# Optimizing the Operation of Renewable Energy-Driven Reverse Osmosis Desalination

A joint research project

Aston University and University of Bahrain

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Aston University, UK

# Outline

- Introduction
- Research Aims
- Challenges of driving RO desalination by RES
- Research objectives
  - Preliminary Work
  - Further future work

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# Introduction

**UN**

- Water consumption is growing at twice the rate of population growth.

**WHO**

- By 2025, half of the world's population will live in water stressed areas

**IEA**

- Water demand will increase in MENA region from 9 billion $m^3$ in 2010 to 13.3 billion $m^3$ in 2030.

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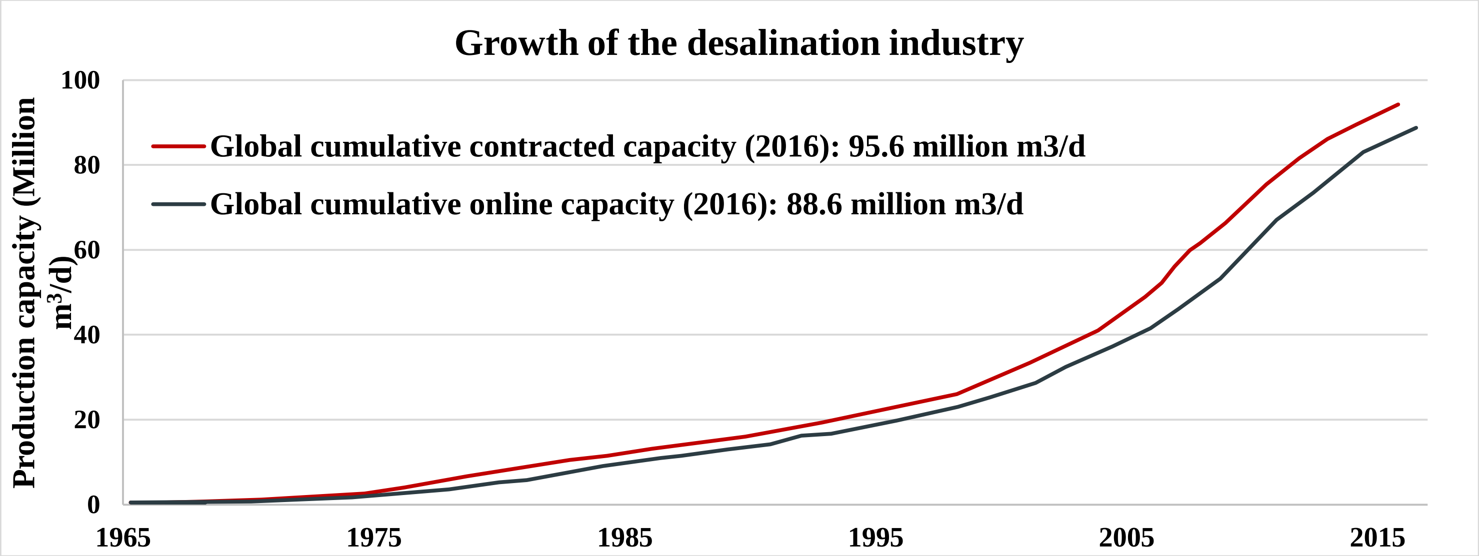
- UNWWAP, *UN world water development report 2017. Wastewater: The Untapped Resource*. 2017: Paris.
- http://www.who.int/mediacentre/factsheets/fs391/en/
- IRENA and IEA-ETSAP, *Water Desalination Using Renewable Energy: Insights for policy makers*. 2013.

# Desalination

- Number of plants operating in June 2015 is 18,426.

- Clean water supply by desalination in 2016 → 95.6 $Mm^3$/day

- Number of people who depend on desalination for daily needs. → More than 300 Million







- International Desalination Association- Desalination by numbers.
- IDA, *IDA desalination yearbook 2016-2017*. 2017.

# Energy consumption of RO plants

- RO desalination is considered an energy intensive process.
- Energy required for RO desalination 3 – 4 kWh/$m^3$.
- The daily constant production of 95.6 $Mm^3$/day requires approximately 882 million Ton of fuel is burned per year in 2016.
- In 2017, globally installed desalination plants generated approximately 76 million ton of $CO_2$ emission.

