IMPACT OF MODEL SIMPLIFICATIONS ON THE ANNUAL YIELD OF CSP SYSTEMS

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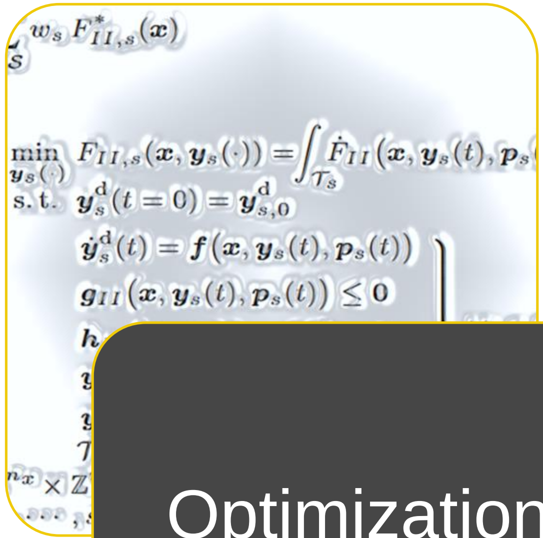
28th SolarPACES Conference

DLR

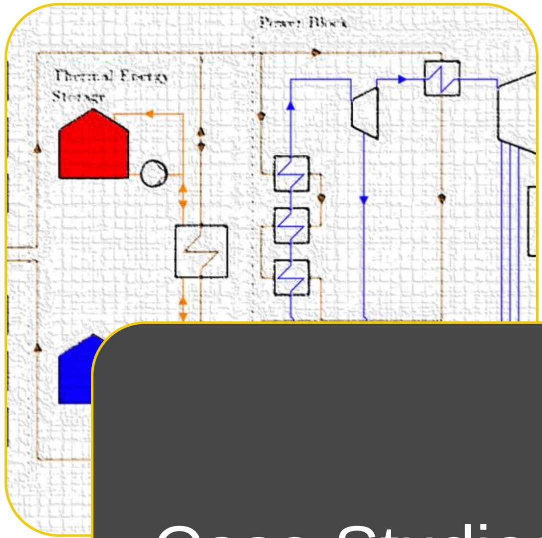
What is the best Approach to optimize CSP Systems?

