High recovery rate solar driven reverse osmosis and membrane distillation plants for brackish groundwater desalination in Egypt

A Nashed

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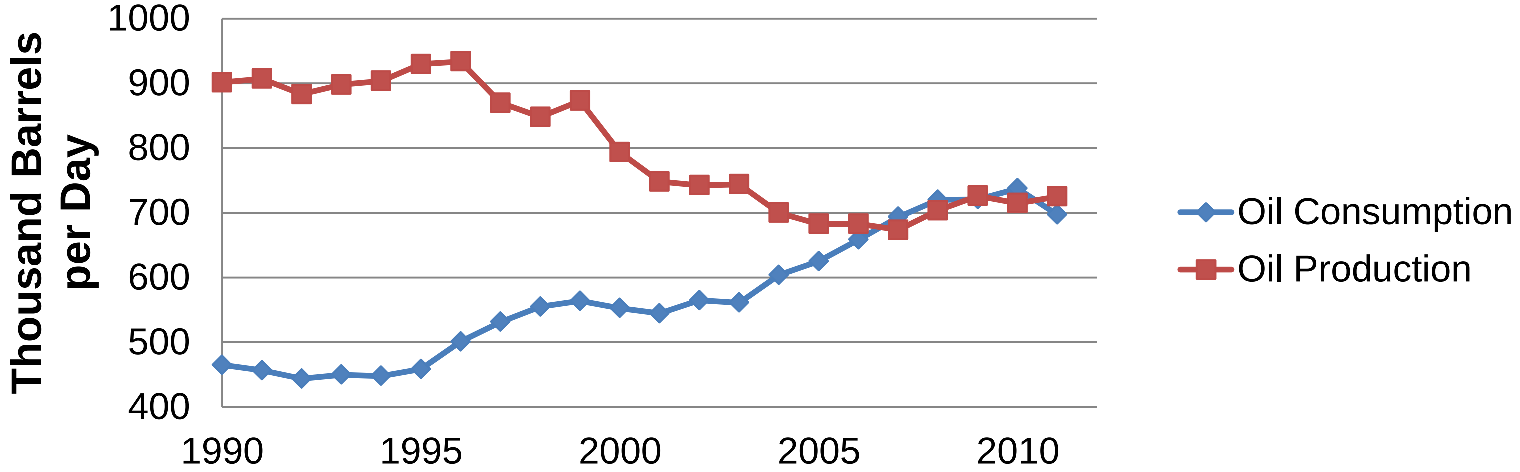
Main Investigation

- Why decentralized high recovery rate solar driven plants for brackish groundwater (GW) extraction and desalination could be beneficial to Egypt?
- Is it more economical to use PV instead of diesel generators to drive the reverse osmosis (RO) plant?
- Is there an economic advantage of replacing PV modules with Photovoltaic thermal (PVT) collectors to drive the RO plant?
- Is it feasible to use a membrane distillation (MD) process to enhance the recovery rate of the RO plant?

Energy and water availability in Egypt

Limited Fossil Fuel Resources

- Egypt is a net oil importer



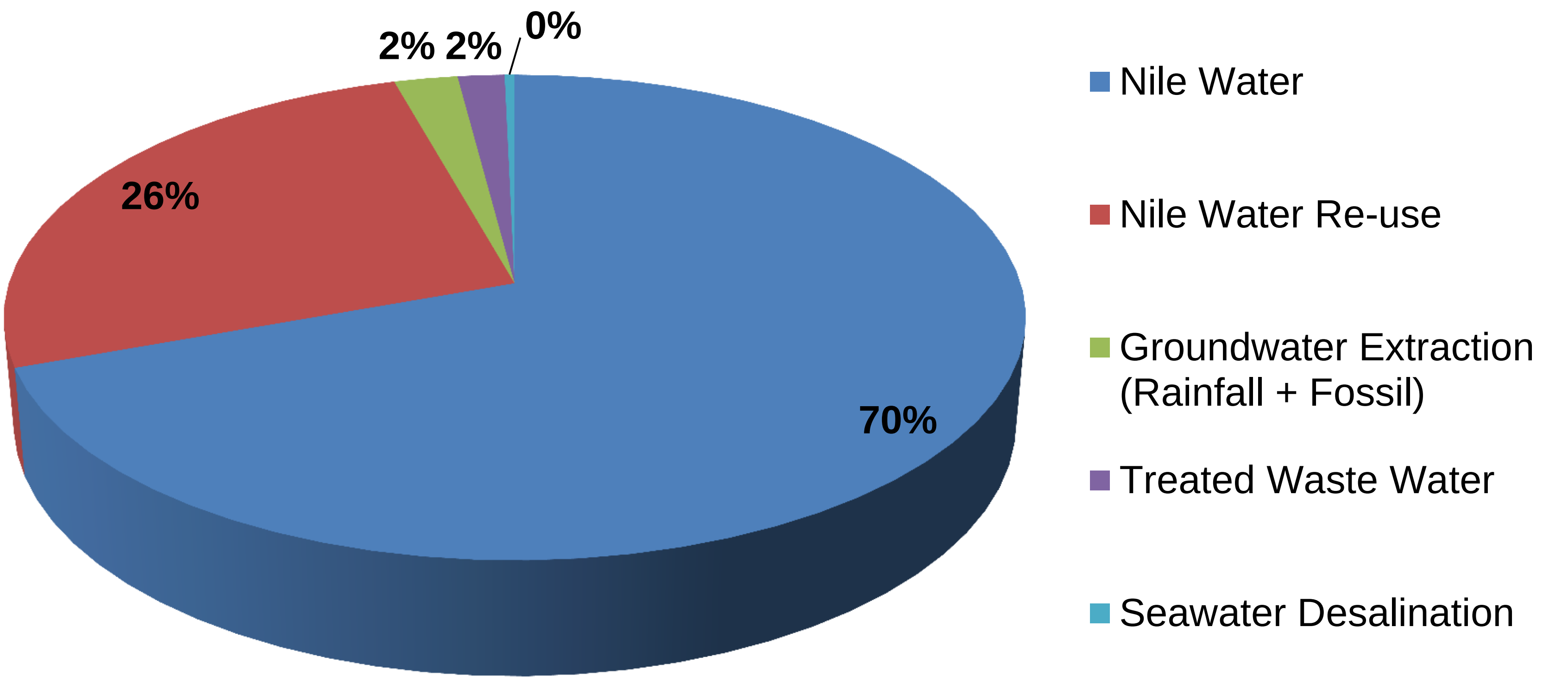
Egypt Total Oil Production and Consumption from 2000 to 2011

Source: U.S. Energy Information Administration (2013)

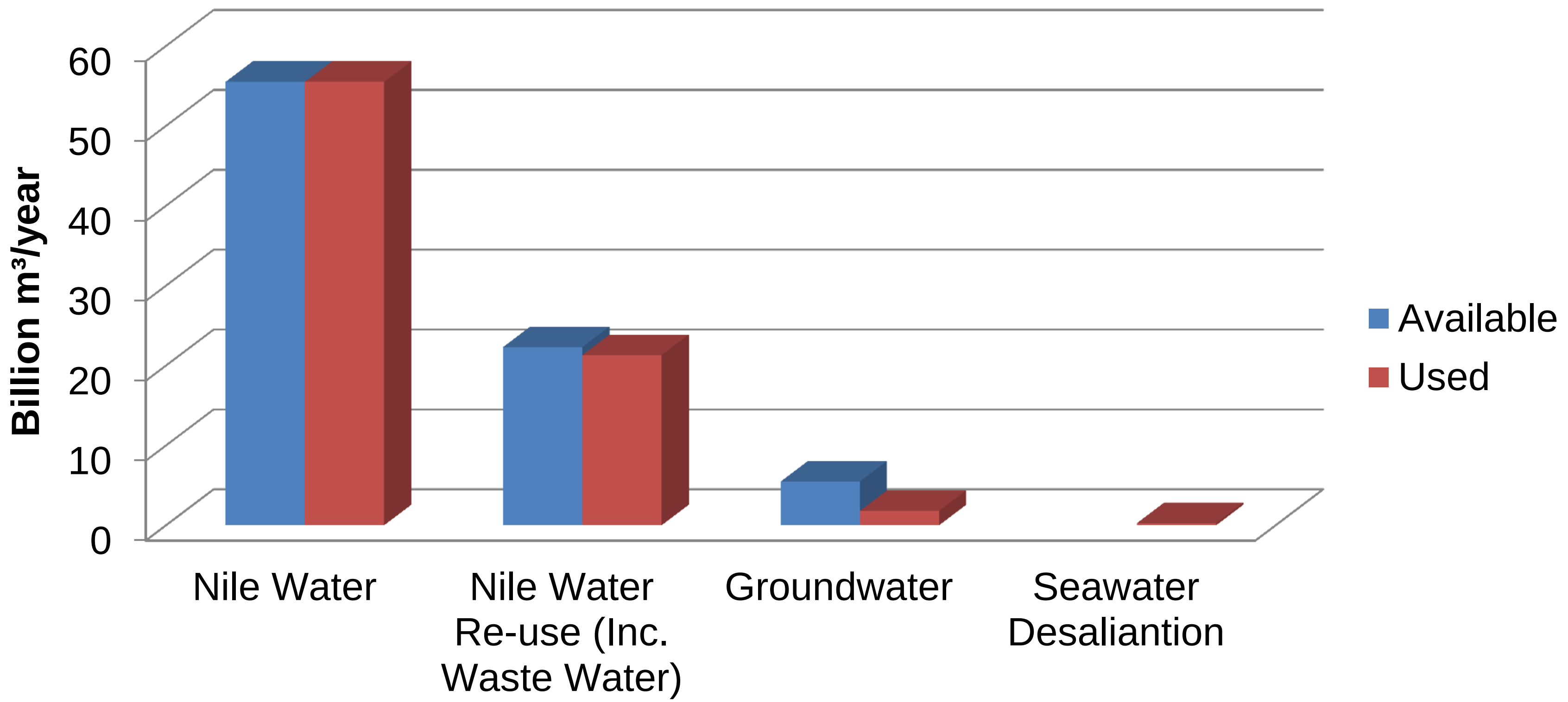
- Current natural gas reserves could be exhausted by 2028

Egypt experienced severe shortages in electricity during summer peak hours since 2010!

Water Status in Egypt: Water Sources



Egypt is on the verge of becoming an absolutely water scarce country!



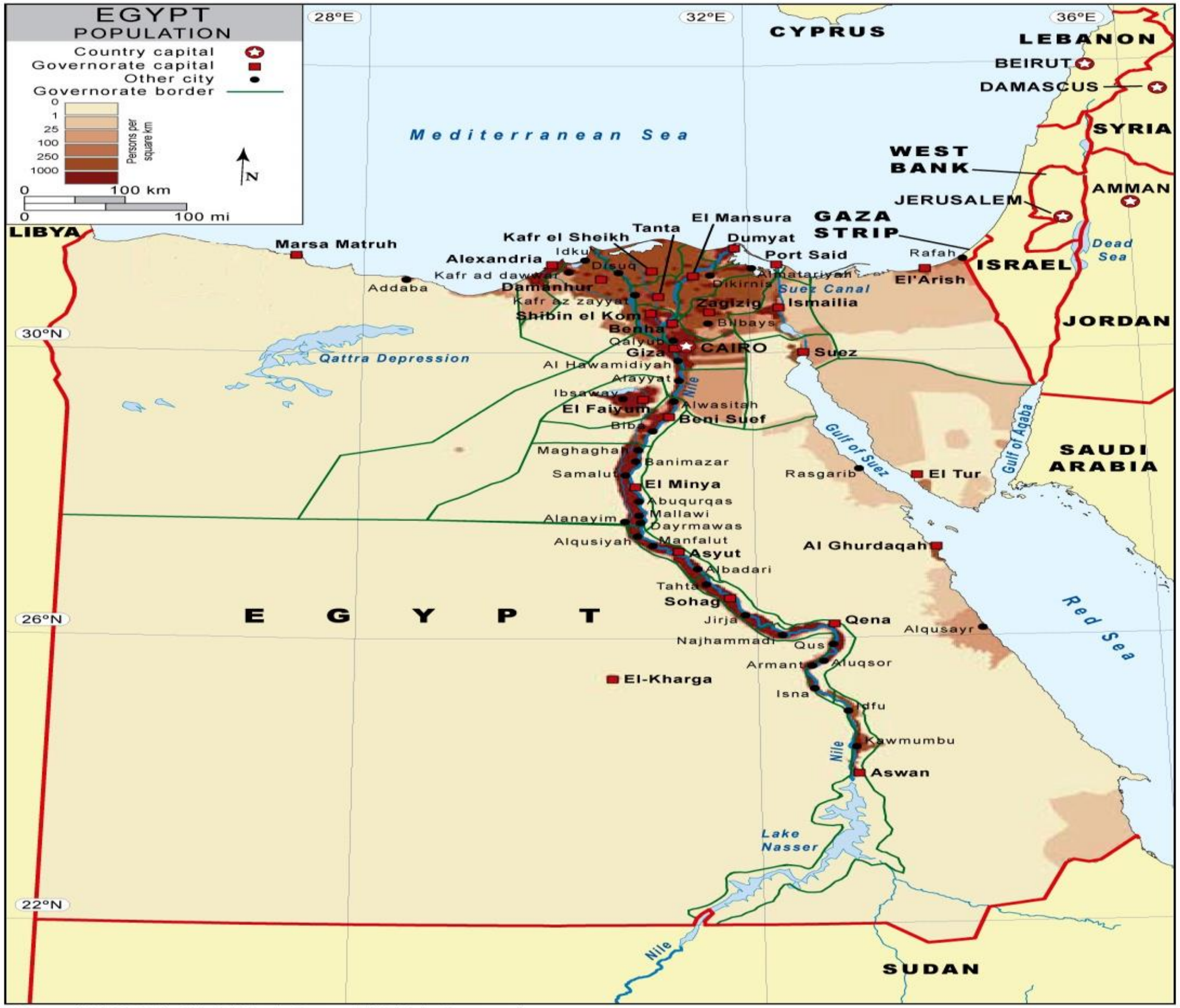
Foreseen Reduction in Nile Water Availability

- Nile water is shared with 9 other countries
- 85% of Nile water originates from the Blue Nile in Ethiopia
- Ethiopia is building a huge dam with 74 billion cubic meter of storage

Options: Groundwater extraction and Seawater desalination

- Seawater → Essentially infinite
- Groundwater → Limited availability

Potential Benefits to GW Extraction?



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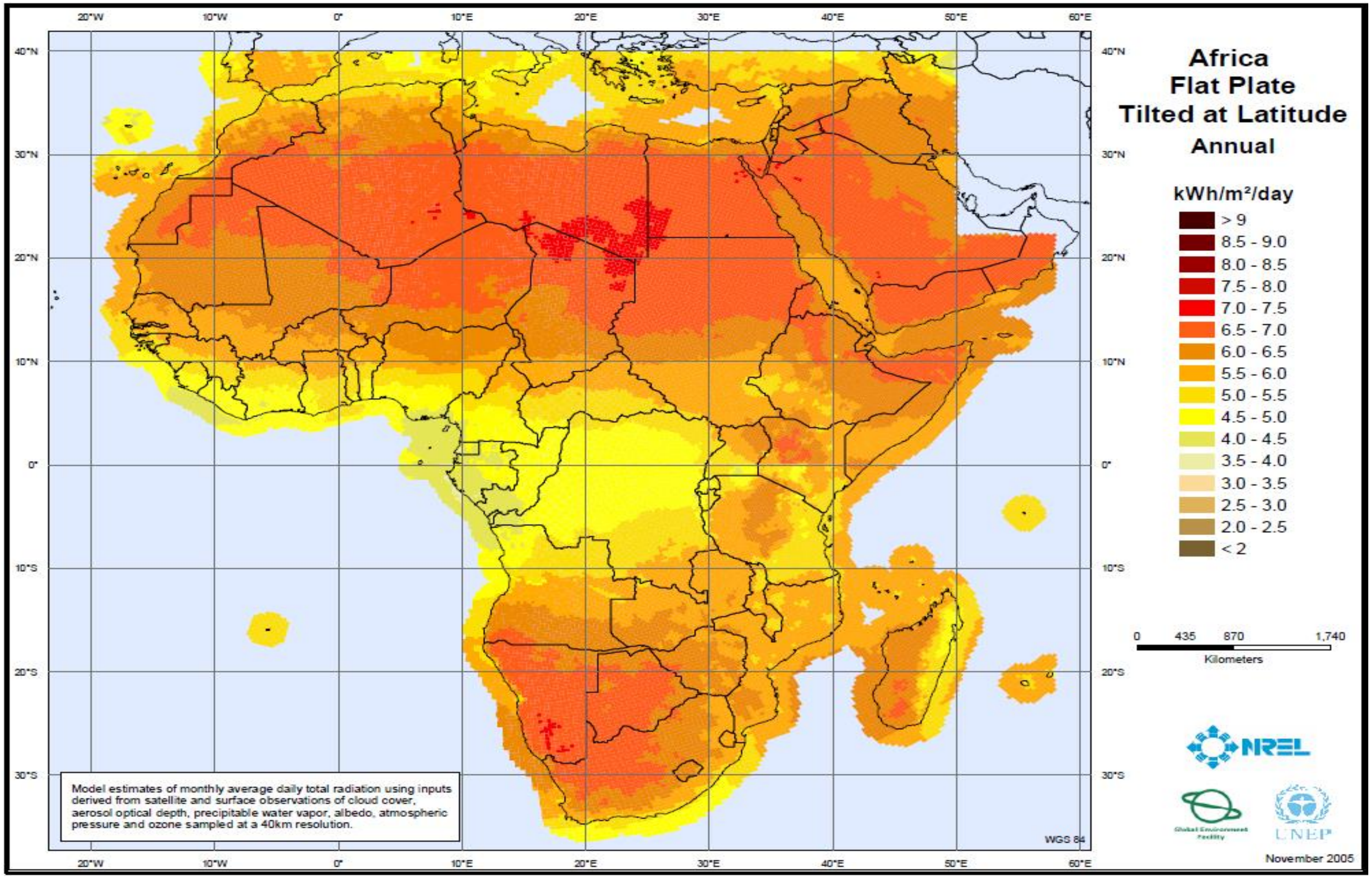
Centralisation vs. Decentralisation

- Centralised development described as unsustainable and promoting inequity (Schumacher, 1974)
- Decentralized communities require decentralized small scale infrastructure which can be easily financed
- Decentralized communities increases the resiliency of the population particularly when the workplace is in the area where people are living and where local skills can be exploited

Decentralized agricultural communities with local access to water from the ground and energy from the sun

- Shortages in water and energy availability
- 1/3 of the workforce are in the agriculture sector and mostly concentrated in rural areas where poverty rates are the highest
- Government plans to gradually remove current subsidies on food and energy
- Farmers are losing their jobs due to land degradation caused by urban encroachment

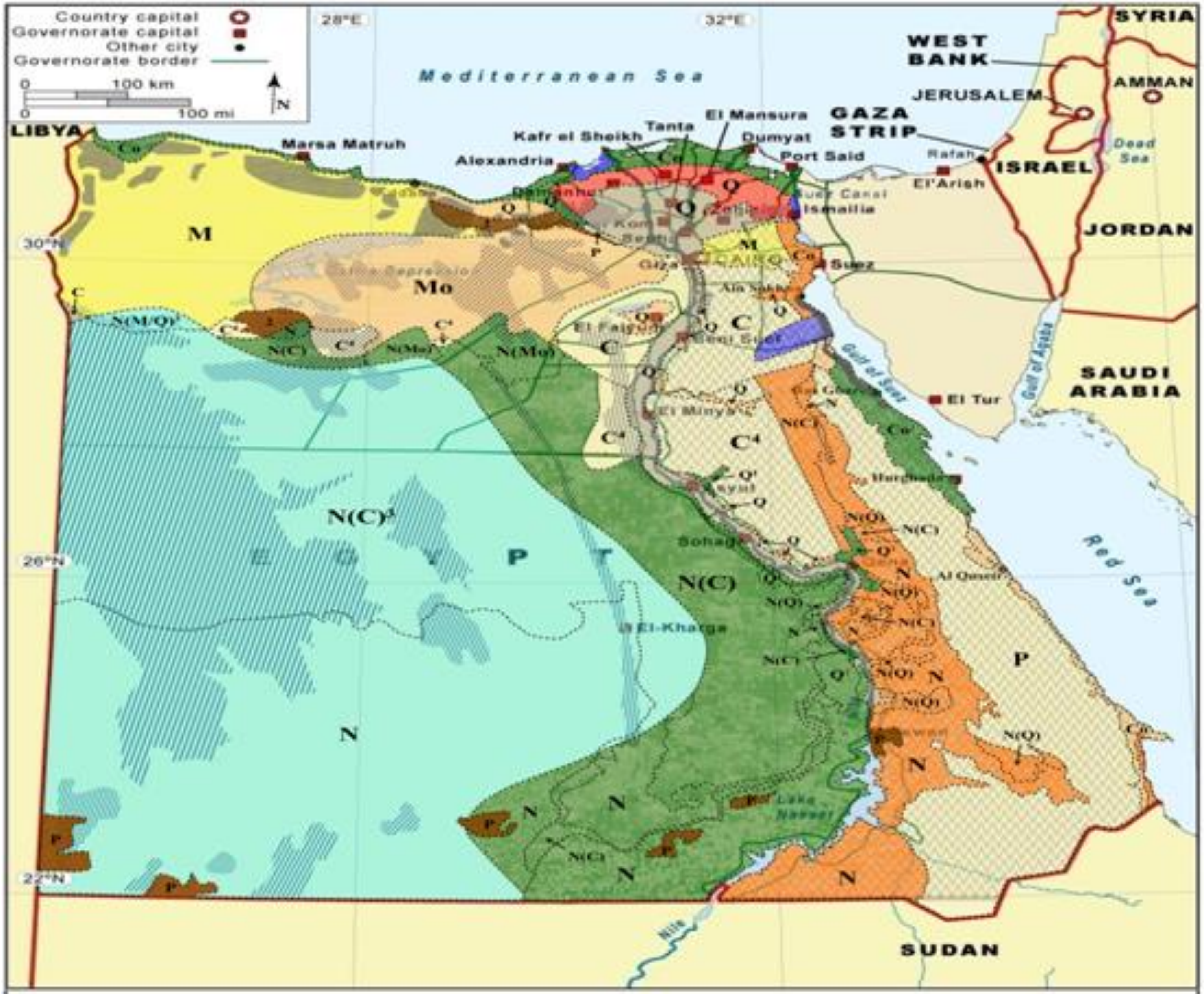
Huge Solar Resources



Africa Flat Plate Tilted at Latitude Annual Solar Irradiance (kWh/m²/day)
Source: (Solar and Wind Energy Resource Assessment (SWERA, 2005)

Ground water availability in Egypt

- Where can groundwater be found?
- Is the groundwater suitable for drinking and irrigation?
- What is the aquifers' potential for sustainable development?