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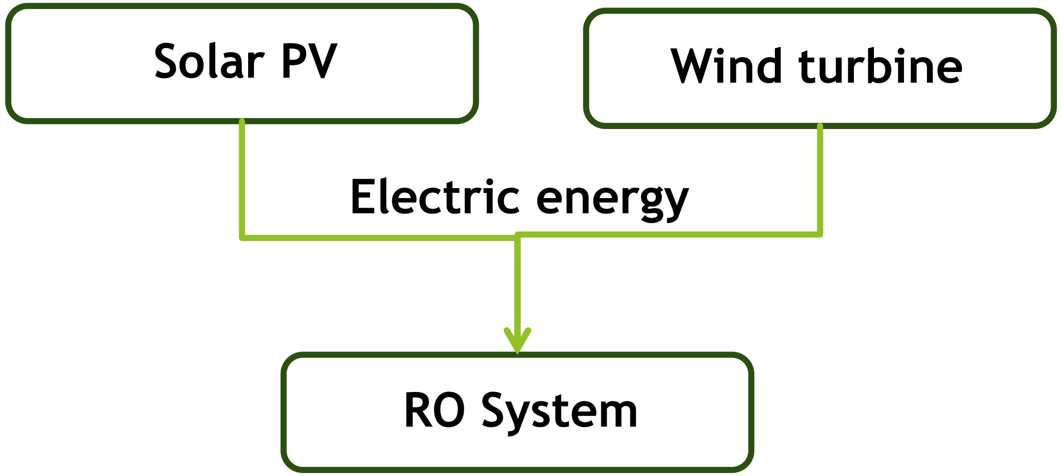
- Abdelkareem, M.A., et al., *Recent progress in the use of renewable energy sources to power water desalination plants.* Desalination, 2017.
- *M.W. Shahzad, M. Burhan, L. Ang, K.C. Ng. Energy-water-environment nexus underpinning future desalination sustainability. Desalination. 413 (2017) 52-64.*

# Renewable energy-driven desalination

- Deployment price for renewable energy is decreasing.
- **Benefits of employing renewable energy in desalination for:**

1) Countries with high energy availability
2) Developing countries

- **Suitable renewable energy sources for Reverse Osmosis plants**

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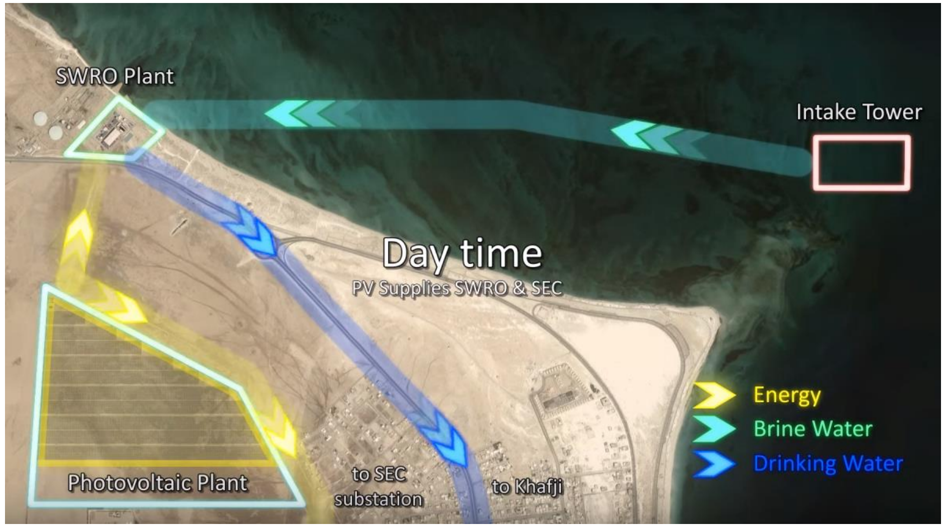
# Current Technologies