Matthias Loevenich, DLR Institute of Solar Research, 2022-09-29

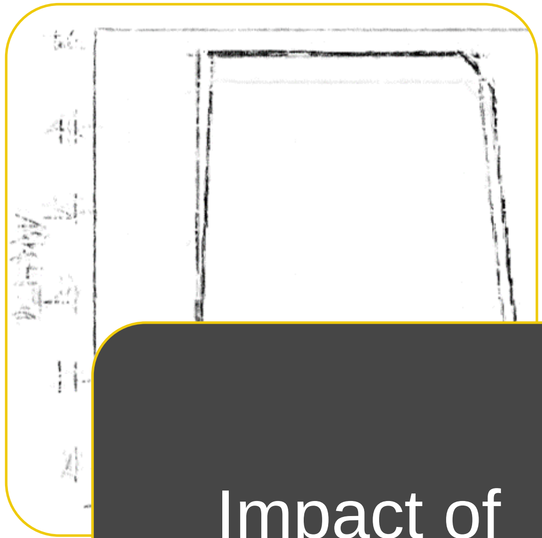
Outline



Optimization of CSP Systems



Case Studies and Models



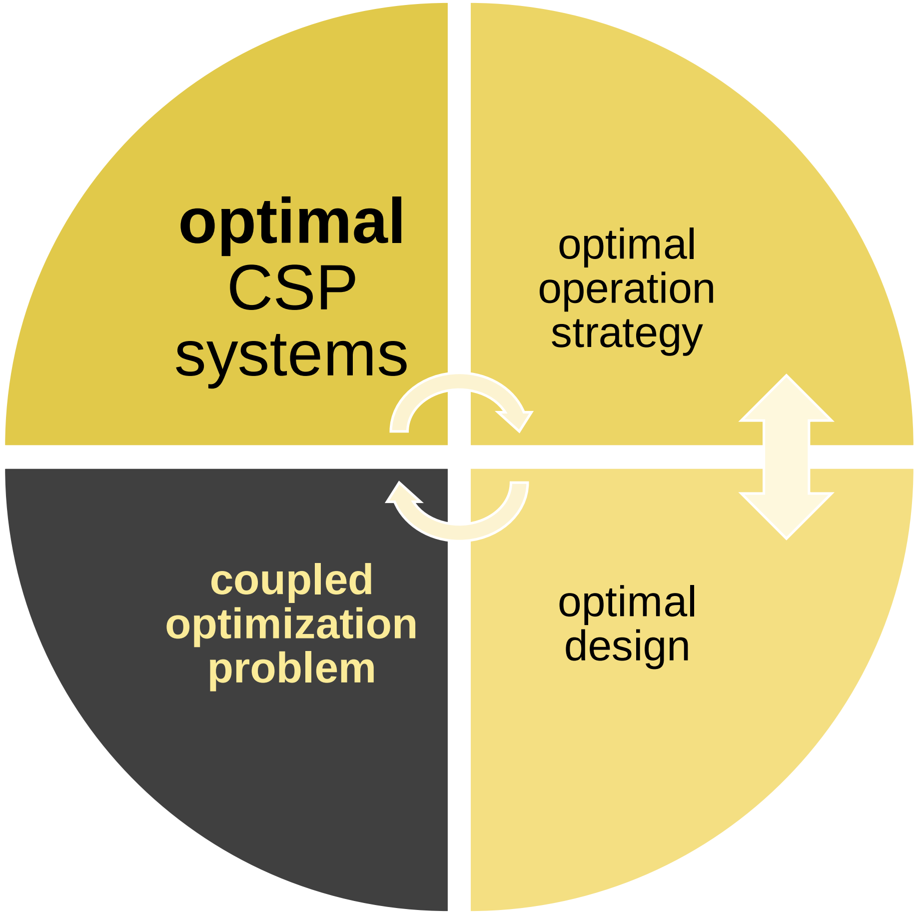
Impact of Model Simplifications

$$
\begin{aligned}
\min_{\boldsymbol{x}}\ & F_I(\boldsymbol{x}) + \sum_{s\in\mathcal{S}} w_s\, F^*_{II,s}(\boldsymbol{x}) \\
\text{s.t.}\ & \boldsymbol{g}_I(\boldsymbol{x}) \le 0 \\
& \boldsymbol{h}_I(\boldsymbol{x}) = 0 \\
& \left.\begin{aligned}
F^*_{II,s}(\boldsymbol{x}) = \min_{\boldsymbol{y}_s(\cdot)}\ & F_{II,s}(\boldsymbol{x}, \boldsymbol{y}_s(\cdot)) = \int_{\mathcal{T}_s} \dot{F}_{II}(\boldsymbol{x}, \boldsymbol{y}_s(t), \boldsymbol{p}_s(t))\, \mathrm{d}t \\
\text{s.t.}\ & \boldsymbol{y}^{\mathrm{d}}_s(t=0) = \boldsymbol{y}^{\mathrm{d}}_{s,0} \\
