Renewable Steam Generation Assessment for an Industrial Demand in Brazil

Juan Márquez, Lucas Saborido, Mahmoud Abouelamaim

CARL VON OSSIETZKY universität OLDENBURG

INTRODUCTION

MOTIVATION

- ✓ *Steam is one of the most used process fluids in industry*
- ✓ *Replacing fossil fuels (e.g., NG) with renewables*
- ✓ *Good marketing – greener and more innovative plants*

OBJECTIVES

- ✓ *Analyze the feasibility of supplying heat for a specific process steam demand by means of solar thermal collectors*
- ✓ *Size the system from a thermal perspective and select the solar heat collector and thermal fluid*
- ✓ *Investigate different loading conditions and the response of the system to the heat demand*

ASSUMPTIONS

- ✓ *Constant demand – No seasonal variation*
- ✓ *The water supply (input) is always at the indicated temperature*
- ✓ *There is no installation area restriction for the system*
- ✓ *Only steady-state behavior was considered*
- ✓ *Temperature ranges were selected based on a cross-flow heat exchanger*
- ✓ *The efficiency of heat exchanger is 100%*
- ✓ *F-chart method is not applicable due to its temperature range restriction (process temperature higher than 50°C).*

EXCLUSIONS

- x *Sizing of heat storage units*
- x *Layout development*
- x *Economical analysis (CapEx and OpEx)*
- x *Selection of other system components (pumps, heat exchangers, valves, etc.)*
- x *System control (on/off)*

DEMAND

INPUT [2]

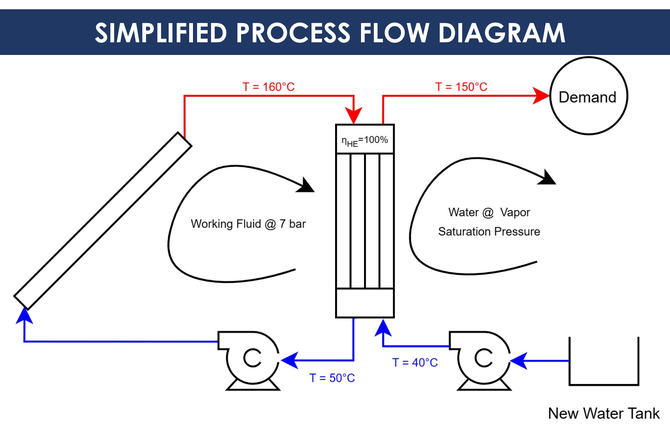
Parameter	Unit	Value
Input		
Water flow	*m³/h*	*2.30*
Water temperature	*°C*	*40*
Water density	*kg/m³*	*1000*
Water pressure	*kPa (a)*	*101.3*
Output		
Steam temper.	*°C*	*150°C*
Steam quality	*-*	*1.00*

MONTHLY HEAT DEMAND

Water shall be pressurized (pumped) at the desired vapor saturation pressure

Scenario	Unit	Value
1 - Saturated Steam @150°C	*kWh/month*	**1.177*10⁶**
2 – Water @90°C	*kWh/month*	**9.600*10⁴**

SIMPLIFIED PROCESS FLOW DIAGRAM



CALCULATION PROCEDURE

1. *Calculate the heat demand for the first scenario (provide saturated steam at 150°C)*
2. *Select the working fluid and define the required working fluid mass flow*
3. *Import the irradiation and temperature data (PVGIS).*
4. *Determine the optimal tilt angle (throughout the whole year).*
5. *Select the solar thermal collector.*
6. *For each month, calculate the collector efficiency based on the monthly average of the non-zero irradiation [W/m²] and temperature [°C]* **[1]**.

$$\eta_{coll} = \eta_0 - a_1\frac{(T_m - T_a)}{G_T} - a_2\frac{(T_m - T_a)^2}{G_T}$$

7. *Calculate the required system area for each month, based on the available solar energy (monthly average irradiation)* **[1]**.

$$A_{coll} = \frac{\int \dot{Q}_u dt}{\eta_{coll}\int G_T dt} = \frac{Q_u[kWh/month]}{\eta_{coll} G_T[kWh/month.m^2]}$$

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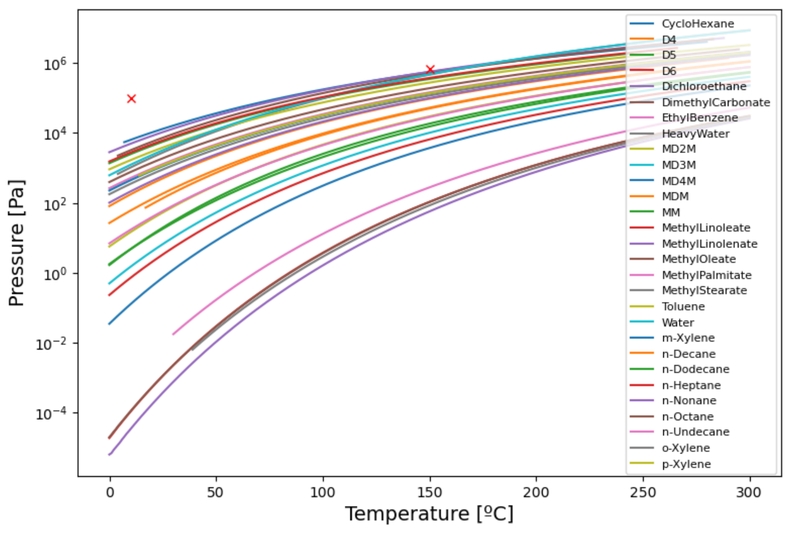
WORKING FLUID SELECTION

REQUIREMENTS

- ✓ *Fluid at 7 bar and 160°C*
- ✓ *Good heat transfer properties*
- ✓ *Used as a heat transfer medium*

CoolProp FLUIDS ASSESSMENT [3]



- x *No available thermal fluid in the CoolProp database*
- x *Water is possible but there would be risk of evaporation in the solar thermal collector*

