Dynamic Modelling, Simulation and Control of a Solar Thermal Power Plant

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Background

- Increased availability of energy needed for improved quality of human life.
- Fossil fuels- coal, natural gas, oil major sources of energy.

Background

- **Import** of oil, coal from other countries necessary to meet domestic and commercial energy demand.
- Heavy use of these causing **global warming** and **climate change.**
- All the fossil fuels will be depleted within **150 years**.*
- Need alternate energy sources.

*Pimentel et al. (2015)

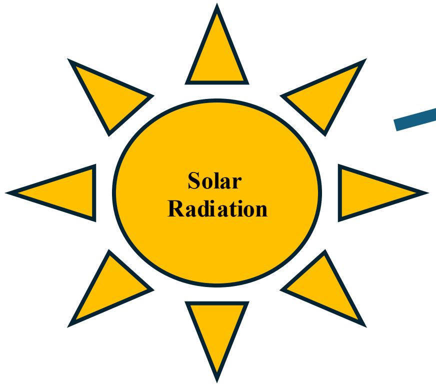
Background

Indian electricity capacity background ***(As on 31.05.2023)*** **-** Source: Central Electricity Authority (CEA)

Category		Installed generation capacity (MW)	% of share in total
Fossil fuel	Coal	2,05,235	49.1
	Gas	24,824	6.0
	Lignite	6,620	1.6
	Diesel	589	0.1
Total fossil fuel		2,37,268	56.7
Non fossil fuel	**Solar**	**67,078**	**16.1**
	Hydro	46,850	11.2
	Wind	42,868	10.3
	BM power/Cogen	10,248	2.5
	Nuclear	6,780	1.6
	Small hydro power	4944	1.2
	Waste energy	554	0.1
Total non-fossil fuel		1,79,322	43
Other		1078	0.3
Total Installed capacity		417668	100%

- Solar energy is one of the most promising and rapidly growing source of renewable energy in India today.

Solar energy



Solar thermal power plant

Concentrated Solar Power (CSP) system

Parabolic trough collector (PTC)

Solar tower

Linear fresnel reflector (LFR)

Solar dish

Line-Focusing

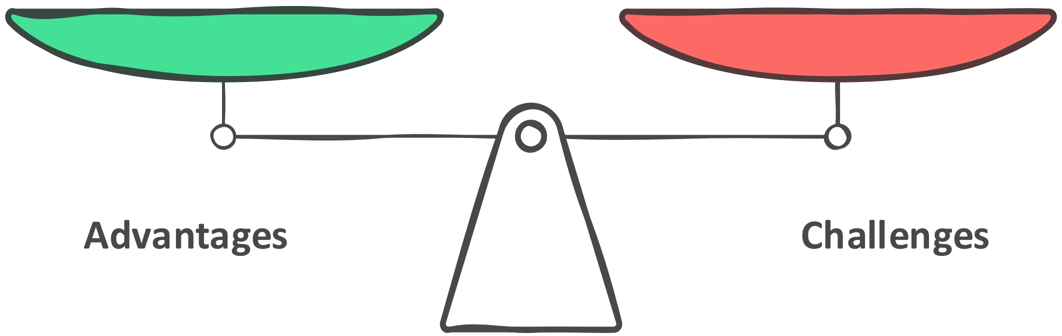
Point-Focusing

Photovoltaic system

Solar Thermal Energy: Pros and Cons

- Renewable energy source
- Low environmental impact
- Thermal energy storage capability

- Weather dependency
- High initial costs
- Land use requirements



Time-Varying Phenomena

Diurnal & Seasonal variation, Cloud Cover

Solar energy availability is affected by diurnal and seasonal variations as well as cloud cover.

Atmospheric Effects

Atmospheric conditions scatter and absorb solar energy, impacting efficiency.

Dust Accumulation

Dust on mirrors reduces reflectivity.

Operational Complexities

Highly dynamic operation

Unsteady state operation with high variability.

Temperature variation

Maintaining optimal heat transfer fluid (HTF) temperature critical.

Thermal stress

Managing thermal stress on materials ensures plant longevity.

Steam generation variation

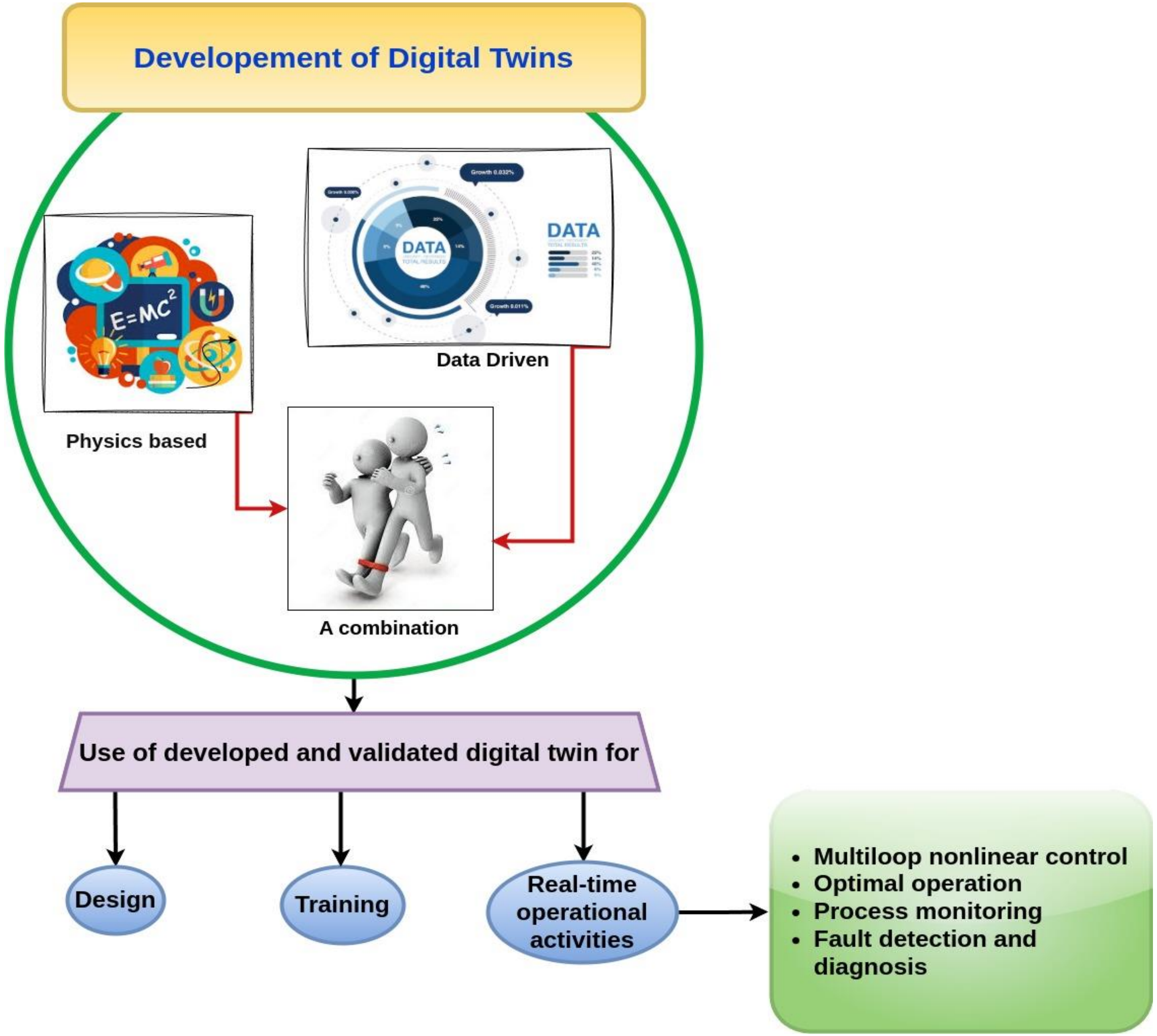
Consistent steam generation essential for continuous power.