& \left.\begin{aligned}
& \dot{\boldsymbol{y}}^{\mathrm{d}}_s(t) = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}_s(t), \boldsymbol{p}_s(t)) \\
& \boldsymbol{g}_{II}(\boldsymbol{x}, \boldsymbol{y}_s(t), \boldsymbol{p}_s(t)) \le 0 \\
& \boldsymbol{h}_{II}(\boldsymbol{x}, \boldsymbol{y}_s(t), \boldsymbol{p}_s(t)) = 0 \\
& \boldsymbol{y}_s(t) = [\boldsymbol{y}^{\mathrm{d}}_s(t), \ldots] \\
& \boldsymbol{y}_s(t) \in \mathcal{Y}_s(t) \subset \mathbb{R}^{n_y} \times \mathbb{Z}^{m_y}
\end{aligned}\right\}\ \forall t \in \mathcal{T}_s \\
& \mathcal{T}_s = [0, T_s]
\end{aligned}\right\}\ \forall s \in \mathcal{S} \\
& \boldsymbol{x} \in \mathcal{X} \subset \mathbb{R}^{n_x} \times \mathbb{Z}^{m_x} \\
& \mathcal{S} = \{s_1, s_2, \cdots, s_{|\mathcal{S}|}\}
\end{aligned}
$$