Country capital
Governorate capital
Other city
Governorate border
0 100 km
0 100 mi
N
28°E
32°E
Mediterranean Sea
WEST BANK
SYRIA
AMMAN
JERUSALEM
GAZA STRIP
Dead Sea
ISRAEL
JORDAN
LIBYA
Marsa Matruh
Alexandria
Kafr el Sheikh
Tanta
El Mansura
Dumyat
Port Said
Rafah
El'Arish
Ismailia
Suez
Giza
CAIRO
El Faiyum
Beni Suef
El Tur
Gulf of Suez
Gulf of Aqaba
SAUDI ARABIA
Hurghada
Sohag
Al Quseir
El-Kharga
Red Sea
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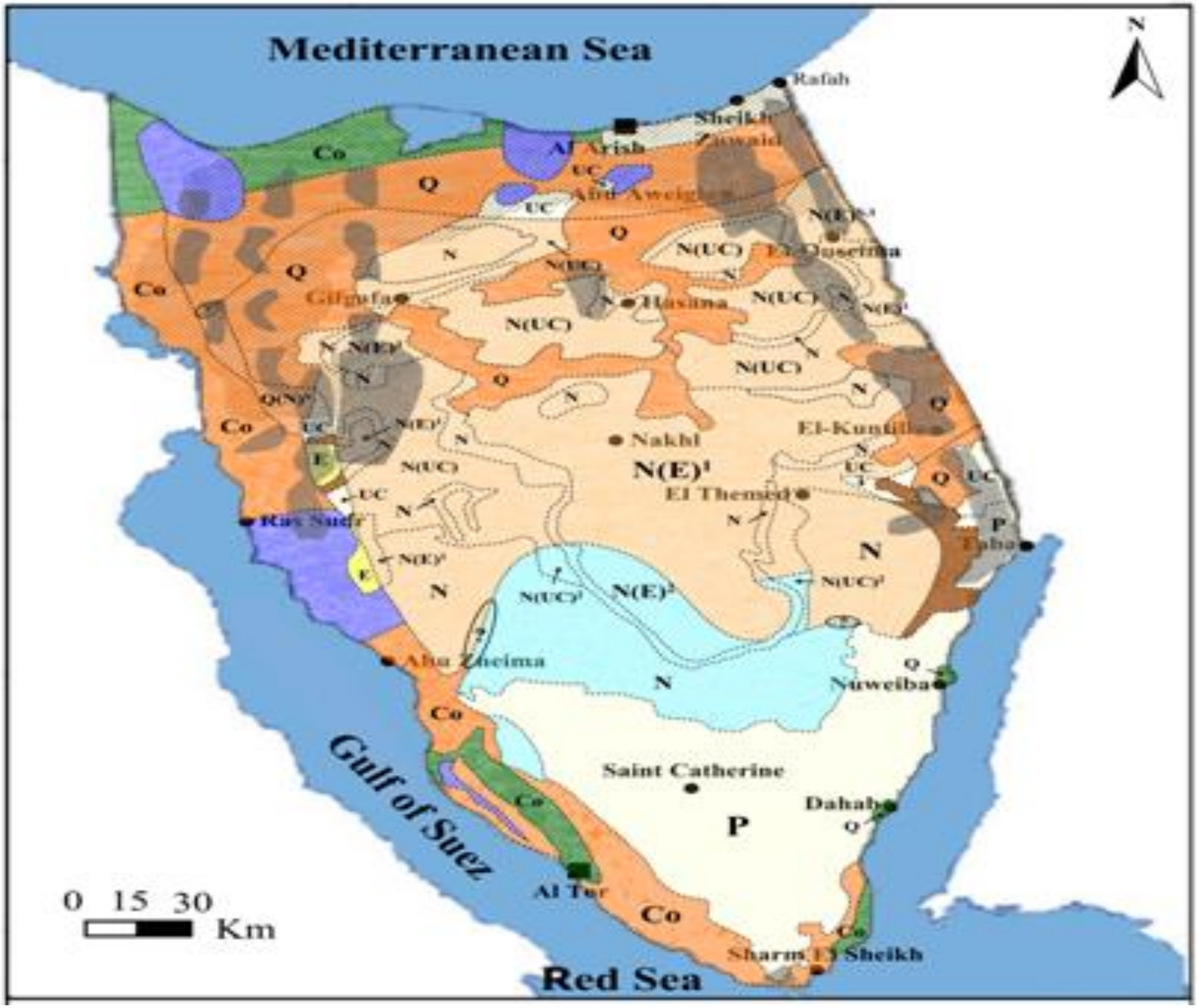
Mediterranean Sea
N
Rafah
Sheikh Zuwaid
Al Arish
Abu Aweigila
El Quseima
Gifgafa
Hasana
Nakhl
El-Kuntilla
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Ras Sudr
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Abu Zneima
Nuweiba
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Al Tor
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Sharm El Sheikh
Red Sea
0 15 30
Km

Challenges!

- Brackish GW definition (1,000-10,000 mg/l)
- Drinking water → Salinity <1,000 mg/l

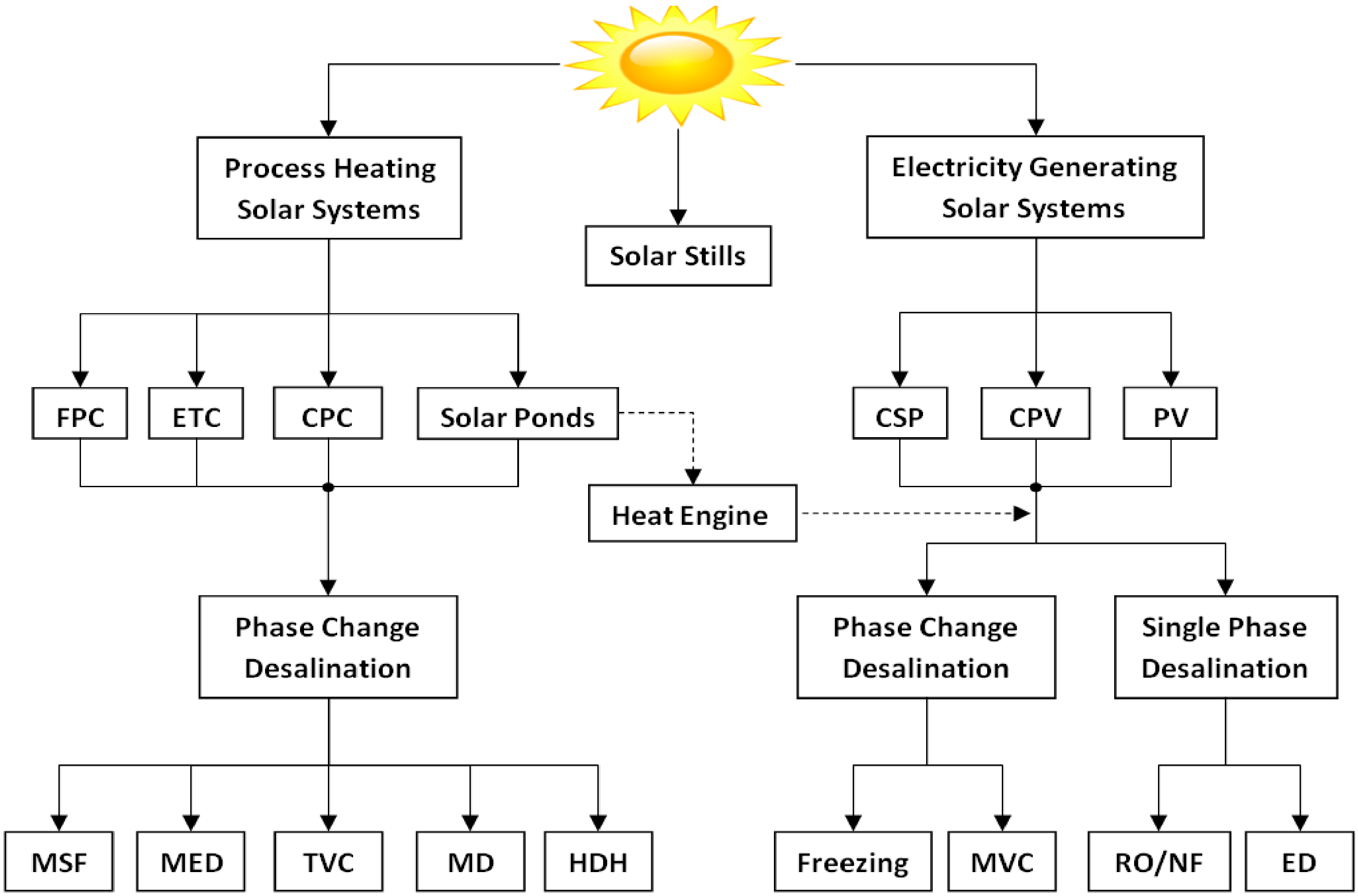
Desalination required!

Challenges!

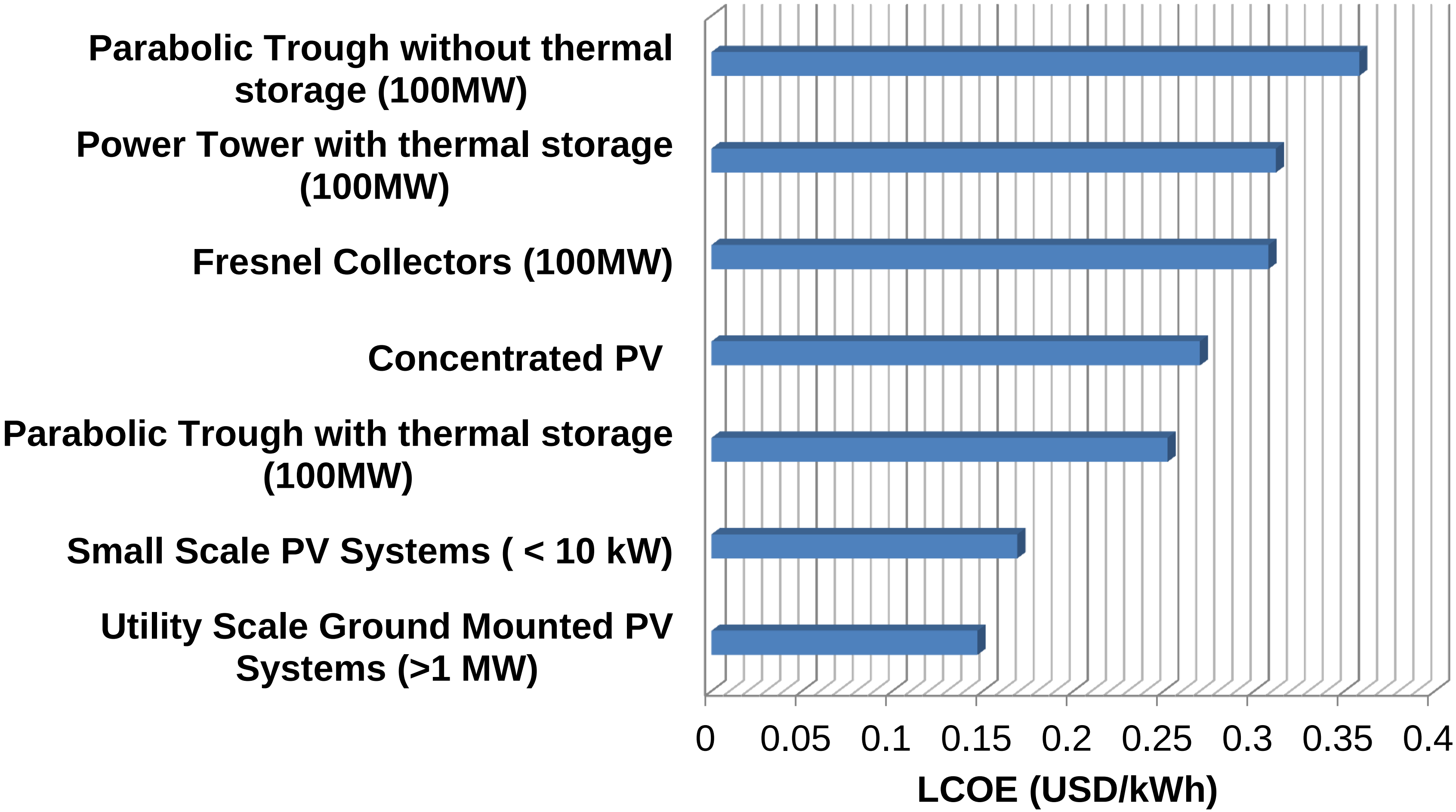
- Energy intensive and expensive process →Energy and cost reduction required
- Brine disposal and limited groundwater availability→ High recovery rate desalination required

High recovery rate solar driven plants for brackish ground water extraction and desalination

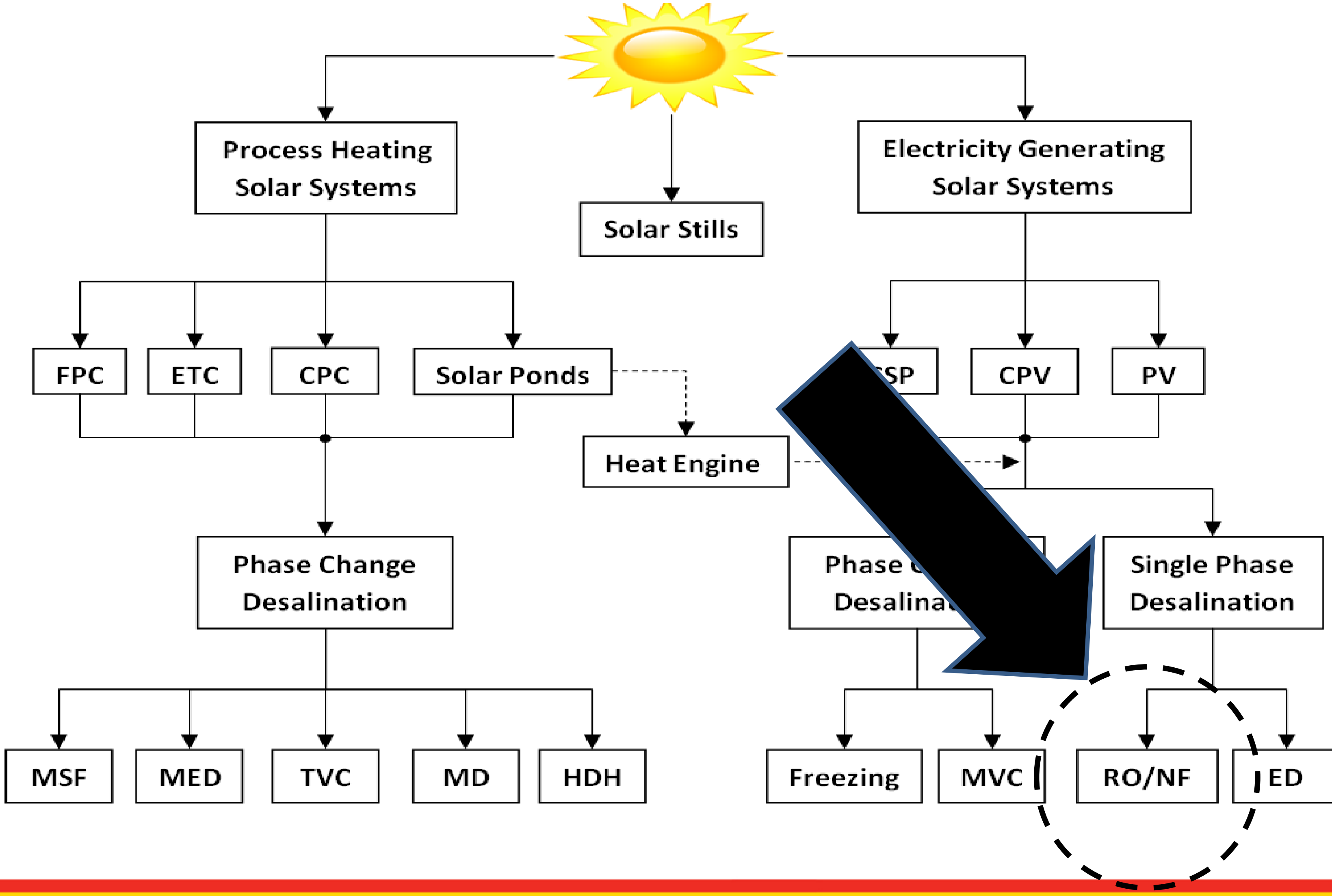
Solar Driven Desalination



Most Suitable Solar Technology



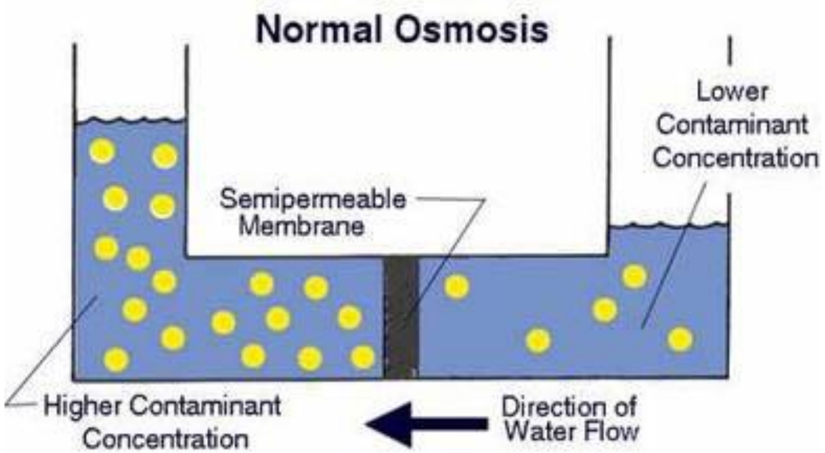
Solar Driven Desalination



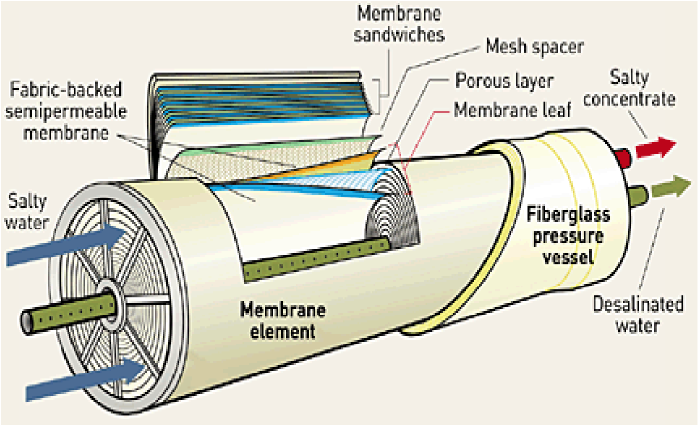
Suitability of RO for Decentralized Applications

- Lowest energy demand particularly with BW
- Lowest LCOW
- Most widely used
- Local experience
- Modularity

