PhD Synopsis

Improvement in Energy Efficiency of Solar Powered Reverse Osmosis by
Modification in Membrane Morphology and Recovery of Thermal Energy from
Solar Photovoltaic Panel

GUJARAT TECHNOLOGICAL UNIVERSITY

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Graphical Abstract

Water → Solar PV panel efficiency improvement

High temperature feed water to reverse osmosis

Membrane modification for high permeability

Ultra-low energy reverse osmosis

% TRANSMITTANCE vs WAVE NUMBER

Polyamides
HClO4
NaOH
N-chlorination

Gradually
Irreversible
Oxon Rearrangement

Degradation products
Solution
Ring-chlorination

A
B

A
B
A. Title of the thesis and Abstract:

Title: Improvement in Energy Efficiency of Solar Powered Reverse Osmosis by Modification in Membrane Morphology and Recovery of Thermal Energy from Solar Photovoltaic Panel

Abstract: Water, sanitation and hygiene was responsible for 842,000 deaths in 2012; out of them, majority are from developing world according to the World Health Organization. Thus, the access to safe drinking water is placed in top global challenges and more so, for the developing country like India.

Reverse osmosis has been established as the technological solution to treat impaired water/brackish water/seawater. Reverse Osmosis uses semi-permeable membranes to convert saline water into fresh water. The membrane used in reverse osmosis is a thin film composite comprising of nonwoven polyester, polysulfone and polyamide barrier layer; capable of removing salts, bacteria, virus and suspended solids. Membrane process requires energy to produce water since the driving force for water transport is pressure. In this way, reverse osmosis plants need stable power supply source for its operation. Plants installed at remote locations in developing countries where, the power supply is not constant, but endowed with very good solar radiation intensity, solar powered reverse osmosis offers an attractive solution. Solar powered Reverse Osmosis has been recognized as one of the promising technologies to curtail green-house gas emissions and also for stand-alone reverse osmosis systems at remote locations.

Reverse Osmosis has become a quite a matured technology in last decade and has been successfully implemented at various locations in the world. However, the energy needed to produce water has remained a major cause of concern. Energy required to produce fresh water from seawater and brackish water are about 3-4 KWH per cubic meter and 1-2 KWH per cubic meter respectively, depending on the total dissolved solids concentration of feed water.

Traditional Photovoltaic (PV) collectors have a low efficiency i.e. 4–7% for the amorphous one (a-Si) and 14–17% for the crystalline technology (c-Si). This means the large part of
incident solar radiation is wastefully utilized in heating up the solar PV panel raising its
temperature. The mono-crystalline (m-C) and poly-crystalline (PC) cells’ electricity
production decreases when, their temperature increases because of their negative temperature
coefficient (approximately -0.4%/K). Considering the low conversion efficiency and negative
temperature coefficient of PV cells, there is a higher potential for thermal energy production
than electrical energy from a given surface of a PV module. However; the efficient utilization
of captured thermal energy is a challenge.
Many researchers realized this problem and attempted to cool the solar photovoltaic module.
Different heat transfer fluids have been used and different design configurations have been
devised. The research gap is to optimize the solar PV panel performance, achieve maximum
thermal energy recovery and also to harness the recovered heat for useful application.
Moreover; the membrane morphology can also be altered for achieving the high-flux
membrane, thereby reducing energy requirement. The present doctoral work addresses the
challenge of reducing overall energy requirement as an interdisciplinary problem and aims at
making combinations of different approaches i.e. capturing thermal energy from photovoltaics,
thereby increasing their output, utilizing the captured thermal energy in
Reverse Osmosis to increase its productivity and making the membrane surface more
hydrophilic by surface modification to achieve the least energy consumption. Thus, a multi-
pronged approach can significantly lower the energy requirement of Reverse osmosis.
Reflectors have been used to concentrate input solar radiations on PV panels world-over.
Because of the use of reflectors, the temperature of PV panels increases substantially high i.e.
approx. 90°C. The efficiency of solar PV panel drastically falls at this high temperature and
the efficient heat exchange becomes imperative to bring down the temperature. Moreover, the
life of solar panel also decreases if operated at very high temperature. The present work is
aimed at designing and implementing the heat exchange to bring down the temperature of a
solar panel where it works at its optimal efficiency. A study has been made regarding the heat
extraction aspects from solar PV panels to increase the temperature of feed water for
desalination.
At high temperature feed water, the permeability of membrane increases with a slight decline
in selectivity. This can be implemented for low salinity feed water for which lower selectivity
of membrane will be acceptable to avoid re-mineralization of product water. Moreover, the
present work also studied the membrane modification to tailor-make the membrane for very
high permeability that requires lower pressure to generate the same quantity of water.
Moreover, such membrane is more temperature-sensitive. Thus, rise in water flux with rise in
temperature is more pronounced. Such low pressure membrane will be suited for solar powered brackish water RO plant since the array surface area required will be low. In this way, the present PhD work takes solar powered RO in a holistic way to achieve overall energy efficiency by following:

1. **Extracting waste heat from solar PV panels**
   Direct cooling with water has been attempted for controlling the temperature of photovoltaic panel. Two experimental approaches were undertaken: cooling from top of the panel with insulation on the back and sides to tap the maximum possible thermal energy, cooling from back side of the panel. It is observed that there is an improvement in panel performance and simultaneously there is an increase in water temperature in both the cases.
   ANSYS Computational fluid dynamics software has been used to simulate the panel temperature and the simulated temperature has also been experimentally validated.

2. **Utilization of captured thermal energy:**
   The recovered thermal energy has been capitalized to elevate the temperature of feed water to reverse osmosis. In other words; the cooling water in objective 1 was the feed water to reverse osmosis. As a result of heat transfer to feed water, the temperature of feed water increases. At higher temperature, the viscosity of water decreases and therefore the resistance to flow decreases. Thus, the higher temperature feed water improves the trans-membrane water flux at applied pressure. Thus, energy consumption to produce definite quantity of fresh water decreases, which have been quantified.

3. **Modification in polyamide layer of thin film composite membrane to improve permeability:**
   Improvement in TFC RO Membrane permeability is very important alternative for reducing the overall energy consumption of Reverse osmosis. A step change in membrane permeability has been achieved by surface modification on account of chemical reaction i.e. controlled oxidation with sodium hypochlorite, polyamide-chitosan composite membrane (with increased water permeance and selectivity). Such membrane was found to be more temperature-sensitive i.e. higher rise in water flux with given rise in water temperature. The objective is to make the process highly energy efficient and frugal for reverse osmosis application.
   This interdisciplinary approach is novel and demonstrated the substantial decline in energy consumption of renewable powered desalination. It will lead to energy
efficient solution and thus increase the green quotient of the reverse osmosis plants. Thus, this interdisciplinary approach makes the overall process very attractive from the energy consumption point of view and all the objectives of the PhD work have been achieved.

A. Brief description on the state of the art of research topic:

Solar energy is one of the most significant, unlimited, clean and environmentally friendly source of renewable energy. The rapidly developing technology as of date is solar photovoltaics (PV). The major impediment to its wide popularity is low efficiency of converting the solar energy into electricity i.e. 5-17%. More than 80% of the absorbed solar radiation gets converted by the PV cells as waste heat. This heat is generated in two ways. Firstly, the power corresponding to $I^2R$, as an outcome of the current ($I$) flowing through the resistance, $R$ of the solar cell. Secondly, the thermal energy which represents the variation in the absorbed photons and the electrical energy generated out of the electron–hole pairs. Cell temperature is of vital significance for performance of PV cells in a panel [1, 2]. If the temperature of solar PV panel increases, its efficiency to convert solar radiation into electric current decreases because of its negative temperature co-efficient (about -0.4% per °C rise in temperature) with temperature. Temperature dependence of photovoltaic performance and energy conversion in solar PV panels are investigated by many researchers. In gist, the solar photovoltaic panel produces more thermal energy than the electrical energy.

J.K. Tonui and Y. Tripanagnostopoulos attempted air cooling of solar PV panel and for performance improvement of solar PV/T collector with natural flow operation. Performance studies on a finned double-pass photovoltaic-thermal (PV/T) solar collector demonstrated that fins improve efficiency of heat transfer by air cooling [3].

Several researchers attempted to control the temperature of the PV panel. Desiccant cooling system relevant to hot and humid climate equipped with both single glazed standard air and hybrid photovoltaic thermal collector has been studied [4]. A liquid coolant with the heat exchanger system housed within the photovoltaic module to exclude the unwanted solar radiation in order to minimize overheating of the cells [5]. A cooling method for the solar cells under concentrated solar flux was proposed where; the additional heat was removed from both the front and back surfaces of the
module by directly immersing the cells in a dielectric liquid [6]. Unique profile for the reflecting surfaces was developed in such a way that the solar cells are evenly illuminated under any degree of concentration [7].

Liquid immersion cooling was found to eliminate the thermal resistance of back cooling to improve cell performance [8]. Tanaka studied that the use of a shallow liquid layer or a gel layer surrounding solar cells for trapping the radiation and also to wet the cell surface [9, 10, 11]. Carcangiu and co-workers patented an immersed liquid photovoltaic panel. The panel uses a liquid-tight chamber to house solar cells immersed in a poly-dimethylsilicone liquid, being circulated [12].