OPTIMIZATION OF CSP SYSTEMS

Langiu et al., COMANDO: A Next-Generation Open-Source Framework for Energy Systems Optimization, Computers and Chemical Engineering 2021

Optimization of CSP Systems: A Coupled Optimization Problem

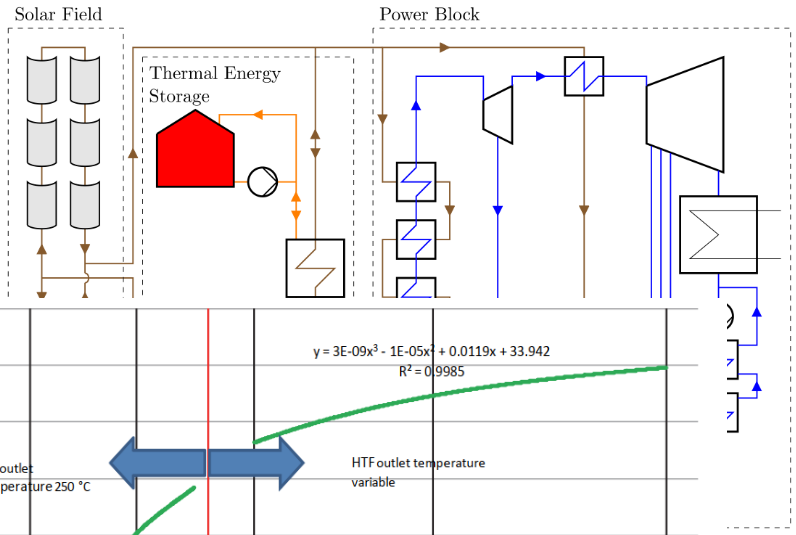


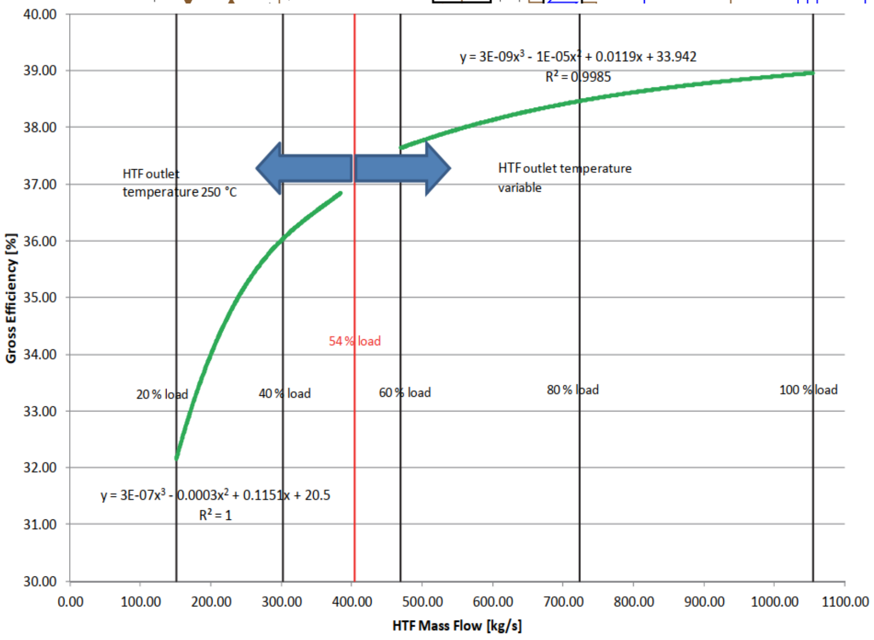
Annual Yield Assessment of CSP Systems

$$\frac{dE^{SF}}{dt} = \dot{Q}_{avail} - \sum \dot{Q}_{loss} + \sum \dot{Q}_{gain}$$

$$\dot{Q}^{SF} = \dot{Q}_{avail} - \sum \dot{Q}_{loss} + \sum \dot{Q}_{gain}$$

- annual yield assessment
  - typical operational year
  - time steps of 15 - 60 min
  - quasi-dynamic modeling
  - mass flow based approach
  - equation based and data driven models
  - discrete and continuous variables
  - non linear dependencies