RO Process Description



(Water Quality Association,2008)

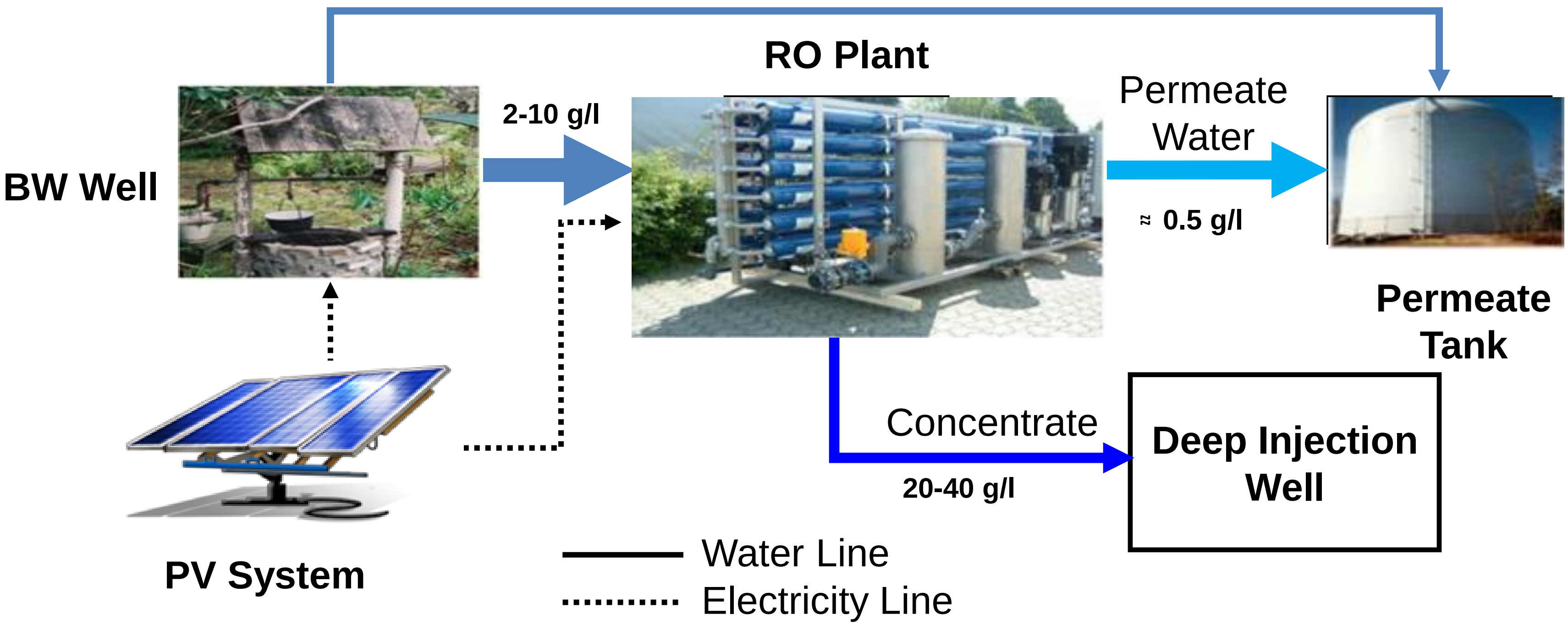


Spiral wound RO membrane (Brennan,2001)

Techno-Economic Feasibility of High RR PV-RO Plants

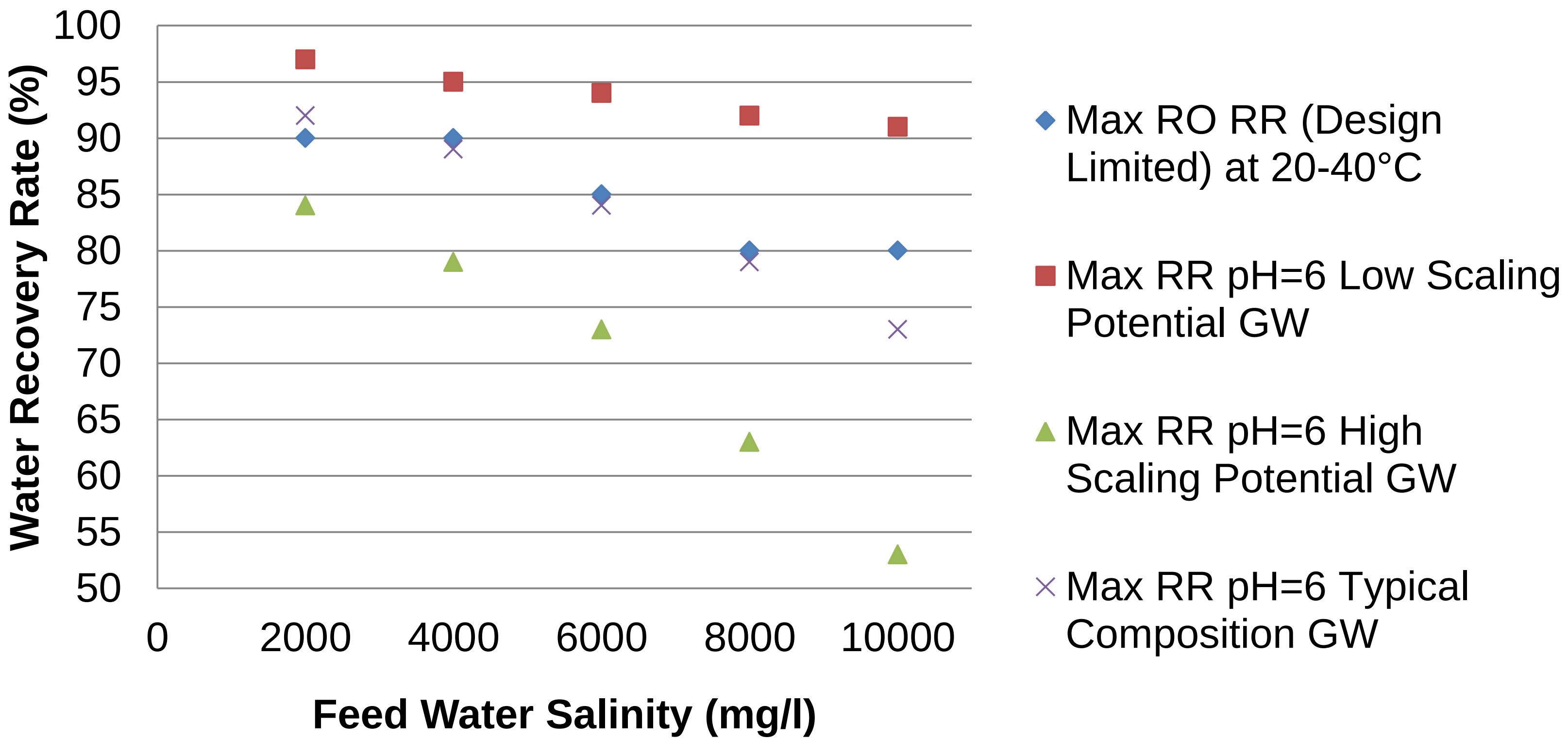
- What is the maximum attainable recovery rate?
- Is it more economical to use PV instead of diesel generators to drive the RO plant?

PV-RO Plant Configuration



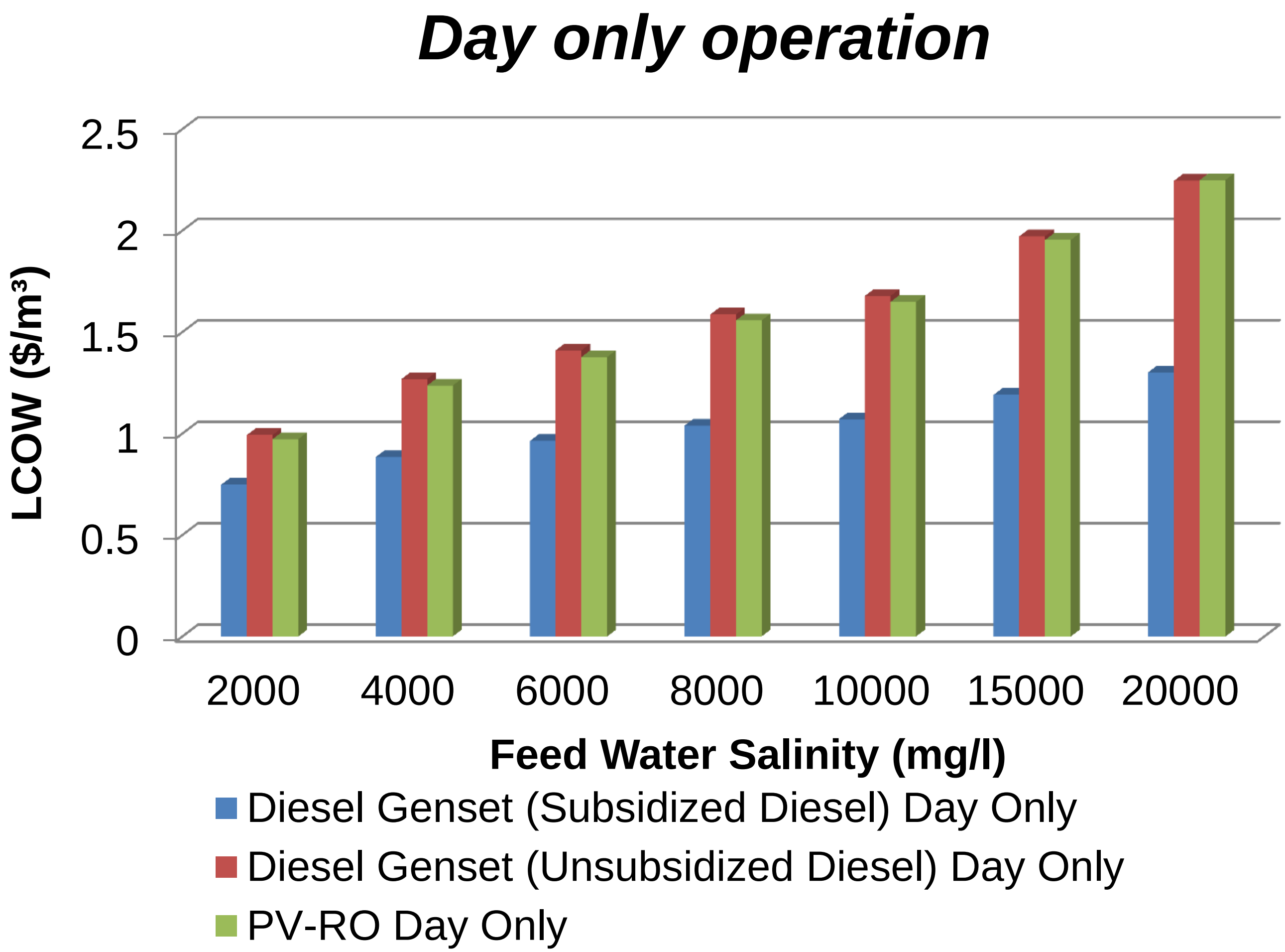
- Simulation carried out using PVSYST and ROSA
- PV-RO plant designed to operate only during daytime and for 24 hours

Maximum Attainable RR

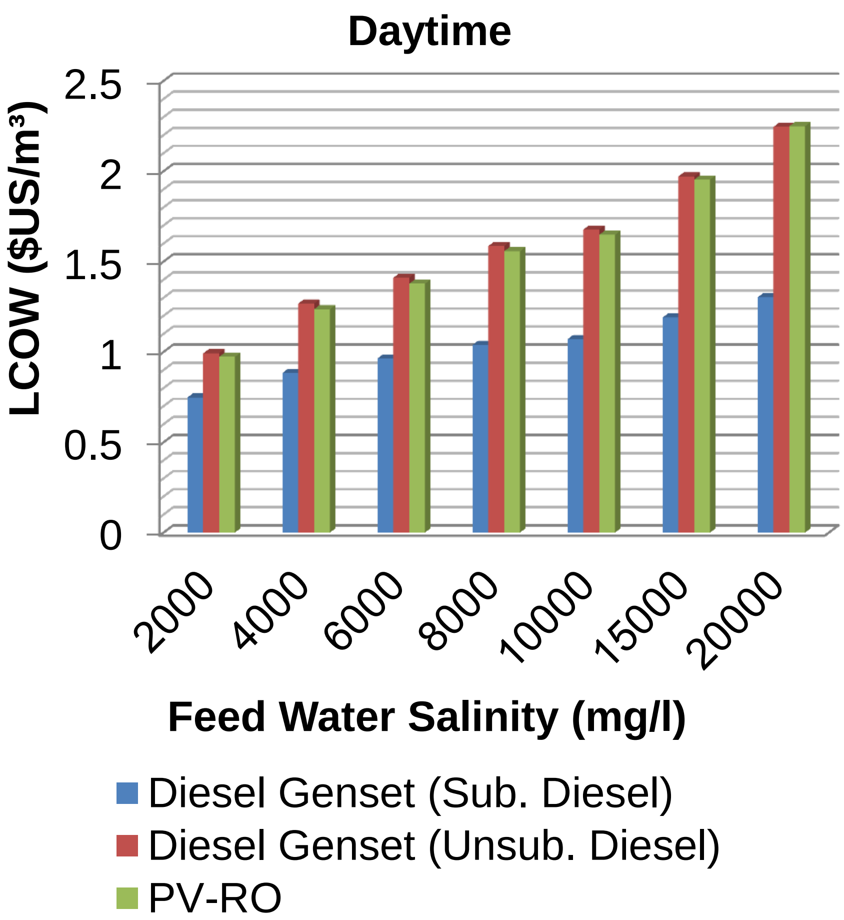


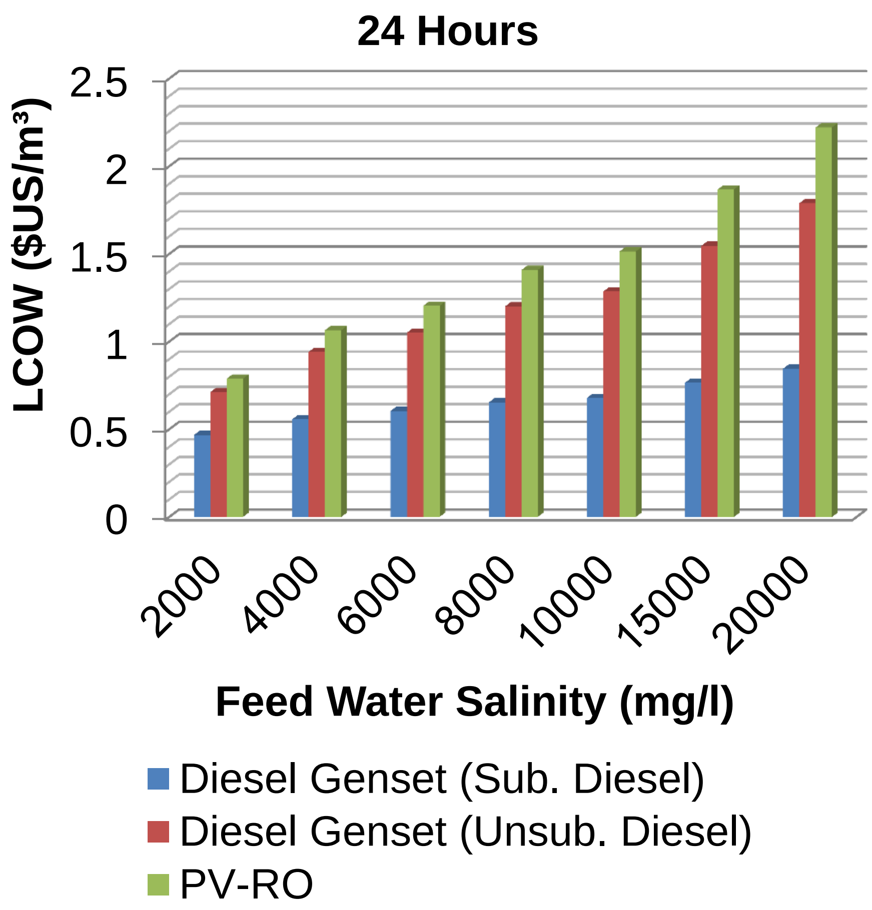
75 to 90% RR with the typical brackish GW composition found in Egypt with simple pre-treatment requirements

Economic Feasibility: Diesel Generators vs. PV



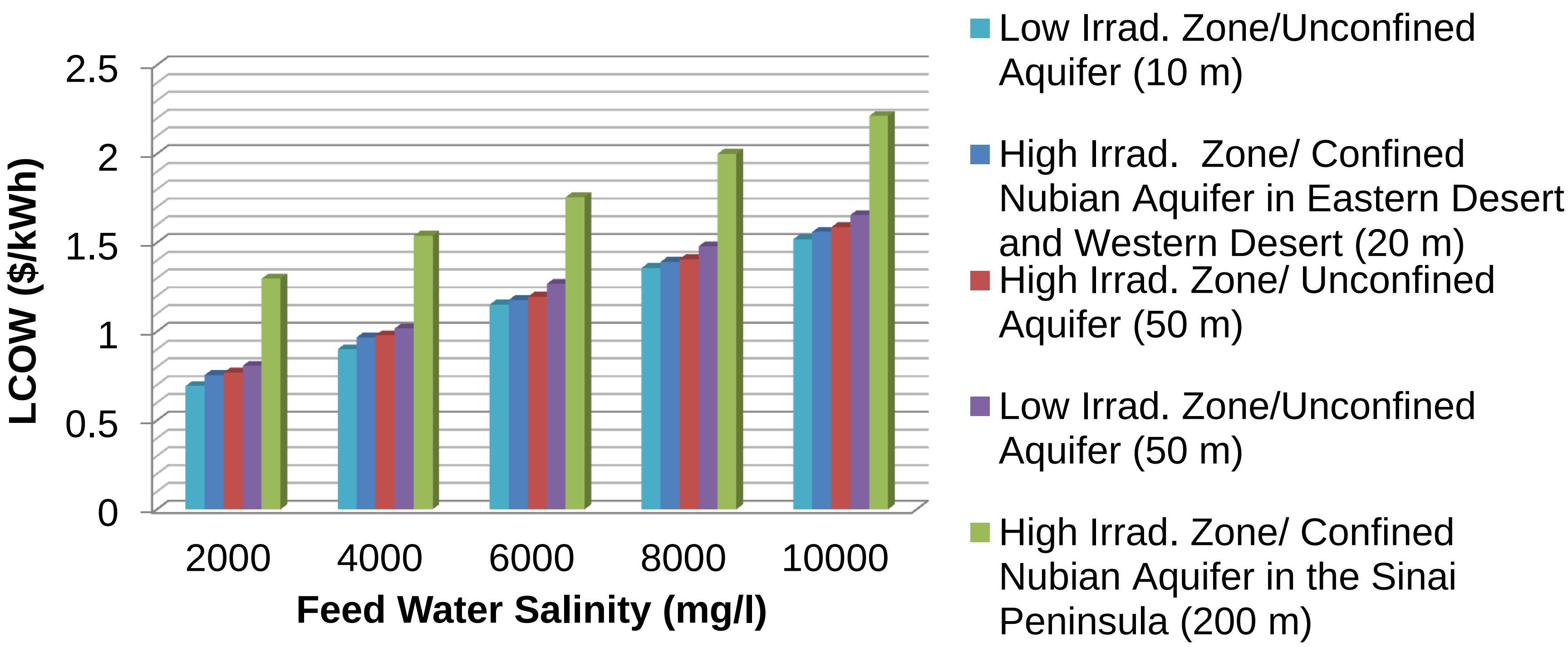
Economic Feasibility: Diesel Generators vs. PV





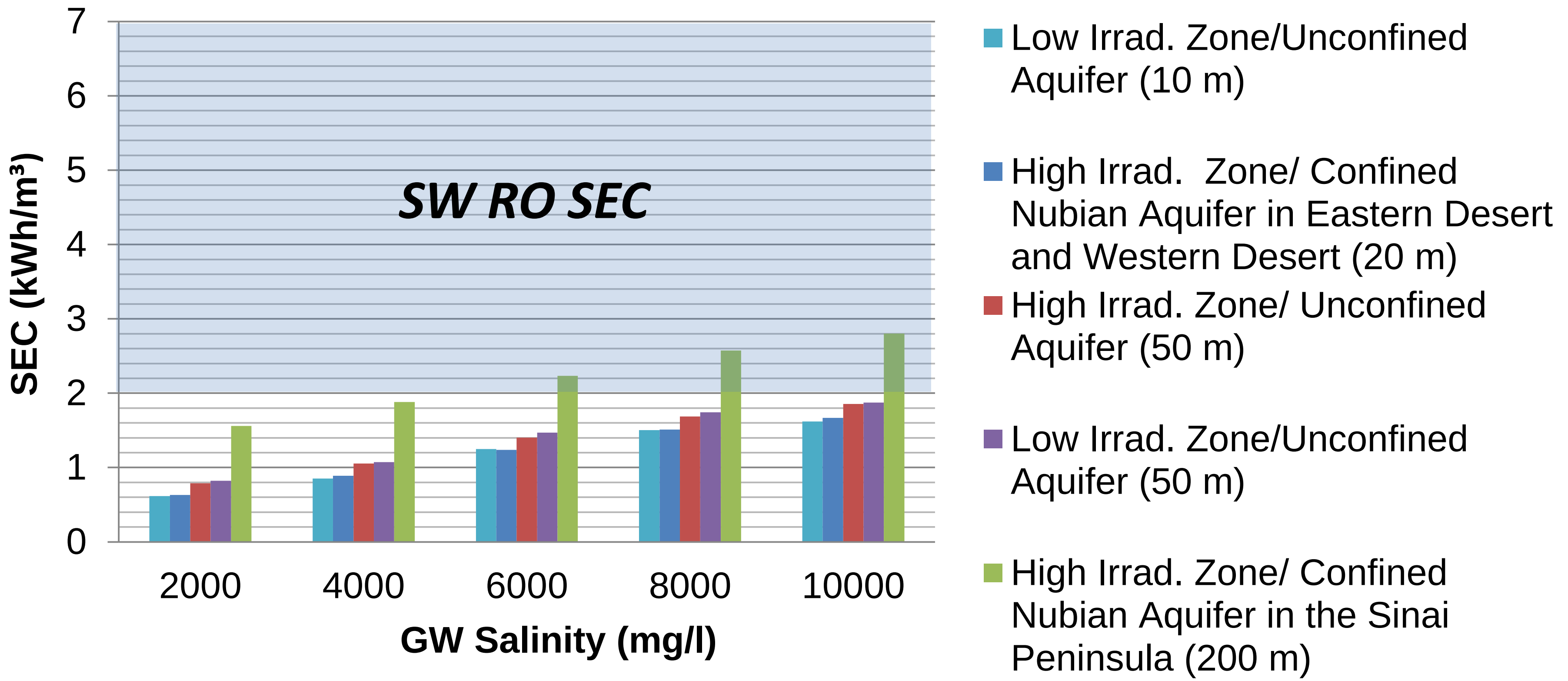
It is more economical to design a brackish water PV-RO plant to operate for 24 hours!

