Thermal Resistance Model for CSP Central Receivers

by Oelof de Meyer

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Introduction

Presenter Oelof de Meyer

Qualifications 2010, B.Eng. (Mechatronics), Stellenbosch University

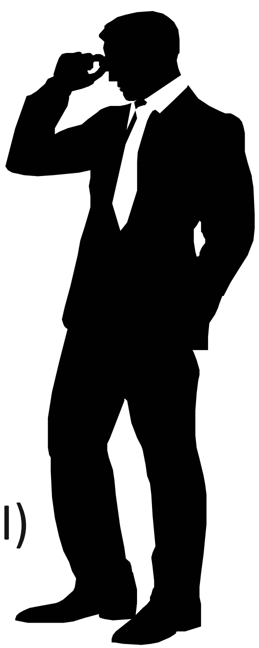
2012, M.Sc. (Electrical Eng.), University of Cape Town

Work Experience 2011, Eskom : Control & Instrumentation

- Matimba C&I Refurbishment,
  2011/11 - 2012/06
- Lead Discipline Engineer for:
  - Eskom 100MW CSP Plant
    2011/11 - present
  - Solar Augmentation
    2013/10 - present
  - SERE Wind 100MW
    2014/03 – present

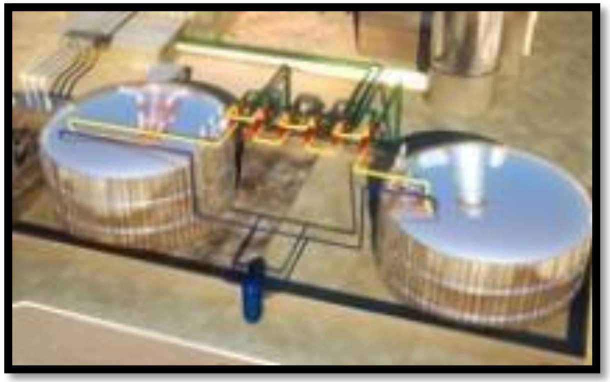
Further Studies 2014, Eskom Power Plant Engineering Institute (EPPEI)

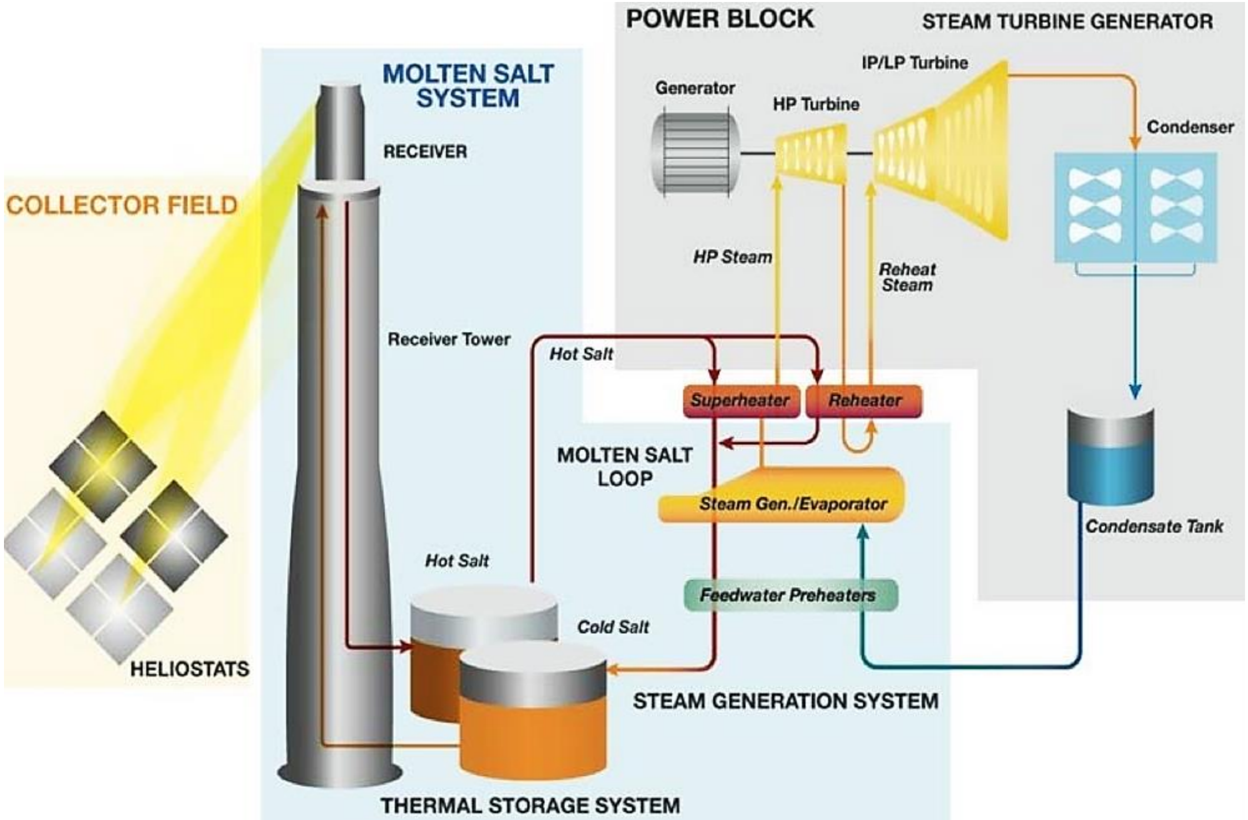
- PhD Program – Stellenbosch University




Concentrated Solar Power
173 500 heliostats
140m tower
Ivanpah, 337 MW

Introduction : Molten Salt Central Receiver





Molten Salt Central Receivers


10MW Solar Two

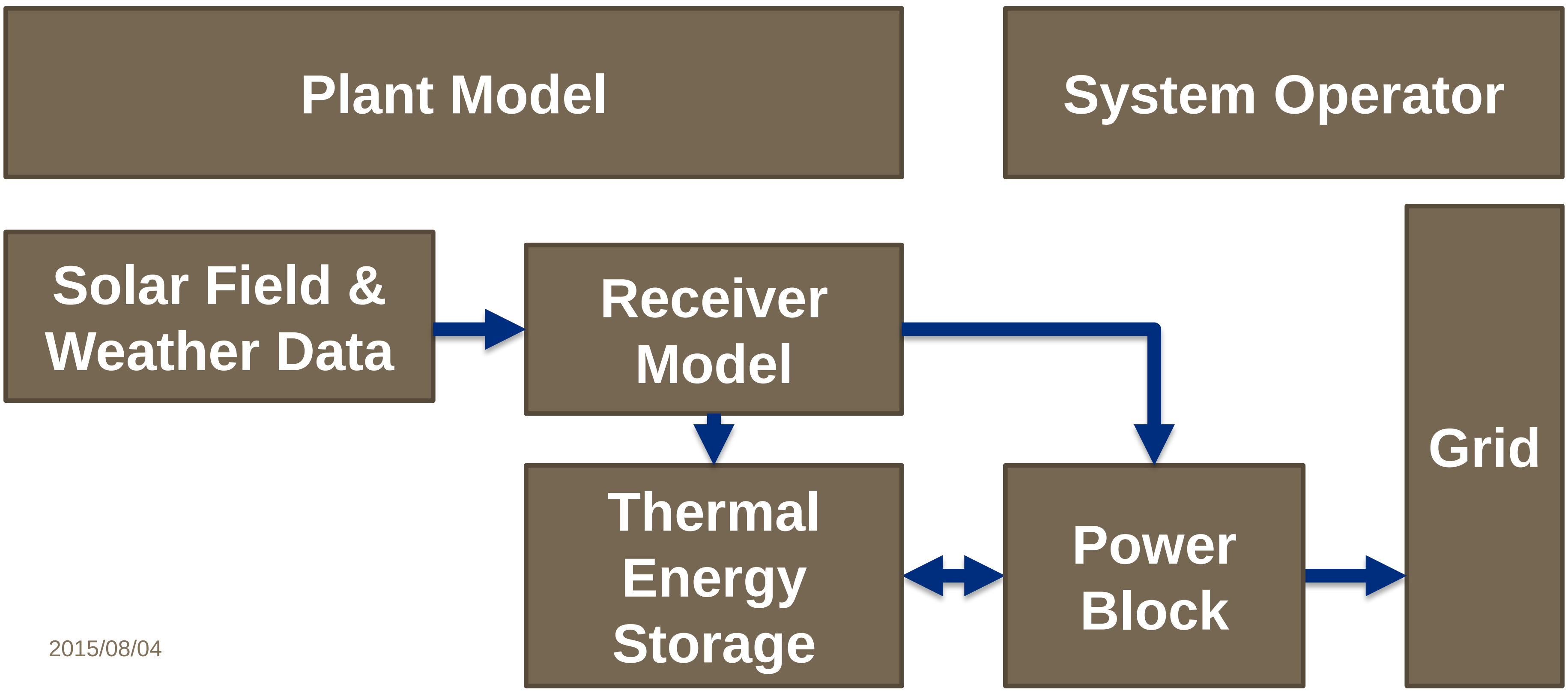

110MW Crescent Dunes


20MW Gemasolar

Operating Strategy and Philosophy optimisation for a 100 MW CSP Plant

Operating Philosophy (Process Plant)