Grid integration challenge

Seamless integration with electricity grid and energy storage systems vital.

- These factors necessitate real-time monitoring, real-time optimization and advanced control.
- Need a dynamic model.

Dynamic model of a system (Digital Twin)



Use of dynamic modelling in Solar Thermal Power Plant

Dynamic Modelling

- Optimization
- Control Strategies
- Operation, Design and Site selection

Simulate Scenarios

Operators create various operational scenarios

Assess Impact

Evaluate how scenarios affect plant performance

Develop Contingency Plans

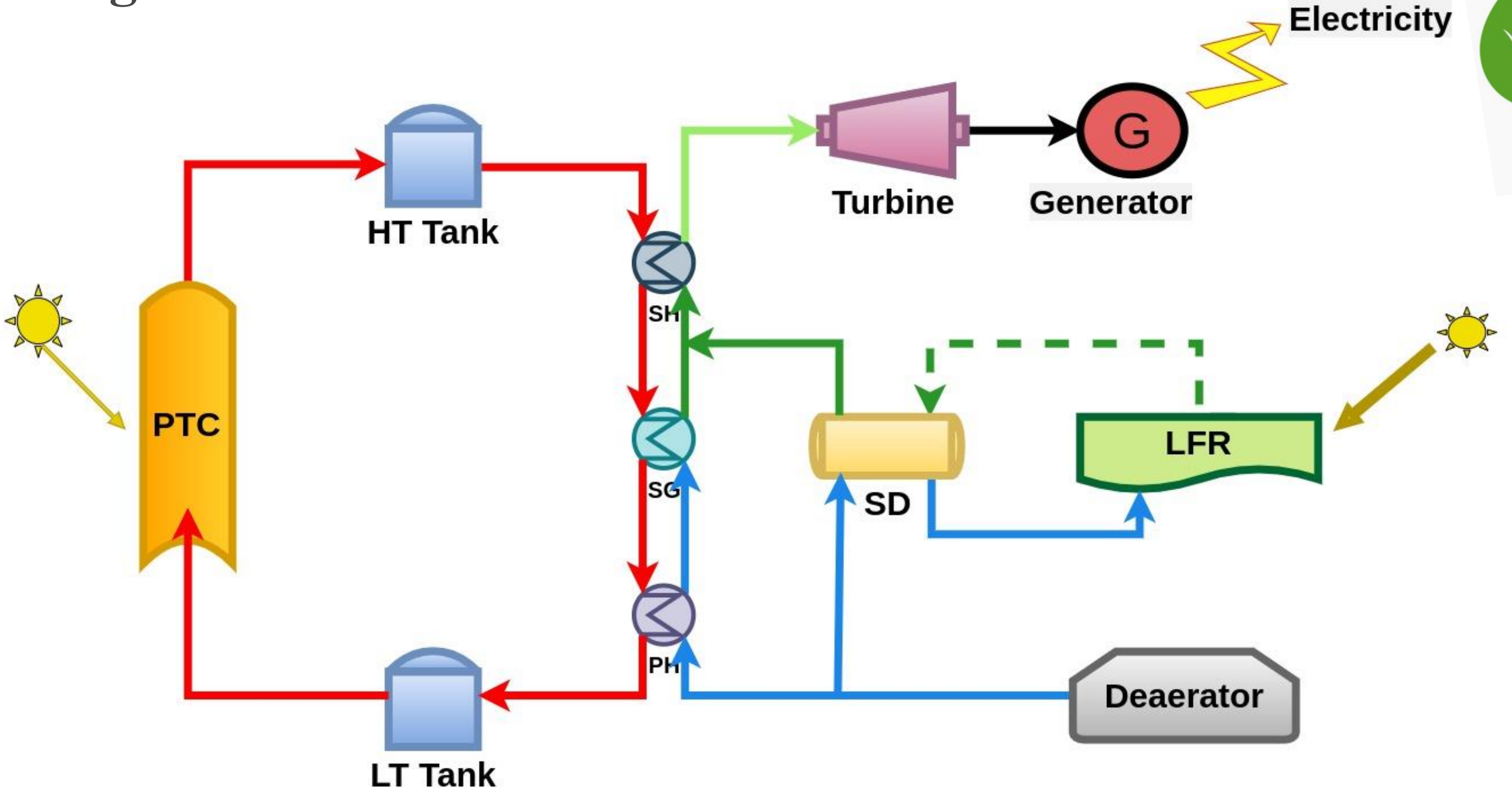
Create strategies to mitigate potential issues

Gurgaon based Hybrid Solar Thermal Power Plant (HSTPP)

- 1 MWe solar thermal power plant conceptualized, designed, and commissioned by a team from IIT Bombay
- Amongst the first ones in India

[Nayak et al., 2015]

PFD of Gurgaon HSTPP

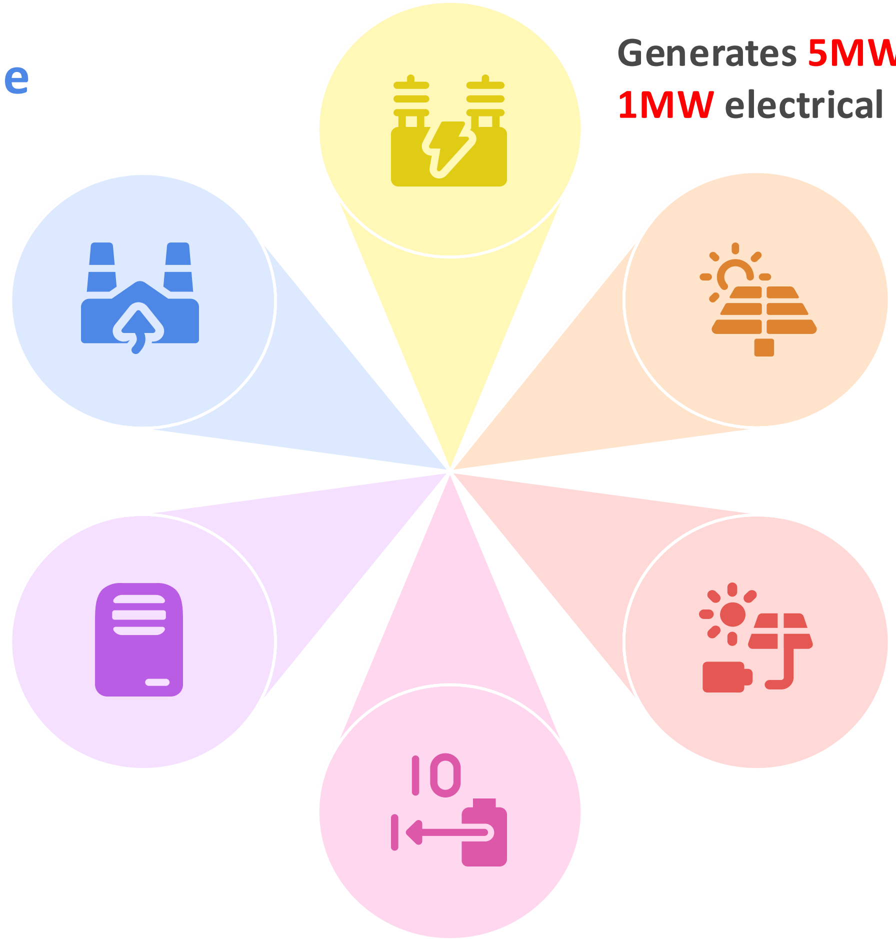


PTC: Parabolic Trough Collector
LFR: Linear Fresnel Reflector
SG: Steam generator
SH: Super Heater

SD: Steam Drum
HT: High Temperature Tank
LT: Low Temperature Tank
PH: Pre Heater

Water
Oil
Steam
Two phase mixture
Superheated Steam

Components Gurgaon HSTPP



Power Generation

Generates 5MW thermal/ 1MW electrical power.

