SOLAR THERMAL ENERGY DRIVEN ORGANIC RANKINE CYCLE SYSTEMS FOR ELECTRICITY AND FRESH WATER GENERATION

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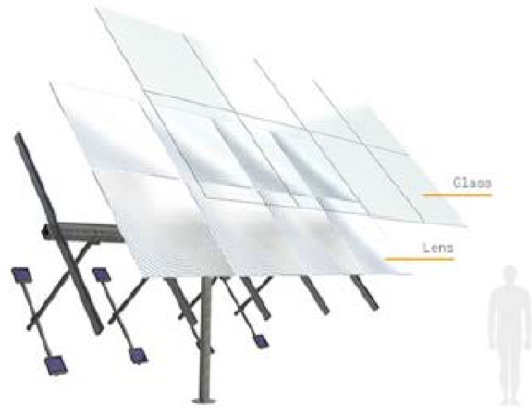
Introduction

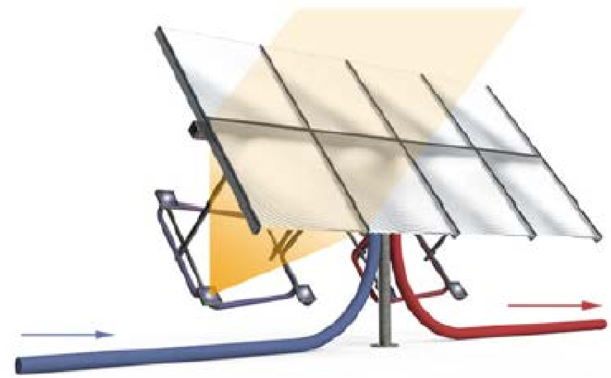
– Small to medium-scale systems for dispatchable electricity and fresh water
  - Diesel generator based systems using reverse osmosis (RO)
  - Solar photovoltaic with battery storage system using reverse osmosis
  - Expensive large-scale battery systems
  - Concentrated solar power (CSP)
    – Thermal energy storage
    – Thermal energy driven desalination system

Conventional CSP plants

- Parabolic trough collector (PTC), linear Fresnel reflector (LFR), solar tower, paraboloid dish
- Heavy and very expensive glass mirrors and receivers
- High capital and O&M cost
- Suitable for large-scale and places with high solar radiation

Foil-based concentrating solar collector





Actual installation on Møn, Denmark (a 2 MW solar field for district heating purposes) and at DTU Civil Engineering's test facilities

Comparison between foil-based solar field and parabolic trough collector field

DTU

	Foil-based solar field	Parabolic trough collector field
1	Low cost concentrators	High cost concentrators
2	Low precision requirements	High precision requirements
3	Standard components	Specialized components
4	Light construction	Heavy construction
5	Two-axis tracking	Single-axis tracking
6	Less sensitive to dirt	Difficult to clean
7	Any terrain usable	Level terrain required

– **Potential to reduce about 40 % LCOE compared to medium-scale PTC-based plants [1]**

CSP integrated ORC system with reverse osmosis desalination

- Promising working fluids: Toluene, isopentane, R134a, hexamethyldisiloxane (MM) and n-octane