Operating Strategy (SA Grid)



PhD Research Topic (In Short)

Eskom

Power Purchase Agreement (PPA)

- Power Purchase Agreement (PPA) initials “Operating Strategy”
  - Agreement between Independent Power Producer (IPP) and Utility / System Operator
- IPP design, build and optimise plant to adhere to PPA
- IPP business is <u>money</u>,
  - thus maximise power production
  - Minimise energy losses
  - Minimise O&M costs
  - = Max Revenue

For Example:
PPA = 75 MW between 4-10 pm

Thus storage of about 6 hours
Start/Stop turbine each day
Etc...
“Design Plant accordingly”

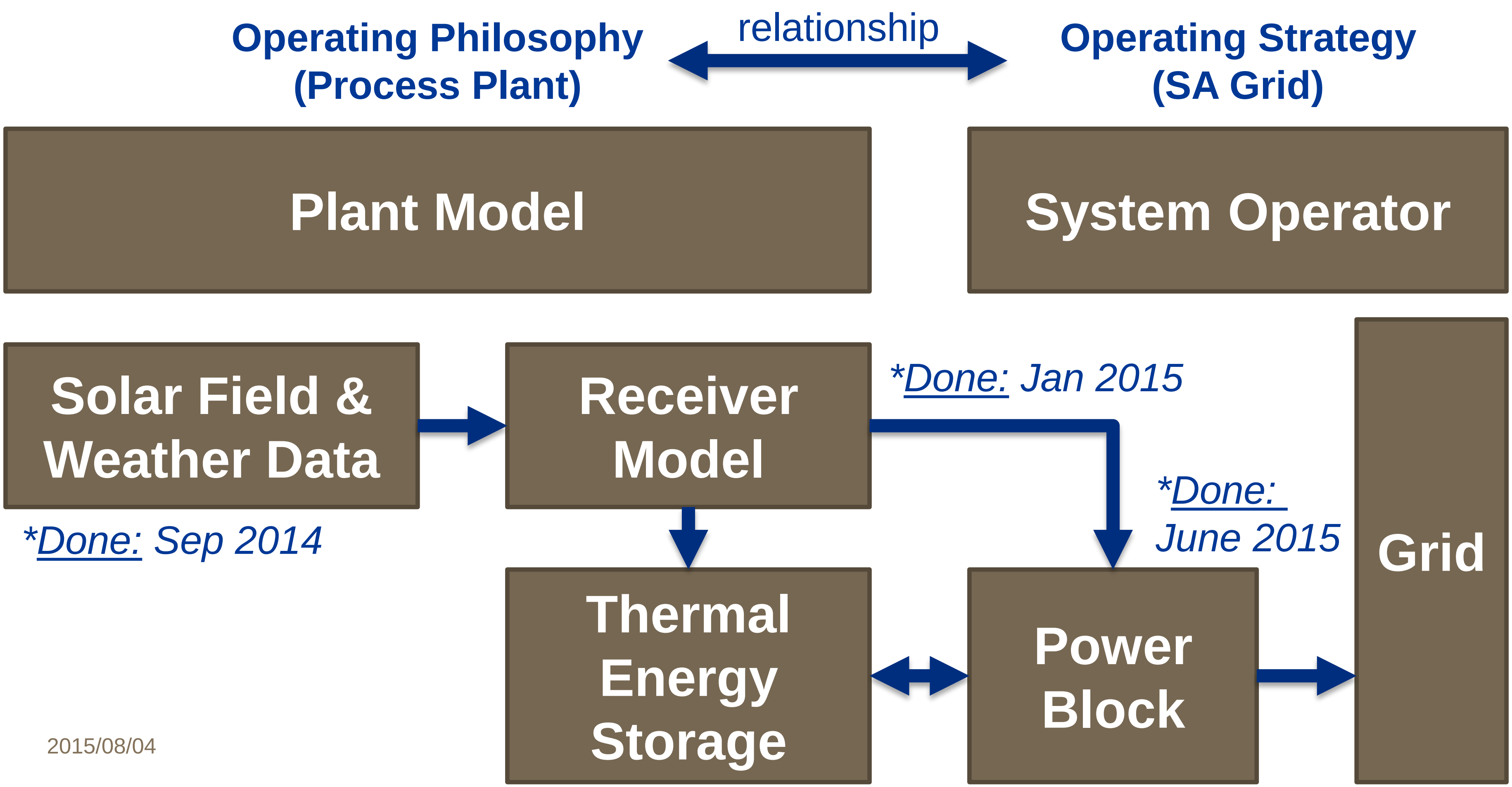
- What happens if you have a varying operating strategy?
  - “Flexible Plant required”
  - Optimisation of plant operation