Steam Turbine

Superheated steam drives the turbine at 40 bar and $350\ ^{o}C$.

Thermal Fields

Contains 3MW PTC field and 2MW LFR field.

Heat Exchanger

Shell and tube type heat exchanger component.

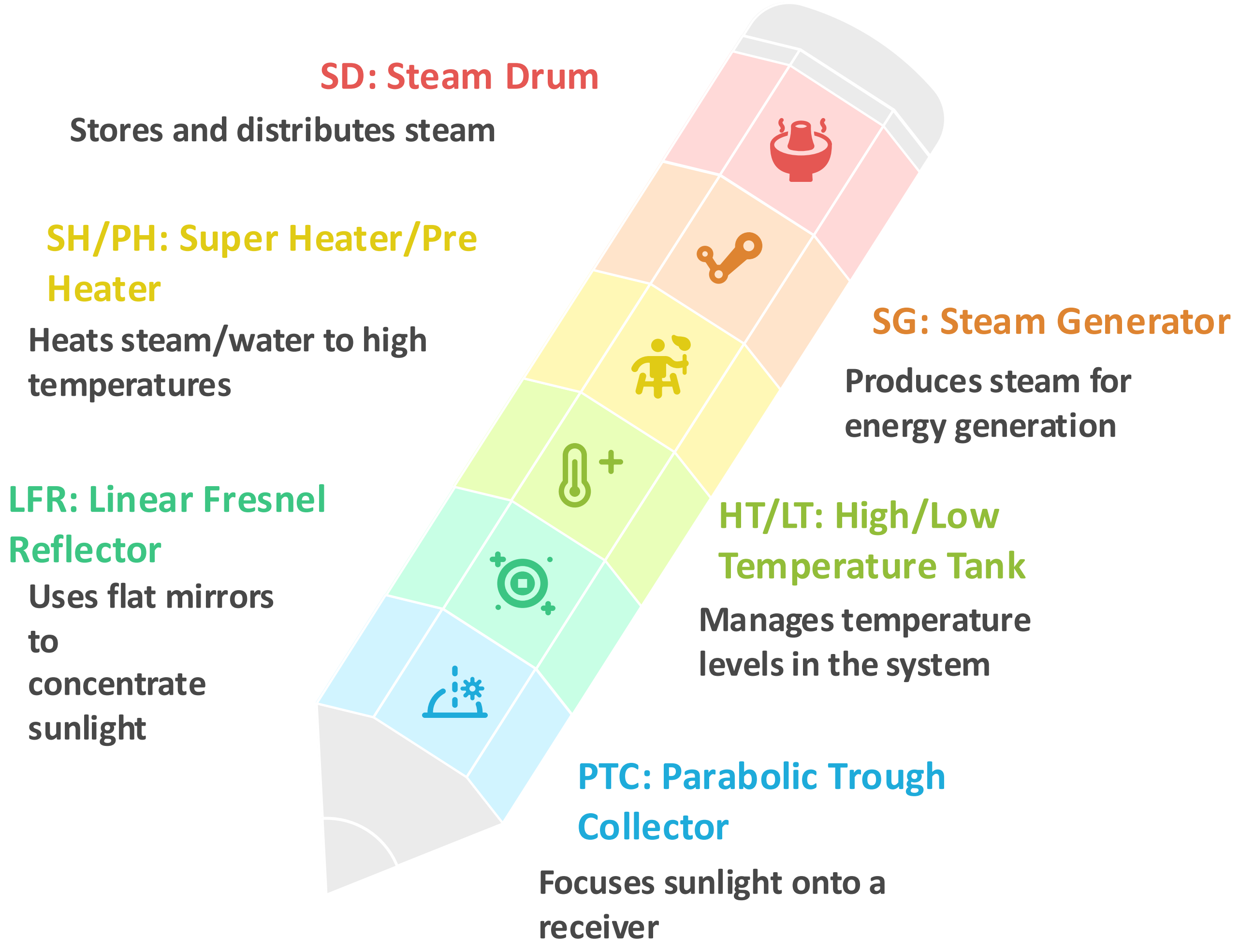
Design point

$600\ W/m^2$ DNI criteria

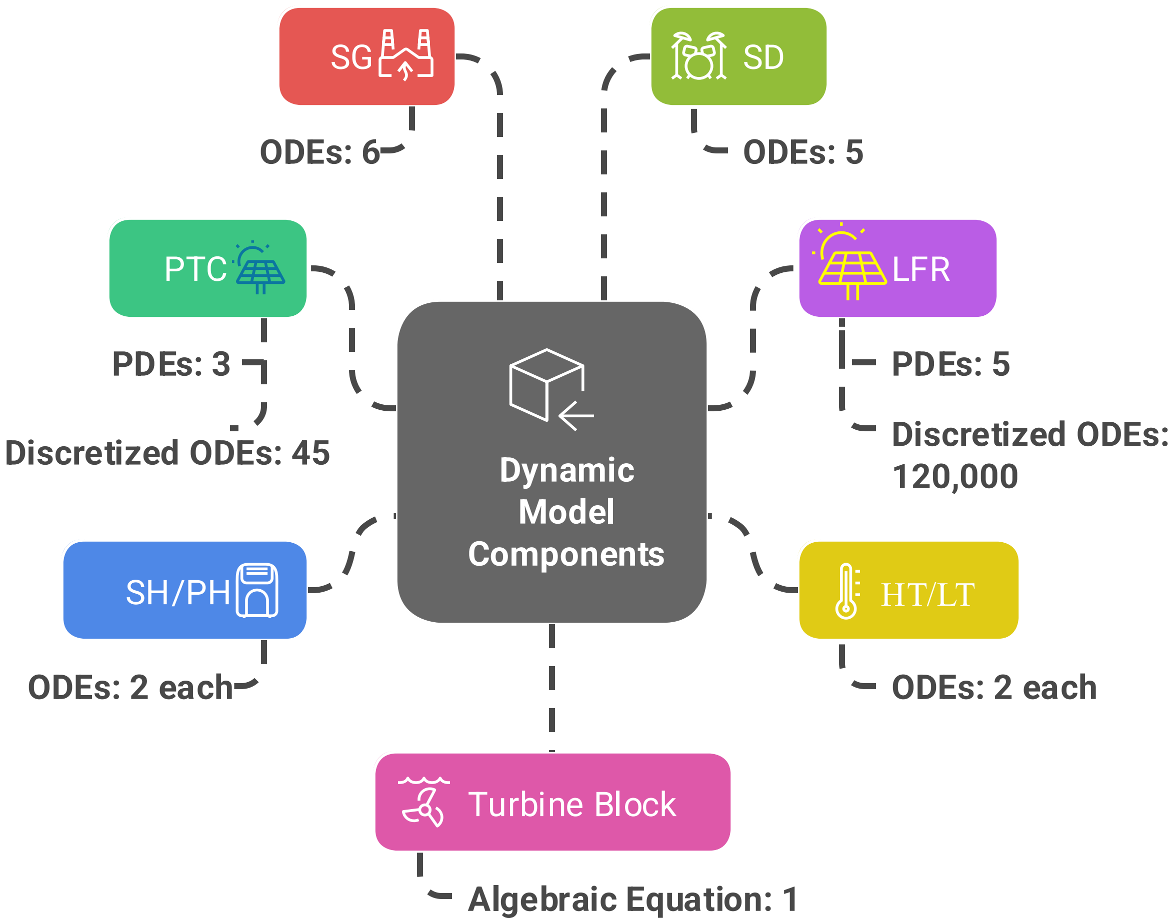
Storage Tank

Stores 0.3 MWh of electricity for 15-20 mins of operation at full load.