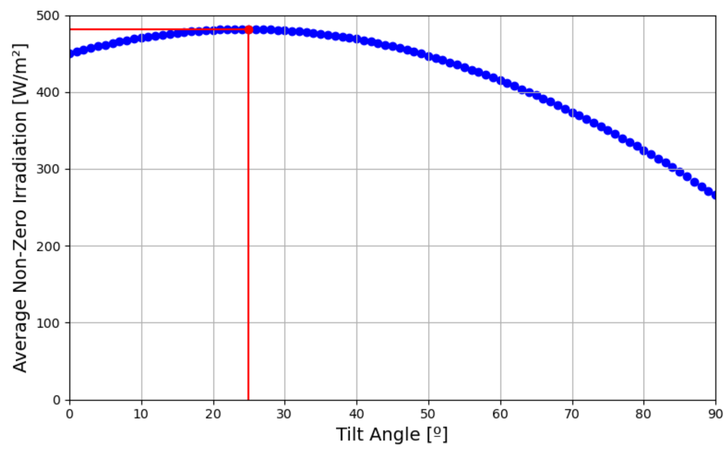
SELECTED FLUID [4]

- ✓ *Selected fluid for the application is Silicone Oil*
- ✓ *Product name is Omnisol: a heat-transfer fluid intended for in open and closed systems under operating conditions from -40°C - 425°C in the liquid phase*
- ✓ *Manufacturer is Globaltherm*
- ✓ *Density: 0.92 g/cm³ [4]*
- ✓ *Cp –1250 J/kg.°C (not mentioned in the technical datasheet, average number was adopted based on the fluid characteristics)*
- ✓ *Boiling point at 0.6 hPa ≥ 200 °C [4]*

TILT ANGLE DEFINITION

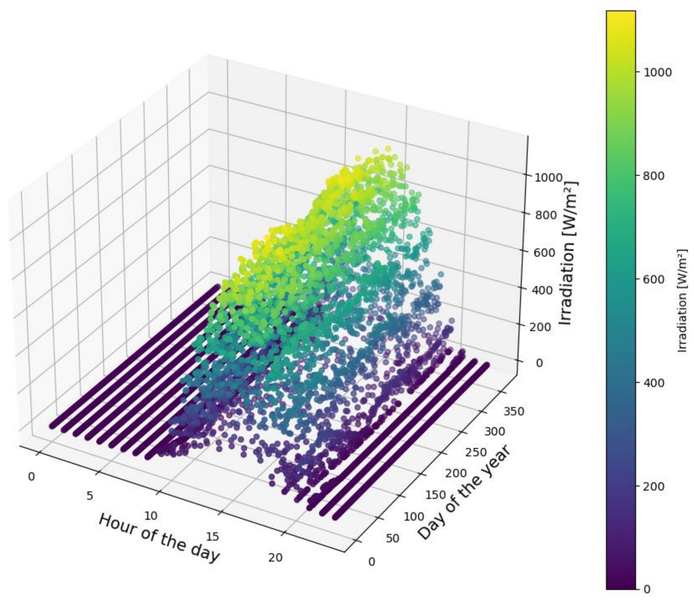
Given that the demand is constant (no seasonal variation), the tilt angle that produces the best yearly energy yield was selected

Average Non-Zero Irradiation (Azimuth North) vs Tilt Angle [5]



BEST TILT ANGLE = 26°

Irradiation on the Tilted Plane (26°)



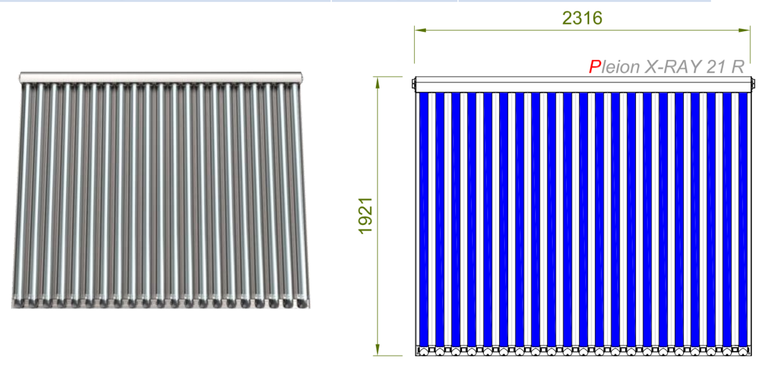
SOLAR THERMAL COLLECTOR SELECTION

SELECTION CRITERIA

- ✓ *High zero-loss efficiency (η_0)*
- ✓ *Low a_1 (most impact in the efficiency)*
- ✓ *Operation at high temperatures*
- ✓ *Sufficient operating pressure*
- ✓ *High flow rate*

SELECTED COLLECTOR [6]

Parameters	Unit	Value
Manufacturer	*text*	*Pleion S.p.A. (Italy)*
Model	*text*	*X-RAY 21 R*
Type	*text*	*Evacuated tube*
η_0	*-*	*0.611*
a_1	*-*	*0.690*
a_2	*-*	*0.005*
Gross collector area	*m²*	*4.45*
Mass flow	*kg/s*	*0.089*
Max. operating temperature	*°C*	*130*
Max. operating pressure	*kPa*	*1000*
Heat transfer medium	*text*	*Water-Glycol*
Maximum temperature difference during thermal performance test (ϑ_m-ϑ_a)max	*°C*	*64.3*
Empty weight	*kg*	*73*



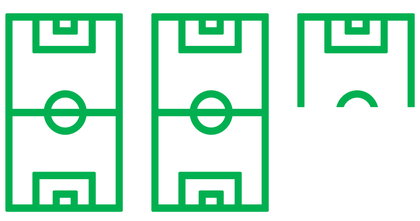
OBSERVATIONS

- x *The thermal fluid considered in this assessment is not the same as the collector heat transfer medium*
- x *For scenario 1, the maximum difference between T_m and T_a exceeds the manufacturer tested limits*

RESULTS

Parameters / Scenarios	Saturated vapor @150°C	Water @ 90°C
% of total process heat demand supplied	*100%*	*8.1%*
# of collectors (parallel / series)	*134 * 28*	*24 * 13*
Total number of collectors	*3752*	*312*
Total system area (m²)	**16521.3**	*1289.6*
Total collector field weight (kg)	**273,896**	*22,776*

