.0 are readily achievable in realistic scenarios.

The authors believe that the LP-HEMI will find widespread use in BWRO systems due to quantifiable economic advantage for both the system builder and the end-user.

7.0 ACKNOWLEDGEMENTS

The authors wish to express thanks to Mr. Chris Cusick and Mr. Eric Bell of Mitsubishi Electric Automation for sharing their considerable technical expertise on line regenerative VFDs.

8.0 REFERENCE

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