HSTPP: components working



HSTPP: dynamic model of components



Dynamic model of PTC*

Heat Transfer Fluid (HTF): Based on energy balance, HTF temperature with respect to both time and axial length of the pipe:

$$\frac{\partial(\rho_o C_{p,o} A_A T_o)}{\partial t} = -\dot{m}_o C_{p,o} \frac{\partial T_o}{\partial x} + h_p P_{Ai}(T_A - T_o)$$

Absorber pipe: The energy balance for the absorber pipe:

$$\rho_A C_{PA} A_A \frac{\partial T_A}{\partial t} = h_p P_{Ai}(T_o - T_A) + I\eta_{opt} W - \frac{\sigma}{\frac{1}{\xi_A} \frac{1-\xi_E}{\xi_E} \left(\frac{r_{Ao}}{r_{Ei}}\right)} P_{Ai} \left(T_A^4 - T_E^4\right)$$

Glass envelope: The energy balance for the glass envelope:

$$\rho_E C_{PE} A_E \frac{\partial T_E}{\partial t} = \frac{\sigma}{\frac{1}{\xi_A} \frac{1-\xi_E}{\xi_E} \left(\frac{r_{Ao}}{r_{Ei}}\right)} P_{Ai} \left(T_A^4 - T_E^4\right) - h_{air} P_{Eo}(T_E - T_{air}) - \sigma P_{Eo}(T_E^4 - T_{sky}^4)$$

*Dynamic model validated with preliminary plant data

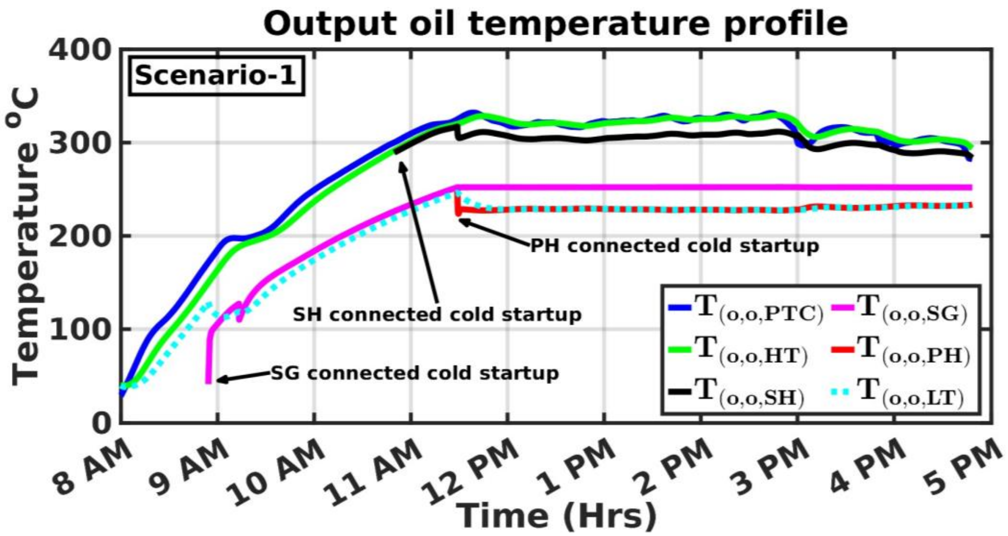
* Kannaiyan et al. (2019), Baidya et al. (2024)

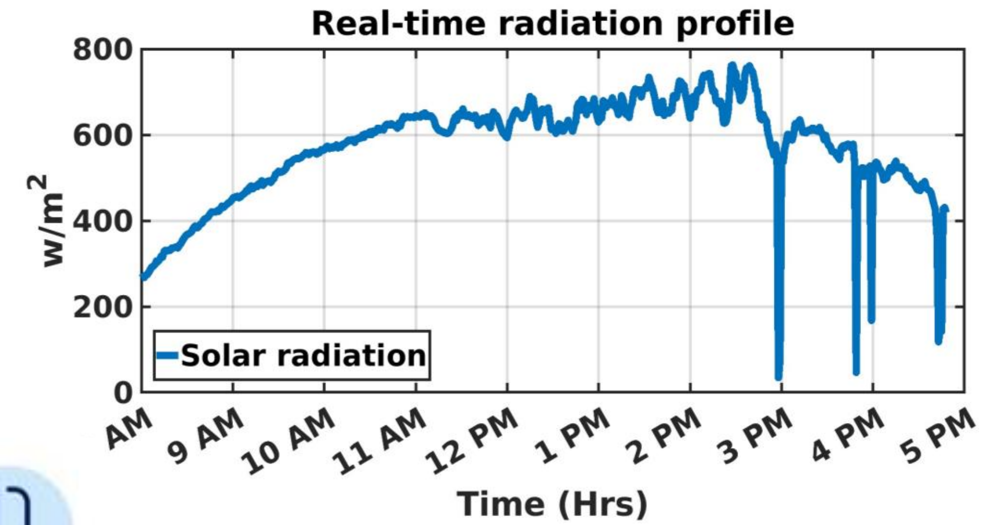
What can we do with dynamic model of HSTPP