Estimated LCOW of PV-RO Plants in Egypt



- LCOW: 0.7 USD/m^3 to 1.65 \$US/m^3 in most locations
- Current Water Prices: 0.03 to 0.34 \$US/m^3 X
- LCOW Seawater PV-RO: 2 to 3 \$US/m^3

SW Desalination vs. BW Extraction and Desalination: Energy Requirements

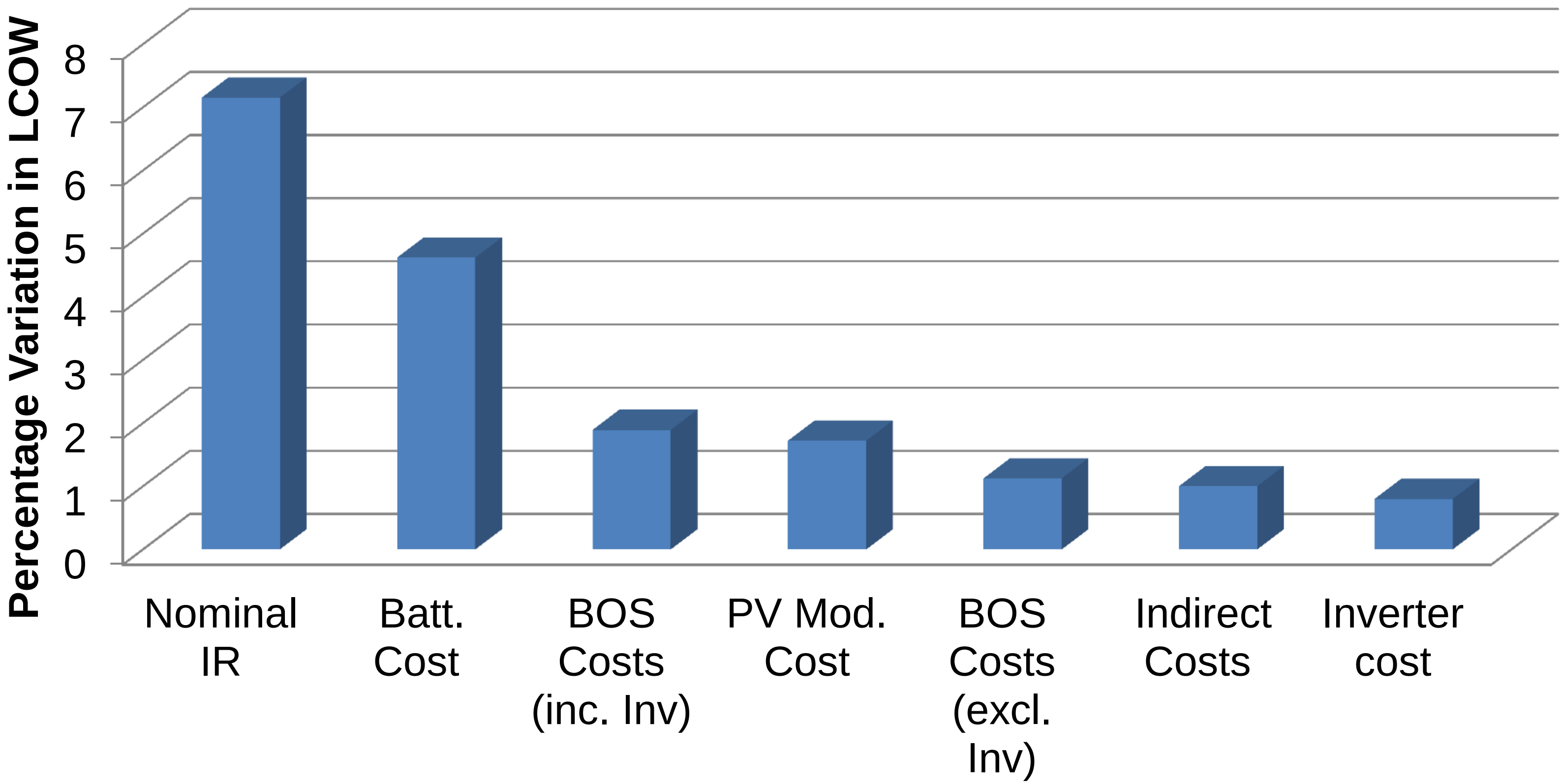


- **PV-RO can be only described as cost competitive with DG-RO**

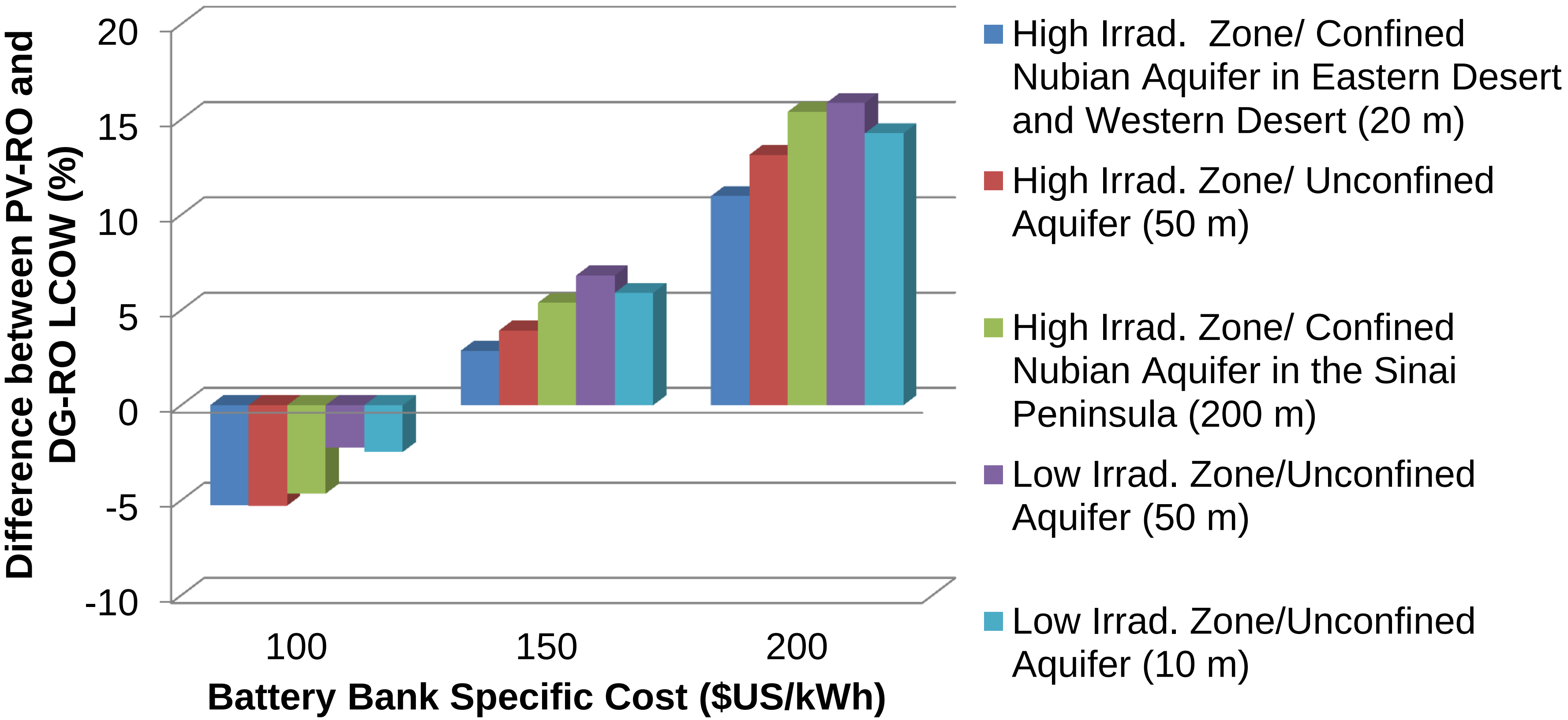
- **7 to 16% higher LCOW with the typical composition, and expected range of GW depths and solar irradiance found in Egypt**

Is there a possibility to reduce the LCOW of the PV-RO Plant?

Sensitivity Analysis



- After reducing the nominal interest rate from 13 to 9% PV-RO LCOW is only 2 to 5% higher than that of DG-RO
- Reducing battery costs from 200 to 100 $US/kWh makes a PV-RO clearly more economical



Is there any other possibility to reduce the LCOW of a PV-RO plant?

What about coupling the RO plant with PVT collectors?

A Double Benefit!

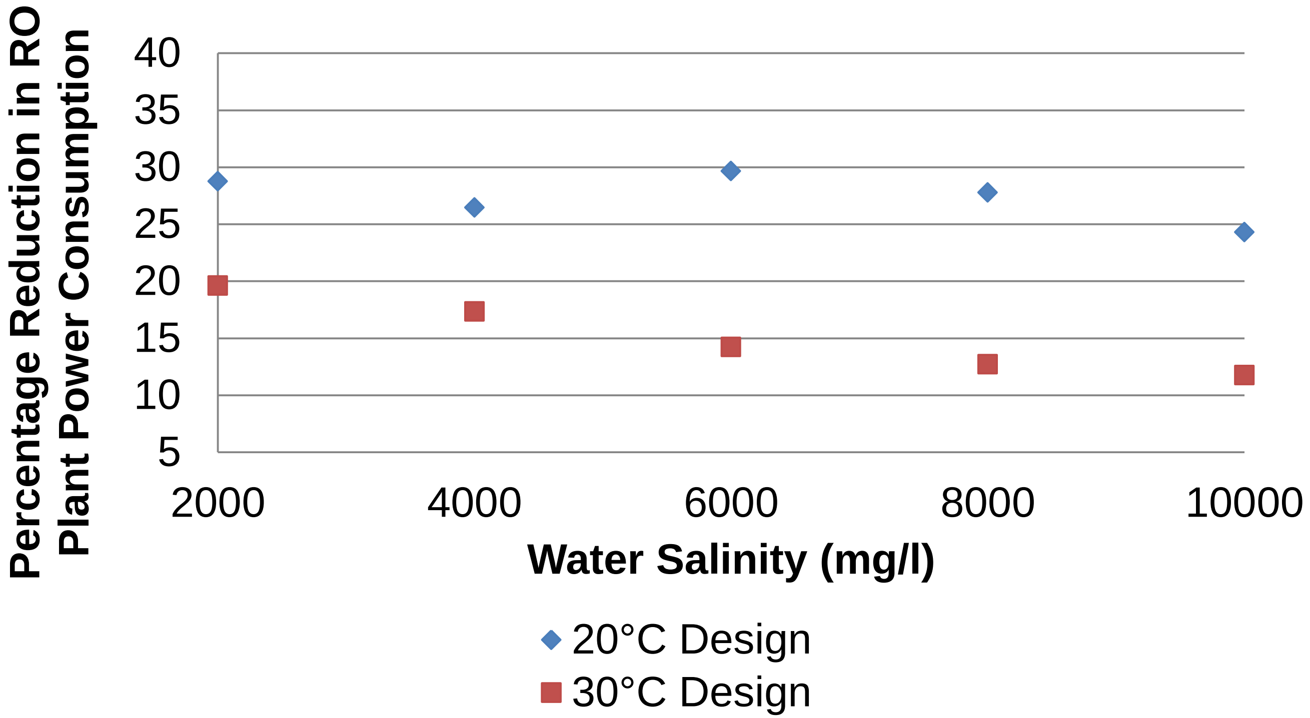
- **Potential decrease in the array size through cooling the PV cells using the pumped GW**

- **Reducing the energy consumption of the RO plant through heating the feed water**

  → Lowers water viscosity→ makes it easier for water molecules to cross the membrane

  → Less salt rejection

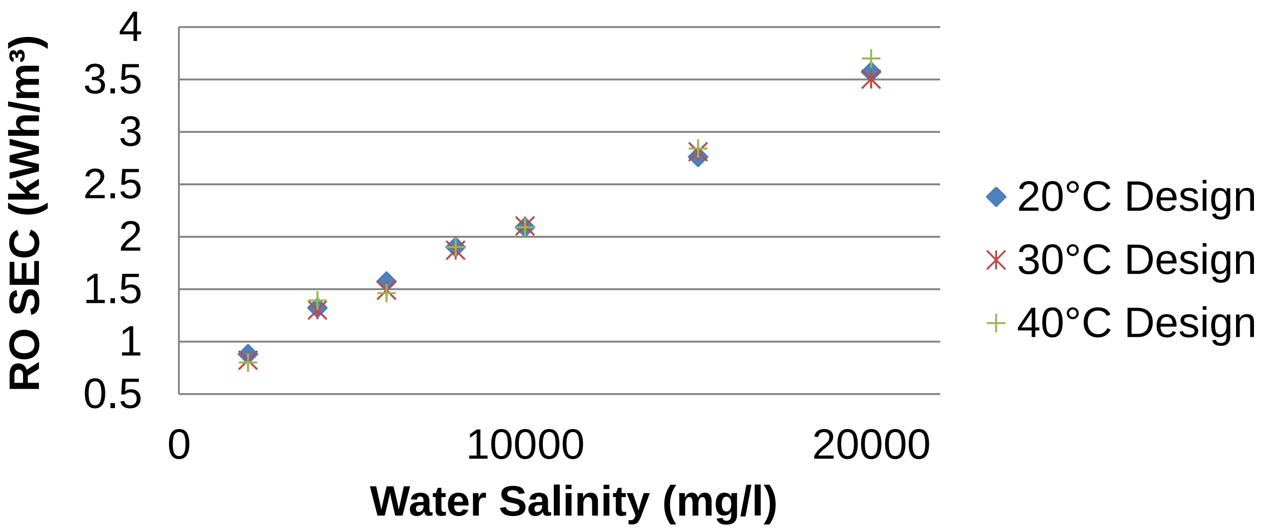
Effect of Water Temperature on the RO Plant Power Consumption



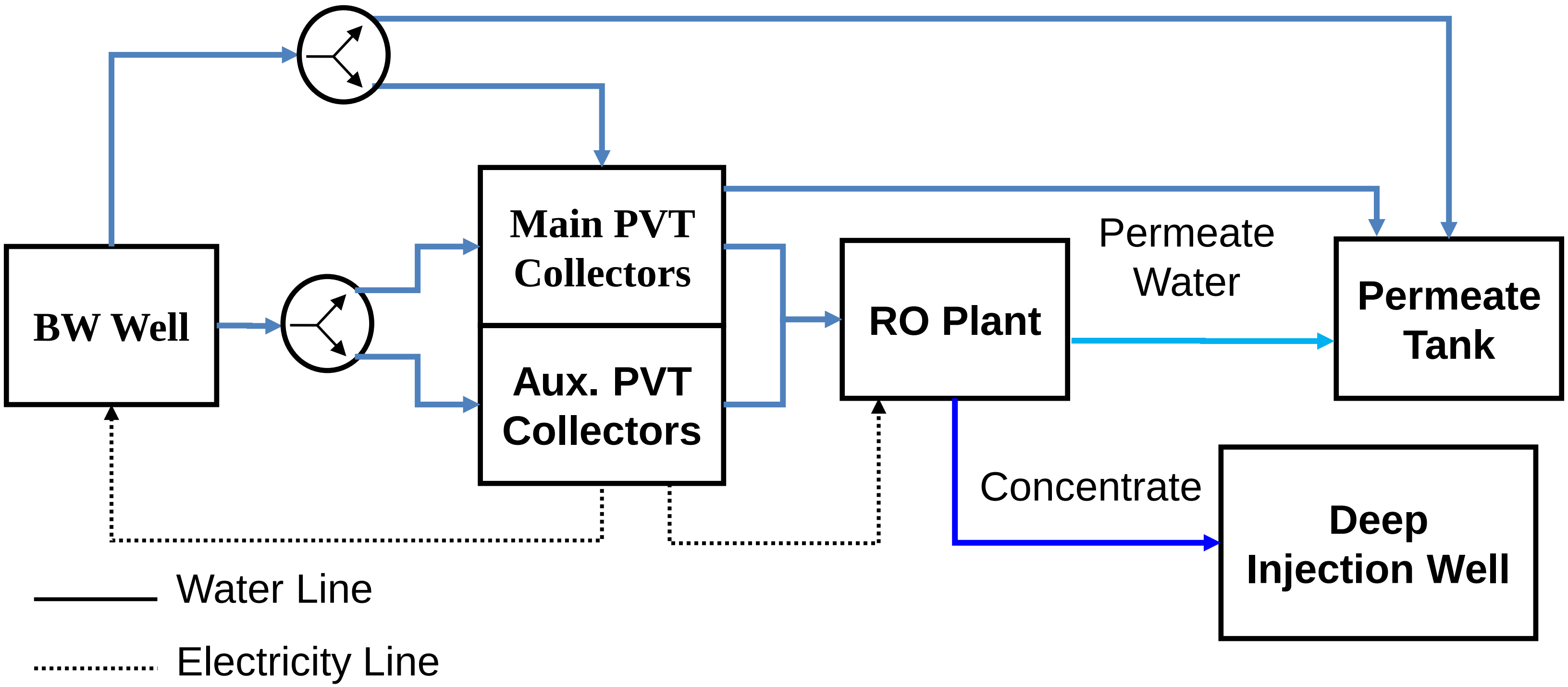
12 to 30% reduction in the power consumption by heating the water to 40°C without compromising the permeate water quality

There is a “catch”, however!