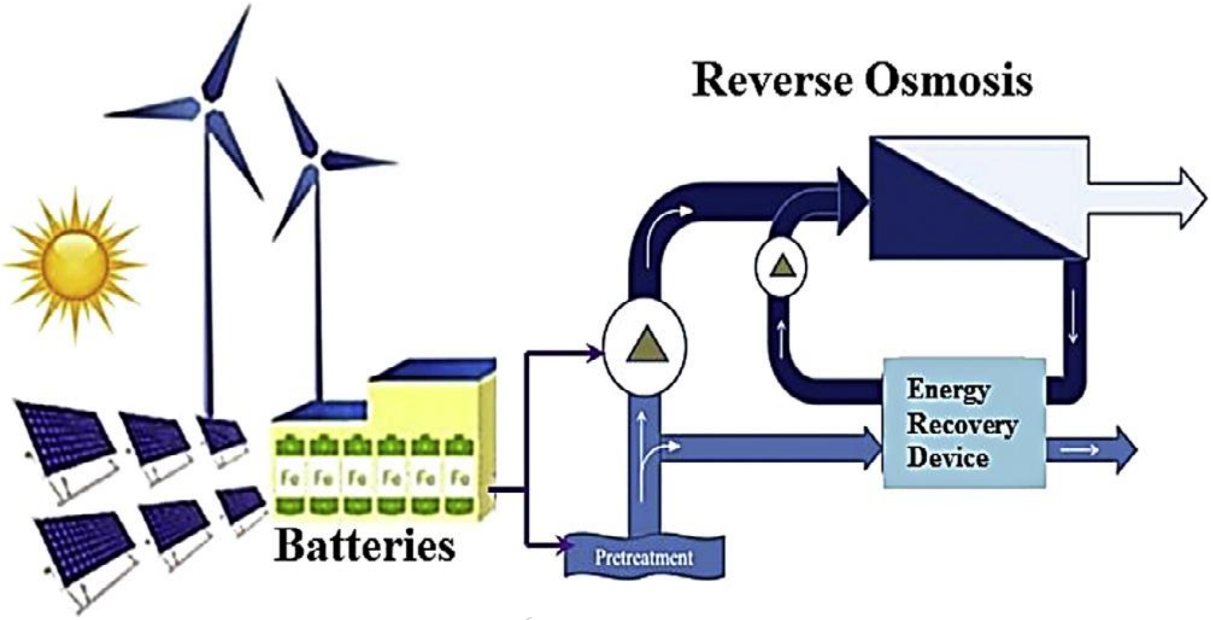
1) **Grid connected plants**

- **Example:** Al Khafji plant in Saudi Arabia




2) **Energy storage systems**

- Complicate the system
- Increase the capital cost
- Increase water production cost







- Advanced water technology. [cited 2017 30 November]; Available from: http://www.awatertech.com/projects.
- V.G. Gude, Energy storage for desalination processes powered by renewable energy and waste heat sources, Applied Energy, 137 (2015) 877-898.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# Research Aim


- The aim is to **design** and **optimize** a renewable energy-driven RO desalination plant that is **directly coupled** to the renewable energy source.
- Accommodate the **variable** and **intermittent** nature of RESs (that is opposite to the design nature of steady operating RO plant) to allow for large scale implementation.

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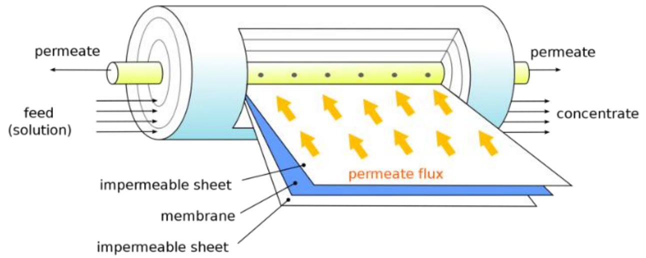
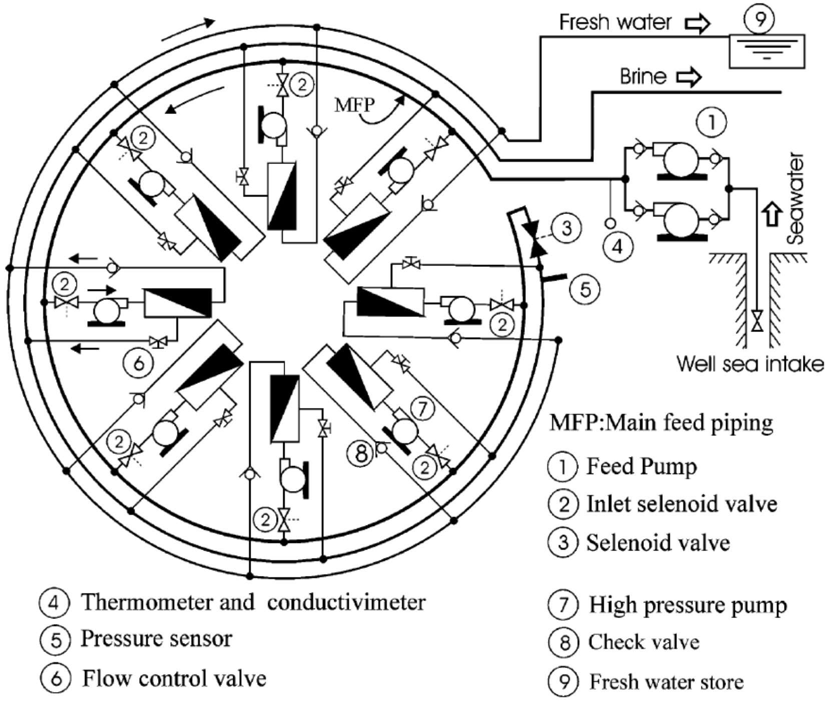
# Challenges of driving RO desalination by RES