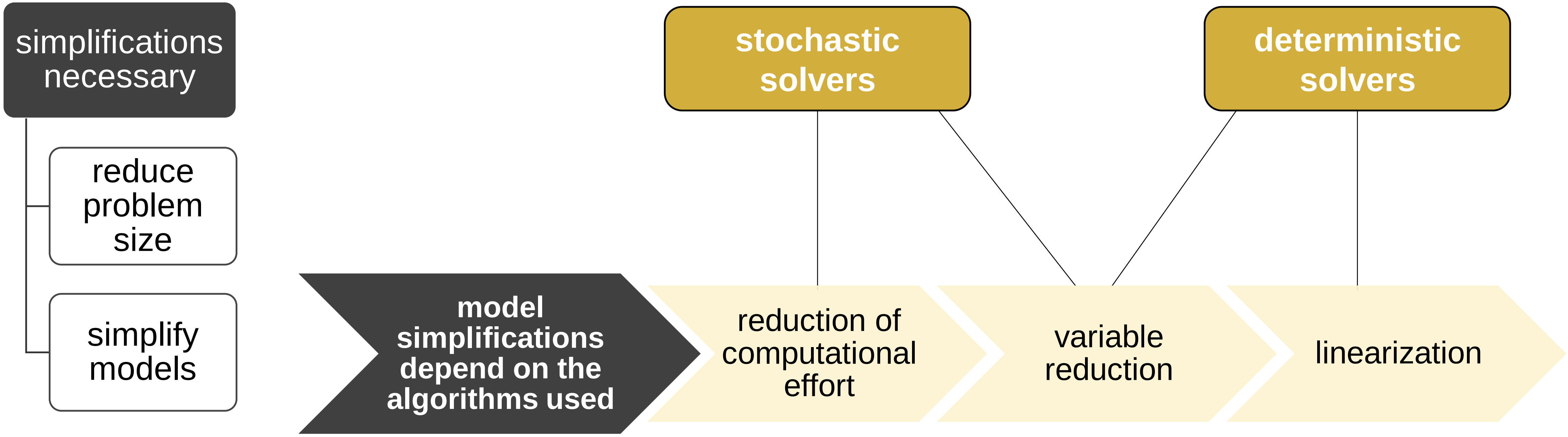




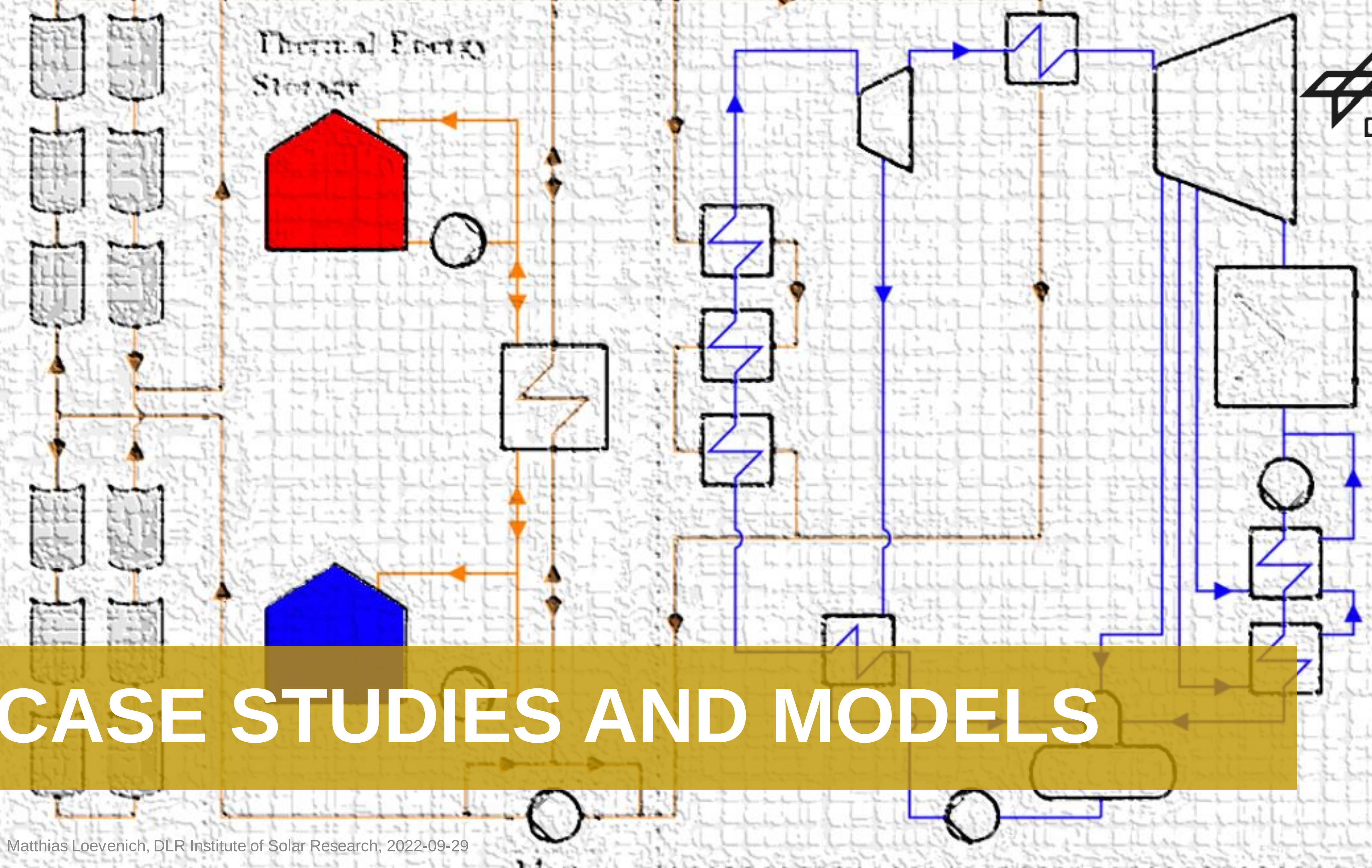
SolarPACES Guideline for bankable STE Yield Assessment

- complex Mixed Integer Nonlinear Problem (MINLP)
- simplifications are necessary to solve the optimization problem efficiently