EQUIVALENT INSTALLATION AREA – VAPOR @ 150°C



Boiler efficiency improvement and fuel consumption reduction Water @ 90°C scenario [7]	
Boiler efficiency improvement	*14.3%*
Fuel consumption reduction	*9.1%*

BOILER ALTERNATIVE [8]

Parameter	Unit	Value
Required area	*m²*	*12.5*
Installed power	*kW*	*17*
Design LNG flow	*kg/h*	*145*
Total equipment weight	*kg*	*9,500*

CONCLUSIONS

- ✓ *The system proposed is unfeasible.*
  - *Large installation area required*
  - *There would be a significant* **pressure loss** *along the collector field (**±126km** of piping, which would also require a high-pressure pump or multiple pumping stations)*
  - *Large* **heat storage at high temperature** *requirement*
  - *Probable* **high CapEx and OpEx** *(large numbers of solar collectors, special thermal fluid, heat storage insulation etc.)*
  - *High system complexity and* **weight:** *collector field alone weights ±274,000 kg, which is ±30 times heavier than a complete boiler package*
- ✓ *The group members developed a better understanding of solar thermal systems and the challenges when operating high temperature systems*

RECOMMENDATIONS FOR FUTURE WORK

- ✓ *The maximum operating temperature of the solar collectors shall be considered as a limiting factor.*
- ✓ *A better distribution of the temperature increase at each collector series string should be considered. We went with a linear increase to get the maximum efficiency.*
- ✓ *Use different solar collectors for the different temperature ranges of the series strings (to achieve higher efficiencies).*
- ✓ *Evaluate the feasibility of concentrated solar power (CSP) for this type of demand.*
- ✓ *Consider all the other system components, including the storage and a system control.*
- ✓ *Perform a detailed economical analysis.*

REFERENCES

Calculation Procedure

[1] H. Torio, Lectures Notes – Renewable Energy Heat: Solar Thermal Collectors [PDF Document], Oldenburg, 2023.

Demand

[2] Adapted demand from a real-case project – Hatch Ltd.

Working Fluid Selection

[3] I. H. Bell, J. Wronski, S. Quoilin, and V. Lemort, "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp," Industrial & Engineering Chemistry Research, vol. 53, no. 6, pp. 2498-2508, 2014. doi: 10.1021/ie4033999

[4] Globaltherm, "Global Therm Omnisol product information," globaltherm.org,https://globalhtf.com/wpcontent/uploads/2018/02/Globaltherm-Omnisol-Product-Information-sheet.pdf (accessed Jan. 31, 2024).

Tilt Angle Definition

[5] Solar Power and Photovoltaic Resources. (n.d.). PVGIS - Photovoltaic Geographical Information System. [Online]. Available: https://re.jrc.ec.europa.eu/pvgis

Solar Thermal Collector Selection

[6] Pleion. (n.d.). X-Ray 21R Forced Circulation Collectors. Pleion. Available: https://pleion.it/gb/products/forced-circulation-collectors/x-ray-r/x-ray-21r (accessed: January 25th, 2024).

Results

[7] R. M. Kiesow, "Desenvolvimento de um Sistema para Pré-aquecimento de Água de Alimentação de uma Caldeira Fumotubular," M.S. thesis, Universidade de Caxias do Sul, Centro de Ciências Exatas e da Tecnologia, Curso de Engenharia Mecânica, Caxias do Sul, 2015.

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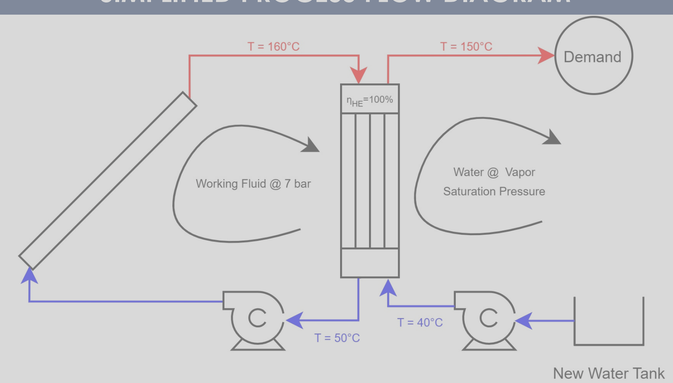

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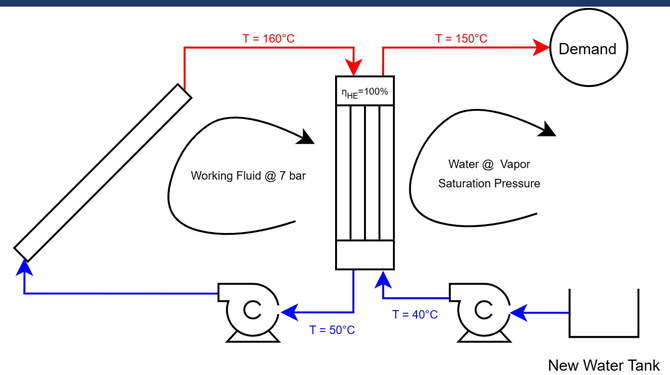

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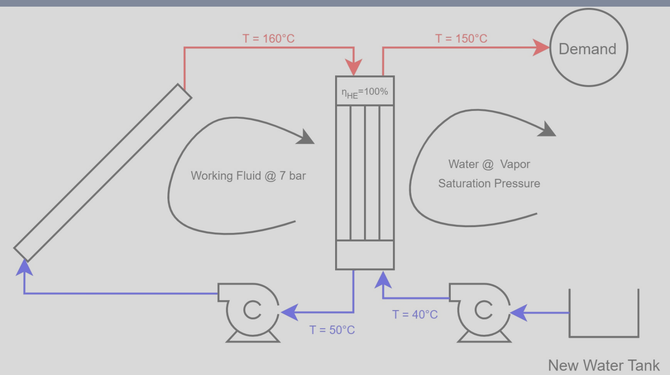