Weather Data
Plant Status
Operating Strategy

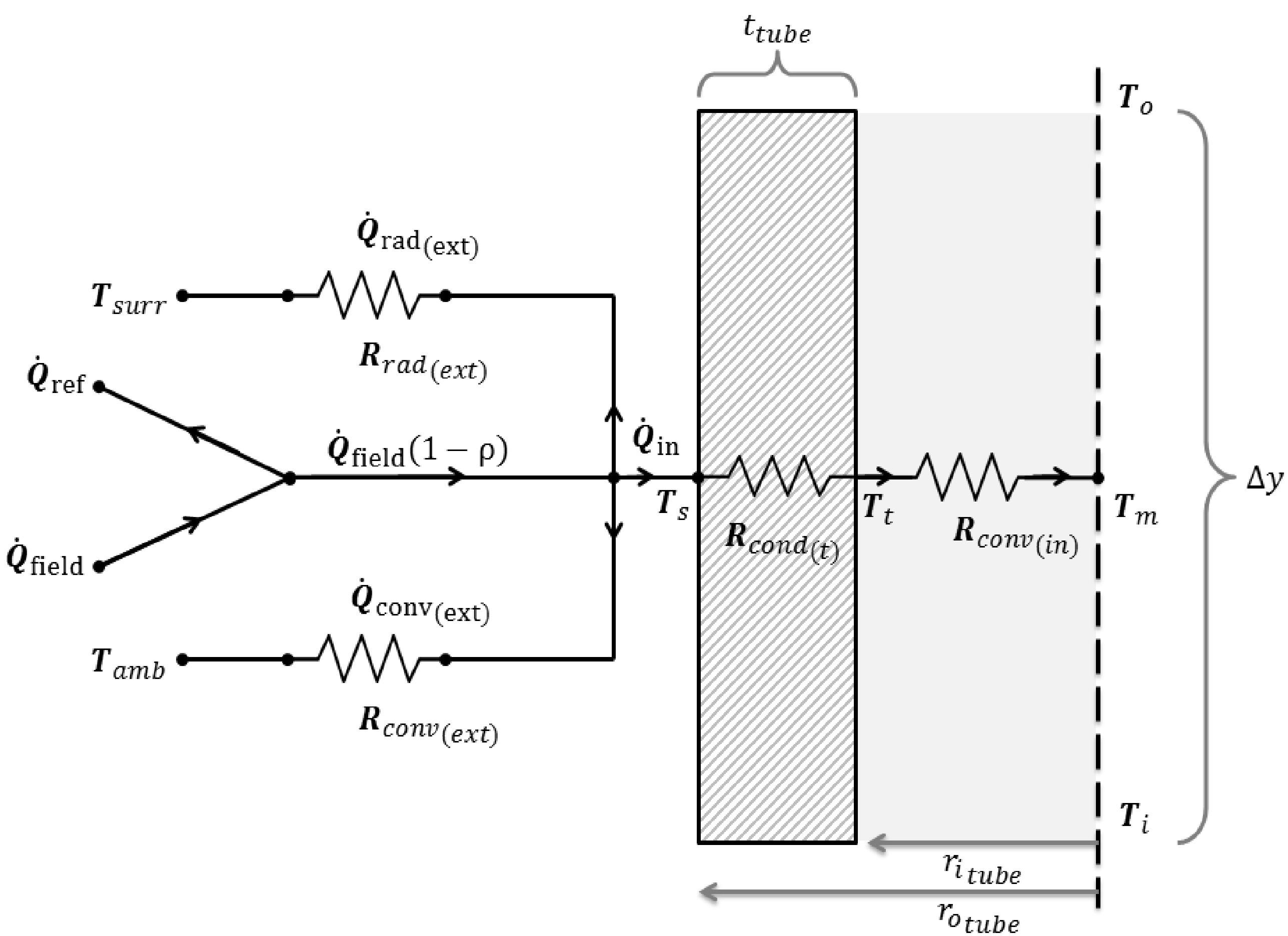
Eskom is not an IPP

PhD Research Topic

Operating Strategy and Philosophy optimisation for a 100 MW CSP Plant



Receiver Thermal Resistance Model



Model Capabilities

Eskom

model

Solar Field & Weather Data

DELSOL3

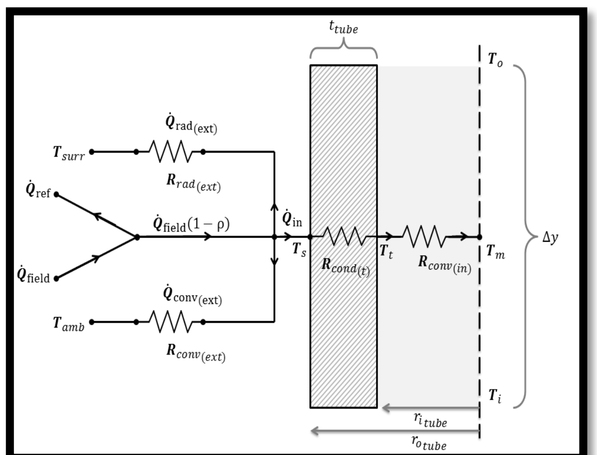
12x10 Receiver Flux Map

TMY Data

- Ambient Temperature
- Wind speed
- DNI etc.

Evaluate:

- Aiming Strategy used
- Receiver design/materials
- Tube strain per panel, O&M



Evaluate:

- Receiver design/materials
- Pressure drop across receiver

Temperatures:

- Inner tube
- Receiver surface
- HTF outlet temperature

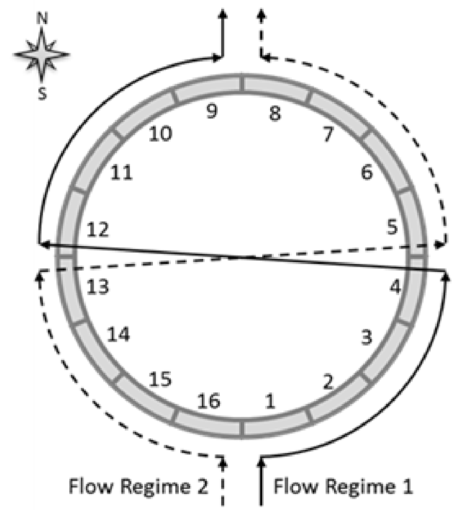
Receiver Efficiency

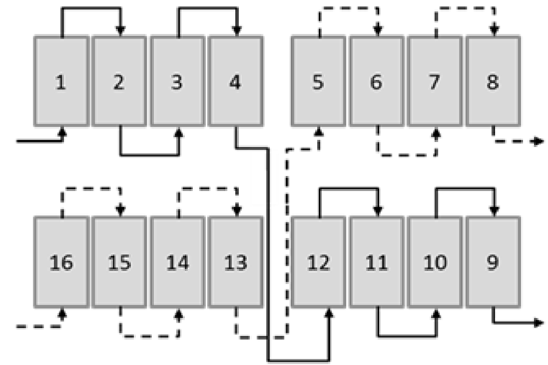
- Receiver heat losses
- HTF thermal energy gained
- HTF mass flow rate

How does the model work?

<u>Receiver design & configuration:</u>

Height 19.24 m
Diameter 16.32 m
Panels 16
Tube diameter 50 mm
Tube thickness 1.5 mm





Flow regime:

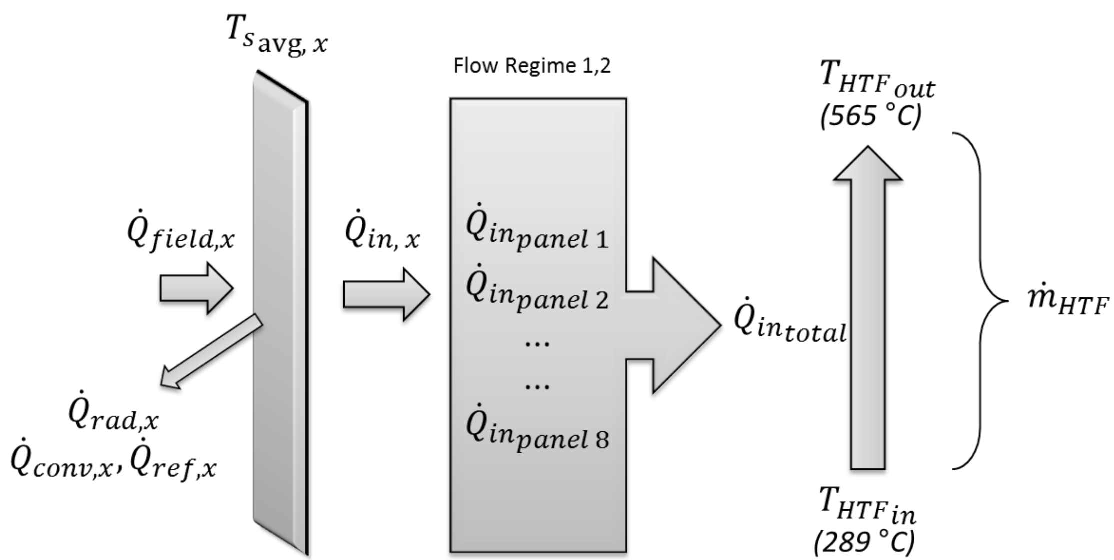
- 2x flows with cross over halfway
- HTF enters from South panel
- HTF exit through North panel

Step 1:

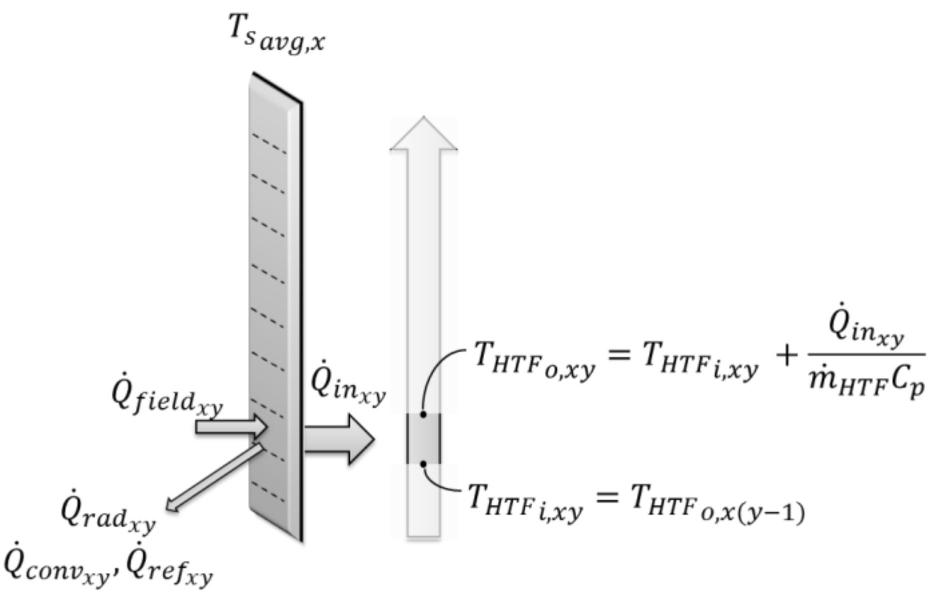
Determine HTF mass flow rate in flow regimes by determining:

- Heat loss per panel
- Heat gained per panel

**Initial surface temperature guess values required*



How does the model work?