- **1. Complications of variable operation on RO membranes**
- Membrane performance and lifetime

| Study | Methodology | Outcome |
|---|---|---|
| Carta et al. (2003) | Modules had different number of start-ups and shutdowns. | No membrane deterioration was noted. |
| Pestana et al. (2004)<br>Latorre et al. (2015) | Operated the plant for 7000 and 6000 hrs at variable conditions. | |
| Rodger et al. (1992)<br>Winzler et al. (1993)<br>Al-Bastaki and Abbas (1999) | Effect of fluid instabilities and pulsating transmembrane pressure. | Improvement in performance was reported. |





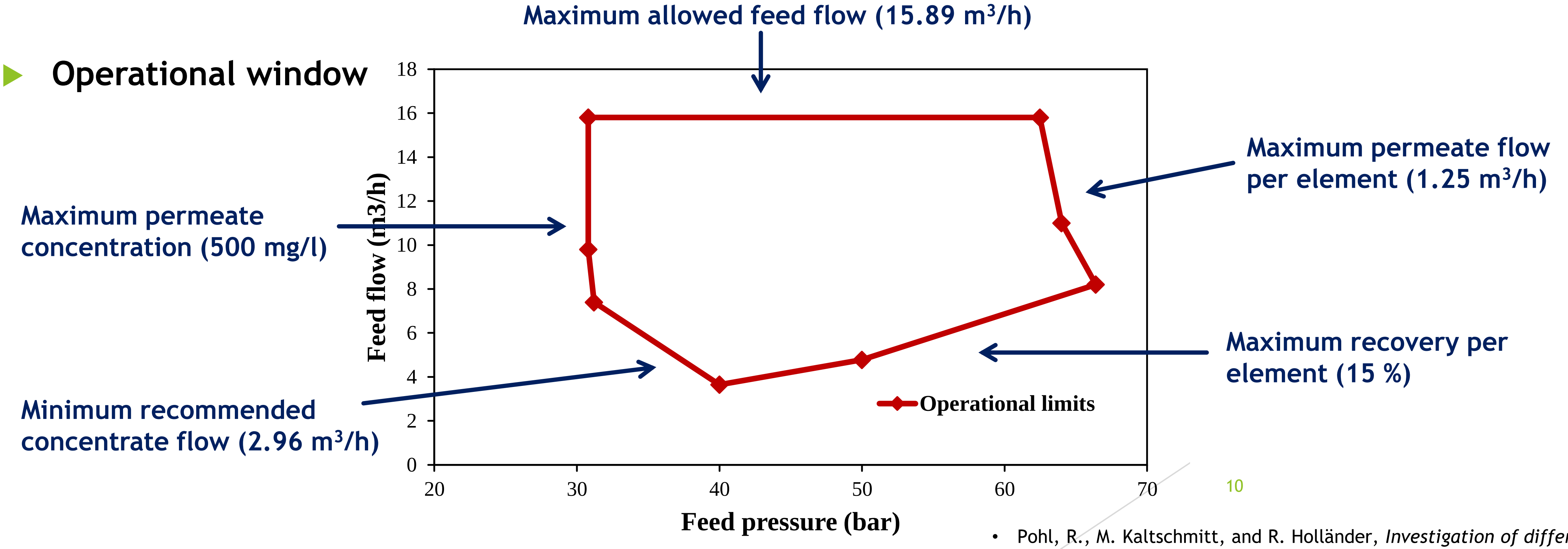

• J.A. Carta, J. González, V. Subiela. Operational analysis of an innovative wind powered reverse osmosis system installed in the Canary Islands. Solar Energy. 75 (2003) 153-68.

# Challenges of driving RO desalination by RES

## 2. Operational window of RO plant

- Operational window is dependent on the hydraulic limitations of the RO membranes.