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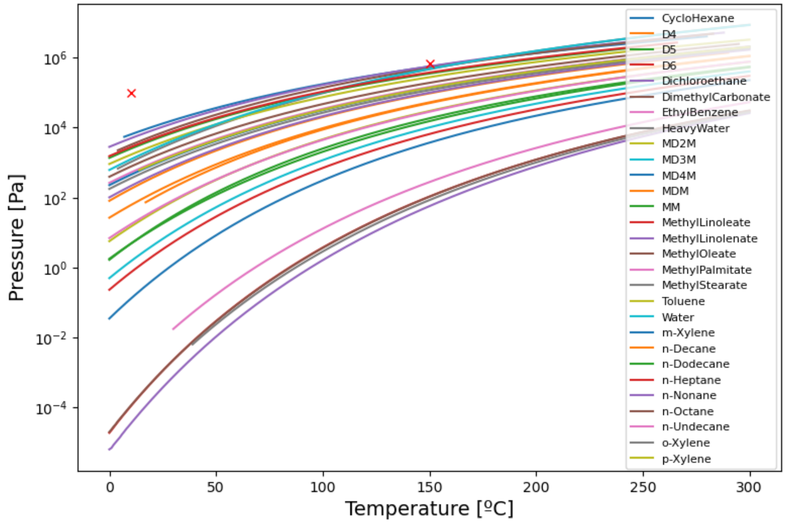

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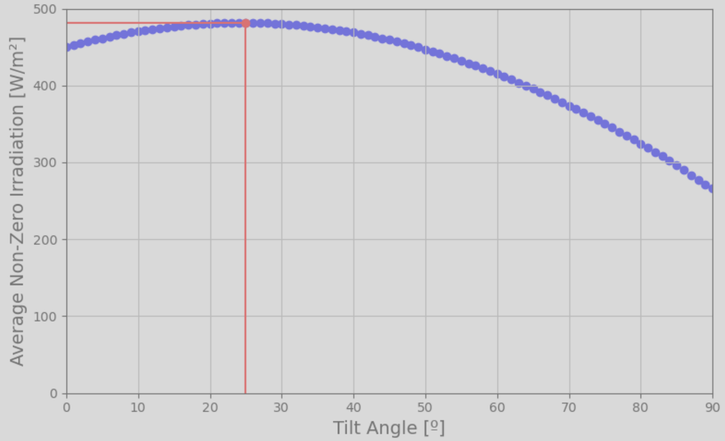

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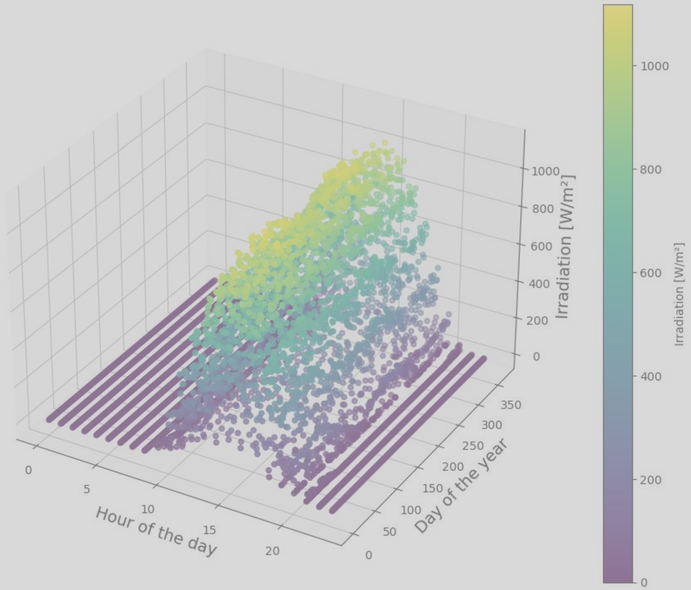

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a_2	-	0.005
Gross collector area	m²	4.45
Mass flow	kg/s	0.089
Max. operating temperature	°C	130
Max. operating pressure	kPa	1000
Heat transfer medium	text	Water-Glycol
Maximum temperature difference during thermal performance test $(\vartheta_m-\vartheta_a)max$	°C	64.3
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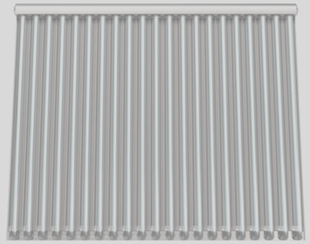

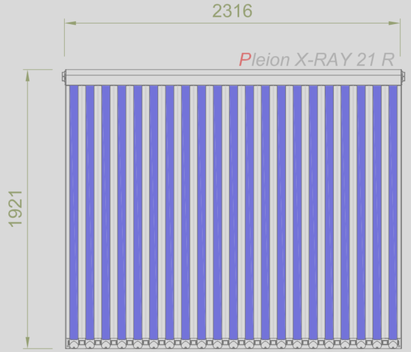

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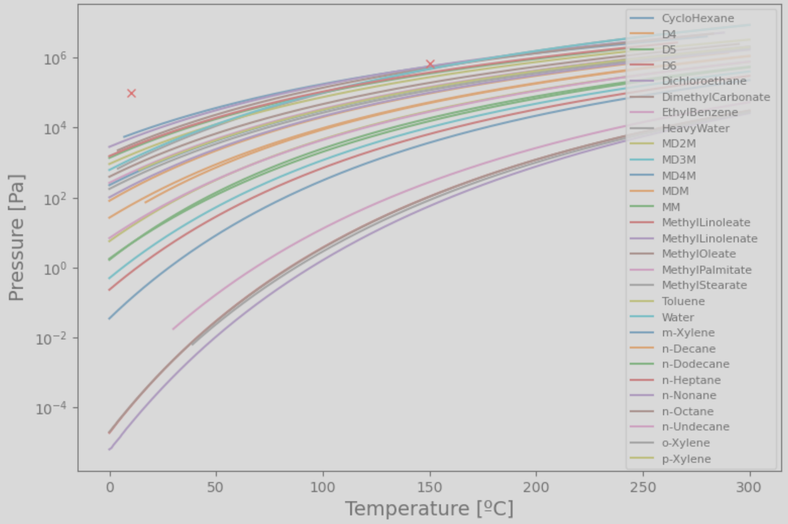