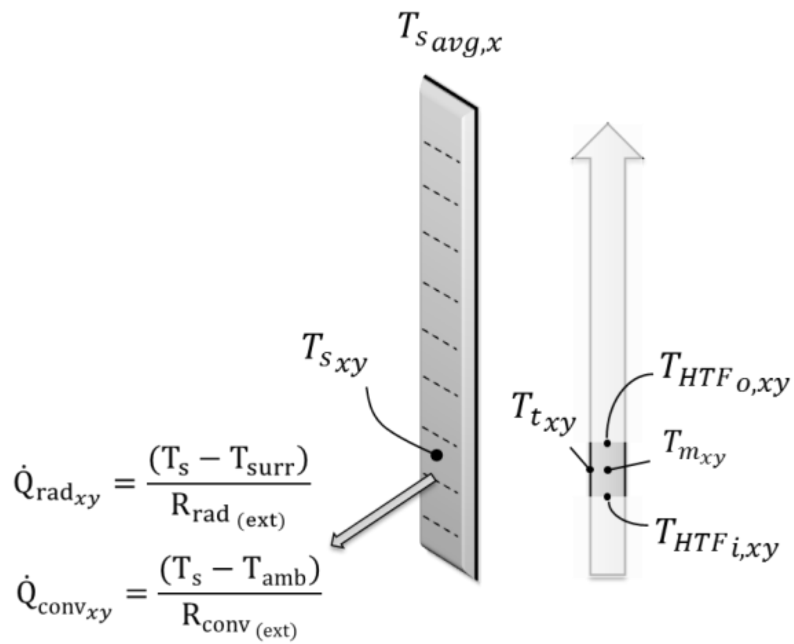
Step 2:

Use HTF mass flow rate to determine temperature rise in HTF

Step 3:

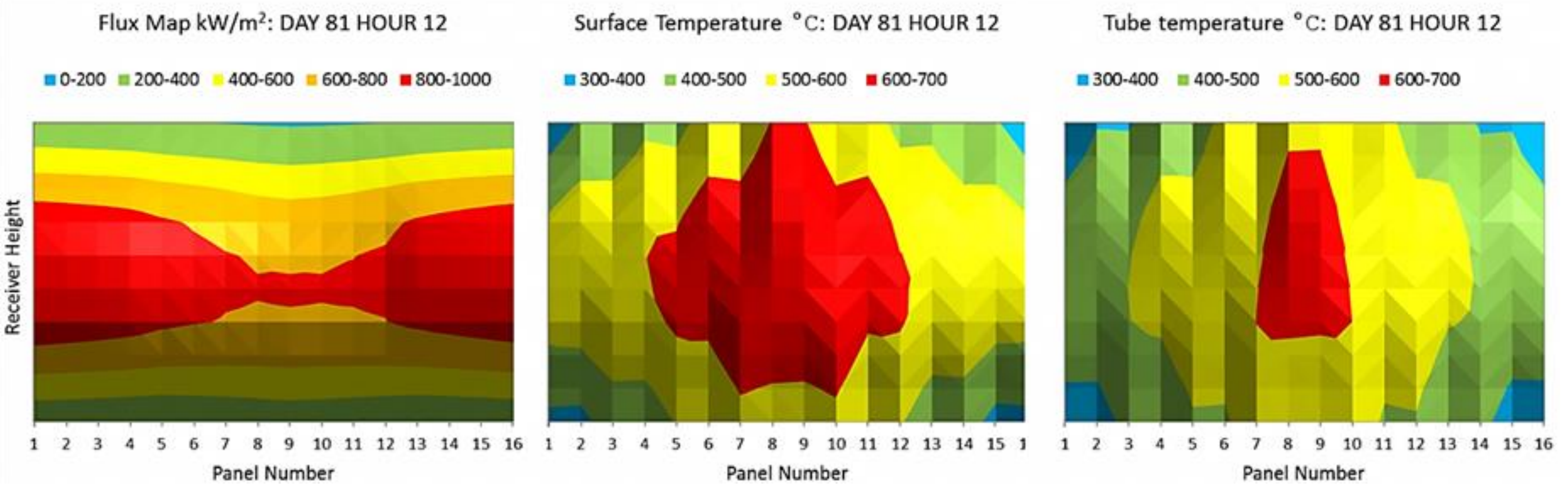
Use bulk fluid temperature to determine:

- Inner tube temperature
- Outer tube temperature (surface)
- Corresponding heat loss
    - Radiation, convection

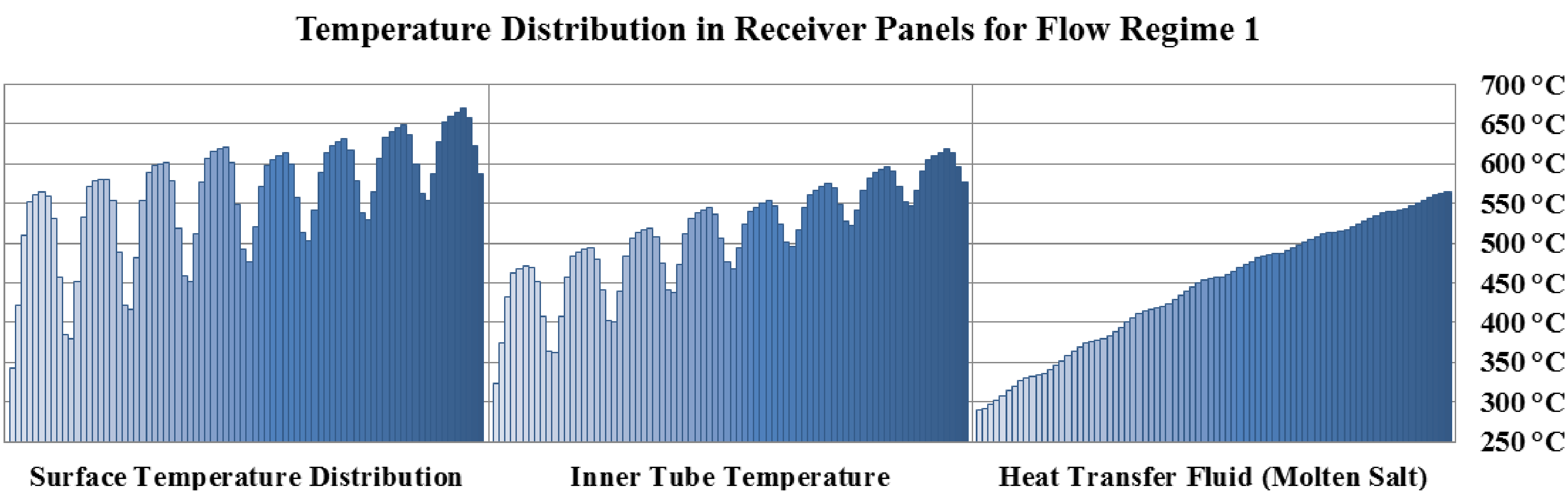


**Steady state model requires iterations due to initial surface temperature guess values*

Results

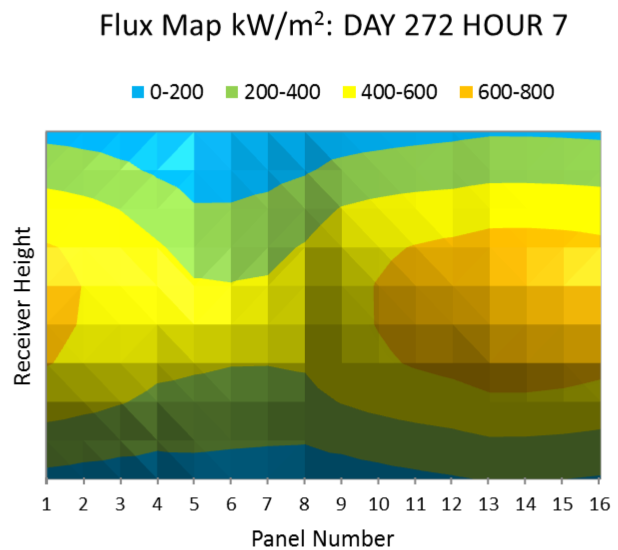


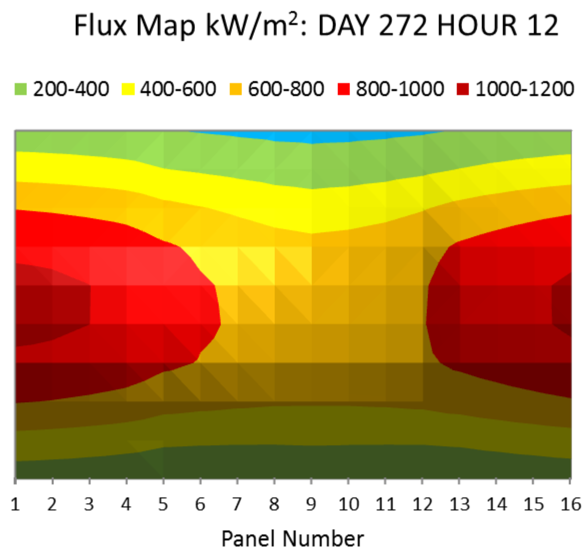
Flux Map kW/m²: DAY 81 HOUR 12
0-200 200-400 400-600 600-800 800-1000
Surface Temperature °C: DAY 81 HOUR 12
300-400 400-500 500-600 600-700
Tube temperature °C: DAY 81 HOUR 12
300-400 400-500 500-600 600-700
Receiver Height
Panel Number
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