- RO modules have to operate outside the recommended operating parameters
- In some designs the maximum recommended permeate flow rate was exceeded by 58%
- A properly designed RO plant results in no energy savings



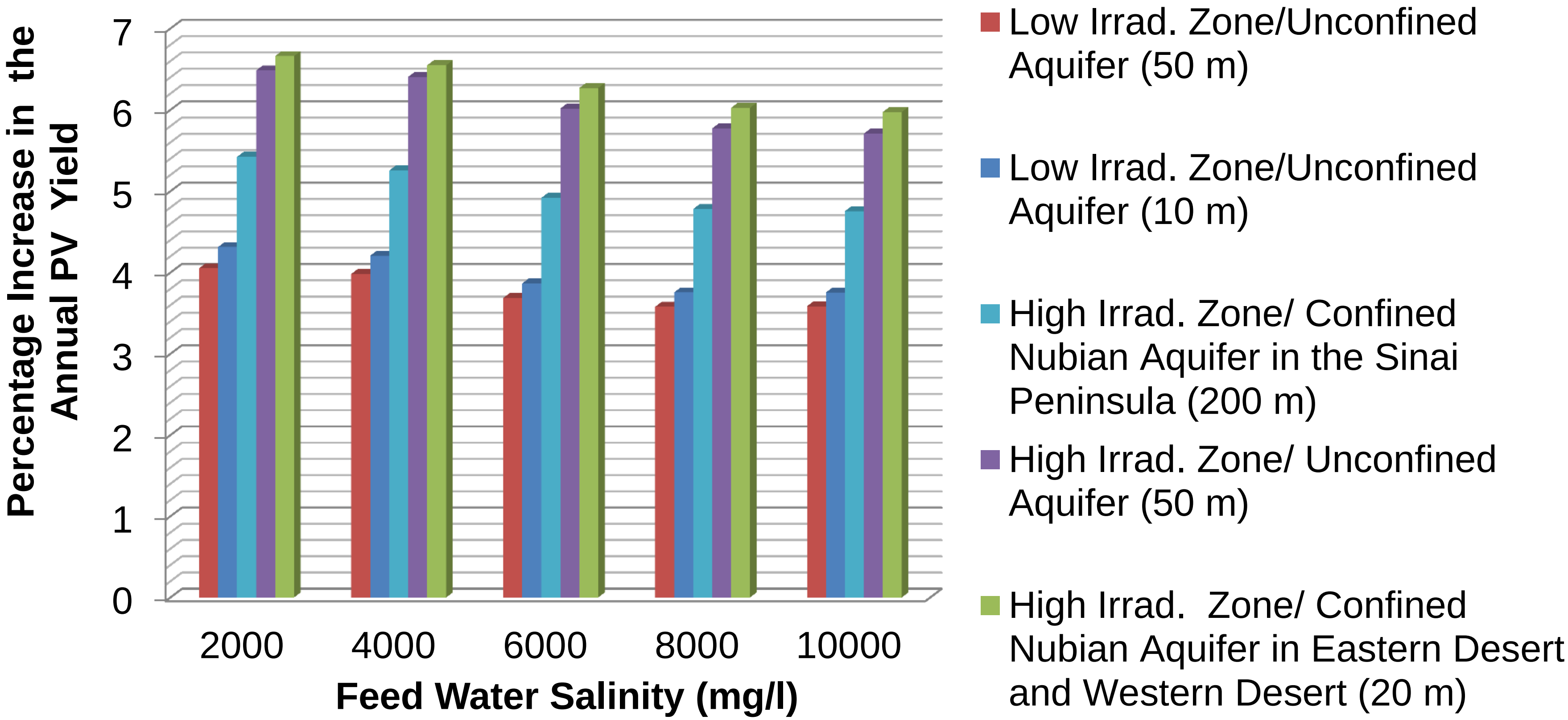
PVT-RO Plant Configuration



- Yearly simulation performed using TRNSYS
- Used a more accurate PVT model developed by Bilbao and Sproul (2012)

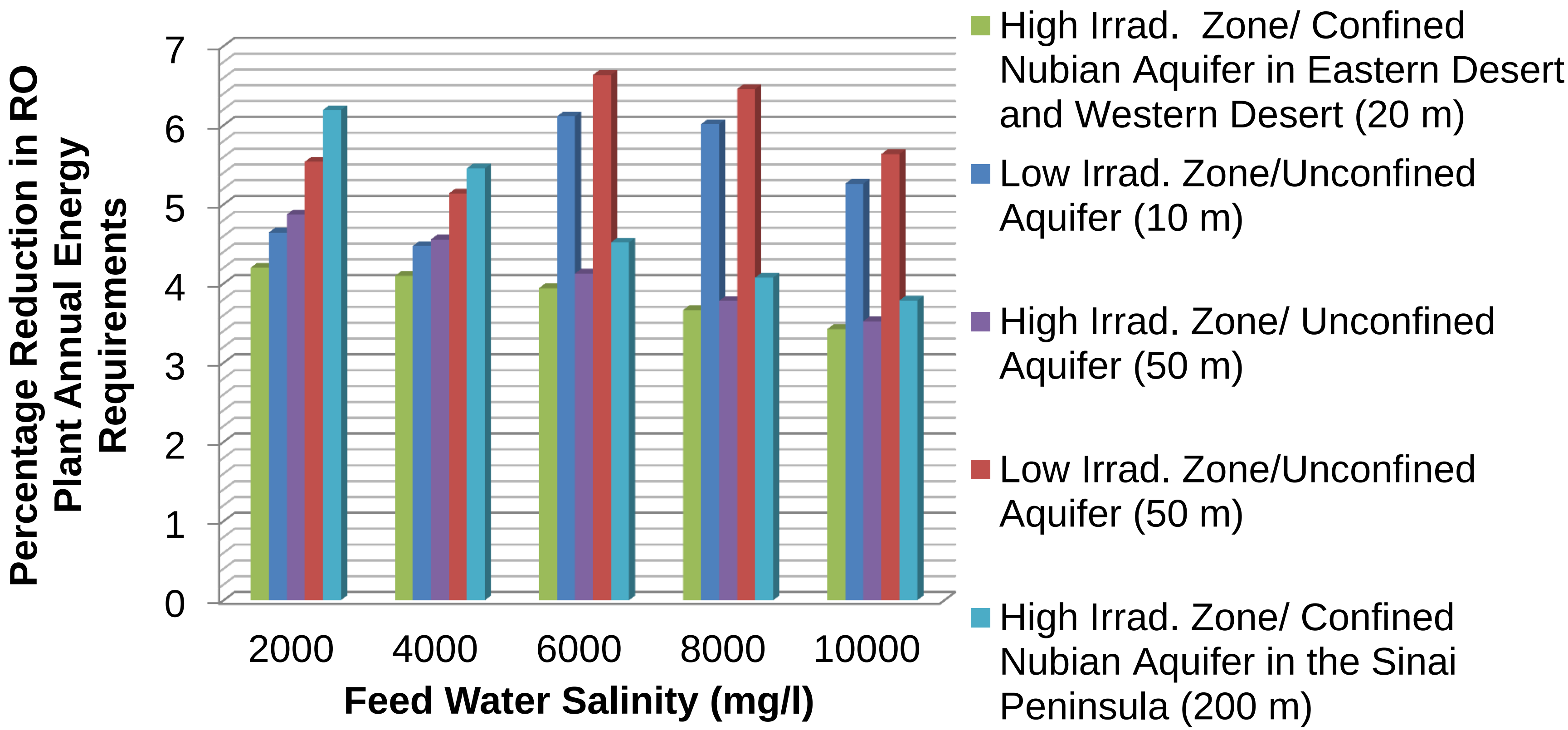
Results

PV-RO vs. PVT-RO: Increase in the annual PV yield



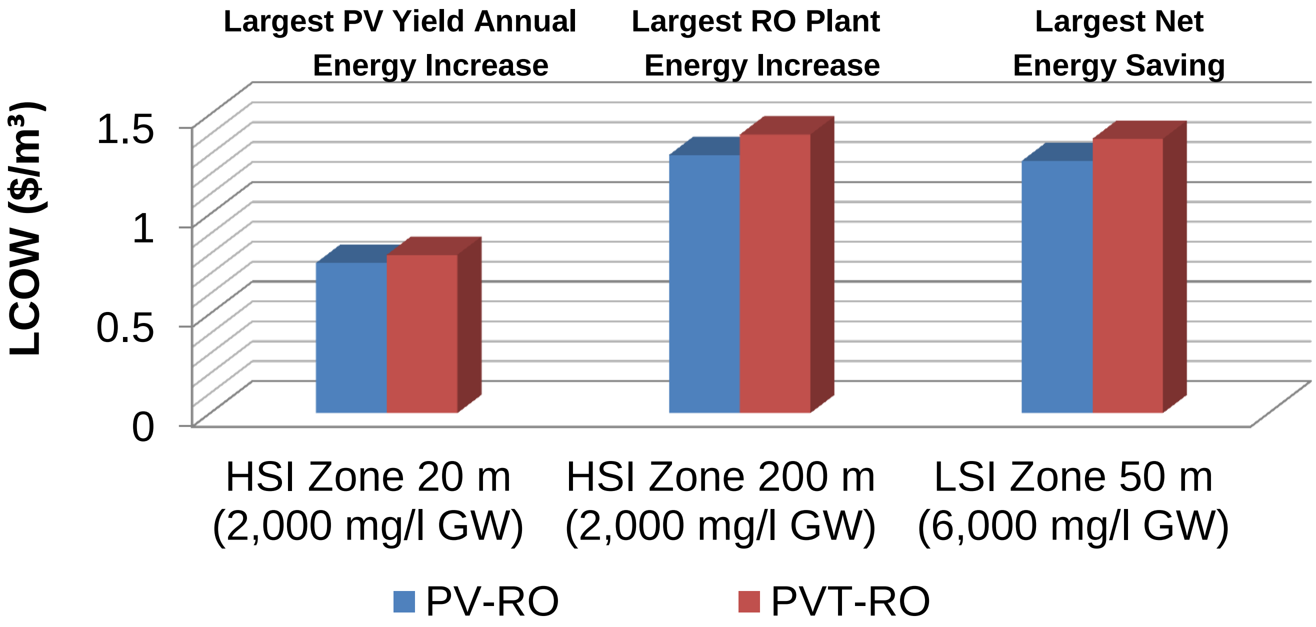
A modest increase in the annual energy yield ranging from approximately 3.6% to less than 6.7%

PV-RO vs. PVT-RO: Reduction in RO Plant Annual Energy Requirements



A modest reduction in the RO plant energy requirements ranging from approximately 3.4% to less than 6.6%

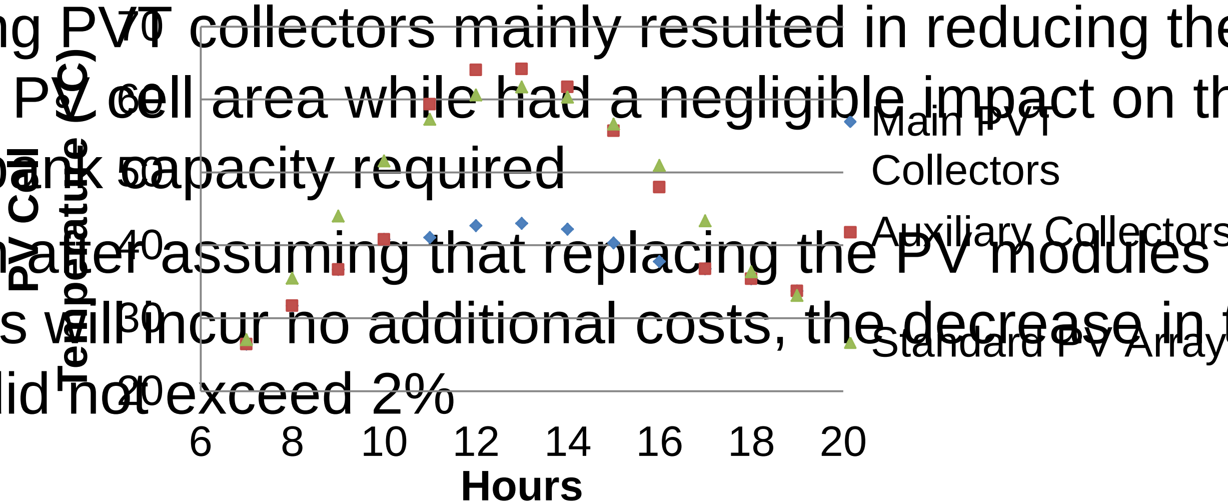
Economic Feasibility of PVT-RO



Even with the best possible cases, there is no economic advantage of replacing PV modules with PVT collectors

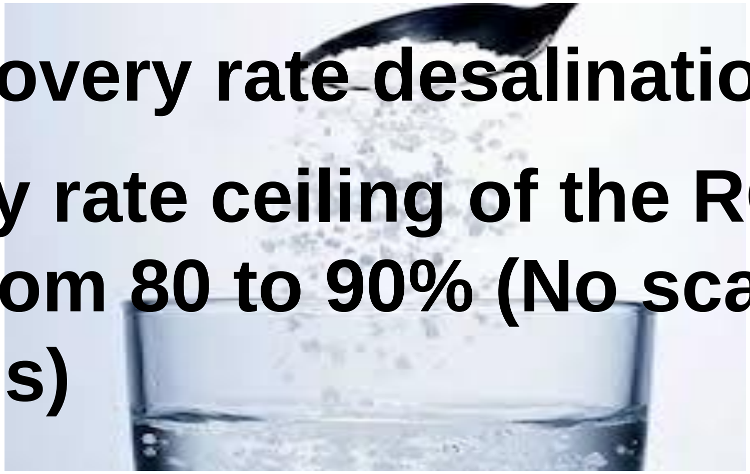
Reasons for the unfeasibility of PVT-RO

- The low capacity factor of the PVT collectors and the variability of solar irradiance → a percentage reduction in the RO plant annual energy consumption not exceeding 6.6% in comparison to values up to approximately 30% if the water was continuously heated to 40°C
- The operating temperature limitation of the RO membranes
- Using PVT collectors mainly resulted in reducing the required PV cell area while had a negligible impact on the battery bank capacity required
- Even after assuming that replacing the PV modules with PVT collectors will incur no additional costs, the decrease in the LCOW did not exceed 2%



Challenges!

- Brackish GW Definition (1,000-10,000 mg/l)
- Drinking Water → Salinity <1,000 mg/l
- Energy Intensive Process
- Brine disposal and water utilization



→ High recovery rate desalination required

→ Recovery rate ceiling of the RO plant ranged from 80 to 90% (No scaling limitations)

Is there a possibility to further increase the recovery rate to values beyond those achieved by an RO plant?

Possible using a thermal desalination process

- No feed pressure limitations
- Production less affected by feed water salinity
- Increasing salinity from 35,000 to 50,000 mg/l

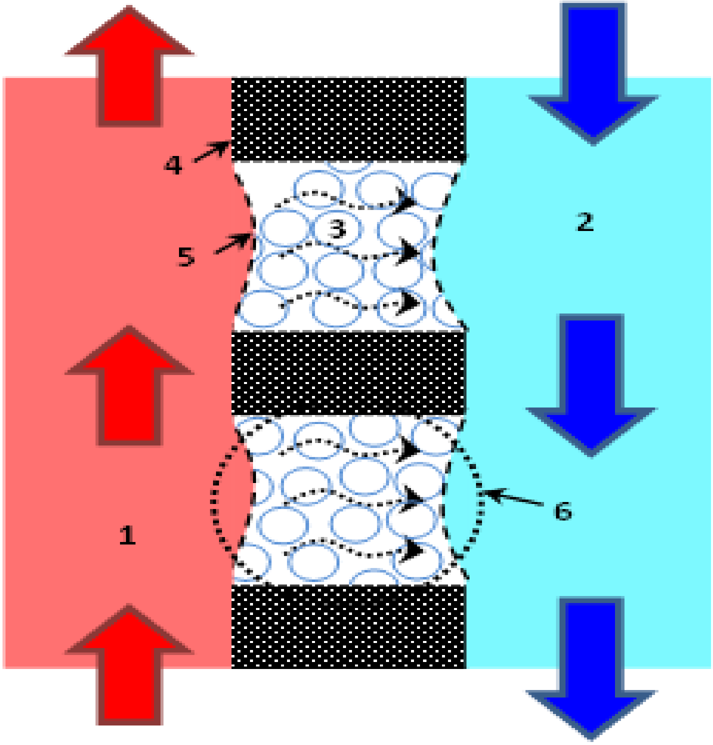
  → 7% increase in MD energy

  → at least 43% increase in RO energy consumption

Using a Membrane Distillation Process?

- Robust and simple to use
- Modular
- Needs a low grade source of energy
- Low pressure operation
- Large potential for improvement

MD Process Description



1- Hot feed water flow

2- Cold water flow mixed with distillate

3- Water vapour molecules

4- Hydrophobic membrane material

5- Vapour-Liquid Interface

6- Membrane Pore

The hybrid RO/MD concept was investigated before

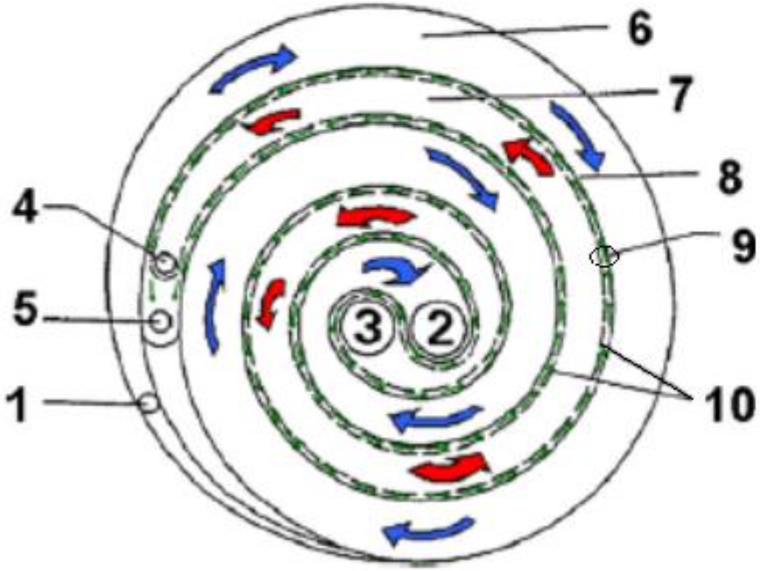
- Only for seawater applications
- Based on the performance of a lab scale module (Drioli et al.,1999)

But..

- Unrealistic specific heat consumption
- High flux at 320 g/l brine concentration→ unrealistic

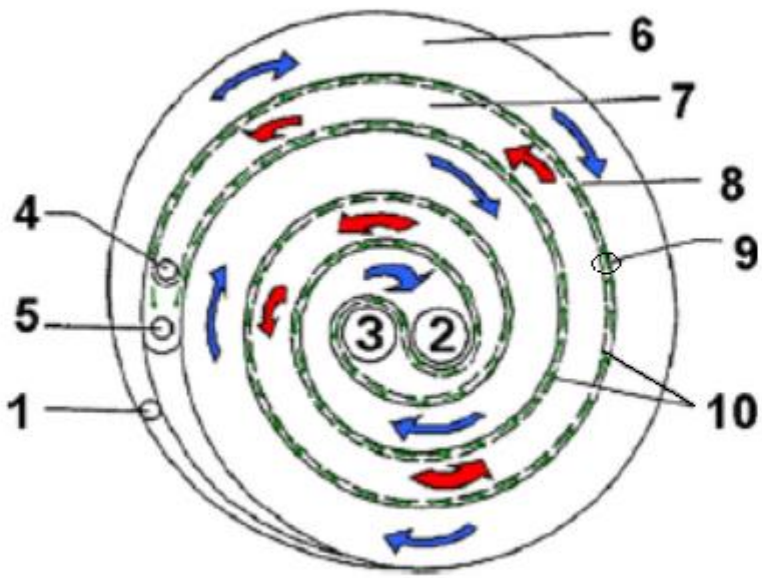
New feasibility study is needed with realistic data from a full scale module!