## Operational window





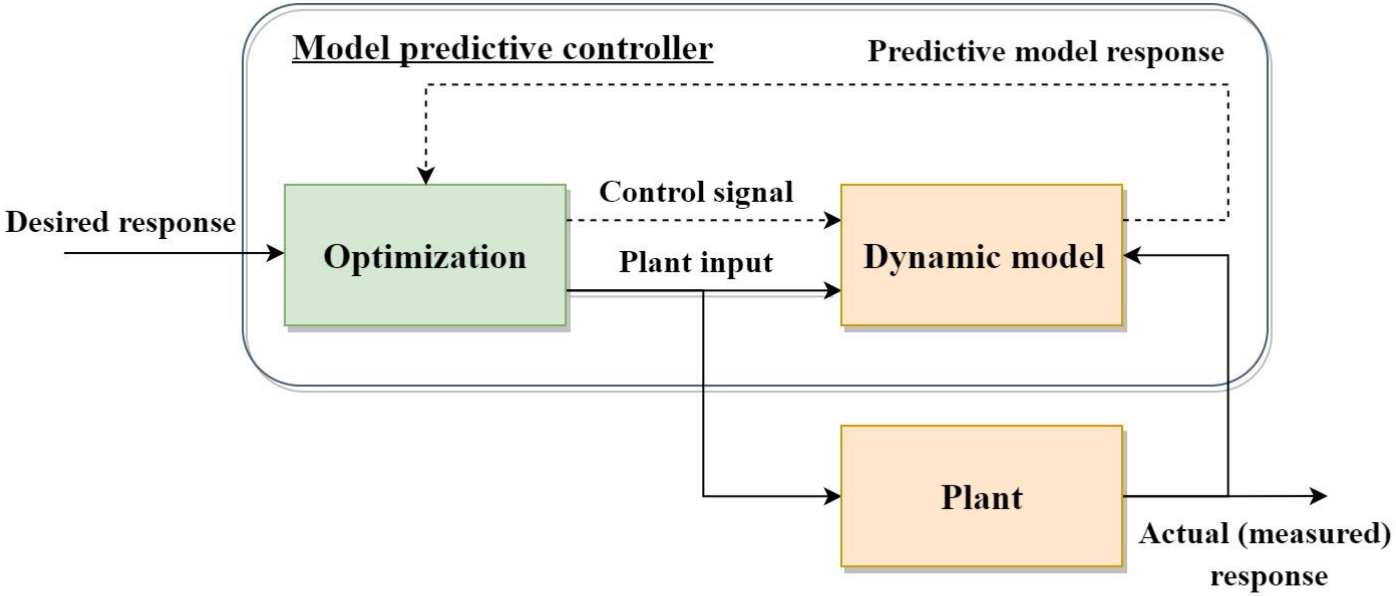


- Pohl, R., M. Kaltschmitt, and R. Holländer, *Investigation of different operational strategies for the variable operation of a simple reverse osmosis unit*. Desalination, 2009. **249**(3): p. 1280-1287.

# Challenges of driving RO desalination by RES

- **3. Control and operation strategy**

- Model predictive control

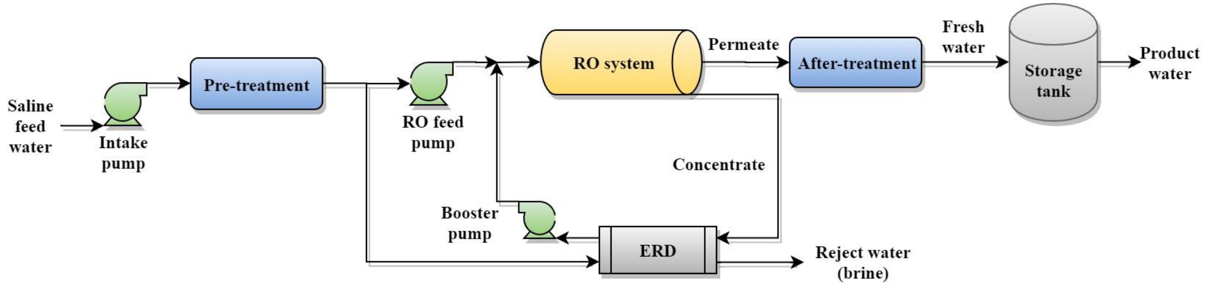



- Control parameters

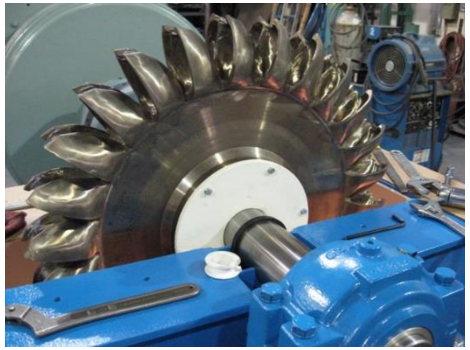
| Manipulated variables | Controlled variables | Measured disturbance variables |
| --- | --- | --- |
| Feed pressure | Permeate flow rate | Available power |
| Feed flow rate | Permeate concentration | Feed concentration |
| Recovery ratio | Specific energy consumption | Feed temperature |

# Challenges of driving RO desalination by RES

- **4. Energy recovery device (ERD)**
- ERDs can recover the pressure energy that resides in the brine stream.
- ERDs helped reduce the SEC below 5kWh/m$^3$.