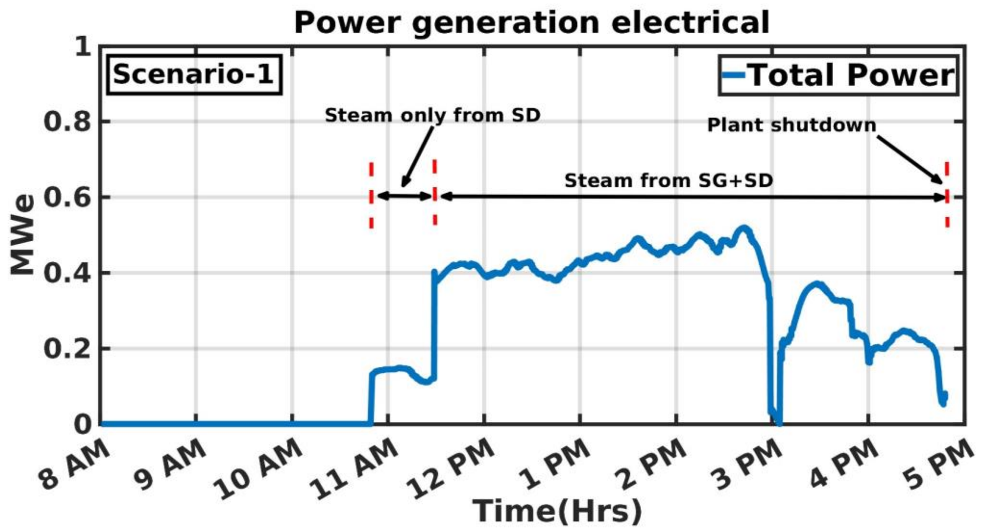
Component Detailed Examination

Time Profile Visualization

Realtime Disturbance Inclusion





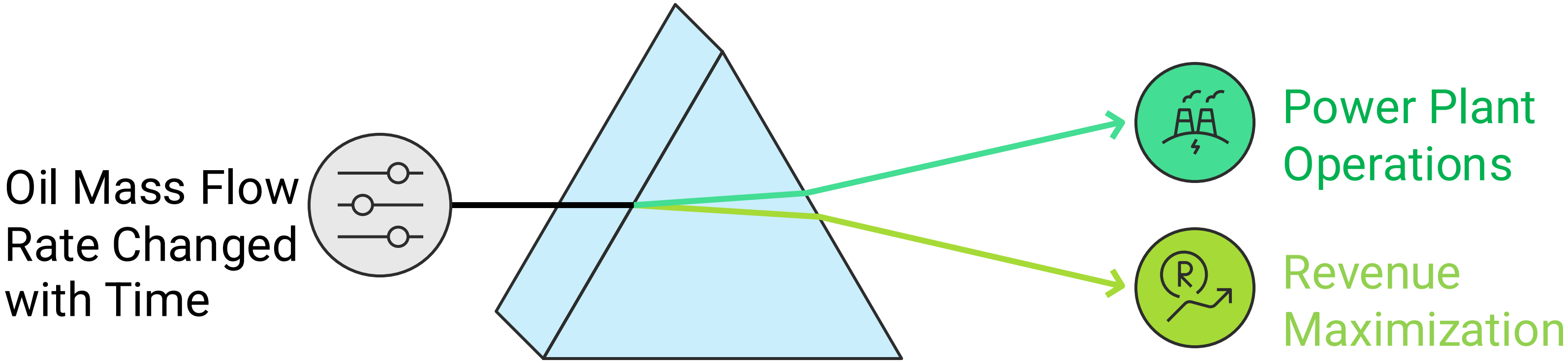


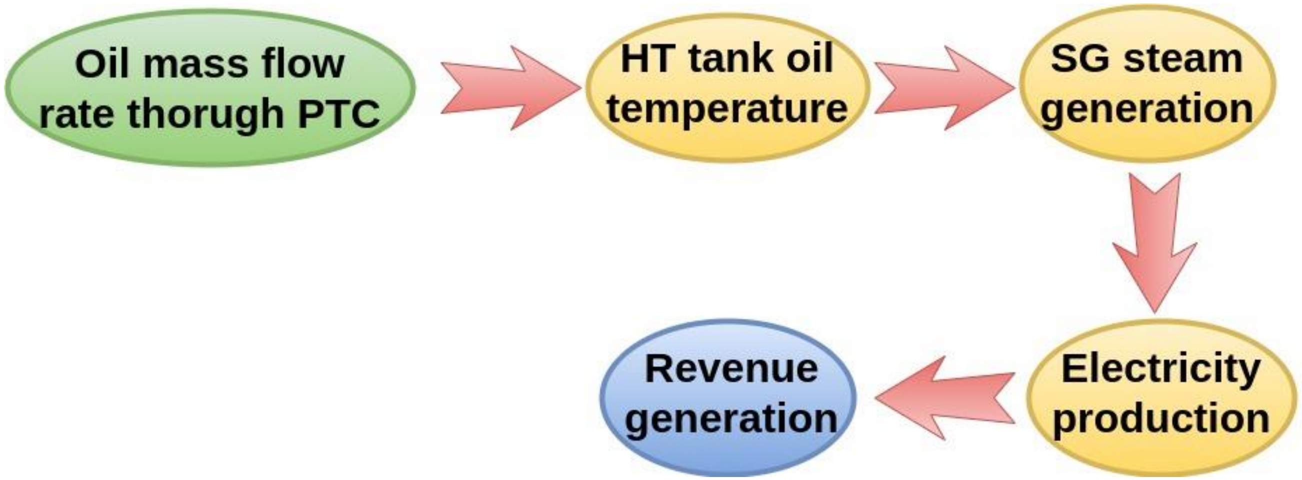
**Dynamic simulator available at: 'HysolSim': https://github.com/DeepRedalert/HysolSim

Case Study-1
Optimization

Revenue **Optimization** with Dynamic Operation of HSTPP

Aim: Optimizing oil flow rate to maximize revenue from sold electricity



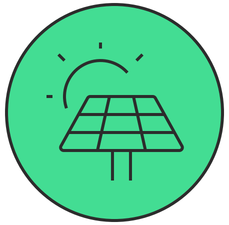


Challenges

In presence of operational constraints

Electricity Market

Fluctuating prices due to demand



Solar Insolation

Time varying solar radiation

Case Study-1 Optimization

Revenue **Optimization** with Dynamic Operation of HSTPP

Objective function: Maximize revenue from produced electricity accounting for time-varying electricity prices.

$$\max_{u(t),\ t_0 \le t < t_f} \int_{t_0}^{t_f} W_{PB}(t) P(t)\ d(t) \quad (1a)$$

$$\text{s.t.} \quad \dot{\tilde{x}} = \tilde{f}(\tilde{x}(t), u(t), s(t)) \quad (1b)$$

$$u_L \le u(t) \le u_U, \quad \forall\, t_0 \le t < t_f \quad (1c)$$

Where:

- W_{PB}: Power output from turbine (MW)
- P: Electricity price (Rs/MWh)
- τ: Varying time
- $\tilde{x}$: State variables of HSTPP
- u: Decision variable (PTC oil flow rate) with lower (u_L) and upper bounds (u_U)
- d: Disturbance input (Solar radiation profile)

Control vector parametrization (CVP) simplification:

$$\max_{u(t_p),\ p=0,1,..,P-1} \sum_{j=1}^{N} W_{PB}(t_j) P(t_j) \Delta t \quad (2a)$$

$$\text{s.t.} \quad x(t_{j+1}) = \int_{t_j}^{t_{j+1}} f(x(t), u(t_j), s(t_j), r(t_j))\ dt + x(t_j) \quad (2b)$$

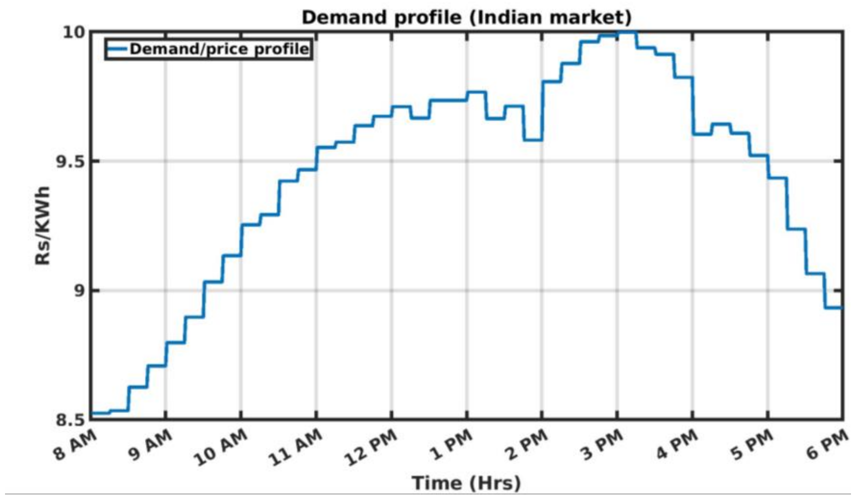
$$u(t_j) = u(t_p), \quad for \quad (p-1)M \le t_j < pM \quad (2c)$$

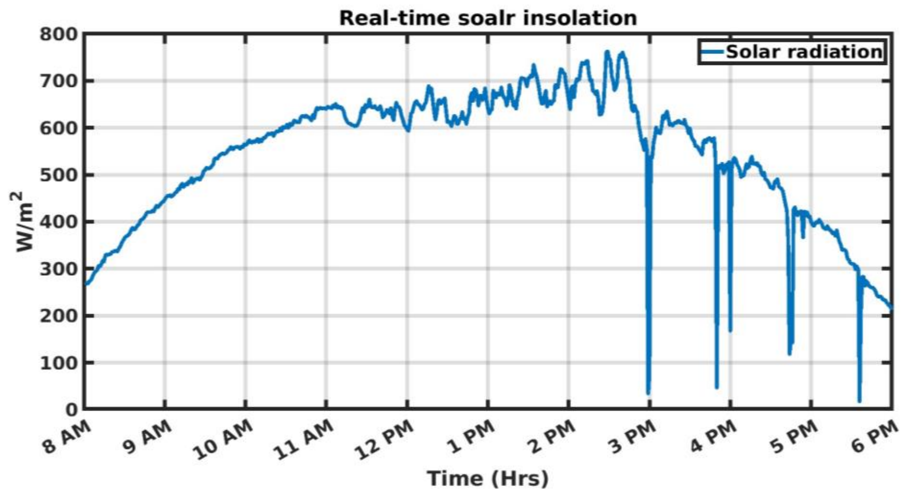
$$u_L \le u(t_p) \le u_U, \quad p = 0,1,\dots,P-1 \quad (2d)$$

- Nonlinear programming (NLP) problem.
- Implicit constraints, Numerical integration of model equations required.
- Nonlinear, non-differentiable models.
- Infinite dimensional to finite dimensional problem conversion using CVP.
- Genetic Algorithm (GA) used in current work.