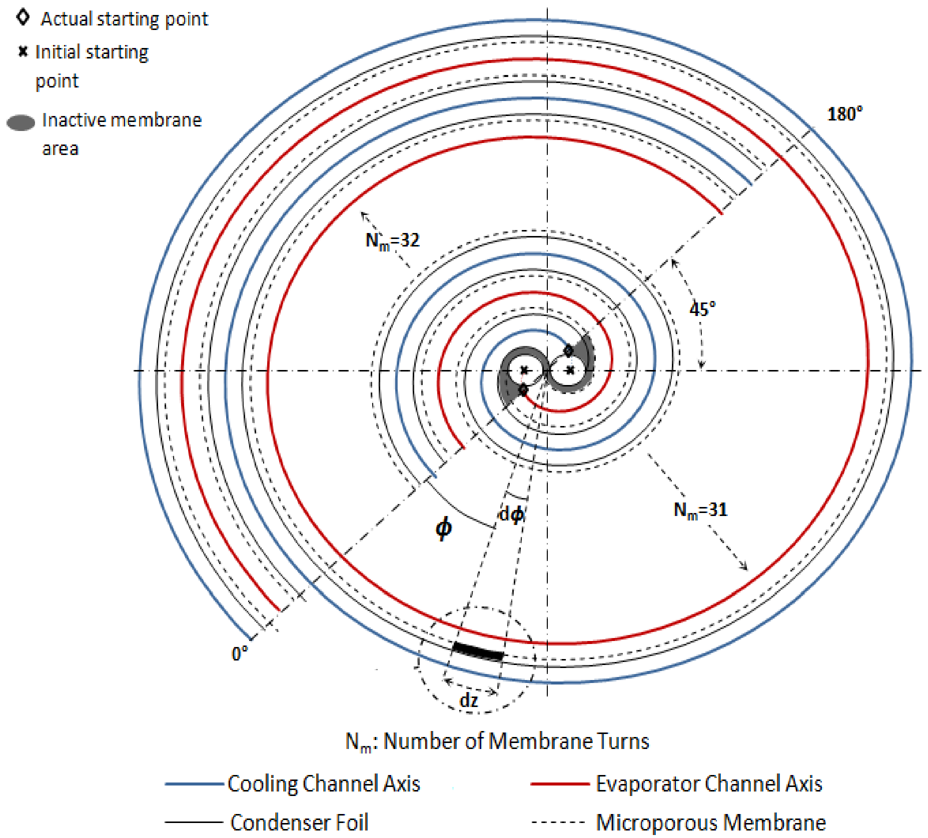
PGMD Module



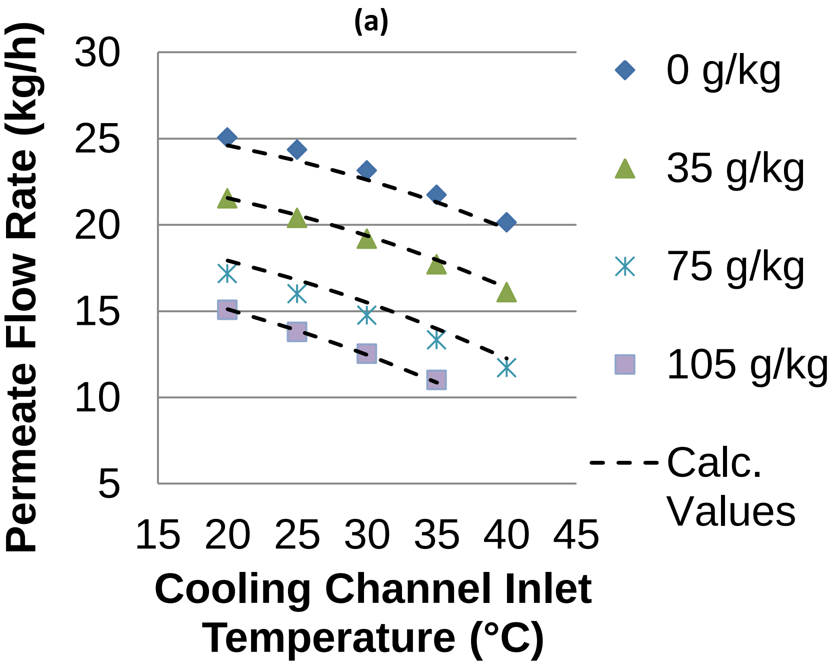
Source: (Winter et al., 2011)

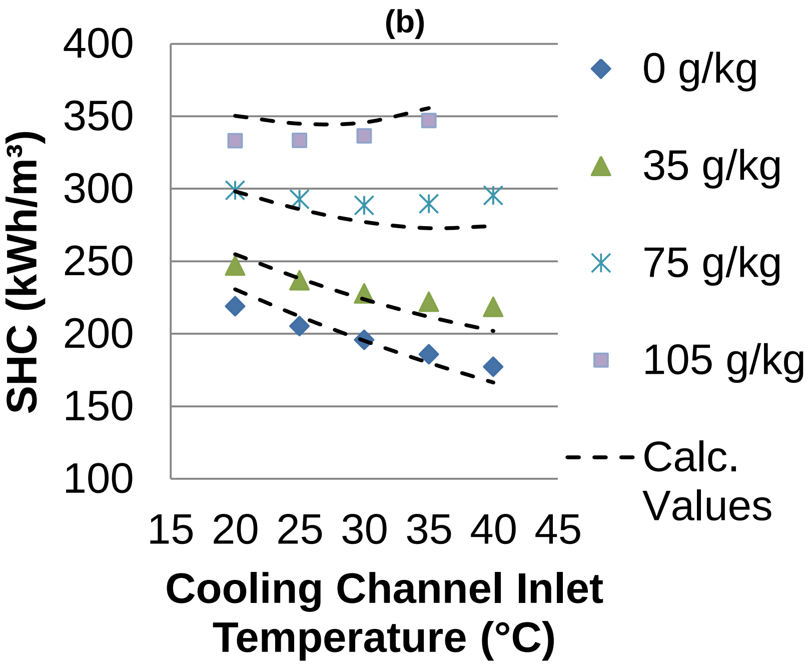
PGMD Module Modelling



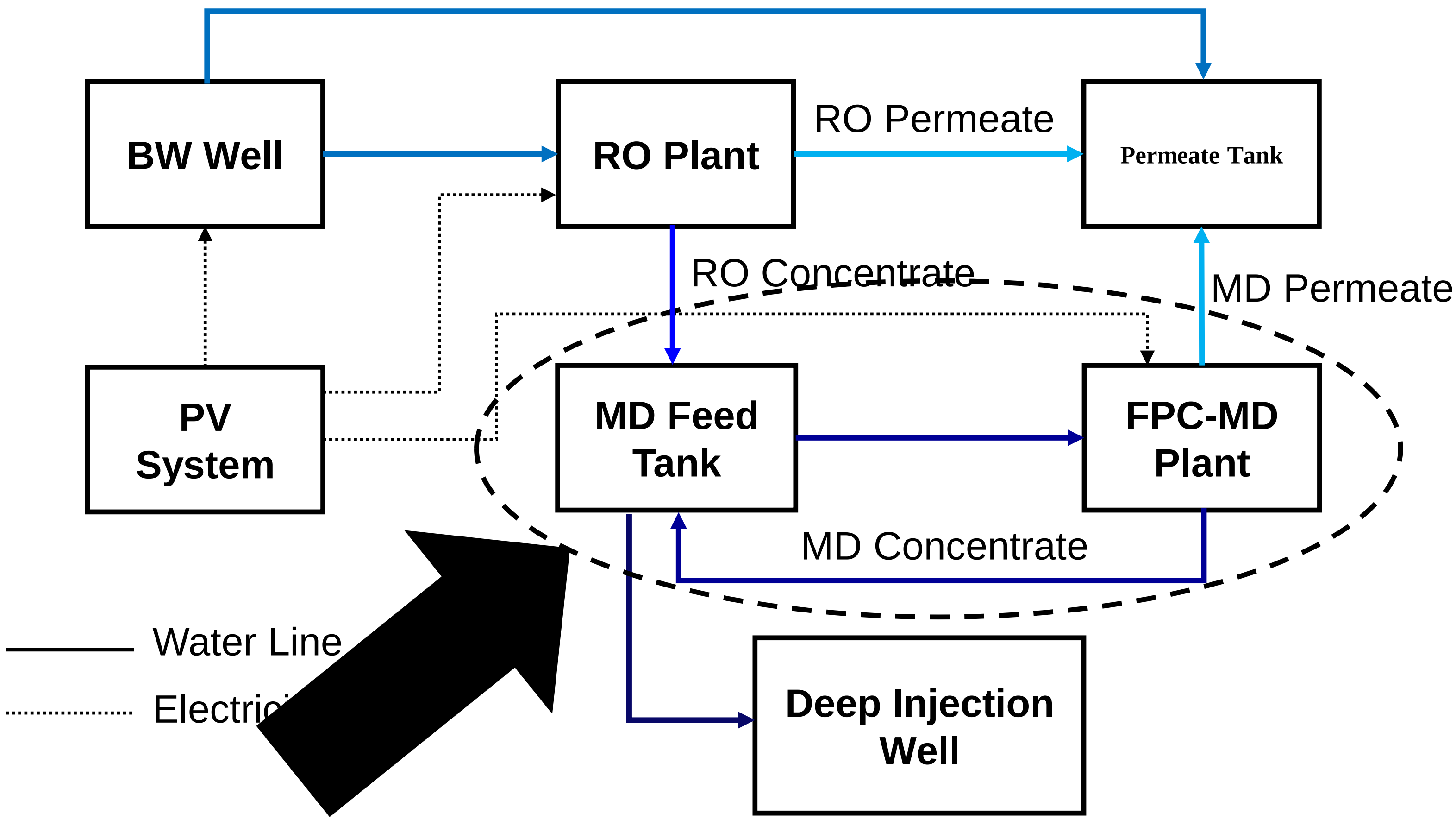


The model gave good agreement with the experimental results with a mean deviation of less than 3.35% from experimental values

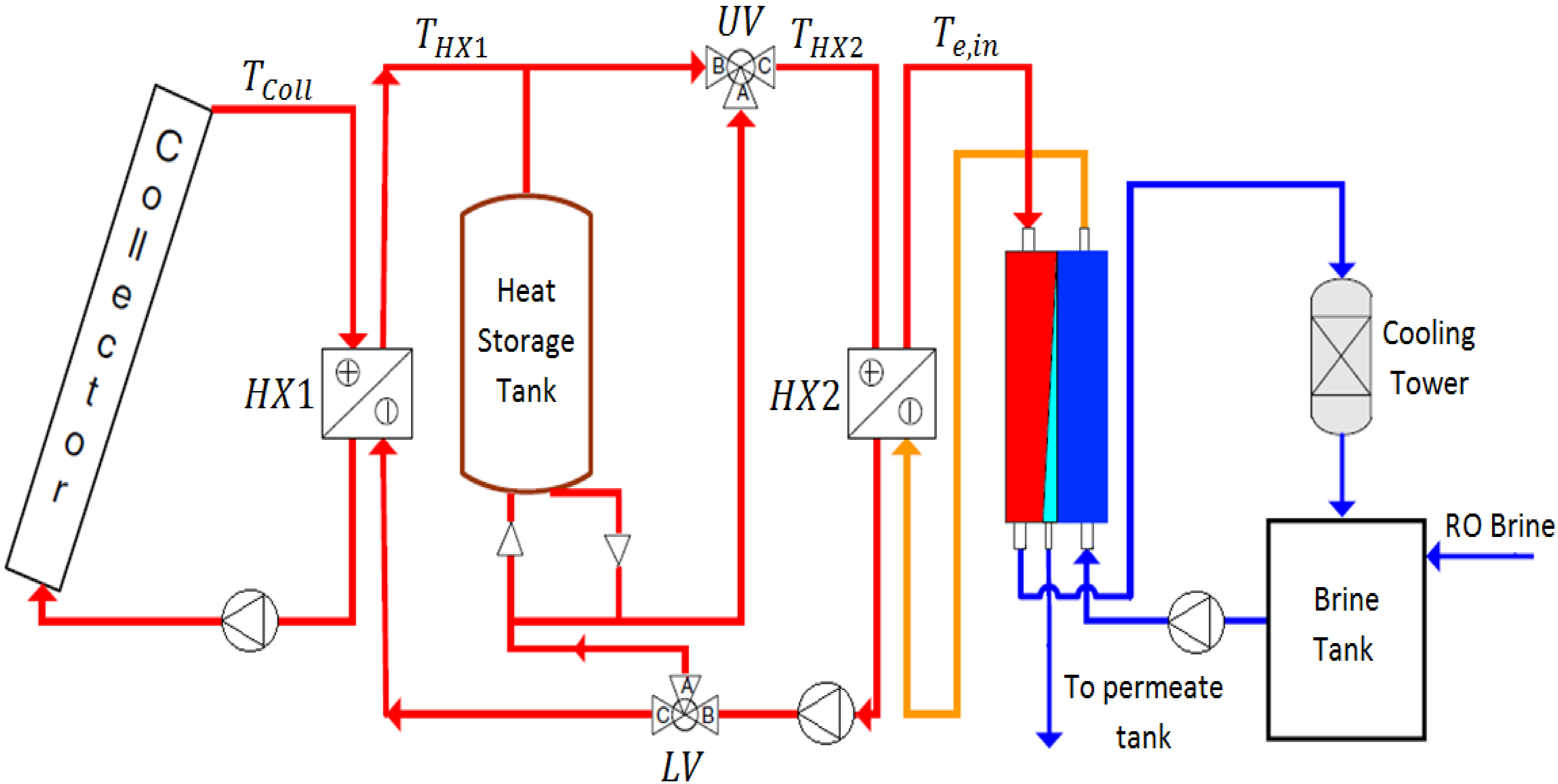




Hybrid RO/MD Plant Configuration

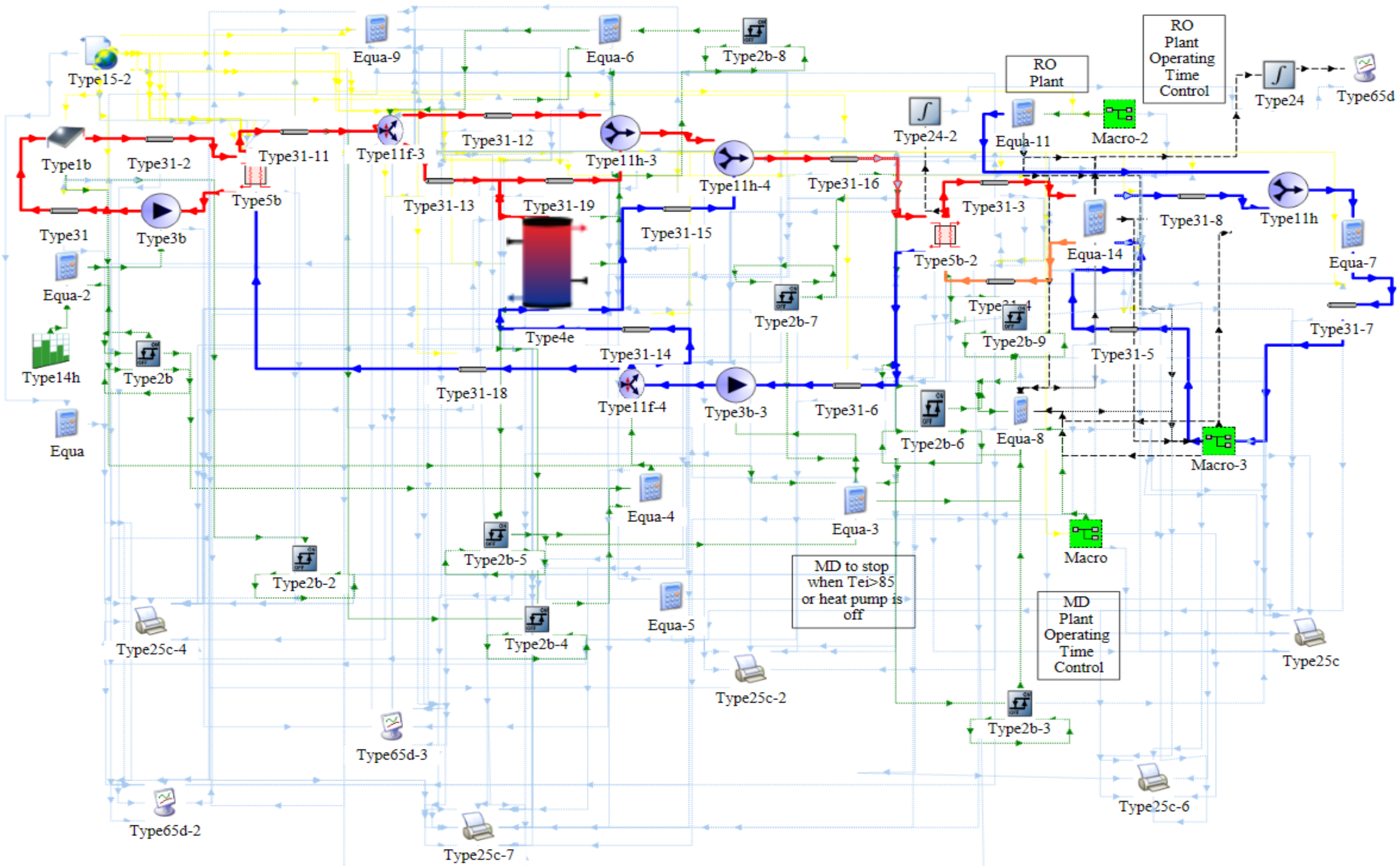


Solar Driven MD Plant Configuration



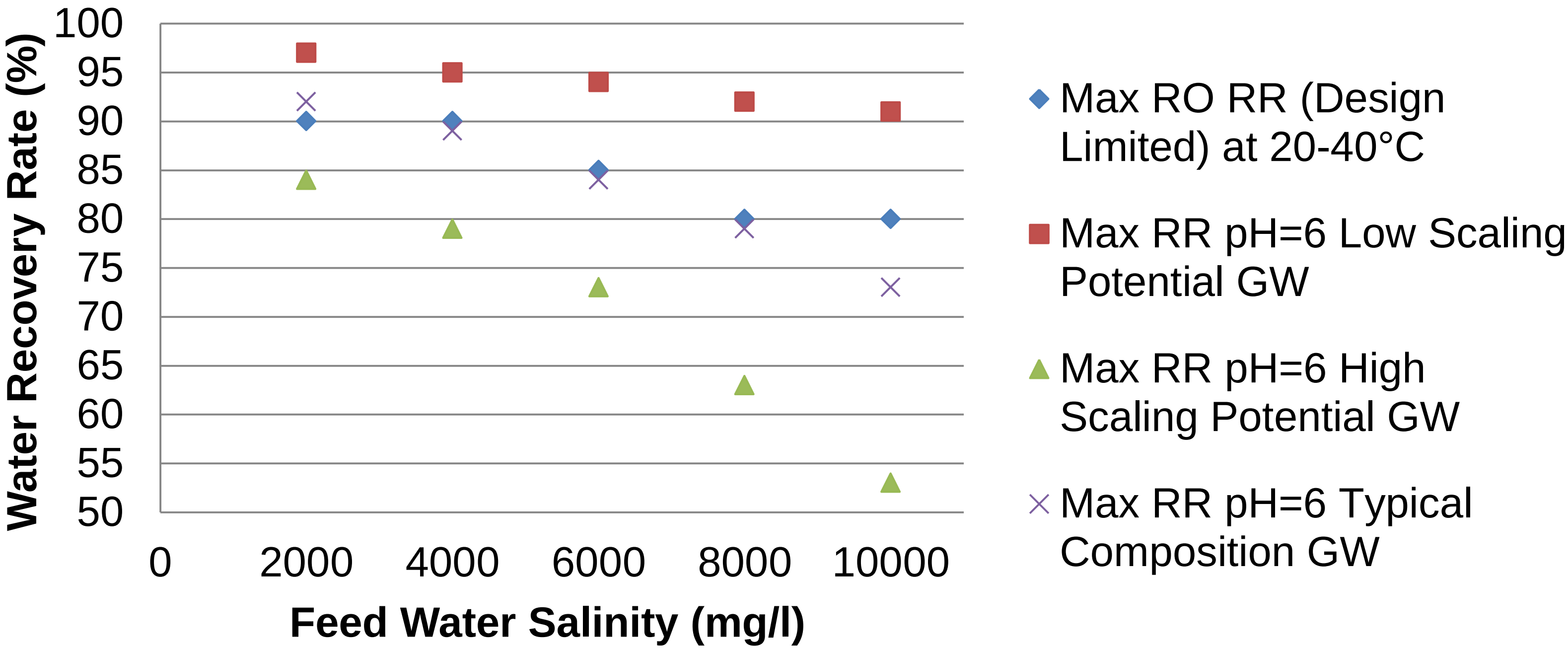
Modified after (Schwantes et al., 2013)

Solar driven MD plant modelled and optimized using TRNSYS



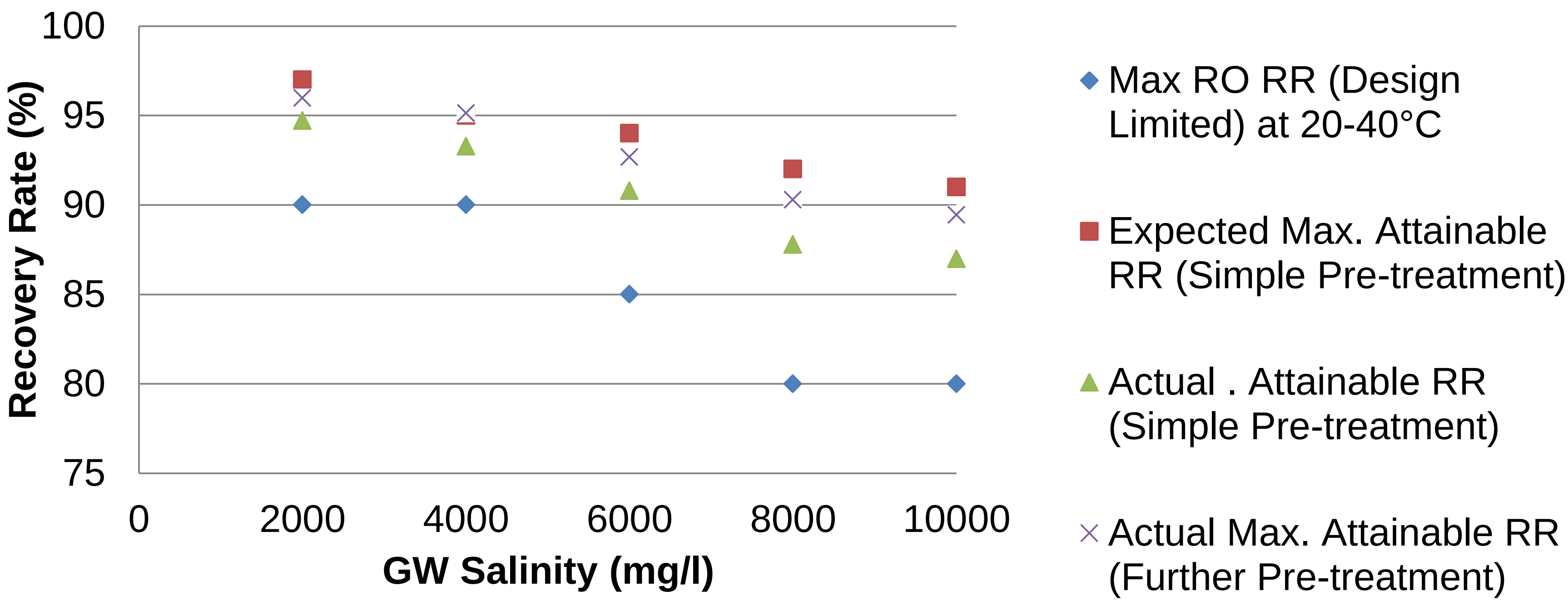
What is the maximum attainable recovery rate from a hybrid RO/MD plant?