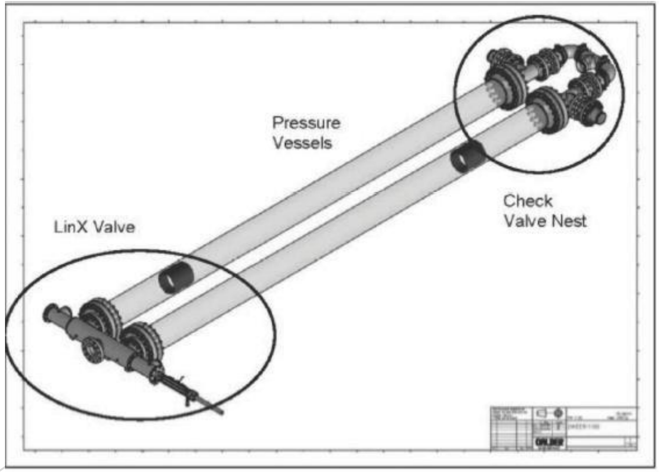



- Example of ERDs:



Pelton wheel

Pressure exchanger



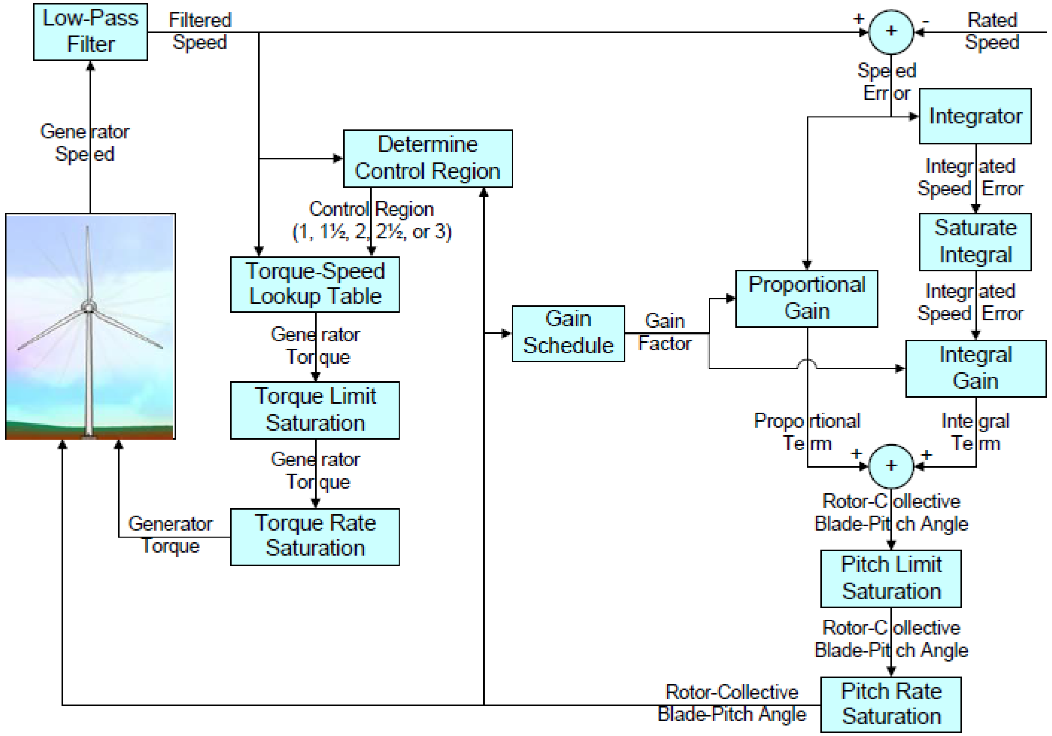

DWEER

- ERI Energy, pressure exchanger URL:https://www.youtube.com/watch?v=PsgTRFDU_p0

# Preliminary work

1. Characterization of the dynamic renewable energy system.

- **Dynamic modeling of wind turbine**




- Jonkman, J., S. Butterfield, and a.G.S. W. Musial, *Definition of a 5-MW Reference Wind Turbine for Offshore System Development*. 2009, National Renewable Energy Laboratory.