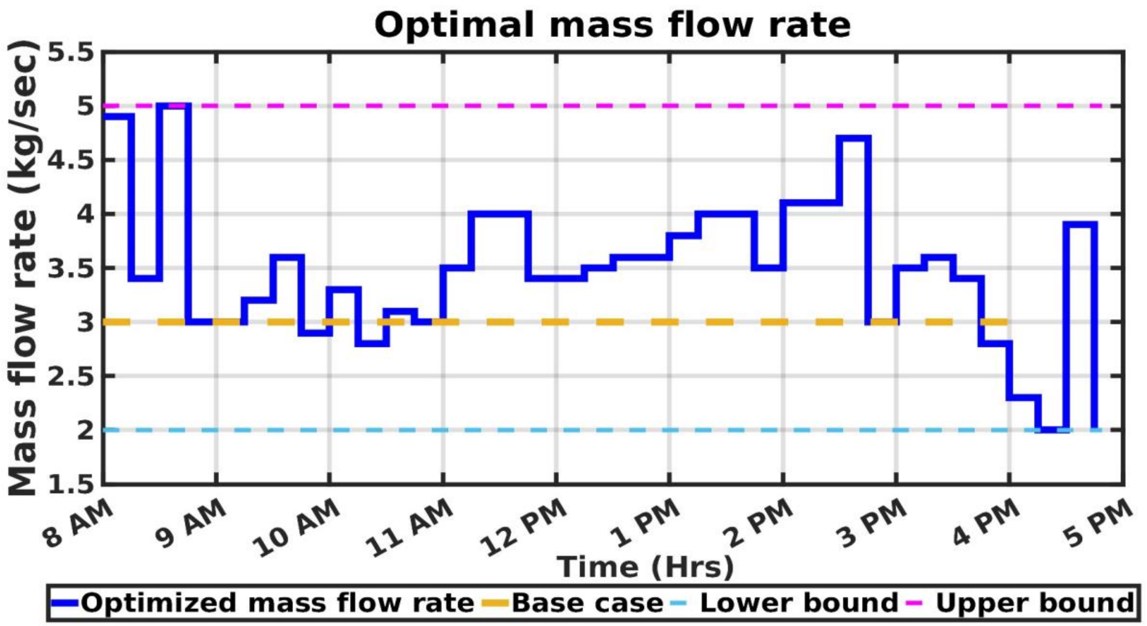
Revenue **Optimization** with Dynamic Operation of HSTPP

Electricity Market





Solar Insolation



Case Study-1
Optimization

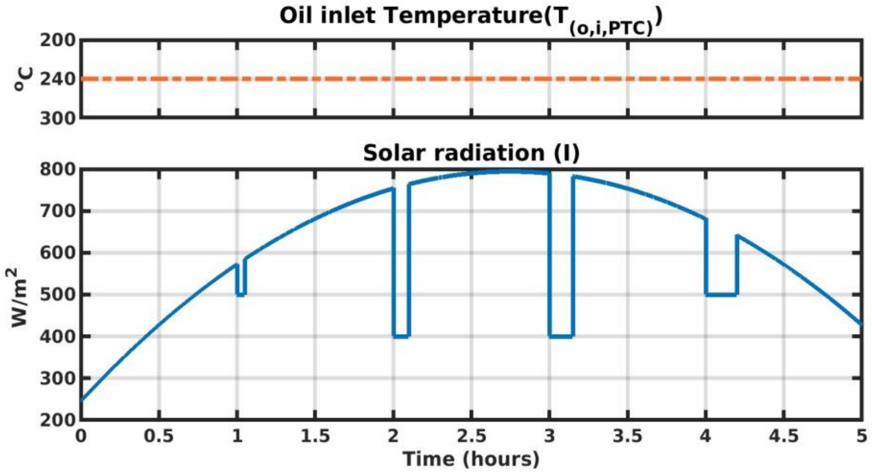
Revenue **Optimization** with Dynamic Operation of HSTPP

Parameters	**Base Case**	**Optimized case**
Steam Generation from SG (kg)	9548.5	10488
Steam Generation from LFR (kg)	17535	18632
Total Steam Produced (kg)	27083	29120
Electric Energy Produced (MWe)	2.54	2.69
Duration of Power Generation (hrs)	7.2	8.75
Revenue (Rs.)	24,462	**25,895**
% Revenue Increase (over Base Case)	-	**5.86%**
Computation Time (days)	-	7

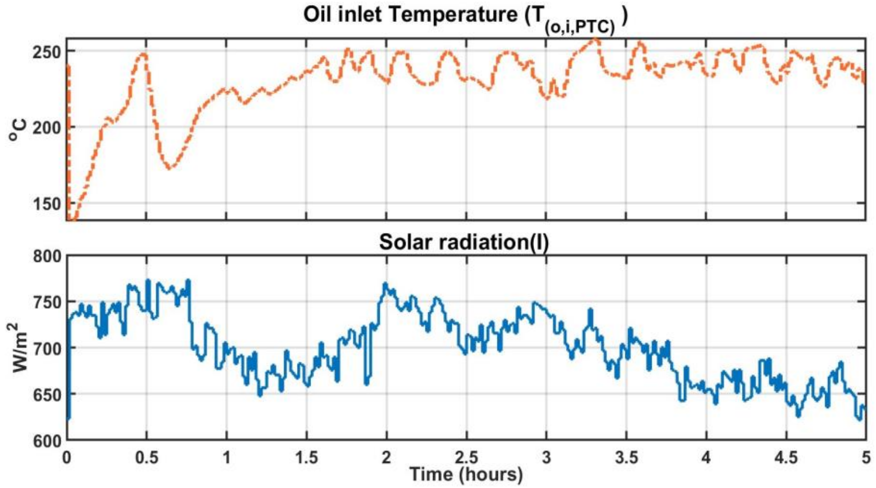
Case Study-2
Control

Control the oil temperature of PTC outlet to maximize efficiency

Aim: To control PTC outlet temperature in presence of various disturbances



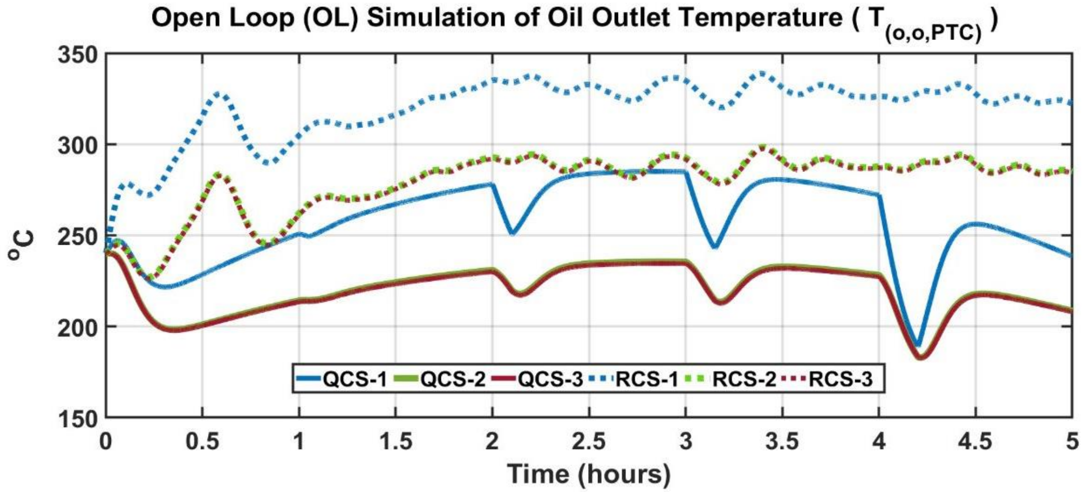
Quadratic solar radiation with cloud cover as the input