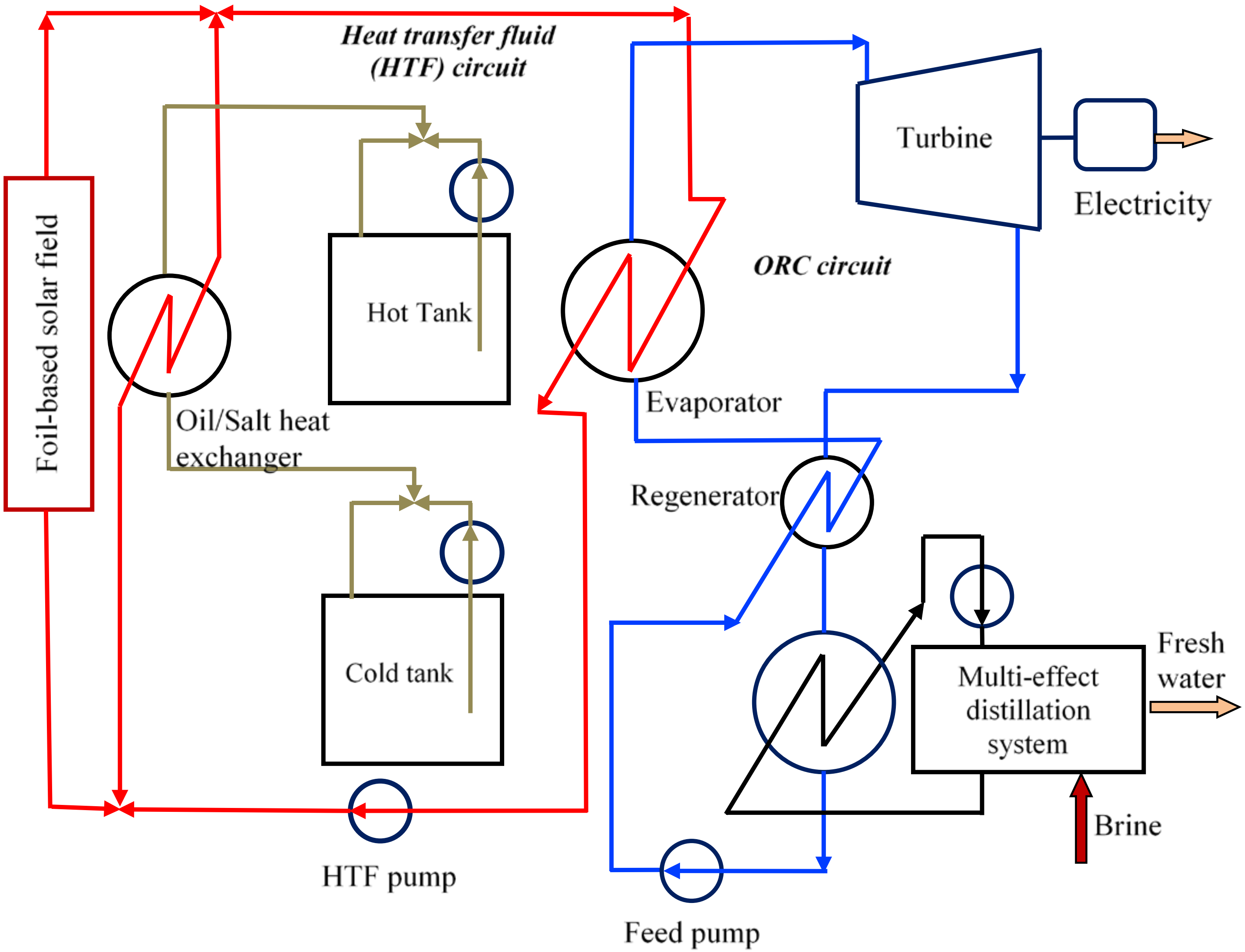
CSP integrated ORC system with thermal desalination

- Parabolic trough collector preferred solar field
- Promising working fluid: Toluene, cyclopentane and n-pentane

List of concentrated solar energy powered organic Rankine cycle based commercial/medium-scale actual plants for different applications

Name (Location)	Start year	Solar field	Solar field area (m^2)	Storage	Application (net capacity)
Saguaro Power Plant (Arizona, USA)	2006	PTC	10,340	-	Electricity generation (1 MW_e) (currently non-operational).
Rende-CSP Plant (Calabria, Italy)	2014	LFR	9,780	-	Electricity generation (1 MW_e). The facility is combined with an already operating biomass based plant (14 MW_e).
Airlight Energy Ait-Baha Pilot Plant (Ait Baha, Morocco)	2014	PTC	6,159	Packed-bed rock (5 h)	Electricity generation from CSP and waste heat from cement industry (hybrid plant) (2 MW_e).
Stillwater GeoSolar Hybrid Plant (Fallon, USA)	2015	PTC	24,778	-	Electricity generation. About 17 MW_{th} from CSP combined with geothermal energy producing 33 MW_e. Additionally, 26.4 MW_e of a solar photovoltaic plant.
Aalborg CSP-Brønderslev CSP with ORC project (Brønderslev, Denmark)	2016	PTC	26,929	-	Combined heat and electricity production from CSP (16.6 MW_{th}) and biomass combustion (hybrid plant) (3.8 MW_e).
Ottana Solar Facility (Sardinia, Italy)	2017	LFR	8,600	Two-tank direct	Power generation (0.6 MW_e), additionally 0.4 MW_e of solar PV

Foil-based solar collector powered system



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Important data used for the analysis