NREL
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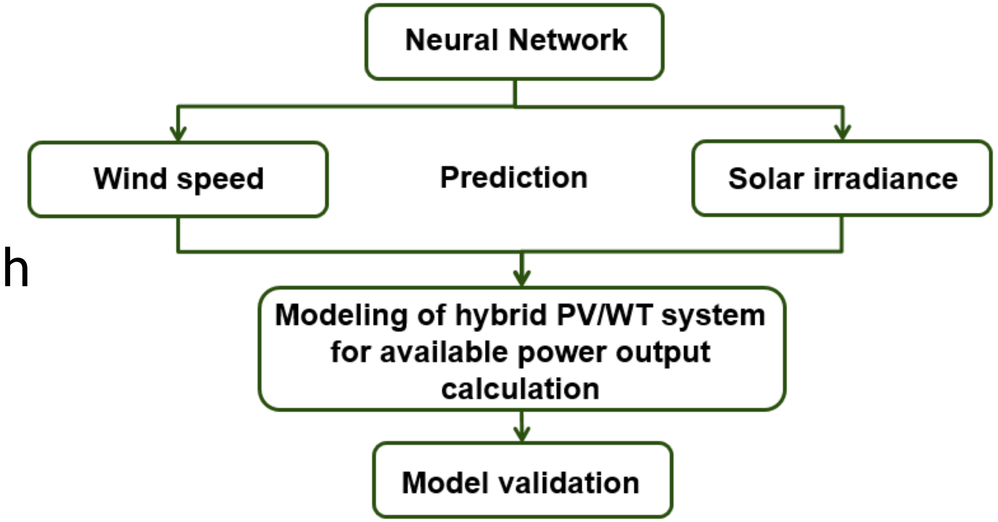
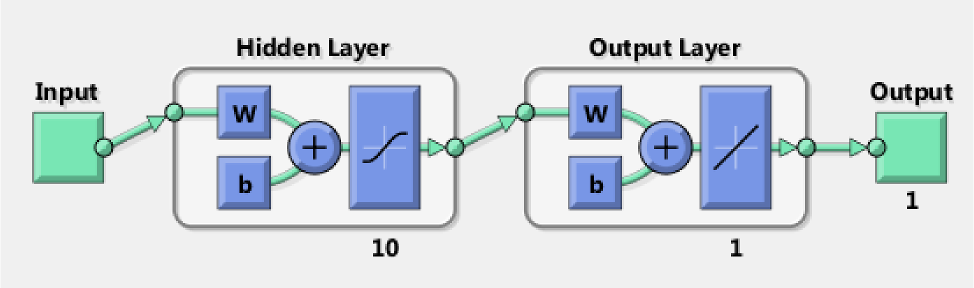
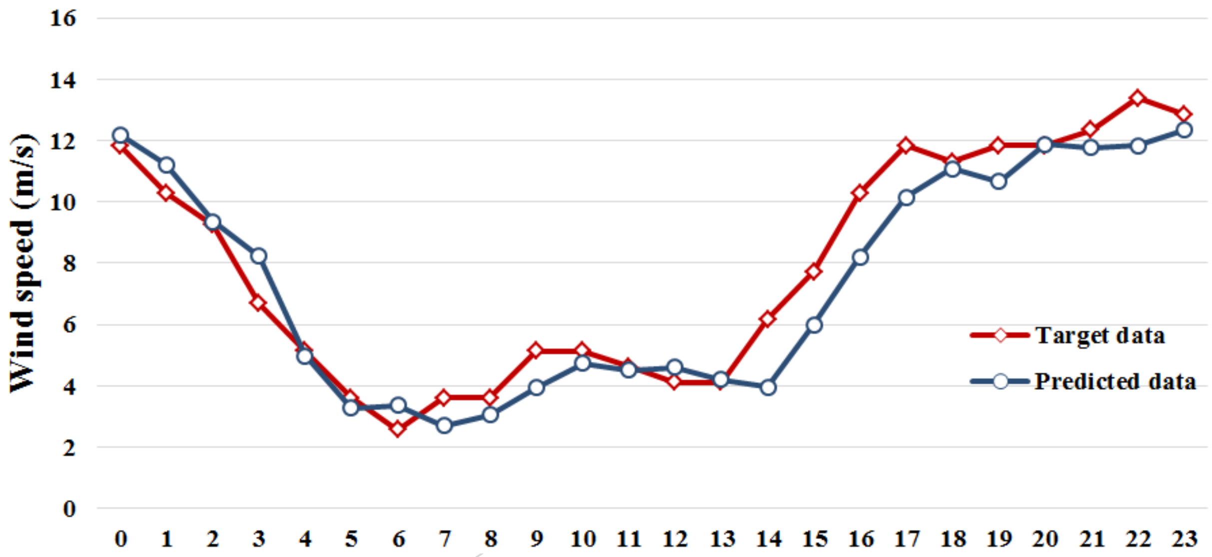
# Preliminary work

2. Implementing short term prediction for the RE availability, to allow for predictive control approach to maximize power capture and scheduling of the plant operation.