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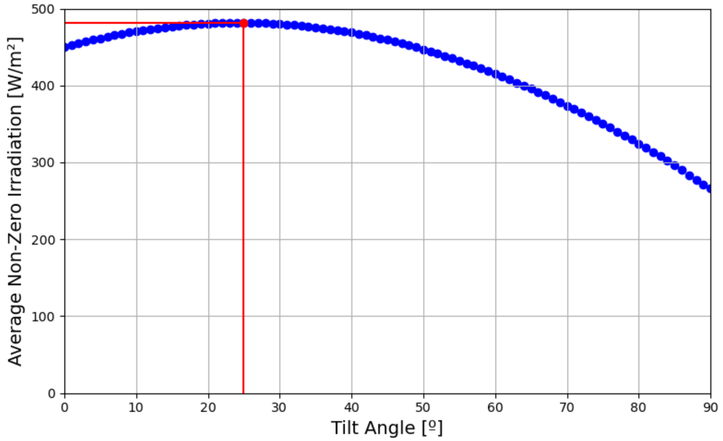

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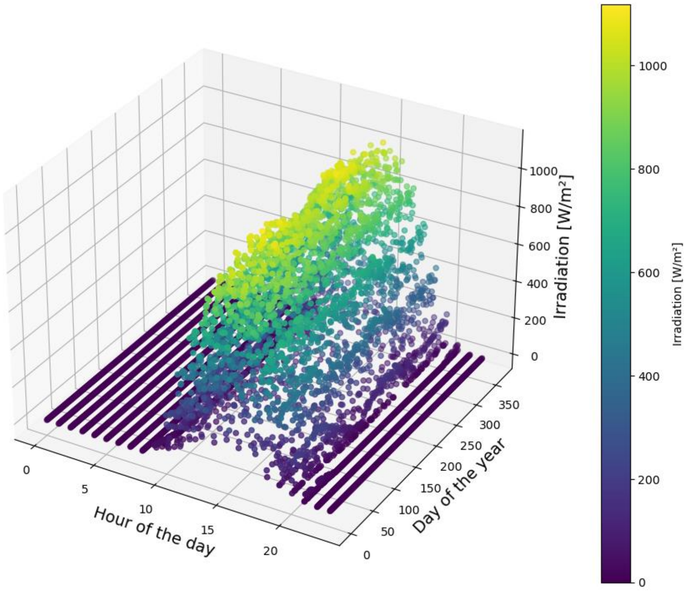
Irradiation on the Tilted Plane (26°)



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SELECTION CRITERIA

- ✓ *High zero-loss efficiency (η_0)*
- ✓ *Low a_1 (most impact in the efficiency)*
- ✓ *Operation at high temperatures*
- ✓ *Sufficient operating pressure*
- ✓ *High flow rate*

SELECTED COLLECTOR [6]

Parameters	Unit	Value
Manufacturer	text	Pleion S.p.A. (Italy)
Model	text	X-RAY 21 R
Type	text	Evacuated tube
η_0	-	0.611
a_1	-	0.690
a_2	-	0.005
Gross collector area	m²	4.45
Mass flow	kg/s	0.089
Max. operating temperature	°C	130
Max. operating pressure	kPa	1000
Heat transfer medium	text	Water-Glycol
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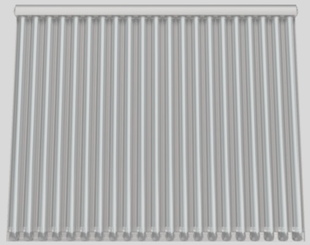

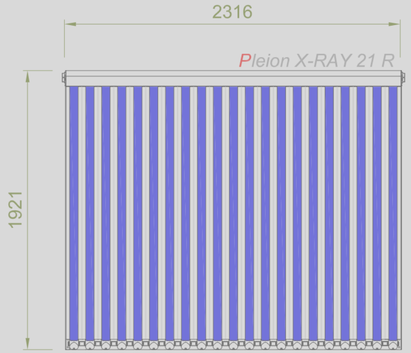

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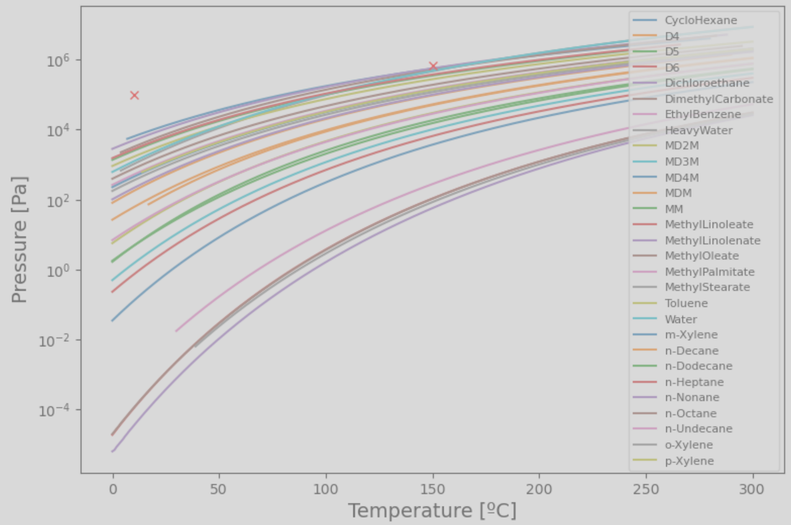