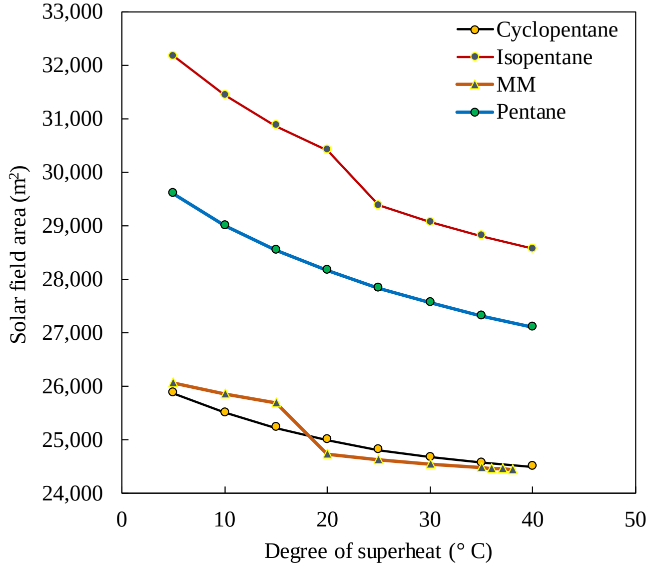
DTU

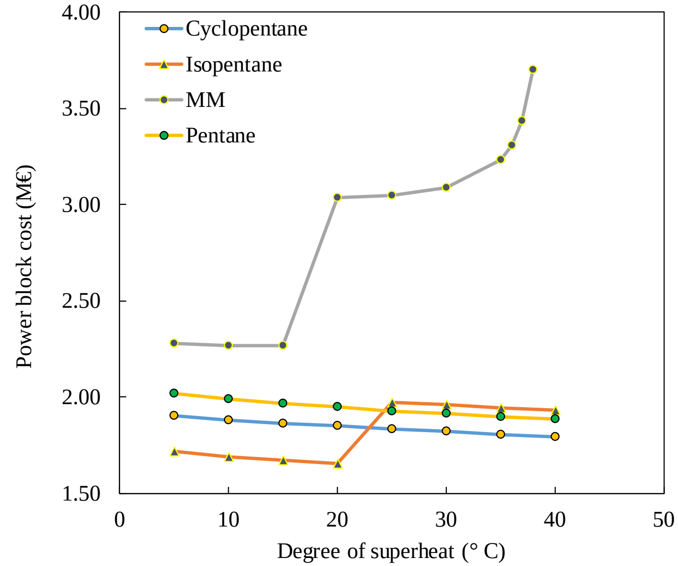
Input Parameter	Value
Place	Cape Town (South Africa)
Solar collector field efficiency parameters	$\eta_{o,CL}$ = 0.833; U_l = 0.85 W/(m^2·K) and 0.68 W/(m^2·K) (with improvements)
Storage tank UA	0.00017·T_{salt} + 0.012 (kW/m^2); T_{salt} is the temperature of salt (° C) [2]
Gross peak plant output at design ($P_{gross,D}$)	1 MWe
Penalty for start-up/shut-down and other losses	10 % of net power output [3]
Parasitic electric energy use for solar field, TES pump, antifreeze pumping	7 % of net power output [4]
Electricity consumption of MED system	1 kWh_e/m^3 [5]
Isentropic efficiency of turbine at design condition ($\eta_{T,D}$)	Based on [6]
Turn down ratio of turbine (P_{min}/P_{max})	0.1 [7]
Generator efficiency parameters ($\eta_{g,D}$)	$\eta_{g,D}$ = 0.93
Isentropic efficiency of pump at design condition ($\eta_{P,D}$)	$\eta_{P,D}$ = 0.7

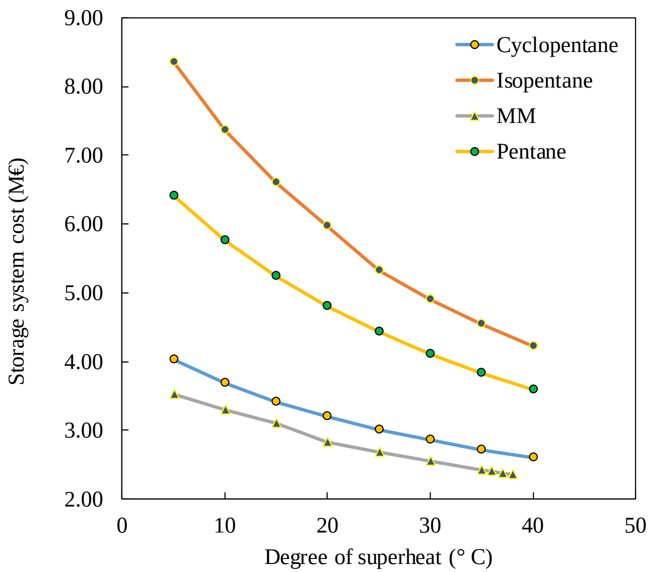
Important data used for the economic analysis