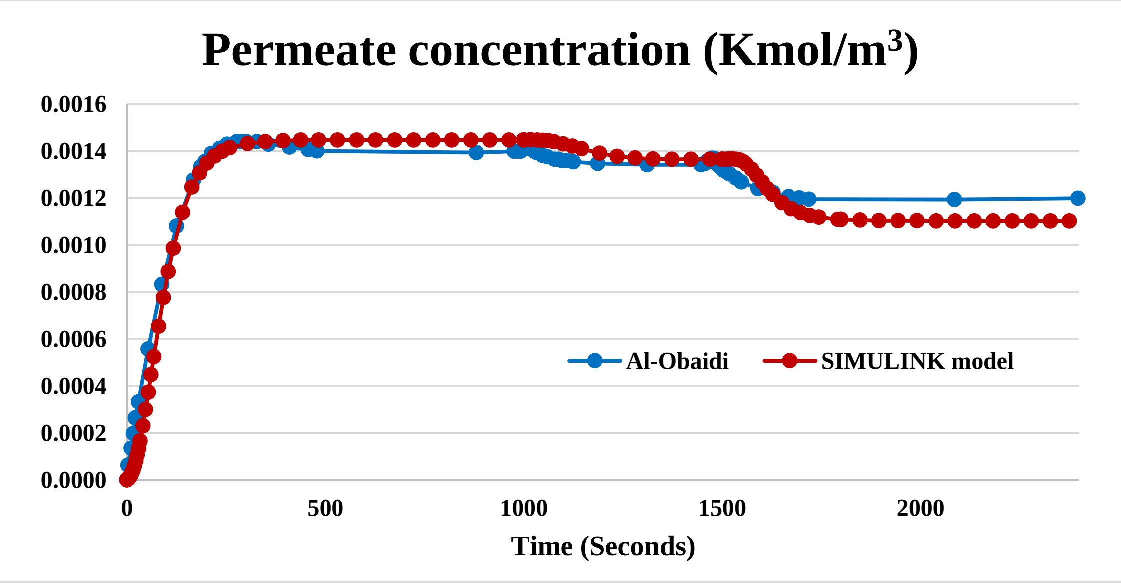
- Gambier, A., *Dynamic modeling of the rotating subsystem of a wind turbine for control design purposes*. IFAC PapersOnLine, 2017(50): p. 9896-9901.

# Preliminary work

- **Dynamic modeling of RO plant**
  - The dynamic model presented by Al-Obaidi et al. was adopted.
  - The figure present the permeate concentration to a step change in feed flow rate at 1000 S and 1500 S.

Table 1
Dynamic model of RO module [Al-Obaidi et al. (2016)].

| | |
|---|---|
| Water flux (m/s) | $\frac{dJ_w}{dt} = \left\{\left(A_w\left((P_b - P_p) - RT_b(C_w - C_p)\right)\right) - J_w\right\}\left(\frac{F_b}{t_f WL}\right)$ |
| Salt molar flux (Kmol/m² S) | $\frac{dJ_s}{dt} = \left\{\left(B_s exp\left(\frac{J_w}{K}\right)(C_b - C_p)\right) - J_s\right\}\left(\frac{F_b}{t_f WL}\right)$ |
| Brine salt concentration (Kmol/m³) | $\frac{dC_b}{dt} = -\frac{C_b}{t_f W}\frac{dF_b}{dx} - \frac{F_b}{t_f W}\frac{dC_b}{dx} + \frac{d}{dx}\left[D_b\frac{dC_b}{dx}\right] - \frac{J_w C_p}{t_f}$ |
| Permeate concentration (Kmol/m³) | $\frac{dC_p}{dt} = -\frac{C_p}{t_p W}\frac{dF_p}{dx} - \frac{F_p}{t_p W}\frac{dC_p}{dx} + \frac{d}{dx}\left[D_p\frac{dC_p}{dx}\right] + \frac{J_w C_p}{t_f}$ |






- * M.A. Al-Obaidi, I.M. Mujtaba. Steady state and dynamic modeling of spiral wound wastewater reverse osmosis process. Computers & Chemical Engineering. 90 (2016) 278-99.

# Further work

1. Defining an operational strategy (power management algorithm) and control system to consider:
    a) Available energy from RES
    b) Adequate net driving pressure and feed water flow rate.
    c) Recovery ratio to avoid concentration polarization and equipment constraints.
    d) Scheduling of daily water production based on daily prediction of available power.
2. Build and validate a model for a large scale desalination plant using classical modeling techniques [Solution-Diffusion model].

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# Further work

3) Build a lab scale prototype with multiple pressure vessel to mimic the modularity of large scale RO plants, with consideration of the ERD.

4) Perform a parametric study to investigate the effect of variable operation on:

   a) Product flow

   b) Recovery rate

   c) Conductivity

   d) Energy consumption

   e) Performance of energy recovery device

   f) Membrane deterioration due to discontinuous operation and different pressure regimes

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# Thank You

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