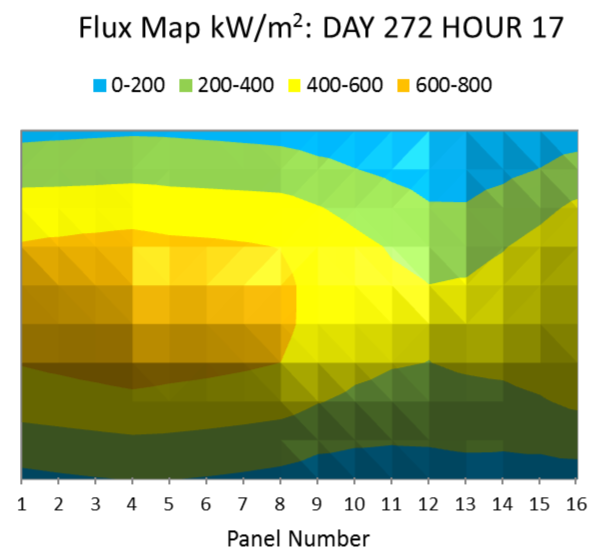


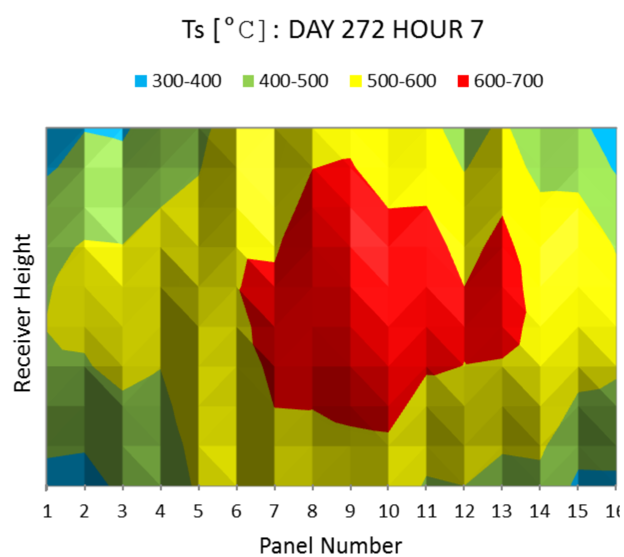
Temperature Distribution in Receiver Panels for Flow Regime 1
700 °C
650 °C
600 °C
550 °C
500 °C
450 °C
400 °C
350 °C
300 °C
250 °C
Surface Temperature Distribution
Inner Tube Temperature
Heat Transfer Fluid (Molten Salt)

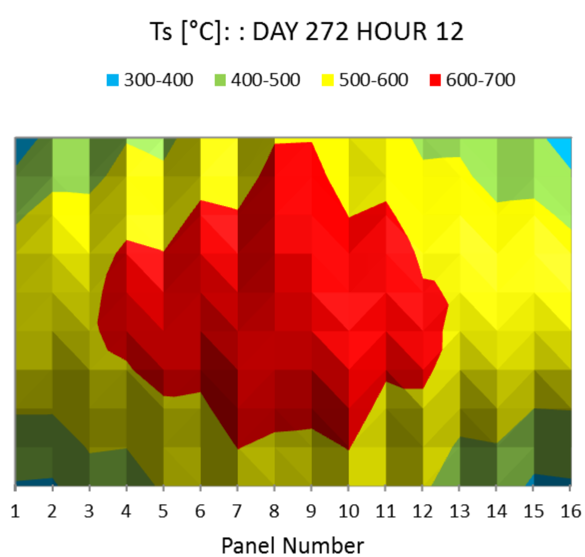
Morning, Mid-day and Afternoon – Case Studies

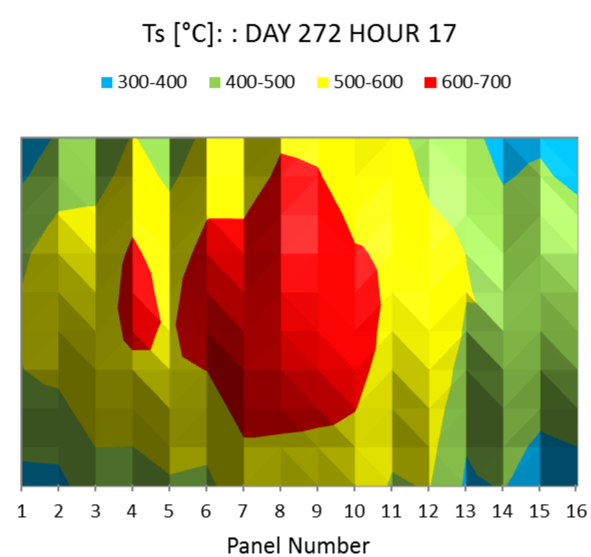






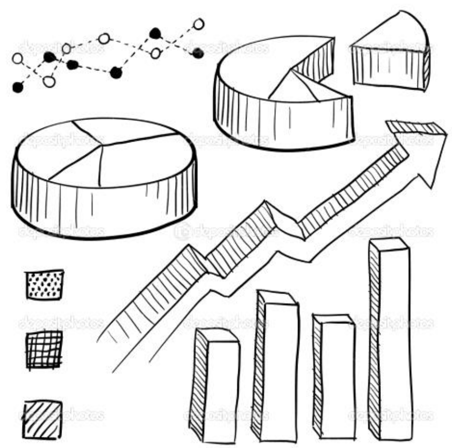






Conclusion

You may think… Yes, results are nice and pretty, but surely someone developed this model already?!



YES!

Similar models are being developed to analyse

- *Receiver design*
- *Receiver material*
- *Pressure drop calculations*
- *Tube-strain of panels*
- *Etc…*

- *My overall research requires a model with the level of similar to results on a basic design.*
- *The model will be assigned some intelligence during the operating philosophy optimisation phase*
- *My model is not a "black box"*
  - *Know what is going in and out – verified!*

	Purpose							Capabilities									Lisence				
Software Platform	Computational Fluid Dynamics	Feasibility	Finite Elements	Heat Balance	Ray-Tracing	Simulation	Heliostat Field Optimisation	Feasibility Economic Impacts	Feasibility Technology	Finite Modelling Mechanical	Finite Modelling Thermal	Heat Transfer Fluid Analysis	Heliostat Field Design Optimisation	Optical Analysis Ray-Tracing	Power Block	System Plant Simulation Performance	Commercial Lisence	Free Lisence	Private Use	Source	References
ANSYS	X	X	X						X	X	X	X					X			ANSYS	ANSYS, 2014
ASAP					X									X			-			Breault	Breault, 2014
ASPOC		X			X		X						X	X			X			Nevada Software	ASPOC, 2014
COMSOL Multiphysics	X	X	X						X	X	X	X					X			COMSOL	COMSOL, 2014
DELSOL3		X					X		X				X			X		X		SANDIA	Kistler, 1986
EnerTracer					X									X				-		CIEMAT PSA	Blanco et al., 2000
EPSILON		X		X		X		X	X						X	X	X			STEAG, DLR	EPSILON, 2014
ESEMflex		X						X	X				X						X	Sun to Market	Sun to Market, 2014
ESEMpro						X						X		X	X	X			X	Sun to Market	Sun to Market, 2014
ESOM						X		X				X			X	X			X	Sun to Market	Sun to Market, 2014
Fiat Lux					X									X				X		CIEMAT PSA	Tellez, 2013
GateCycle				X		X						X			X		X			GE	GateCycle, 2014
Greenius		X				X		X	X							X		X		DLR	Buck, 2013
Helios					X									X				X		SANDIA	Ho, 2008
HFLCAL							X						X				X			DLR	Bode et al., 2012
IPSEpro		X		X				X	X			X			X	X	X			SimTech	ISPEpro, 2014
NowCasting						X		X								X	X			Sun to Market	Sun to Market, 2014
NSPOC		X			X		X						X	X		X	X			Nevada Software	NSPOC, 2014
OPTEC					X									X						-	Schoffel et al., 1991
OptiCAD					X									X			X			OptiCAD	OptiCAD, 2014
SAM		X				X	X	X	X				X			X		X		NREL	SAM, 2014
SCT					X									X					X	CIEMAT PSA	Tellez, 2013
SenRec	X	X	X						X	X	X	X							X	SENER	Martin, 2007
SENSOL		X			X	X	X	X	X				X	X		X			X	SENER	Martin, 2007
SOLERGY		X				X			X							X		X		SANDIA	Alpert et al., 1988
SolTrace					X									X				X		NREL	SolTrace, 2014
SOLUGAS	X	X	X						X	X	X	X					X			DLR	Buck, 2013
SolVer		X			X	X		X	X				X	X		X			X	Solucar / Abengoa	Garcia, 2007
ThermoFlow		X		X				X	X			X			X	X	X			ThermoFlow	ThermoFlow, 2014
TieSol					X		X						X	X			X			Tietronix	Izygon et al., 2011
Tonatiuh					X									X				X		Google-Code	Tonatiuth, 2014
TracePro					X									X					X	Lambda	Lambda, 2014
TRNSYS (STEC)		X		X		X			X						X	X	X	X		DLR	Schwarzbozl, 2006
Visual HFLCAL					X		X						X	X			X			DLR	Schwarzbolz et al, 2009
WINDELSOL					X		X						X	X				X		SANDIA	Tellez, 2013