Todays Topic: Model Simplifications

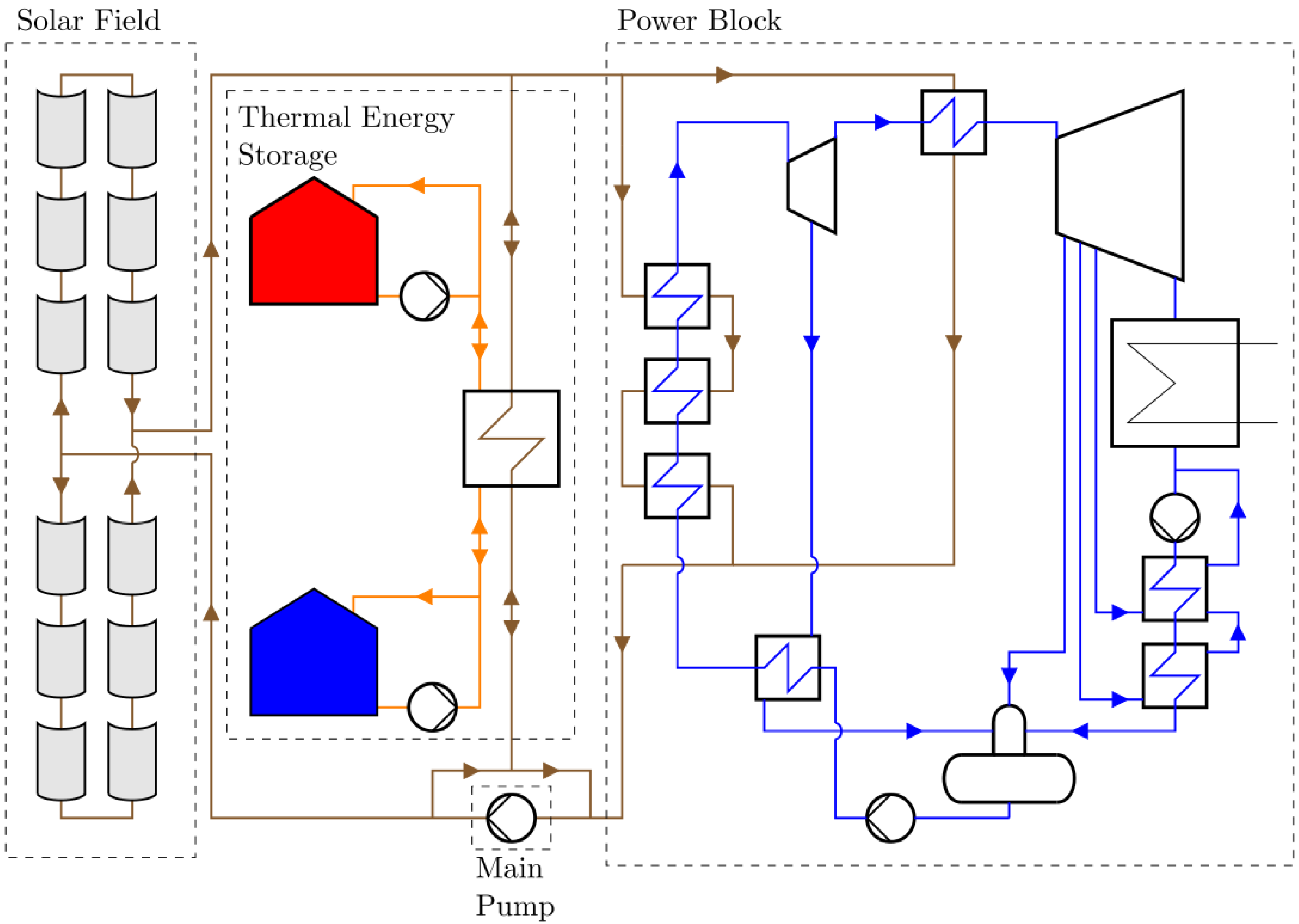


- investigate the **influence of model simplifications** on the typical operational year to **interpret and tune** the results of the **optimization**



CASE STUDIES AND MODELS

Case Study: CSP Trough Plant for 45 MW constant Load



PB gross el. Power	50 MW
PB net el. Power	45 MW
PB gross therm. Efficiency	39,42 %
SF nom. Heat	264 MW
SF Mirror Area	560 000 m^2
SF nom. outlet Temp.	393 °C
TES Capacity	7.5 h
HTF	Therminol VP1

Case Study: Investigated Sites

Site	Annual DNI [kWh/m^2]	Annual GHI [kWh/m^2]	T_{amb} [°C]	φ_{amb} [%]
Cordoba (Spain)	2077	1700	19	62
Riyadh (Saudi Arabia)	2275	2240	26	33
Phoenix (USA)	2704	2119	23	32

Reference Model

- state of the art quasi-dynamic model
- mass flow based modeling approach
- following SolarPACES Guideline for bankable STE Yield Assessment
- 15 min time steps with adaptive time stepping
- solar driven operation fulfilling a load curve
- simulations performed with ***YACOP*** by DLR

Solar Field

- equation based
- no spatial discretization
- instationary energy balance with correction factors for heat up and cool down