Realtime solar radiation as the input

Case Study	η_1	η_2	η_3	η_4	η_5
CS-1	0.5	0.5	0.5	0.5	0.5
CS-2	0.5	0.4	0.3	0.1	0.1
CS-3	0.5	0.4	0.3	0.1	0.08

Disturbance input: Mirror Efficiency(η) Table

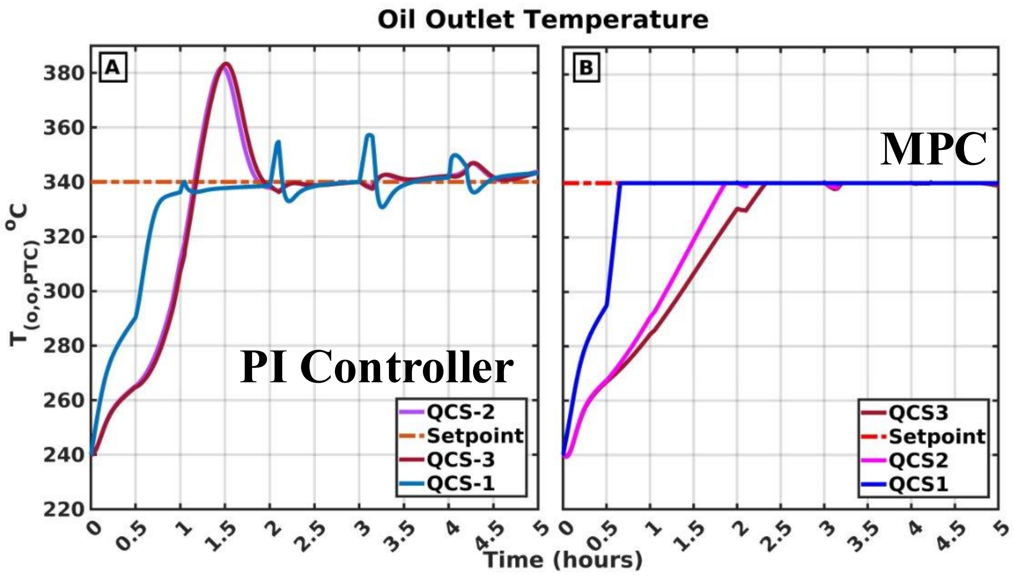


Setpoint: 340 °C

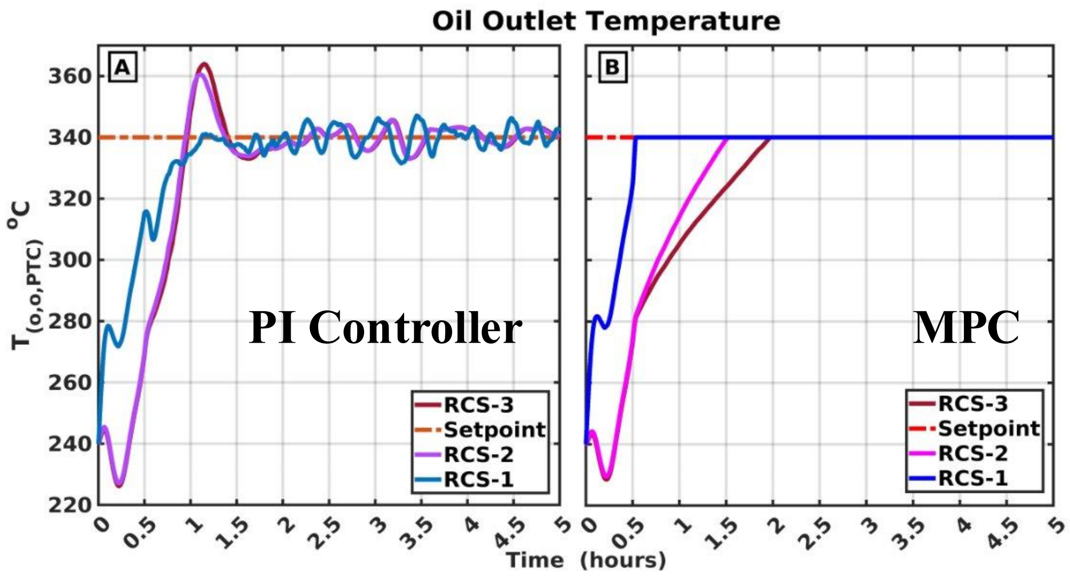
- **Open loop: Desired temperature not attained**

Case Study-2
Control

Closed-Loop Performance: Conventional and Dynamic Model based Controllers



Quadratic solar radiation with cloud cover as the input



Realtime solar radiation as the input

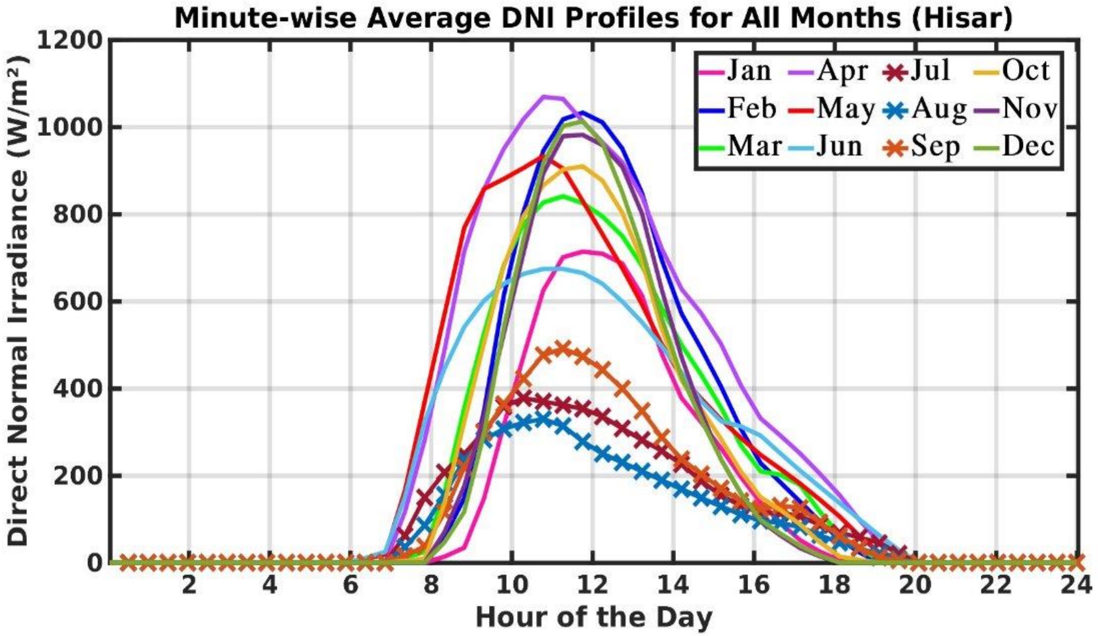
- Proportional Integral (PI): Model free controller, Transfer function based
- Model Predictive Control (MPC): Explicitly used dynamic model

Observation: MPC outperforms PI in set-point tracking, and had lower overshoot.