Summary

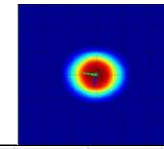
- Model provide methodology used to obtain
  - ✓ HTF mass flow rate through receiver
  - ✓ Surface temperature distribution
  - ✓ Inner tube temperature distribution
  - ✓ Heat losses
  - ✓ Receiver Efficiency
  - ✓ Result of Heliostat field aiming strategy
  - ✓ Corresponding receiver pressure drop
  - ✓ Tube-strain per panel can be obtained


What is next?

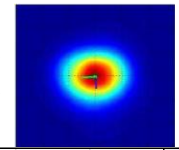
Heliostat Field & Flux Maps – DONE!!

SIGEL= Tracking Error in OPEN-LOOP drive systems
SIGAZ= Foundation motion
SIGSX= Mirror waviness
SIGSY= Panel alignment error
SIGTX= Tracking Error in CLOSED-LOOP drive systems
SIGTY= Tower Sway

Heliostat Aiming Strategy

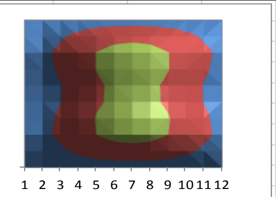


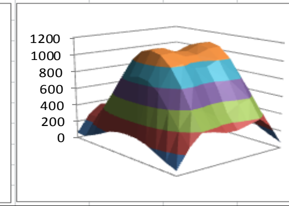
No Heliostat Error (Ideal)



Heliostat Error "Wind"

SIGEL=	0	9.62	69	67	117	175	239	273	282	273	239	175	117	67
SIGAZ=	0	7.48	271	280	441	622	790	886	913	886	790	622	441	280
		5.34	365	394	597	826	1010	1120	1150	1120	1010	826	597	394
SIGSX=	0	3.21	314	362	558	819	1010	1110	1140	1110	1010	819	558	362
SIGSY=	0	1.07	277	328	481	750	949	1060	1080	1060	949	750	481	328
		-1.07	278	330	485	755	956	1060	1090	1060	956	755	485	330
SIGTX=	0	-3.21	319	369	565	829	1020	1120	1150	1120	1020	829	565	369
SIGTY=	0	-5.34	365	394	592	820	1000	1110	1140	1110	1000	820	592	394
#_Helio=	**8965**	-7.48	256	263	419	593	756	847	872	847	756	593	419	263
		-9.62	60	56	102	156	216	246	254	246	216	156	102	56

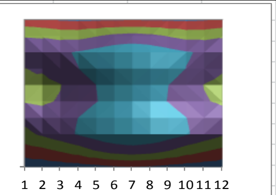


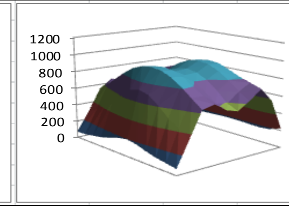


GrossP=	651.72	MWt
Area=	9.13	m2
GrossPM=	660.35	MWt
	-1.32%	
NetP=	87.59	Mwe

DAY	HOUR	COSINE	SHADOW	BLOCK	AIR ATT	SPILLAGE	TOTAL
81.00	0.00	0.83	1.00	0.98	0.92	0.99	0.60

SIGEL=	0	9.62	263	227	181	169	174	181	184	181	174	169	181	227
SIGAZ=	0	7.48	586	576	540	537	590	653	682	653	590	537	540	576
		5.34	678	732	776	815	871	920	936	920	871	815	776	732
SIGSX=	0.003	3.21	595	625	699	797	879	932	948	932	879	797	699	625
SIGSY=	0	1.07	548	537	593	707	801	859	880	859	801	707	593	537
		-1.07	593	575	614	710	795	850	869	850	795	710	614	575
SIGTX=	0	-3.21	649	667	722	802	876	923	938	923	876	802	722	667
SIGTY=	0	-5.34	550	632	725	818	896	943	957	943	896	818	725	632
#_Helio=	**10491**	-7.48	298	349	423	504	611	697	727	697	611	504	423	349
		-9.62	69	72	92	110	140	177	197	177	140	110	92	72

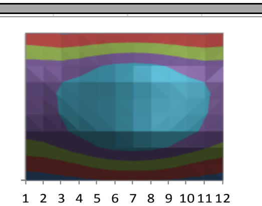


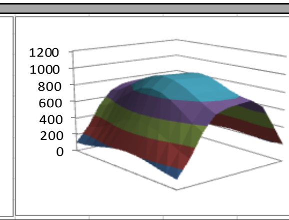


GrossP=	658.42	MWt
Area=	9.13	m2
GrossPM=	660.75	MWt
	-0.35%	
NetP=	88.54	Mwe

DAY	HOUR	COSINE	SHADOW	BLOCK	AIR ATT	SPILLAGE	TOTAL
81.00	0.00	0.80	1.00	0.98	0.92	0.89	0.52

SIGEL=	0	9.62	229	209	186	189	200	211	216	211	200	189	186	209
SIGAZ=	0	7.48	473	449	426	450	493	528	540	528	493	450	426	449
		5.34	688	684	679	723	787	839	857	839	787	723	679	684
SIGSX=	0.003	3.21	760	777	799	841	898	946	963	946	898	841	799	777
SIGSY=	0.002	1.07	753	768	810	854	905	950	966	950	905	854	810	768
		-1.07	734	751	806	860	914	959	976	959	914	860	806	751
SIGTX=	0	-3.21	674	704	771	849	918	969	987	969	918	849	771	704
SIGTY=	0	-5.34	513	544	611	705	791	851	870	851	791	705	611	544
#_Helio=	**11027**	-7.48	279	296	341	408	474	520	536	520	474	408	341	296
		-9.62	103	111	131	157	185	206	212	206	185	157	131	111

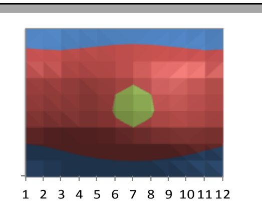


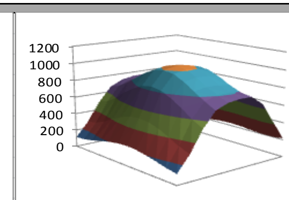


GrossP=	659.40	MWt
Area=	9.13	m2
GrossPM=	668.62	MWt
	-1.40%	
NetP=	88.68	Mwe

DAY	HOUR	COSINE	SHADOW	BLOCK	AIR ATT	SPILLAGE	TOTAL
81.00	0.00	0.79	1.00	0.98	0.92	0.86	0.49

SIGEL=	0	9.62	234	218	199	202	213	226	231	226	213	202	199	218
SIGAZ=	0	7.48	459	440	424	446	476	508	520	508	476	446	424	440
		5.34	672	666	667	714	766	814	832	814	766	714	667	666
SIGSX=	0.003	3.21	758	769	793	847	914	967	987	967	914	847	793	769
SIGSY=	0.002	1.07	753	771	810	864	944	1000	1020	1000	944	864	810	771
		-1.07	729	753	805	866	949	1010	1030	1010	949	866	805	753
SIGTX=	0	-3.21	663	697	764	843	922	983	1000	983	922	843	764	697
SIGTY=	0.003	-5.34	501	531	599	689	763	821	840	821	763	689	599	531
#_Helio=	**11252**	-7.48	280	297	344	408	461	501	515	501	461	408	344	297
		-9.62	115	123	145	175	201	222	229	222	201	175	145	123