Thermal Energy Storage

- equation based
- heat exchanger model using LMTD-method

Fluid Pump

- equation based

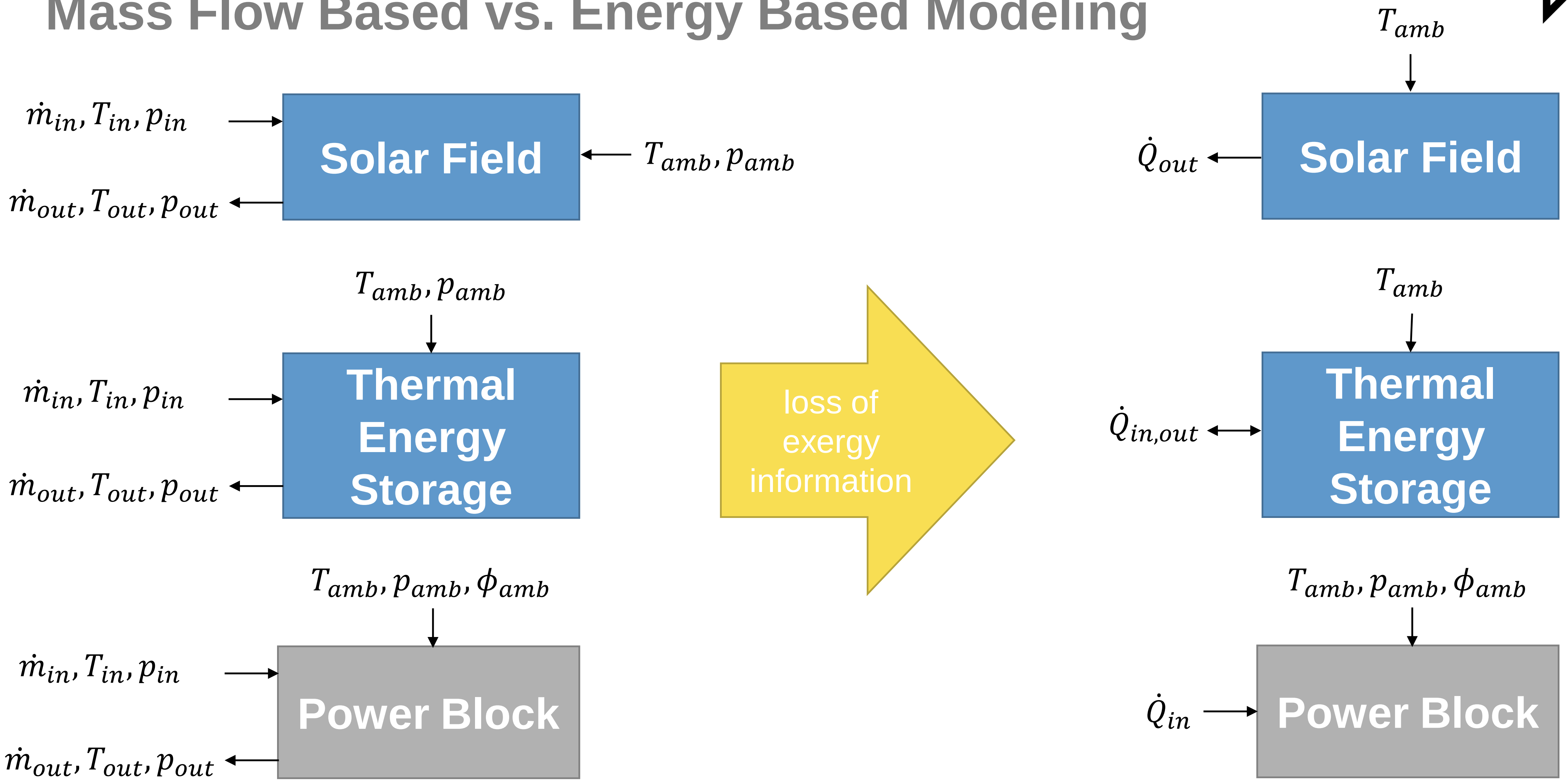
Power Block

- data driven
- steady state points from EBSLION
- T_{in}, $\dot{m}_{in}$, p_{in}, T_{amb}, p_{amb}, φ_{amb}
- instationary energy balance with correction factors for heat up and cool down