Ignacio and co-workers used curved, optically transparent covers to enhance the concentrating effect of the immersion dielectric liquid [13]. Falbel patented a surrounding reflective surface for a solar cell, which reflects back the light rays that are not absorbed by the solar cell [14]. Besides the liquid and gel, Cherney et al. attempted to extend the refractive medium to a solid [15]. Using water as the immersion liquid, the panels are configured with liquid super-concentrators having outwardly disposed liquid imaging lenses [16].

Liquid immersion offers several advantages e.g. the optical and surface wetting, the direct contact between cells and their surrounding liquid decreases the thermal resistance, especially for cells at high concentrations. The conventional cooling has the thermal resistance; eliminating the thermal resistance of the contact wall between solar cell and fluid, the cells can be effectively cooled down for a desirable sunlight-to-electricity conversion efficiency [17].

The plant leaves convert the solar energy into the food; an attempt to mimic the same was done to understand how they control temperature when exposed to sun [18]. Air is very widely studied coolant; an active cooling of PV module by blowing air above the module with Computational fluid dynamics analysis has been attempted [19].

It has been reported that the thin film of water above the solar photovoltaic panel improves the photovoltaic panel performance. However, the comparison with the modelled data is missing and the energy efficiency derived out of the system has not been worked out.[20] Researcher attempted to improve the photovoltaic panel
efficiency by direct water cooling; however the application of recovered energy has not been explored [21].

Despite the extensive research on heat transfer from solar PV panel, modeling and experimental validation of solar panel heat transfer with water cooling from top surface with overall energy perspective remains the research gap and the present work addresses the same. In addition to that, the membrane morphological changes for higher hydrophilicity and lower energy consumption will make the solar powered reverse osmosis an attractive solution. The present work also demonstrates that the membrane surface can be made more hydrophilic in order to achieve higher productivity and thus, lower the energy consumption.

C. Definition of the problem:
The present doctoral work addresses the following problems:

1) **Can we extract the waste thermal energy from solar PV panels in order to control its temperature and increase its efficiency?**

2) **Can we utilize the captured thermal energy for useful application?**

3) **Can we modify modify the polyamide layer of thin film composite membrane to improve permeability and thereby decrease energy consumption of Reverse Osmosis?**

It systematically studies each aspect of the problem to suggest the solution.

D. Objective and scope of work:

**Objectives:**

1. Study heat transfer aspects of solar photovoltaic panel from theoretical and experimental point of view to understand the rise in temperature of solar photovoltaic panel and also study the photovoltaic panel performance with and without heat transfer.

2. Capture the thermal energy and study its application for useful purpose. The captured energy should be directly utilized in order to minimize its loss.

3. Study the Thin film composite Reverse Osmosis membrane and explore the way to increase its permeability and thereby decrease the energy consumption of Reverse Osmosis.
Scope of work: The present doctoral work addresses each objective as mentioned above and studies the heat transfer aspects theoretically by ANSYS Computational fluid dynamics software to evaluate the temperature of photovoltaic panel and also experimentally validates the data. It also demonstrates that the captured thermal energy can be utilized directly in reverse osmosis to achieve higher energy efficiency. It studies the membrane morphology and finds the way to increase the hydrophilicity of the membrane and makes the reverse osmosis very low energy intensive.

E. Original contribution by the thesis:

The original contribution is manifested by 4 international peer-reviewed papers those have been published out of this doctoral work as shown below:

doi: 10.1039/C4RA12610F (5-YEAR IMPACT FACTOR: 3.907)

2. Hiren D. Raval*, Subarna Maiti Ultra- low energy Reverse osmosis with thermal energy recovery from photovoltaic panel cooling and TFC RO membrane modification Desalination and Water Treatment 57 (2016) 1-10
Published online doi: 10.1080/19443994.2014.993725 (5-YEAR IMPACT FACTOR: 1.017)

doi: 10.1063/1.4885178 (5-YEAR IMPACT FACTOR: 1.149)


Presentation in an International conference (USA)
H.D. Raval*, S. Maiti, A. Ghassemi, L. Karimi (2014) “Options for improving attractiveness of renewable energy powered desalination” at AICHE Annual meeting-2014 Atlanta, GA, USA
F. Methodology of research, results/comparison

The methodology involves the experimental as well as modelling work. The solar photovoltaic panel was cooled by flowing water from top as well as bottom at different flow rates. The temperatures of panel with and without cooling were monitored over a period of time. Moreover, the theoretical study was made by ANSYS computational fluid dynamics software to simulate the temperature of photovoltaic panel with given solar insolation. Simulated data were validated by experimental data as they were in close conformity.