Hybrid RO/MD Plant Maximum Attainable RR



- ***RR enhancement only possible with additional pre-treatment requirements***
- ***Up to 98% RR was obtained experimentally (*****Martinetti et al., 2009)**

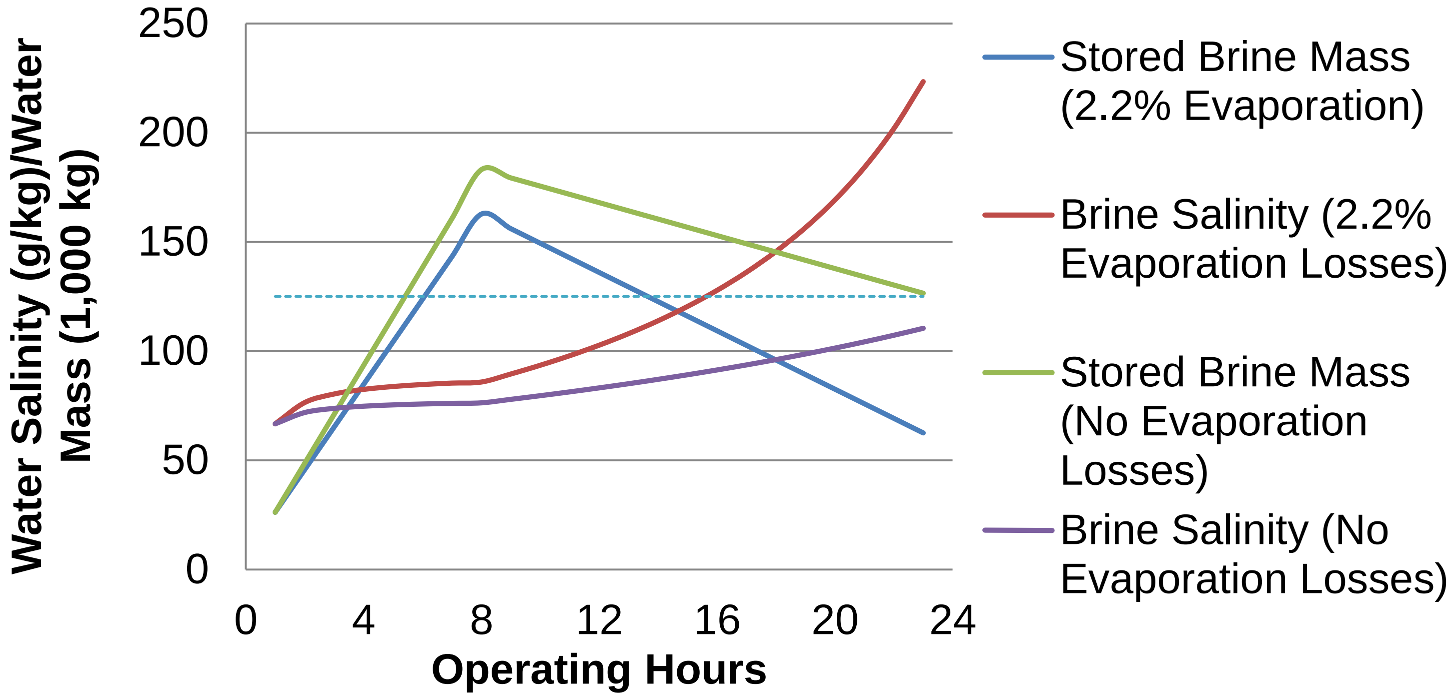
Hybrid RO/MD Plant Maximum Attainable RR



- No more than 10% enhancement in the RR was possible even after the assumption that further pre-treatment is used (i.e. 250 g/kg brine concentration possible)

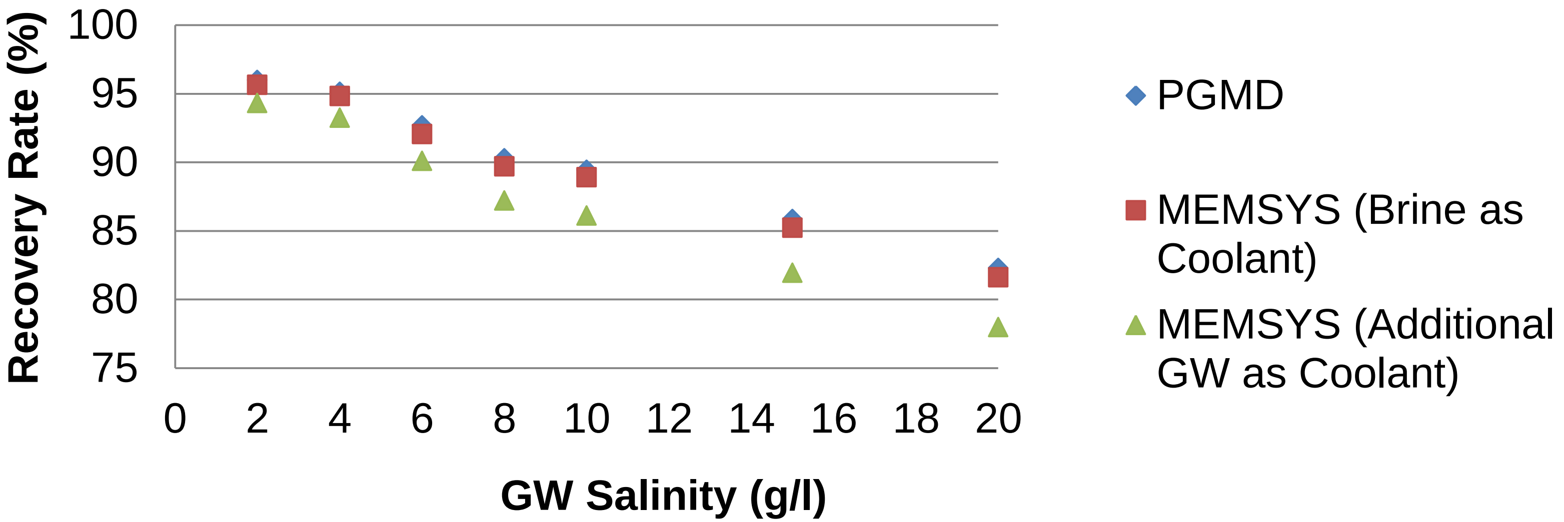
Cooling tower evaporation losses have a significant impact on the max. attainable recovery rate!

- The MD module has very low RR (<5%)
- Large brine needs to be recirculated



Can higher recovery rates be achieved with enhanced MD configurations?

- MEMSYS Module:
  - → VMD process
  - → 9 folds the recovery rate of PGMD module



- The increase in the MD module recovery rate was totally offset by the large cooling flow rate which increased the evaporation losses in the cooling tower

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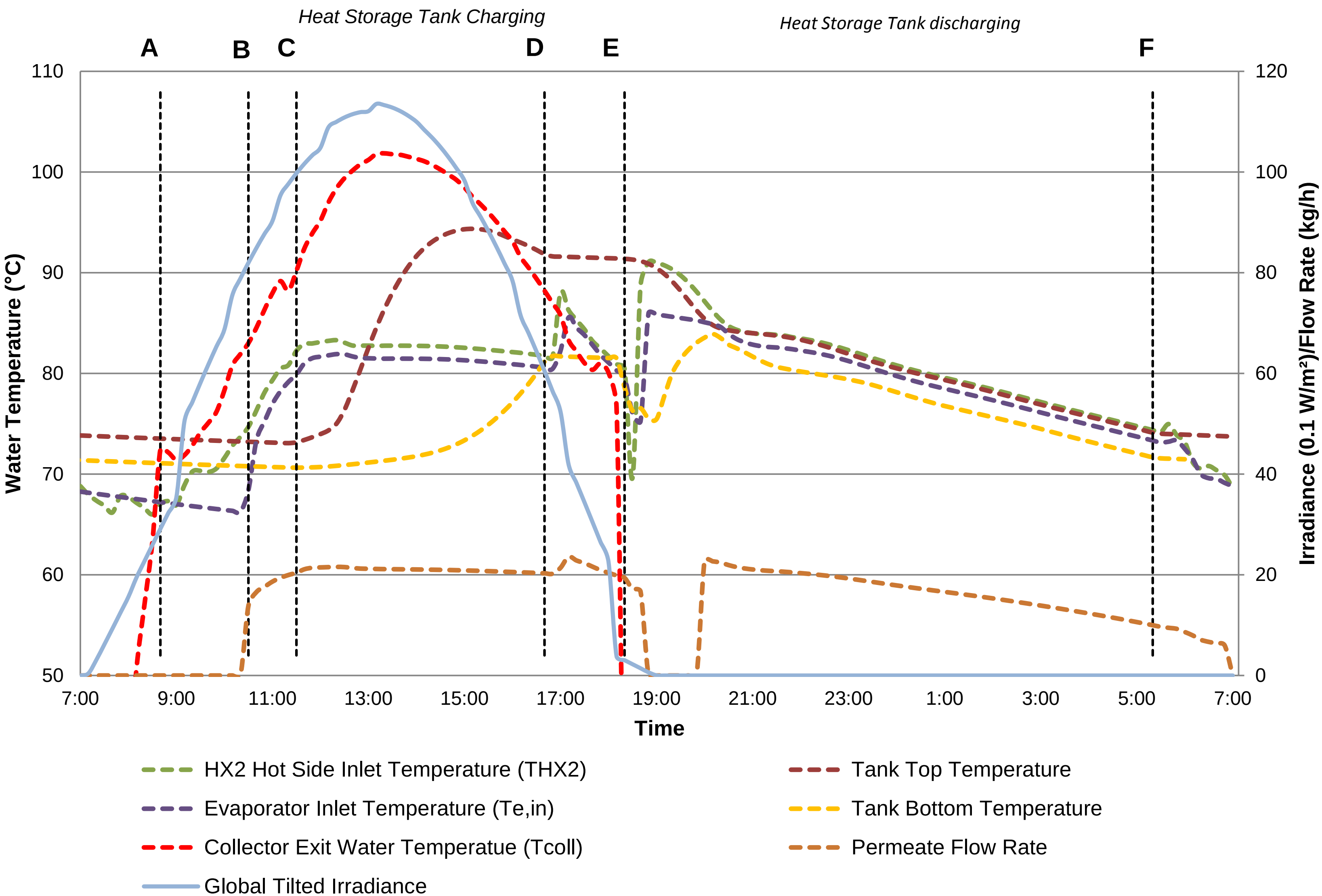
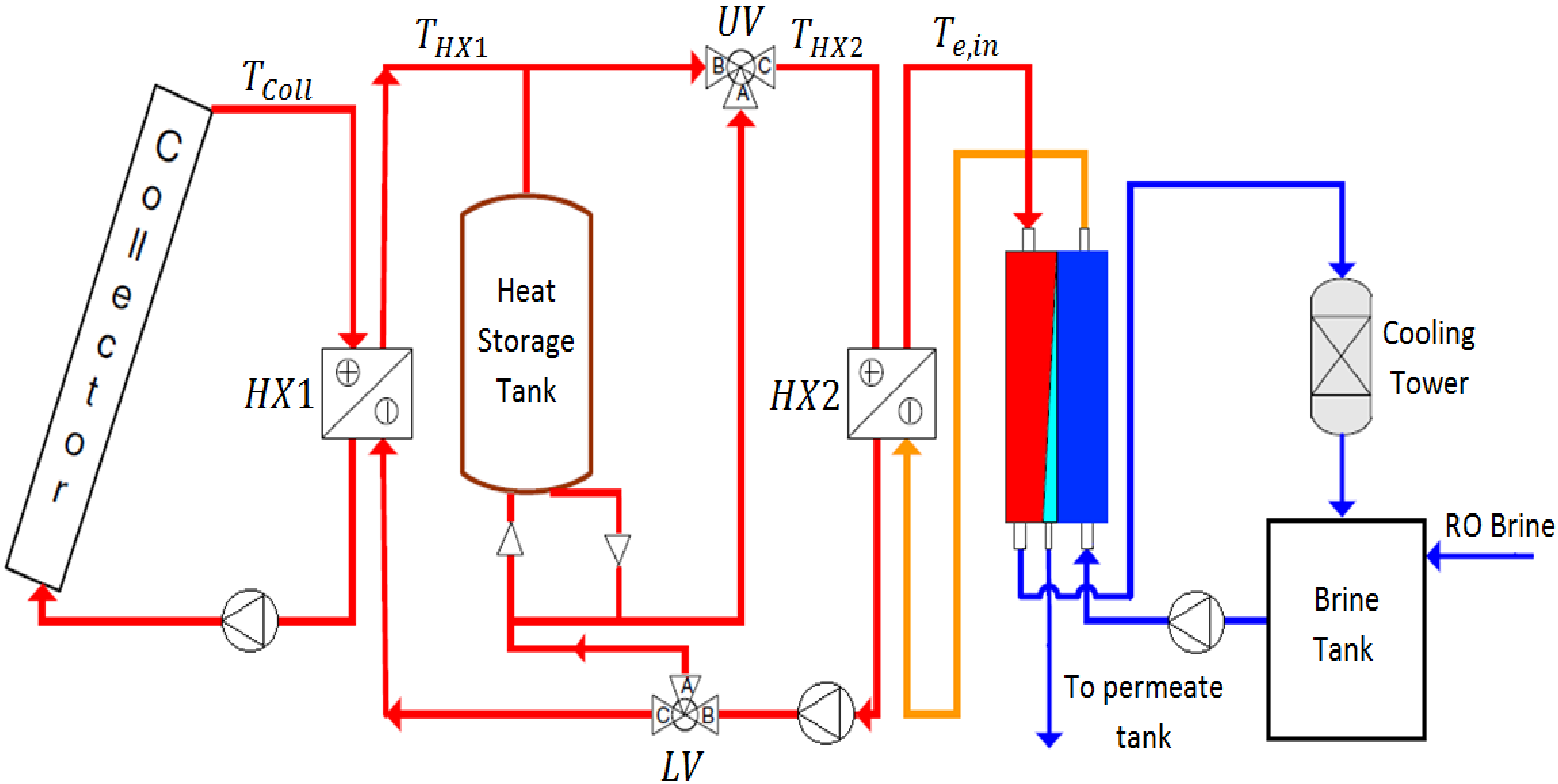
Even with such small enhancement in the recovery rate:

Is it economically feasible to use a hybrid plant?

Solar driven MD plant performance

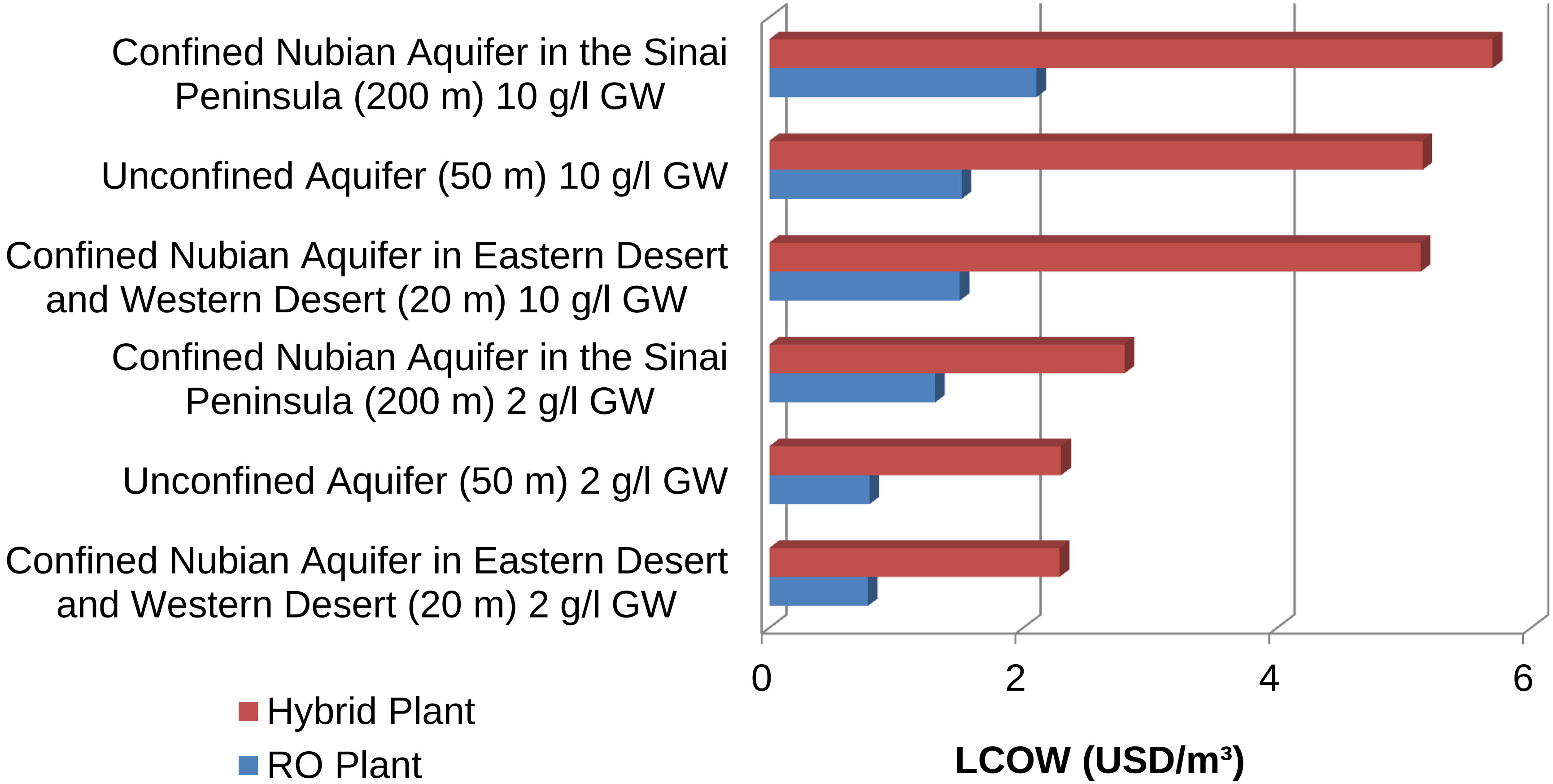


Solar Driven MD Plant Configuration



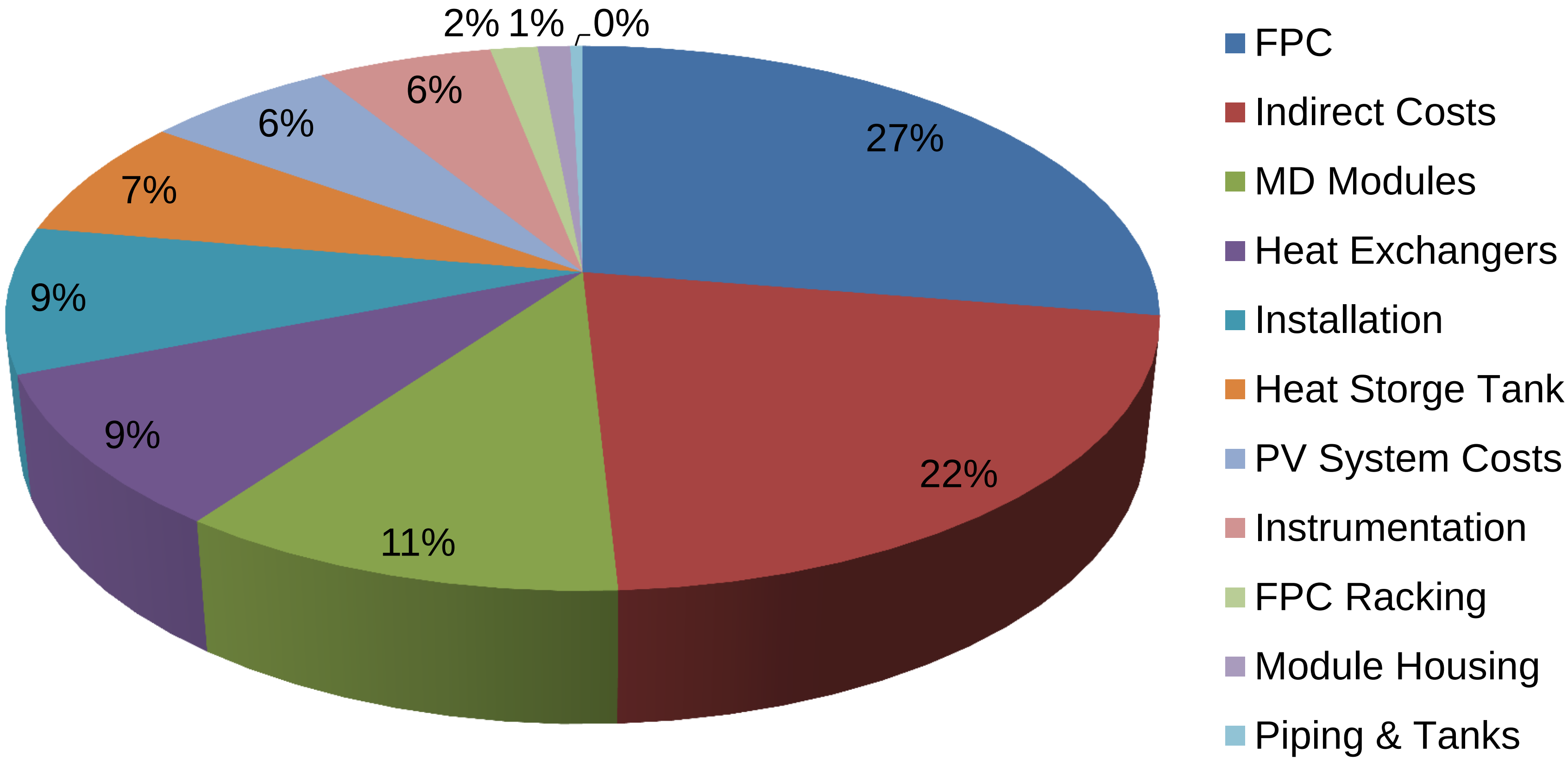
Modified after (Schwantes et al., 2013)