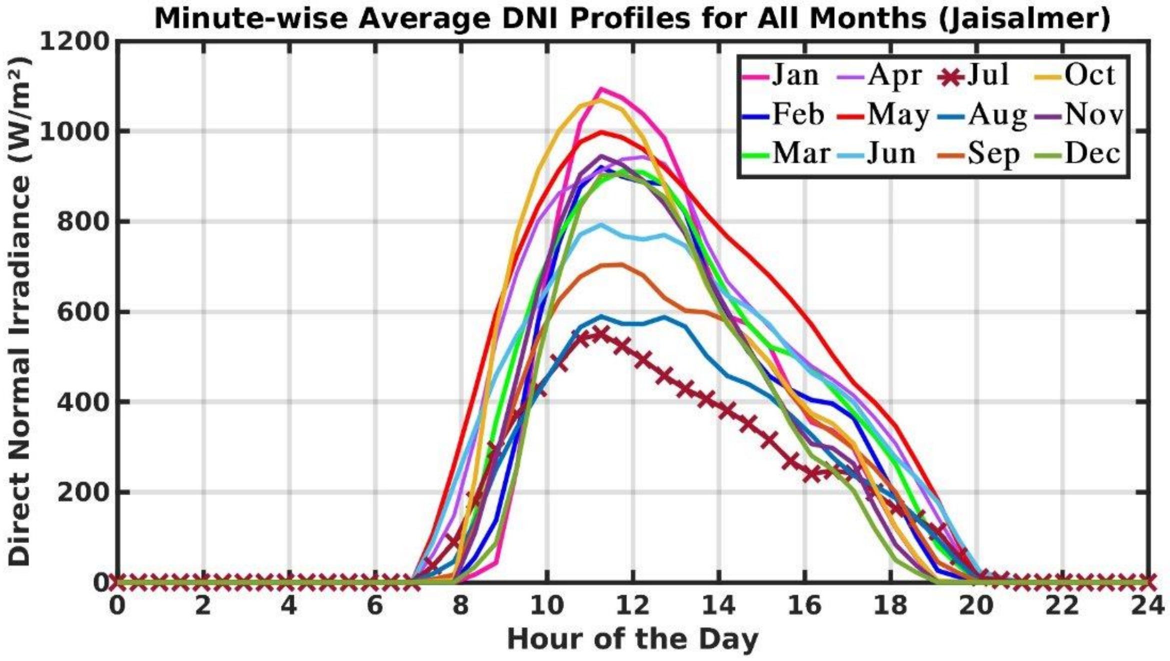
Case Study-3
Operation

Plant **Operation** and Simulation with dynamic model

Aim: Site selection based on dynamic simulations with salt based thermal energy storage



Solar radiation profile (Hisar, Haryana)

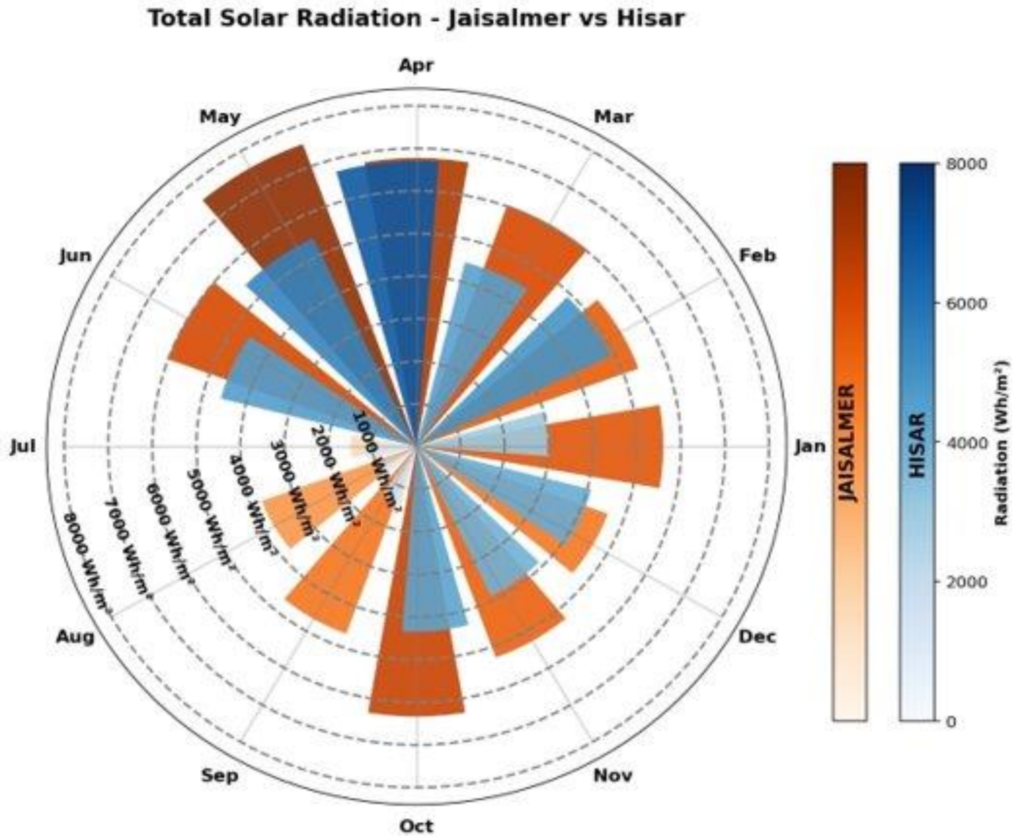


Solar radiation profile (Jaisalmer, Rajasthan)

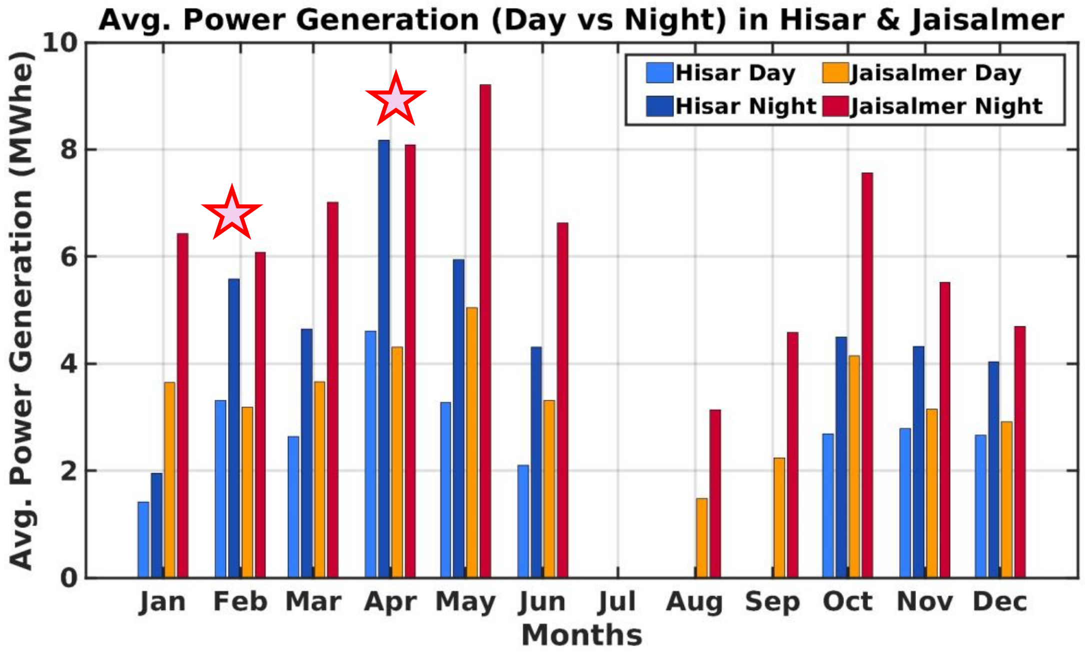
- Hisar: Plant non-operational for 3 months (July–September) due to insufficient solar radiation
- Jaisalmer: Only July is non-operational; better solar availability enables operation in August and September.

Case Study-3
Operation

Plant **Operation** and Simulation with dynamic model



Cumulative solar radiation



Electricity generation from Dynamic simulation

- Jaisalmer received higher solar energy than Hisar for all months.
- **Non-intuitive Outcome:** Jaisalmer produced less electricity in February and April.☆
- **Root Cause:** Lower average DNI, steam temperature (295°C vs. 300°C), and flow rate (1.12 kg/s vs. 1.37 kg/s) in Jaisalmer reduced turbine efficiency.

Conclusions

- Critical Backbone: Dynamic modeling underpins robust control, optimal operation, and future-proofing of plants.
- Hybrid solar thermal power plant simulator available for public use
- Generate high-fidelity datasets to train machine learning models enabling faster, near-real-time predictions and control.

Thank You

Questions?

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