The rise in temperature of water was monitored. The heated water was subjected to domestic reverse osmosis membrane element. The performance of reverse osmosis membrane element (i.e. solute rejection/flow rate) was monitored during the experiment. The membrane element was also treated with sodium hypochlorite at pH 11.0 to increase its productivity and the performance of membrane element was monitored. Thin film composite RO membrane was also modified by a supramolecular assembly of chitosan over polyamide to enhance the productivity and temperature sensitivity of the membrane. Such modified membranes and virgin TFC RO membrane were characterized: surface morphology by atomic force microscope, chemical structural changes by attenuated total reflectance-Fourier Transform Infrared Spectroscopy, surface hydrophilicity by contact angle, surface charge by Zeta potential analyzer.

Following conclusions were derived out of the studies:

- Photovoltaic panel temperature can be effectively controlled by transferring heat from top at low flow rate e.g. 1 and 2 Liters per minute and insulation at the back surface and sides. The insulation makes sure that the heat is not lost from bottom and the direction of heat transfer is bottom-up. CFD analysis is in close confirmation with experimental validation for the panel temperature.
- It is demonstrated for the first time that the refraction of incident solar radiation while striking to PV panel through the water film is beneficial. Narrowing the span of angle striking to the panel during the day is better from the point of view of panel performance.

- The rise in water temperature reported indicates that there is a potential to tap the thermal energy. The higher temperature water can be used for desalination systems like membrane distillation, reverse osmosis etc. The higher temperature water can be used for reverse osmosis where, higher feed water temperature offers the advantage of higher product water flow.

- Overall energy efficiency has been increased from about 6% to 40% by direct cooling the array surface of PV panel from top at 1 liter per minute flow.

The feed water to reverse osmosis was used as coolant of PV system. The heated feed water was directly passed through reverse osmosis membrane element. Membrane modifications were made to make it more hydrophilic. This approach resulted in ultra-low energy reverse osmosis with following conclusions:

- Controlled oxidation of polyamide layer at high pH resulted in improved flow performance of the membrane. The TFC RO membrane became more hydrophilic by this treatment. This can synergistically increase the flow of domestic RO membrane module along with higher temperature feed water.

- Overall 67.86% rise in flow with ca. 1% decline in solute rejection has been observed by increasing the feed water temperature by 12°C and treating the membrane with sodium hypochlorite solution at exposure level of 162.5 ppm-hour at 11.5 pH. The novel combination of altering the membrane morphology and using high temperature feed water improved the overall energy efficiency; the energy requirement decreased by about 40%. Also, the overall recovery of domestic RO system increases as the concentrate is re-circulated back to the panel.

Cooling the photovoltaic from the back surface (other than the array surface) of photovoltaic panel and directly utilizing the water for reverse osmosis demonstrated the following results:

- Domestic Reverse Osmosis (RO) membrane permeate flow rate increased from 85 ml/minute to 118 ml/minute when the feed water temperature increased from 35°C to
45°C. The feed water viscosity decreases at higher temperature; thus the resistance to flow decreases. Thus, the tapped thermal energy in feed water improved the productivity of reverse osmosis membrane.

- The cooling water can control the temperature of PV panel. The difference in the average temperature of PV panel with cooling and without cooling is at its highest at 1200 noon when, the temperature of PV panel with cooling was 34.3°C and without cooling was 59.1°C. The power produced by PV panel increased with cooling on the back side as the temperature of PV panel kept lower.

- Total water output over 7 hour period (from 1000 Hrs to 1700 Hrs) was increased by 20% by heating feed water for solar photovoltaic panel cooling.

- It has been demonstrated that the specific energy consumption of reverse osmosis decreases by ca. 28% when the feed water temperature increases by 10°C. The energy consumption for reverse osmosis can be decreased by making very high permeability reverse osmosis membrane and putting it in use. The thin film composite RO membrane can be modified to make a very high flux membrane by successive chemical treatment of sodium hypochlorite and chitosan to make the hydrophilic supra-molecular assembly. Such a composite membrane demonstrated lower contact angle and higher hydrophilicity. Following conclusions were derived:

- The trans-membrane flux increased from 14 gallons per square feet per day (gfd) to 30 gfd with increase in NaCl solute rejection from 92% to 95%, whereas the flux increased from 16 gfd to 28 gfd with increase in MgCl₂ rejection from 86.36% to 95.06% when the membrane was exposed to 1250 mg/l sodium hypochlorite at pH 11.0 for 30 minutes followed by 1000 mg/l chitosan solution at pH 2.5 for 60 minutes.