Using a hybrid plant resulted in a significant increase in the LCOW



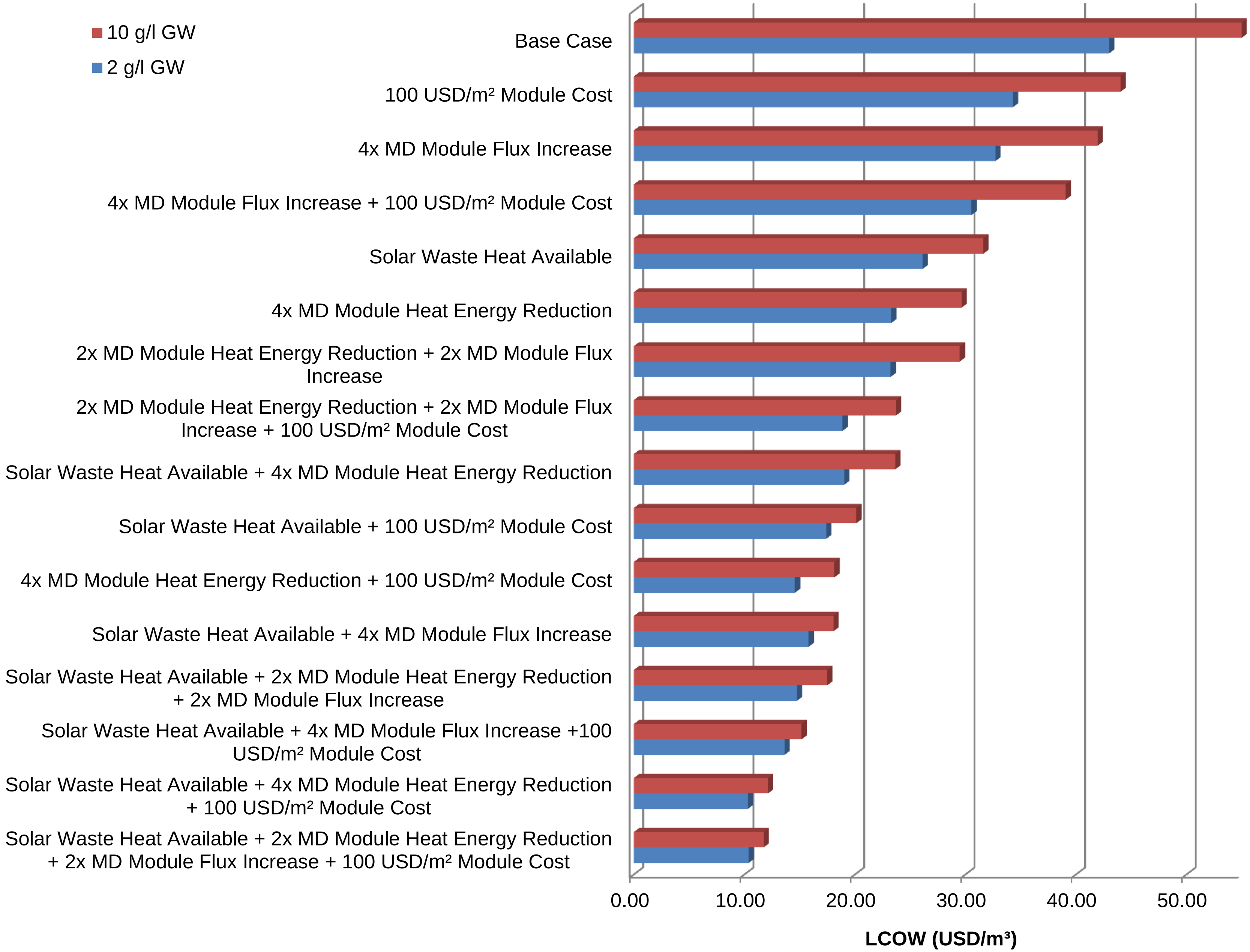
Why so expensive?

MD Plant Cost Breakdown



Conclusion: The low flux and high SHC of the PGMD module are the main reasons behind the high LCOW of the MD plant which ranged from 40.5 to 50.5 $US/m³

Under what conditions can a hybrid RO/MD plant become more economical?



10 g/l GW
2 g/l GW
Base Case
100 USD/m² Module Cost
4x MD Module Flux Increase
4x MD Module Flux Increase + 100 USD/m² Module Cost
Solar Waste Heat Available
4x MD Module Heat Energy Reduction
2x MD Module Heat Energy Reduction + 2x MD Module Flux Increase
2x MD Module Heat Energy Reduction + 2x MD Module Flux Increase + 100 USD/m² Module Cost
Solar Waste Heat Available + 4x MD Module Heat Energy Reduction
Solar Waste Heat Available + 100 USD/m² Module Cost
4x MD Module Heat Energy Reduction + 100 USD/m² Module Cost
Solar Waste Heat Available + 4x MD Module Flux Increase
Solar Waste Heat Available + 2x MD Module Heat Energy Reduction + 2x MD Module Flux Increase
Solar Waste Heat Available + 4x MD Module Flux Increase +100 USD/m² Module Cost
Solar Waste Heat Available + 4x MD Module Heat Energy Reduction + 100 USD/m² Module Cost
Solar Waste Heat Available + 2x MD Module Heat Energy Reduction + 2x MD Module Flux Increase + 100 USD/m² Module Cost
0.00
10.00
20.00
30.00
40.00
50.00
LCOW (USD/m³)

Using a hybrid Plant to enhance the recovery rate of BW PV-RO plant could be more economical under the following conditions:

- The MD plant needs to be driven using waste heat from a renewable energy source such as CPV or CSP plant
- The MD module should experience at least 4 folds reduction in its heat consumption or 2 folds increase in its flux and 2 folds reduction in its heat consumption
- MD modules costs needs to drop to 100 $US/m^2

Only 26 to 47% increase in the LCOW is expected in this case for brackish water applications

Is it worth to combine a thermal process with an RO plant to increase the RR?

- RR's ranging from 75 to 90% were already attainable from the RO plant
- Higher RR requires additional pre-treatment requirements
- Using other thermal processes is likely to have the same limitations
- Salt retrieval?

Conclusion

- Why decentralized high recovery rate solar driven plants for brackish groundwater (GW) extraction and desalination could be beneficial to Egypt?
- Is it more economical to use PV instead of diesel generators to drive the reverse osmosis (RO) plant?
- Is there an economic advantage of replacing PV modules with Photovoltaic thermal (PVT) collectors to drive the RO plant?
- Is it feasible to use a membrane distillation (MD) process to enhance the recovery rate of the RO plant?

Conclusion

Decentralized high recovery rate solar driven plants for brackish GW extraction and desalination are suggested to establish decentralized agricultural communities in Egypt with a degree of autonomy to increase the resiliency of a large sector of the population

Conclusion

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Conclusion

- A PV driven RO plant operating for 24 hours is cost competitive with a DG-RO if the current subsidies on diesel are removed and becomes more economical if the battery costs dropped to 100 $US/kWh
- The LCOW and the SEC of PV-RO plants used to extract and desalinate brackish water were also found to be lower than those of a SW PV-RO plant

Conclusion

- Why decentralized high recovery rate solar driven plants for brackish groundwater (GW) extraction and desalination could be beneficial to Egypt?
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Conclusion

The Low capacity factor ,variability of solar irradiance and operating temperature limitation of the RO membranes are main barriers for PVT collectors to have any economic advantage over standard PV modules with RO applications

Conclusion

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Conclusion

- Less than 10% enhancement in the RR was achieved using a hybrid RO/MD plant with a corresponding significant increase in the LCOW
- The evaporation losses from the cooling tower were found to have a significant impact on the maximum attainable RR from a hybrid RO/MD plant even with enhanced MD process configurations
- For higher recovery rates to be achieved with a hybrid RO/MD plant, higher recovery rate MD modules with low cooling requirements are needed
- Hybrid RO/MD plants are likely to be only economically feasible if a source of a waste heat is available from a CPV or a CSP plant, the SHC of the process is reduced by 4 folds and the MD module costs become similar to that of an RO module

Future Work

- Dual use of CPV to generate electricity and to drive a low temperature thermal desalination process such as MD
- Battery-less PV-RO plants, is it worth it when brackish water is desalinated?
- Spiral wound vs. planar geometry assumption

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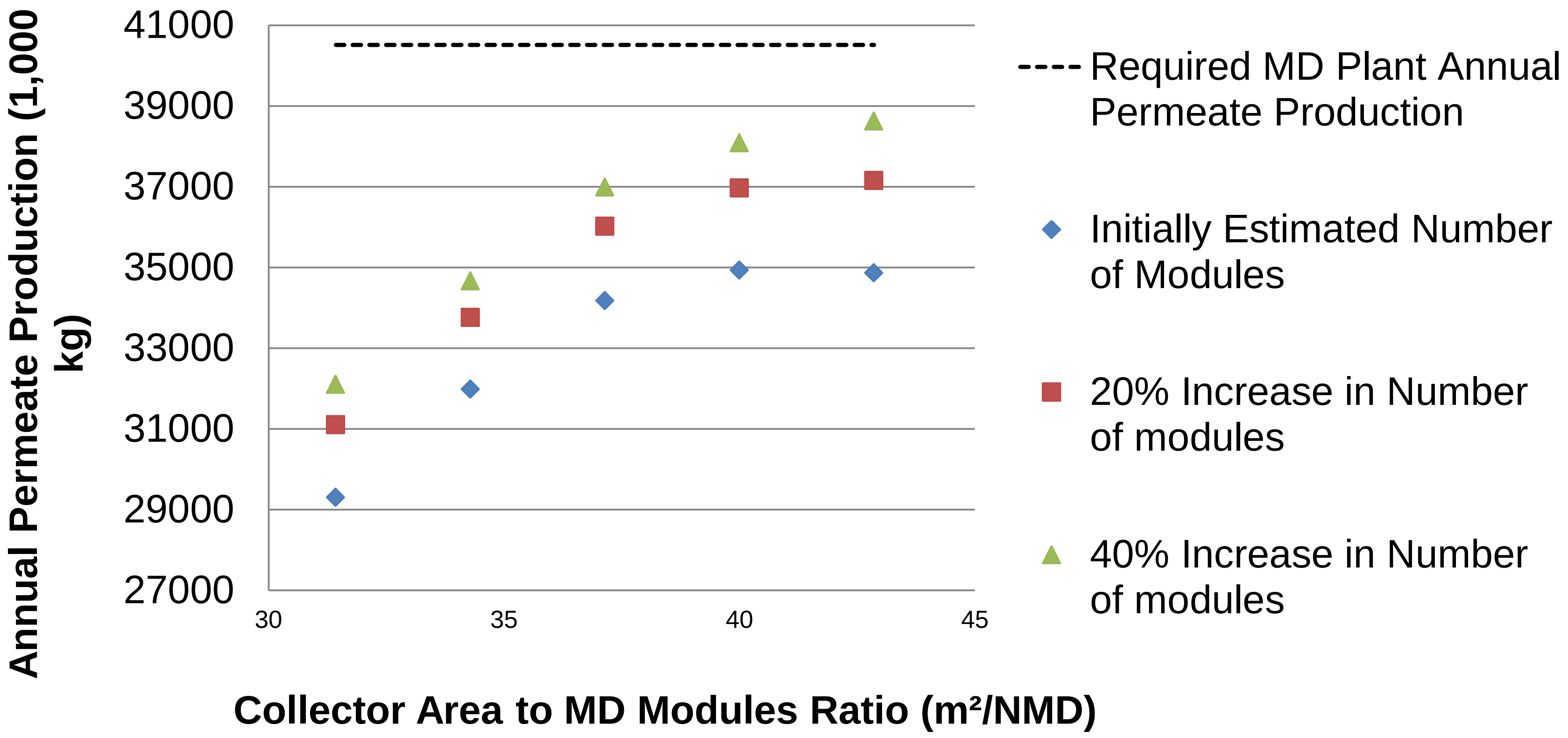
Acknowledgment

I would like to thank the Fraunhofer Institute team for their valuable contribution and support

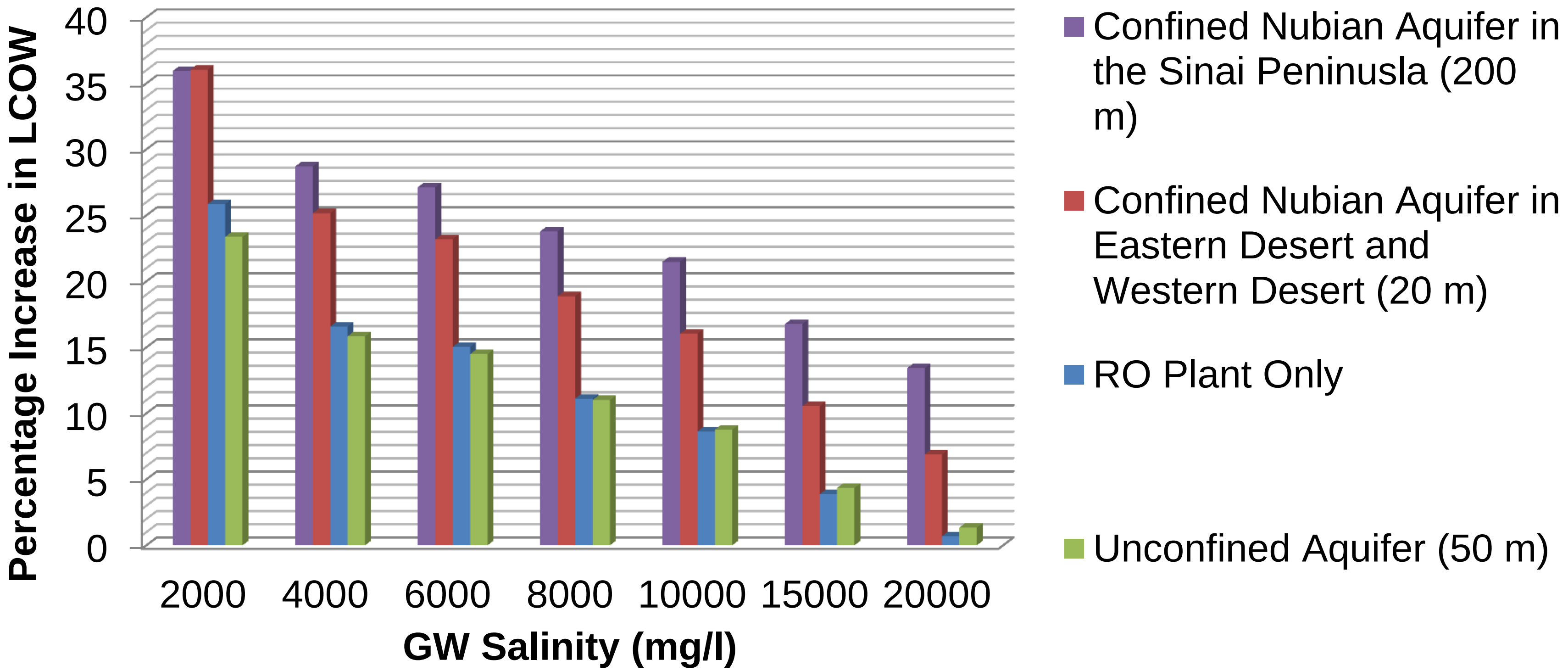
Thank you for your attention

Further Info Slides

Further RR Limitations when driven by solar energy



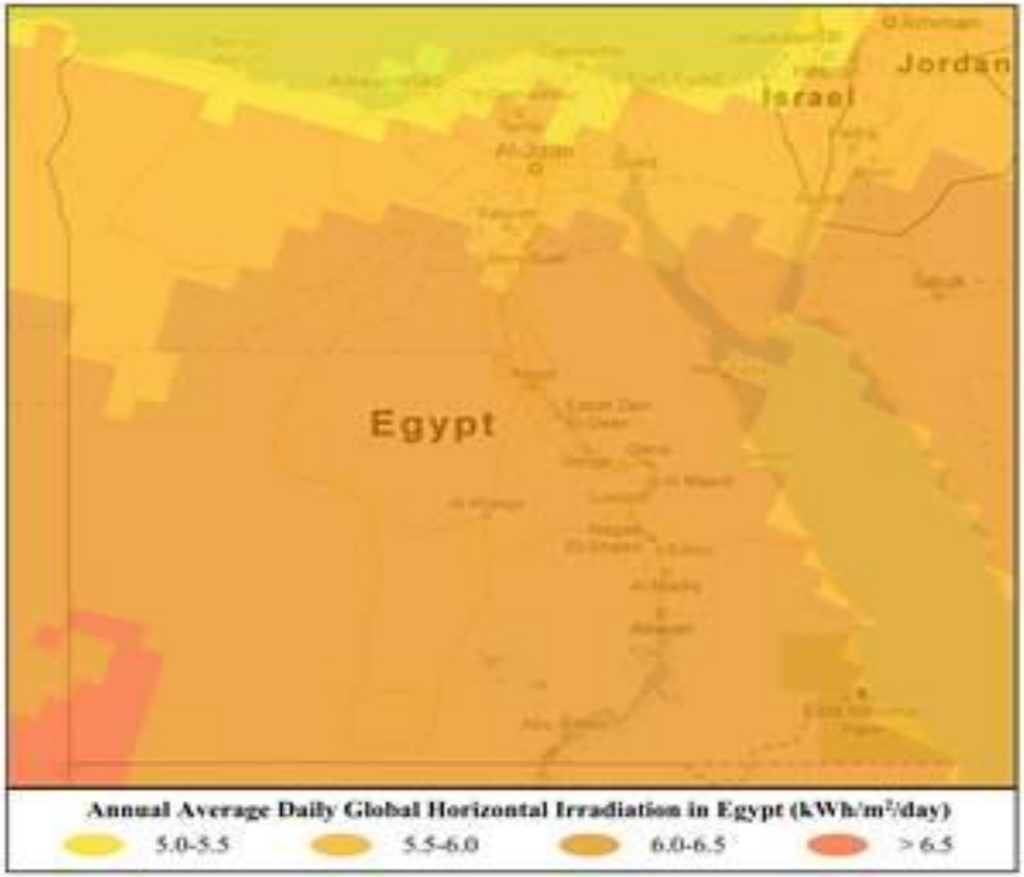
Impact of PV-RO Plant Operating Hours on the LCOW



More economical to design the plant to run for 24 hours with BW applications

Two Locations: Aswan & Marsa-Matruh

→ Two extremes in solar irradiance and groundwater temperatures



Annual Average Daily Global Irradiation in Egypt
Source: NREL

Glazed vs. Unglazed Collectors

- Glazed Collectors: High Thermal Output/Low Electrical Output
- Unglazed Collectors: Low Thermal Output/ High Electrical Output