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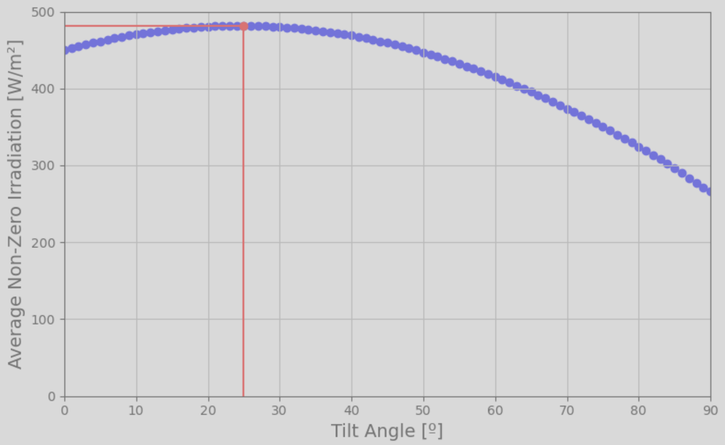

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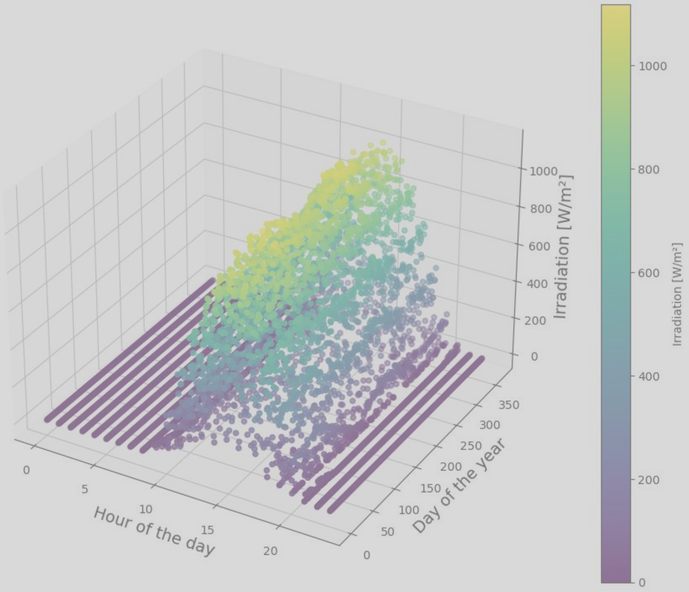

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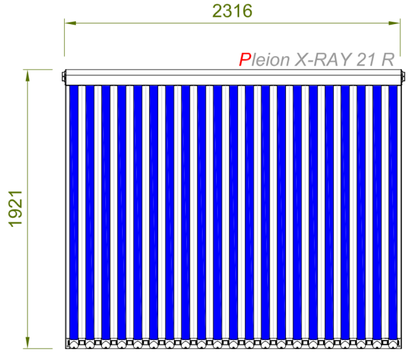

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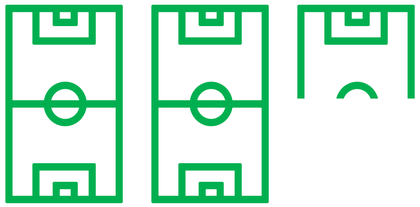
RESULTS

Parameters / Scenarios	Saturated vapor @150°C	Water @ 90°C
% of total process heat demand supplied	100%	8.1%
# of collectors (parallel / series)	134 * 28	24 * 13
Total number of collectors	3752	312
Total system area (m²)	**16521.3**	1289.6
Total collector field weight (kg)	**273,896**	22,776

EQUIVALENT INSTALLATION AREA – VAPOR @ 150°C



Boiler efficiency improvement and fuel consumption reduction Water @ 90°C scenario [7]	
Boiler efficiency improvement	14.3%
Fuel consumption reduction	9.1%

BOILER ALTERNATIVE [8]

Parameter	Unit	Value
Required area	m²	12.5
Installed power	kW	17
Design LNG flow	kg/h	145
Total equipment weight	kg	9,500

CONCLUSIONS

- ✓ *The system proposed is unfeasible.*
  - **Large installation area** *required*
  - *There would be a significant* **pressure loss** *along the collector field (***±126km** *of piping, which would also require a high-pressure pump or multiple pumping stations)*
  - *Large* **heat storage at high temperature** *requirement*
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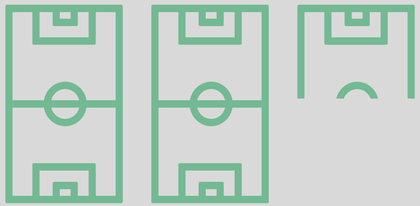

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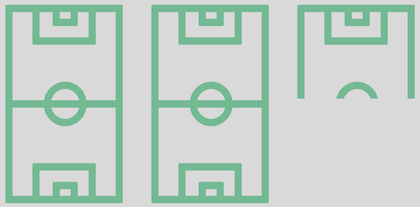

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Renewable Steam Generation Assessment for an Industrial Demand in Brazil

Juan Márquez, Lucas Saborido, Mahmoud Abouelamaim

CARL VON OSSIETZKY universität OLDENBURG

INTRODUCTION

MOTIVATION

- ✓ *Steam is one of the most used process fluids in industry*
- ✓ *Replacing fossil fuels (e.g., NG) with renewables*
- ✓ *Good marketing – greener and more innovative plants*

OBJECTIVES

- ✓ *Analyze the feasibility of supplying heat for a specific process steam demand by means of solar thermal collectors*
- ✓ *Size the system from a thermal perspective and select the solar heat collector and thermal fluid*
- ✓ *Investigate different loading conditions and the response of the system to the heat demand*

ASSUMPTIONS

- ✓ *Constant demand – No seasonal variation*
- ✓ *The water supply (input) is always at the indicated temperature*
- ✓ *There is no installation area restriction for the system*
- ✓ *Only steady-state behavior was considered*
- ✓ *Temperature ranges were selected based on a cross-flow heat exchanger*
- ✓ *The efficiency of heat exchanger is 100%*
- ✓ *F-chart method is not applicable due to its temperature range restriction (process temperature higher than 50°C).*

EXCLUSIONS

- x *Sizing of heat storage units*
- x *Layout development*
- x *Economical analysis (CapEx and OpEx)*
- x *Selection of other system components (pumps, heat exchangers, valves, etc.)*
- x *System control (on/off)*

DEMAND

INPUT [2]