- The trans-membrane flux increased from 14 gfd to 49 gfd with decline in NaCl solute rejection from 92% to 86.36%, whereas, the flux increased from 16 gfd to 43.5 gfd with a slight decline in MgCl₂ rejection from 86.36% to 85.46% when the membrane was exposed to 1250 mg/l sodium hypochlorite at pH 11.0 for 60 minutes followed by 1000 mg/l chitosan solution at pH 2.5 for 60 minutes. This showed the longer sodium hypochlorite exposure compromises on membrane selectivity.

- Zeta potential of the thin film composite RO membrane decreased from -33.8 mV to -37.42 mV and roughness decreased from 225 nm to 117 nm when the membrane was exposed to 30 minutes, 1250 mg/l sodium hypochlorite at pH 11.0 and 1000 mg/l
chitosan at pH 2.5. This shows improvement in divalent ion as the charge becomes more negative.

- The average contact angle decreased from 49° to 32.5° when membrane was exposed to 30 minutes, 1250 mg/l sodium hypochlorite at pH 11.0 and 1000 mg/l chitosan for 60 minutes at pH 2.5. This demonstrates that hydrophilicity of the membrane increased.
- Presence of –OH group and modification in –CO- group in polyamide structure shows the supra-molecular assembly of chitosan over polyamide.
- 1000 mg/l chitosan treated membrane for 60 minutes at pH 2.5 after 1250 mg/l sodium hypochlorite treated membrane at pH 11.0 was more temperature sensitive as compared to TFC RO membrane and demonstrated 5.56% rise in flux per °C rise in feed water temperature. Such a modified membrane may be used in solar photovoltaic powered desalination where, the feed water can capture thermal energy from solar photovoltaic to control its temperature and thus gets heated. The low grade captured thermal energy can be utilized synergistically to increase the permeability of the membrane.

Thus, this doctoral research demonstrates that interdisciplinary approach is essential to make the substantial decline in energy requirement of solar powered reverse osmosis and make it an attractive solution.

G. Achievements with respect to objectives

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<th>Objective</th>
<th>Published Paper for the objective</th>
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<td>- Study heat transfer aspects of solar photovoltaic panel from theoretical and experimental point of view to understand the rise in temperature of solar photovoltaic panel and also study the photovoltaic panel performance with and without heat transfer. - ACHIEVED</td>
<td>1. <strong>Hiren D. Raval</strong>, Subarna Maiti*, Ashish Mittal Computational fluid dynamics analysis and experimental validation of improvement in overall energy efficiency of a solar photovoltaic panel by thermal energy recovery Journal of renewable and sustainable energy 6 (2014) 033138 doi: 10.1063/1.4885178 2. <strong>Hiren D. Raval</strong>, Subarna Maiti,</td>
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### A novel photovoltaic powered Reverse Osmosis with improved productivity of Reverse osmosis and photovoltaic panel

*Journal of Membrane Science and Research* 1 (2015) 113-117 (Peer reviewed international Journal)

**Hiren D. Raval**, Subarna Maiti

**ACHIEVED**

Capture the thermal energy and study its application for useful purpose. The captured energy should be directly utilized in order to minimize its loss. - ACHIEVED

**Hiren D. Raval**, Subarna Maiti

**Ultra-low energy Reverse osmosis with thermal energy recovery from photovoltaic panel cooling and TFC RO membrane modification**

*Desalination and Water Treatment* 57 (2016) 1-10 Published online doi: 10.1080/19443994.2014.993725

**Study the Thin film composite Reverse Osmosis membrane and explore the way to increase its permeability and thereby decrease the energy consumption of reverse osmosis. - ACHIEVED**

**Hiren D. Raval**, Pranav S. Rana, Subarna Maiti

**A novel high-flux thin film composite reverse osmosis membrane modified by chitosan for advanced water treatment**


### H. Conclusion:

All the objectives are addressed and peer reviewed, international papers with impact factors have been published. Thus, the synopsis of doctoral work is hereby, submitted to Gujarat Technological University.

### I.

**Copies of papers published and a List of all publications arising from the thesis**

Copies of the papers published are attached herewith.
doi: 10.1039/C4RA12610F
(5-YEAR IMPACT FACTOR: 3.907)

2. Hiren D. Raval*, Subarna Maiti Ultra- low energy Reverse osmosis with thermal energy recovery from photovoltaic panel cooling and TFC RO membrane modification Desalination and Water Treatment 57 (2016) 1-10
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J. Patents – Nil

K. References