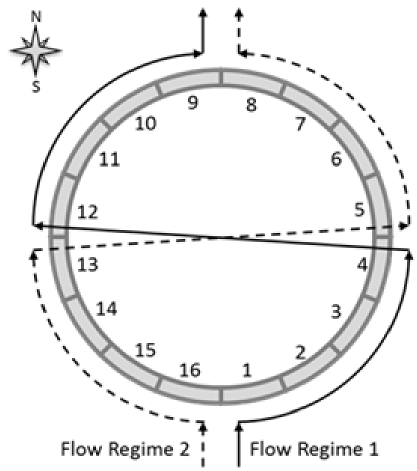


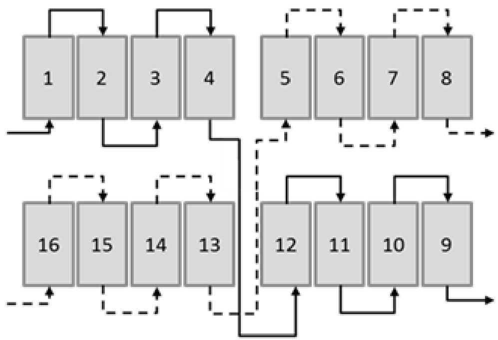


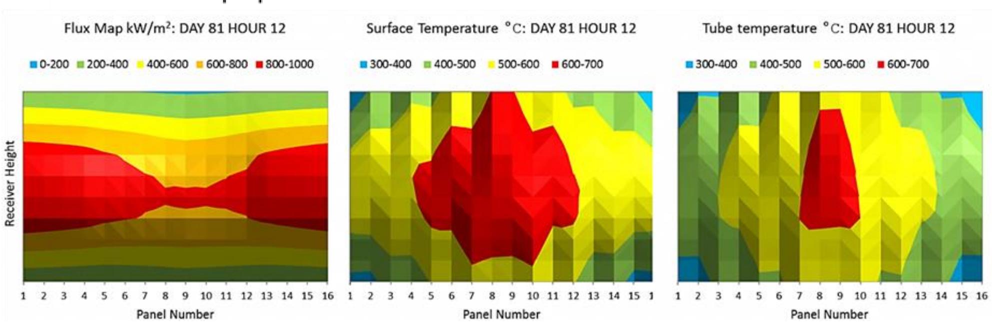
GrossP=	659.33	MWt
Area=	9.13	m2
GrossPM=	670.75	MWt
	-1.73%	
NetP=	88.71	Mwe

DAY	HOUR	COSINE	SHADOW	BLOCK	AIR ATT	SPILLAGE	TOTAL
81.00	0.00	0.79	1.00	0.98	0.91	0.82	0.47

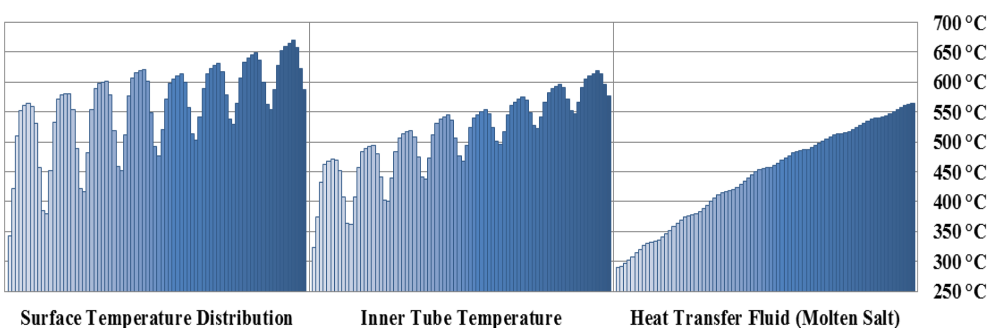
Receiver Model – DONE!!