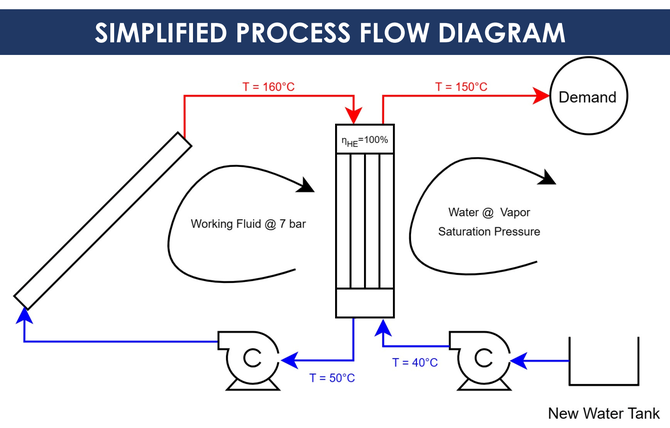
Parameter	Unit	Value
Input		
Water flow	*m³/h*	*2.30*
Water temperature	*°C*	*40*
Water density	*kg/m³*	*1000*
Water pressure	*kPa (a)*	*101.3*
Output		
Steam temper.	*°C*	*150°C*
Steam quality	*-*	*1.00*

MONTHLY HEAT DEMAND

Water shall be pressurized (pumped) at the desired vapor saturation pressure

Scenario	Unit	Value
1 - Saturated Steam @150°C	*kWh/month*	**1.177*10⁶**
2 – Water @90°C	*kWh/month*	**9.600*10⁴**

SIMPLIFIED PROCESS FLOW DIAGRAM



CALCULATION PROCEDURE

1. *Calculate the heat demand for the first scenario (provide saturated steam at 150°C)*
2. *Select the working fluid and define the required working fluid mass flow*
3. *Import the irradiation and temperature data (PVGIS).*
4. *Determine the optimal tilt angle (throughout the whole year).*
5. *Select the solar thermal collector.*
6. *For each month, calculate the collector efficiency based on the monthly average of the non-zero irradiation [W/m²] and temperature [°C]* **[1]**.

$$\eta_{coll} = \eta_0 - a_1\frac{(T_m - T_a)}{G_T} - a_2\frac{(T_m - T_a)^2}{G_T}$$

7. *Calculate the required system area for each month, based on the available solar energy (monthly average irradiation)* **[1]**.

$$A_{coll} = \frac{\int \dot{Q}_u dt}{\eta_{coll}\int G_T dt} = \frac{Q_u[kWh/month]}{\eta_{coll} G_T[kWh/month.m^2]}$$

8. *Adopt the* **area of the worst performing month** *as the total system area.*
9. *Determine the number of collectors in parallel based on the working fluid mass flow.*
10. *Determine the final arrangement of series and parallel collectors.*
11. *Iterate the required area considering the temperature difference along each series string and a linear ΔT distribution.*
12. *Recalculate all the results for the second scenario (provide water heated up to 90°C).*

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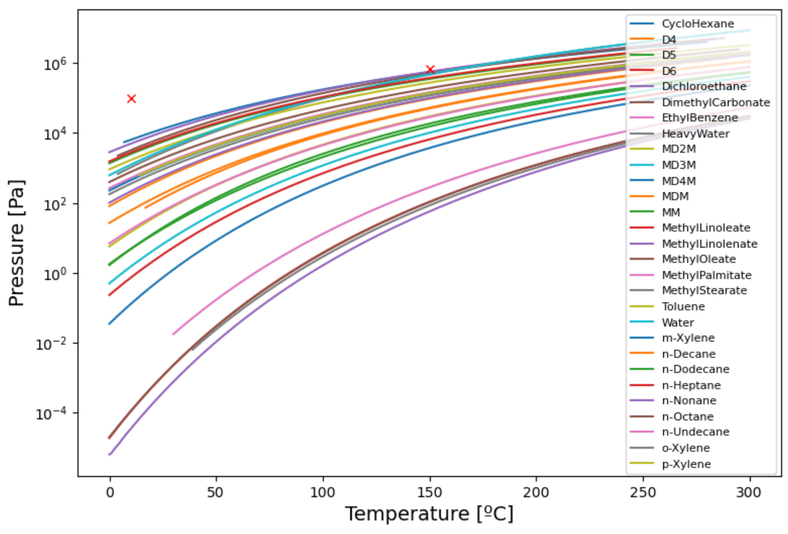

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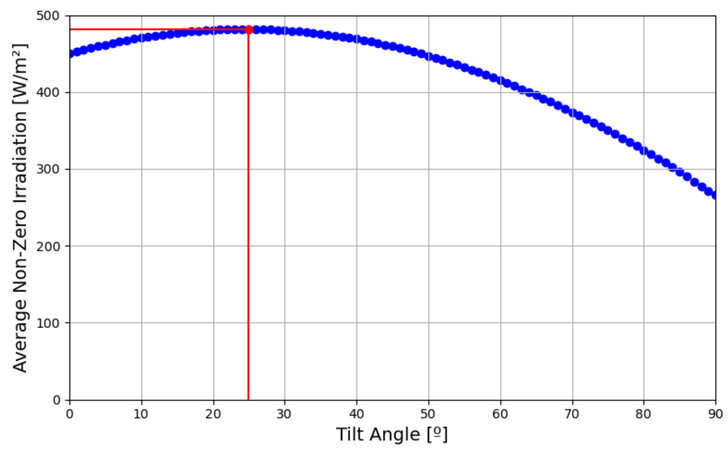
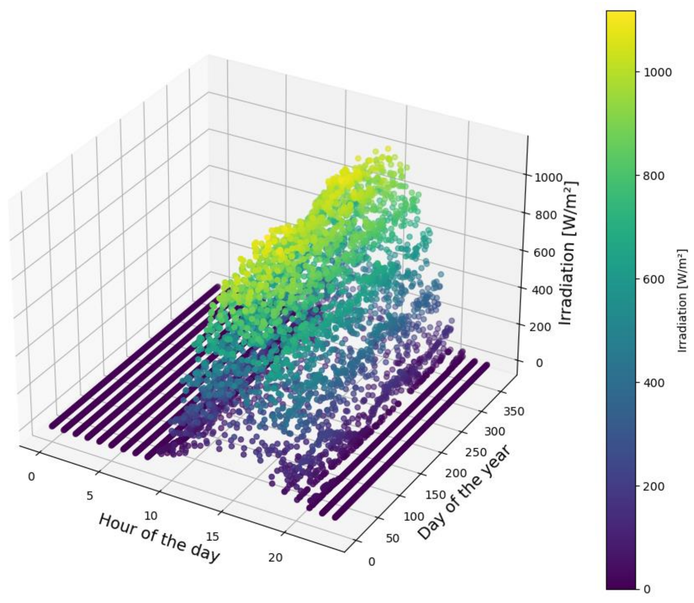
Given that the demand is constant (no seasonal variation), the tilt angle that produces the best yearly energy yield was selected