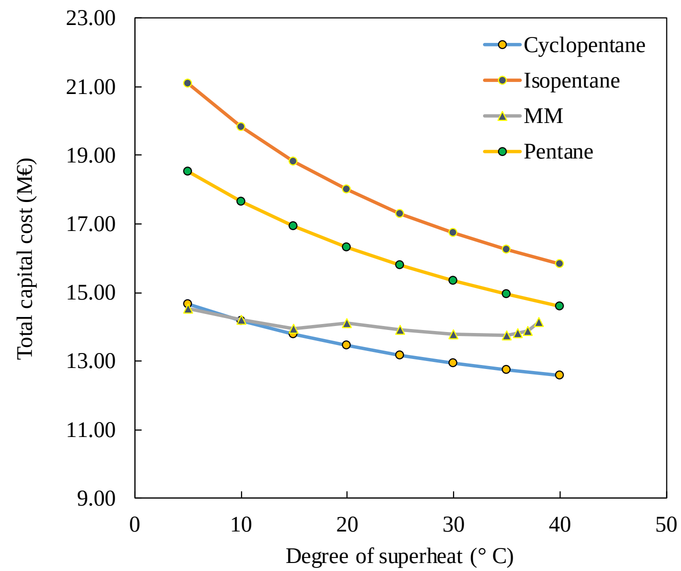
Parameters	Value
Solar field and heat transfer fluid system cost (€)	250 (for current plants) and 150 (for future plants)
Land and site development cost (€/m^2 of land)	4.7 [8]
Specific cost of Hitec XL (€/kg)	0.93 [9]
Storage tank cost (including insulation and foundation) (€/m^3)	$\frac{c_{ST,Tank}}{c_{ref,Tank}} = \left(\frac{Capacity_{ST,Tank}}{Capacity_{ref,Tank}}\right)^{0.85}$; $C_{ref,Tank}$ = 7,932,160 € [1], $Capacity_{ref,Tank}$ = 30,844 m^3 [2]
Oil to salt heat exchanger cost (€)	$\frac{c_{ST,HX}}{c_{ref,HX}} = \left(\frac{Capacity_{ST,HX}}{Capacity_{ref,HX}}\right)^{0.85}$; $C_{ref,HX}$ = 4,580,235 € [1], $Capacity_{ref,HX}$ = 133 MW_{th} [2]
Balance of storage system and salt pump cost (€)	14 % of the storage system cost [2]
ORC system component cost (€)	Based on the correlations given by [10] and water cooled condenser based on [11]
Capital cost of MED system (€/(m^3·d))	1500
Annual operating and maintenance cost	Fixed cost (on total investment) – 1.4 %; Variable cost – 2.8 €/MWh_e
Lifetime (y)	25

Variations in degree of superheat









Results of a techno-economic analysis of the system (1 MW_e plant with 9 h storage capacity)

Parameters	Cyclopentane		MM		N-Pentane		Isopentane	
	Current plants	Future plants	Current plants	Future plants	Current plants	Future plants	Current plants	Future plants
Solar field outlet temperature, $T_{out,CL}$ (° C)	278		290		256		247	
Evaporator pressure, P_{eva} (MPa)	2.569		1.201		2.467		2.464	
Evaporator outlet temperature, $T_{out,eva}$ (° C)	238		250		216		207	
Solar collector field area, $A_{p,CL}$ (m^2)	24,498	21,418	24,476	21,148	27,098	24,004	28,567	25,423
MED system capacity (m^3/day)	908		862		1,087		1,180	
LCOE (€/kWh_e)	0.224	0.176	0.277	0.226	0.238	0.188	0.255	0.206
LCOW (€/m^3)	1.74	1.27	1.48	1.02	2.12	1.65	2.24	1.75

Concluding remarks

- **Foil-based CSP system:** **Promising option**
- **ORC working fluid:** **Cyclopentane**
  - **LCOE:** **5.6–6.1 % lower compared to n-pentane**
  - **LCOE:** **19.6–22.7 % lower compared to MM based plants**
  - **Levelized cost of water (LCOW):** **19.8–39.6 % higher compared to MM**
  - **LCOW:** **25.5–32.3 % lower compared to n-pentane based plants**

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