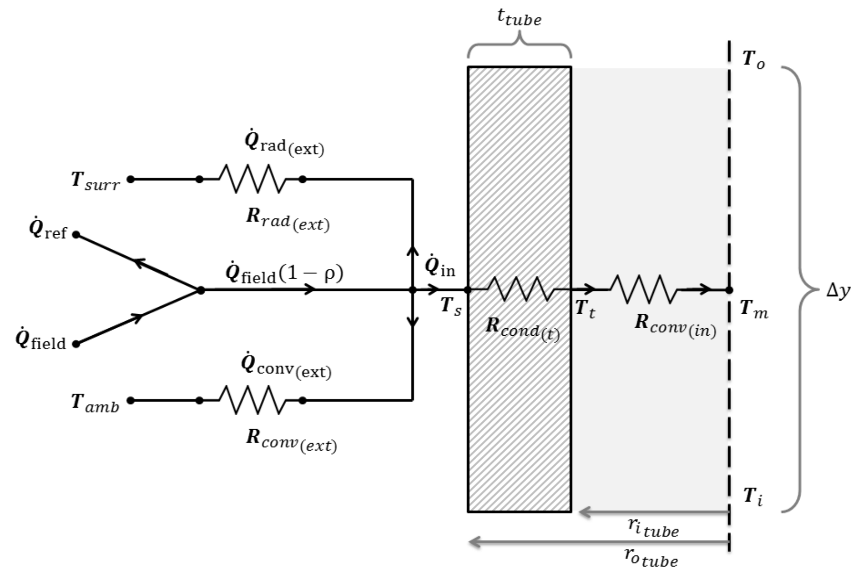


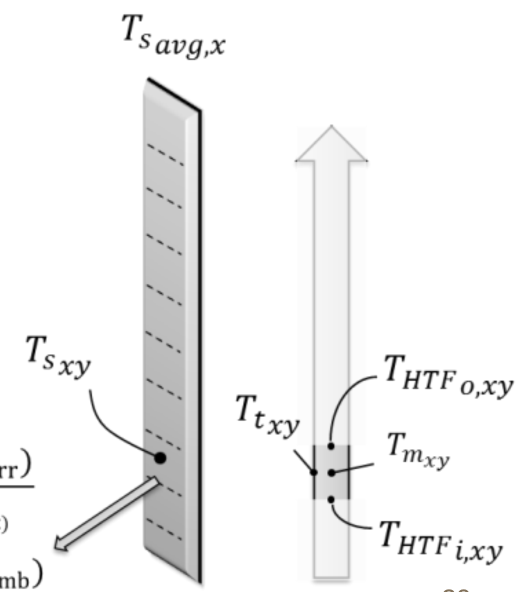




Temperature Distribution in Receiver Panels for Flow Regime 1





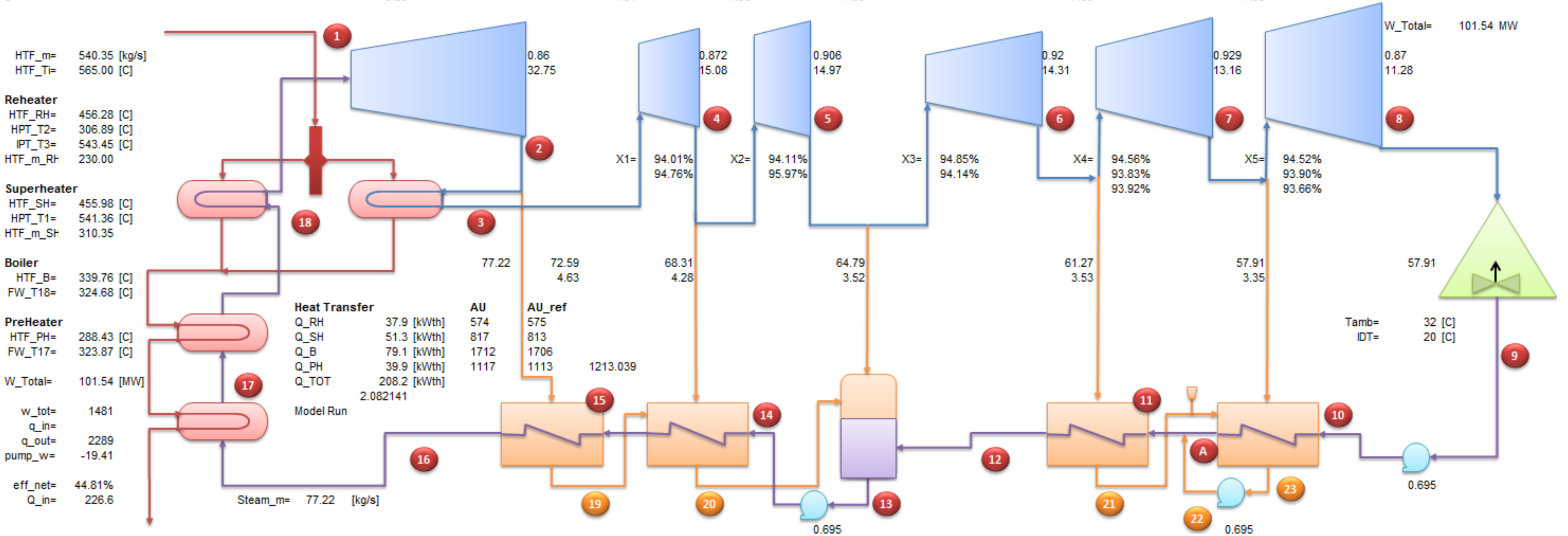


$$\dot{Q}_{rad_{xy}} = \frac{(T_s - T_{surr})}{R_{rad\,(ext)}}$$

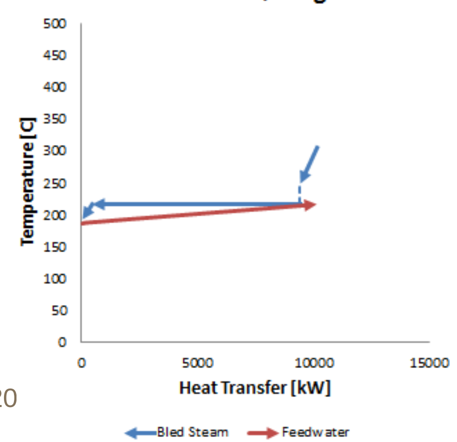
$$\dot{Q}_{conv_{xy}} = \frac{(T_s - T_{amb})}{R_{conv\,(ext)}}$$

Power Block Model – DONE!!!

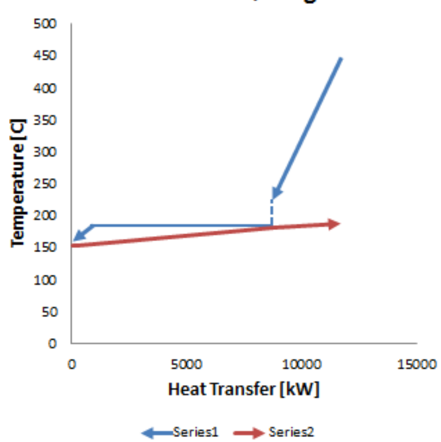
		1	2	3	4	5	6	7	8
Pressure	[bar]	120.00	21.79	21.79	10.94	4.87	1.86	0.58	0.1363
Temperature	[C]	541.36	306.89	543.45	442.99	334.28	221.67	109.47	52.00
Entalphy		3459	3035	3563	3355	3136	2915	2700	2505
s		6.63		7.51	7.56	7.59	7.63	7.68	



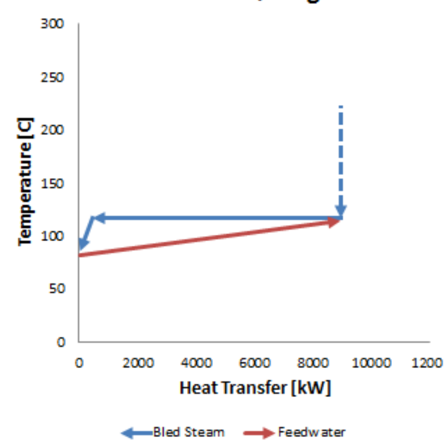
HP FWH 2 : TQ Diagram



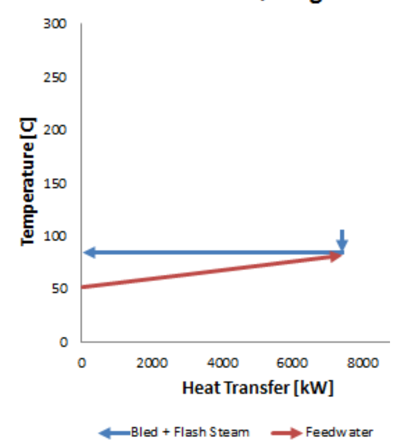
HP FWH 1 : TQ Diagram



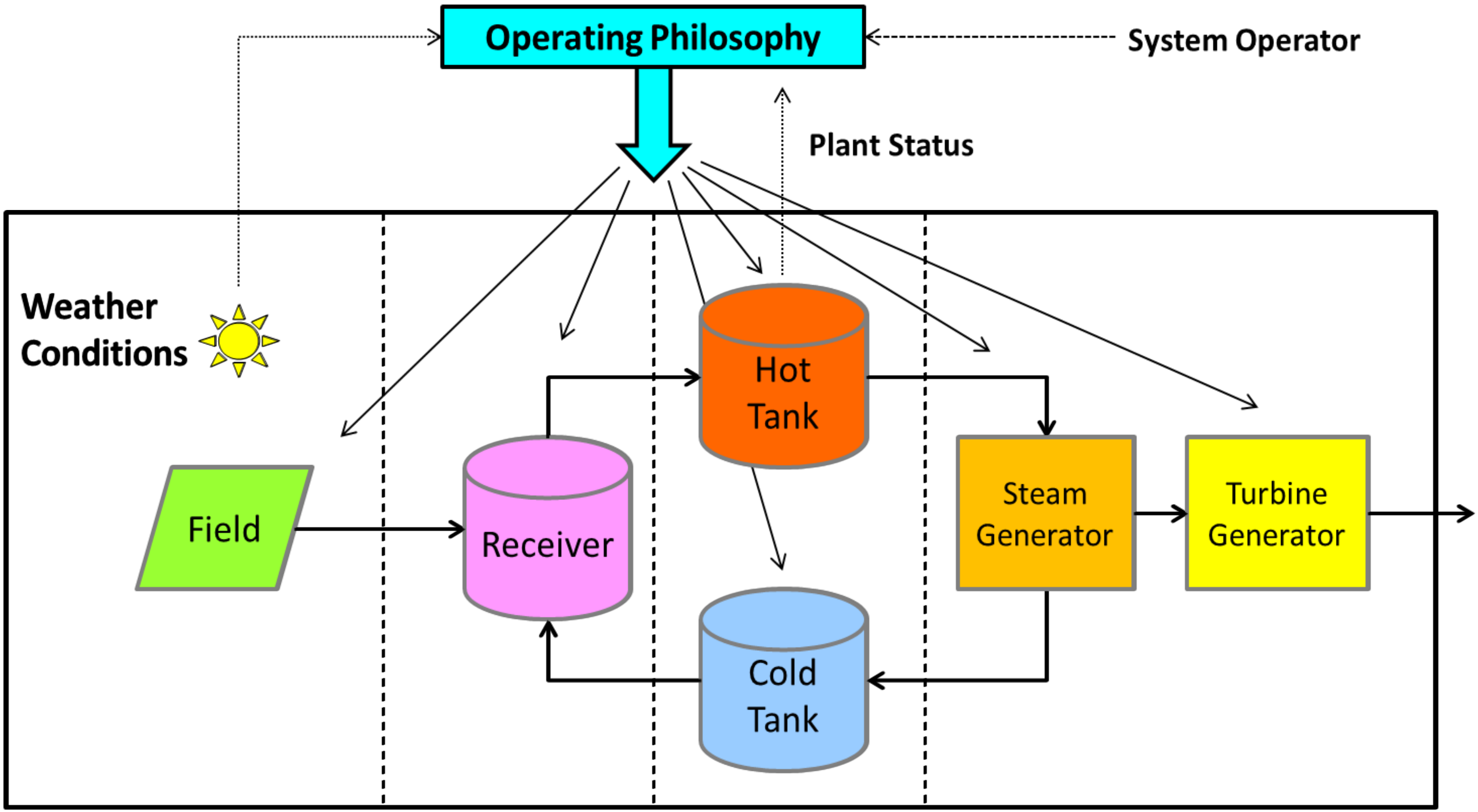
LP FWH 2 : TQ Diagram



LP FWH 1 : TQ Diagram



Start with PhD ☺



Thank you..

Questions