Average Non-Zero Irradiation (Azimuth North) vs Tilt Angle [5]



BEST TILT ANGLE = 26°

Irradiation on the Tilted Plane (26°)



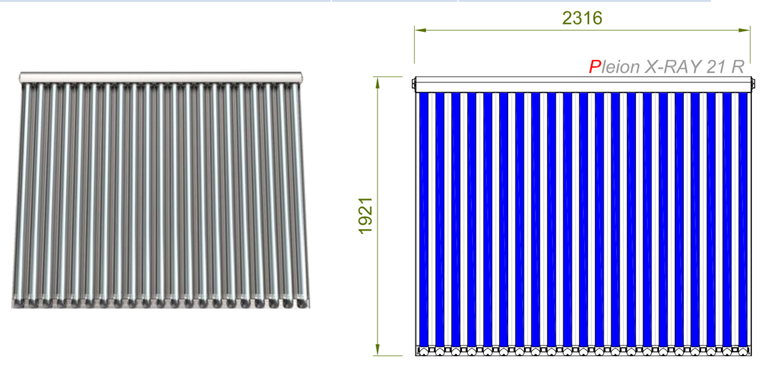
SOLAR THERMAL COLLECTOR SELECTION

SELECTION CRITERIA

- ✓ *High zero-loss efficiency (η_0)*
- ✓ *Low a_1 (most impact in the efficiency)*
- ✓ *Operation at high temperatures*
- ✓ *Sufficient operating pressure*
- ✓ *High flow rate*

SELECTED COLLECTOR [6]

Parameters	Unit	Value
Manufacturer	*text*	*Pleion S.p.A. (Italy)*
Model	*text*	*X-RAY 21 R*
Type	*text*	*Evacuated tube*
η_0	*-*	*0.611*
a_1	*-*	*0.690*
a_2	*-*	*0.005*
Gross collector area	*m²*	*4.45*
Mass flow	*kg/s*	*0.089*
Max. operating temperature	*°C*	*130*
Max. operating pressure	*kPa*	*1000*
Heat transfer medium	*text*	*Water-Glycol*
Maximum temperature difference during thermal performance test (ϑ_m-ϑ_a)max	*°C*	*64.3*
Empty weight	*kg*	*73*



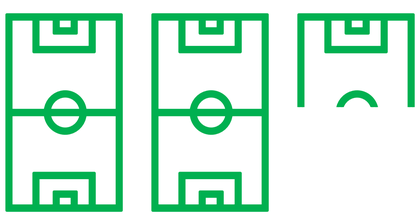
OBSERVATIONS

- x *The thermal fluid considered in this assessment is not the same as the collector heat transfer medium*
- x *For scenario 1, the maximum difference between T_m and T_a exceeds the manufacturer tested limits*

RESULTS

Parameters / Scenarios	Saturated vapor @150°C	Water @ 90°C
% of total process heat demand supplied	*100%*	*8.1%*
# of collectors (parallel / series)	*134 * 28*	*24 * 13*
Total number of collectors	*3752*	*312*
Total system area (m²)	**16521.3**	*1289.6*
Total collector field weight (kg)	**273,896**	*22,776*

EQUIVALENT INSTALLATION AREA – VAPOR @ 150°C



Boiler efficiency improvement and fuel consumption reduction Water @ 90°C scenario [7]	
Boiler efficiency improvement	*14.3%*
Fuel consumption reduction	*9.1%*

BOILER ALTERNATIVE [8]

Parameter	Unit	Value
Required area	*m²*	*12.5*
Installed power	*kW*	*17*
Design LNG flow	*kg/h*	*145*
Total equipment weight	*kg*	*9,500*

CONCLUSIONS

- ✓ *The system proposed is unfeasible.*
  - *Large installation area required*
  - *There would be a significant* **pressure loss** *along the collector field (**±126km** of piping, which would also require a high-pressure pump or multiple pumping stations)*
  - *Large* **heat storage at high temperature** *requirement*
  - *Probable* **high CapEx and OpEx** *(large numbers of solar collectors, special thermal fluid, heat storage insulation etc.)*
  - *High system complexity and* **weight:** *collector field alone weights ±274,000 kg, which is ±30 times heavier than a complete boiler package*
- ✓ *The group members developed a better understanding of solar thermal systems and the challenges when operating high temperature systems*

RECOMMENDATIONS FOR FUTURE WORK

- ✓ *The maximum operating temperature of the solar collectors shall be considered as a limiting factor.*
- ✓ *A better distribution of the temperature increase at each collector series string should be considered. We went with a linear increase to get the maximum efficiency.*
- ✓ *Use different solar collectors for the different temperature ranges of the series strings (to achieve higher efficiencies).*
- ✓ *Evaluate the feasibility of concentrated solar power (CSP) for this type of demand.*
- ✓ *Consider all the other system components, including the storage and a system control.*
- ✓ *Perform a detailed economical analysis.*

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Demand

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Working Fluid Selection

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[5] Solar Power and Photovoltaic Resources. (n.d.). PVGIS - Photovoltaic Geographical Information System. [Online]. Available: https://re.jrc.ec.europa.eu/pvgis

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Results

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[8] Adapted demand from a real-case project – Hatch Ltd