Model Simplifications
Time Step and Energy Based Models

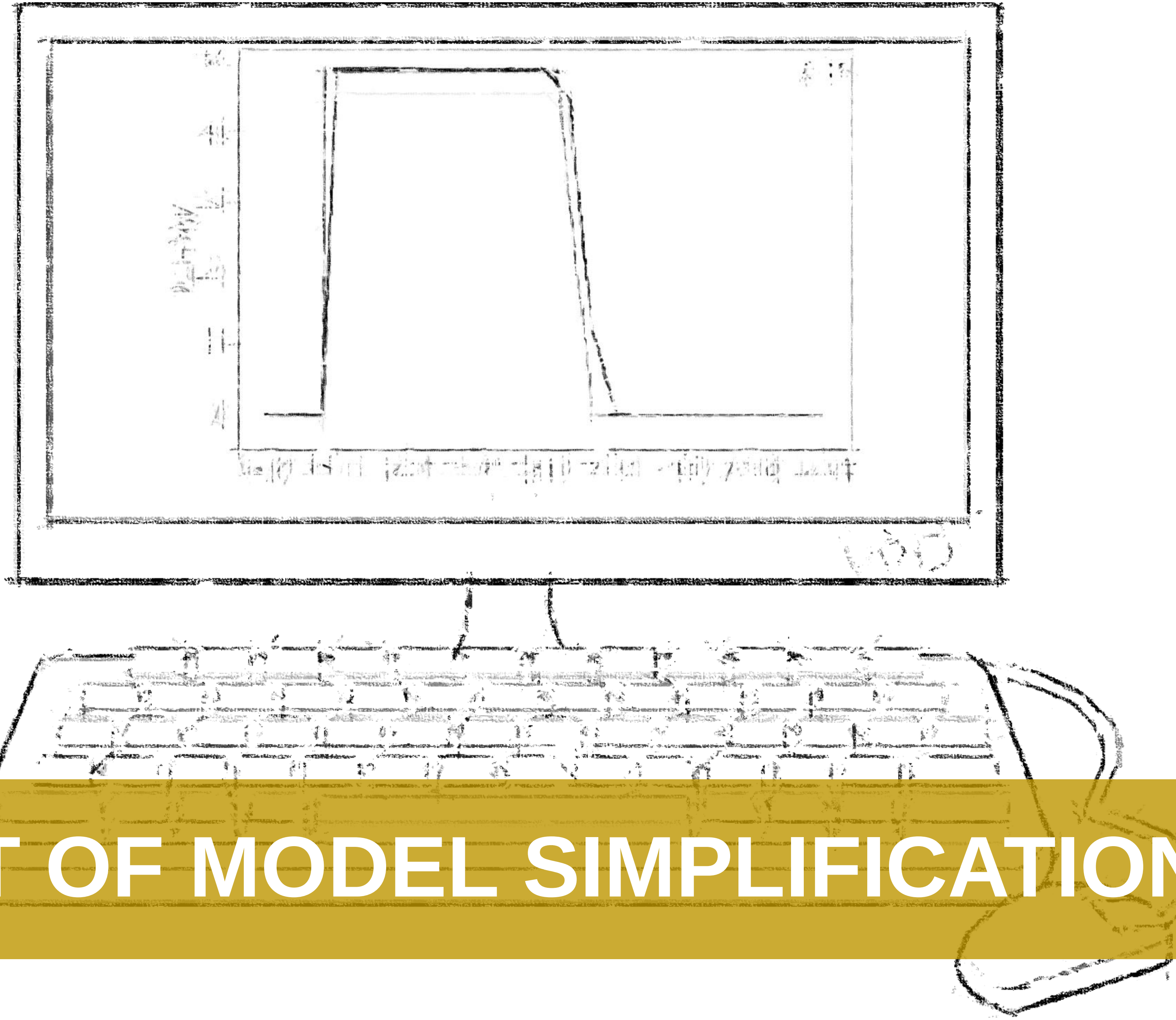
M0	M1	M2	M3
mass flow based model	mass flow based model	energy based model	energy based model
15 min time steps	60 min time steps	15 min time steps	60 min time steps

Model Simplifications
Mass Flow Based vs. Energy Based Modeling



Model Simplifications
Power Block Model

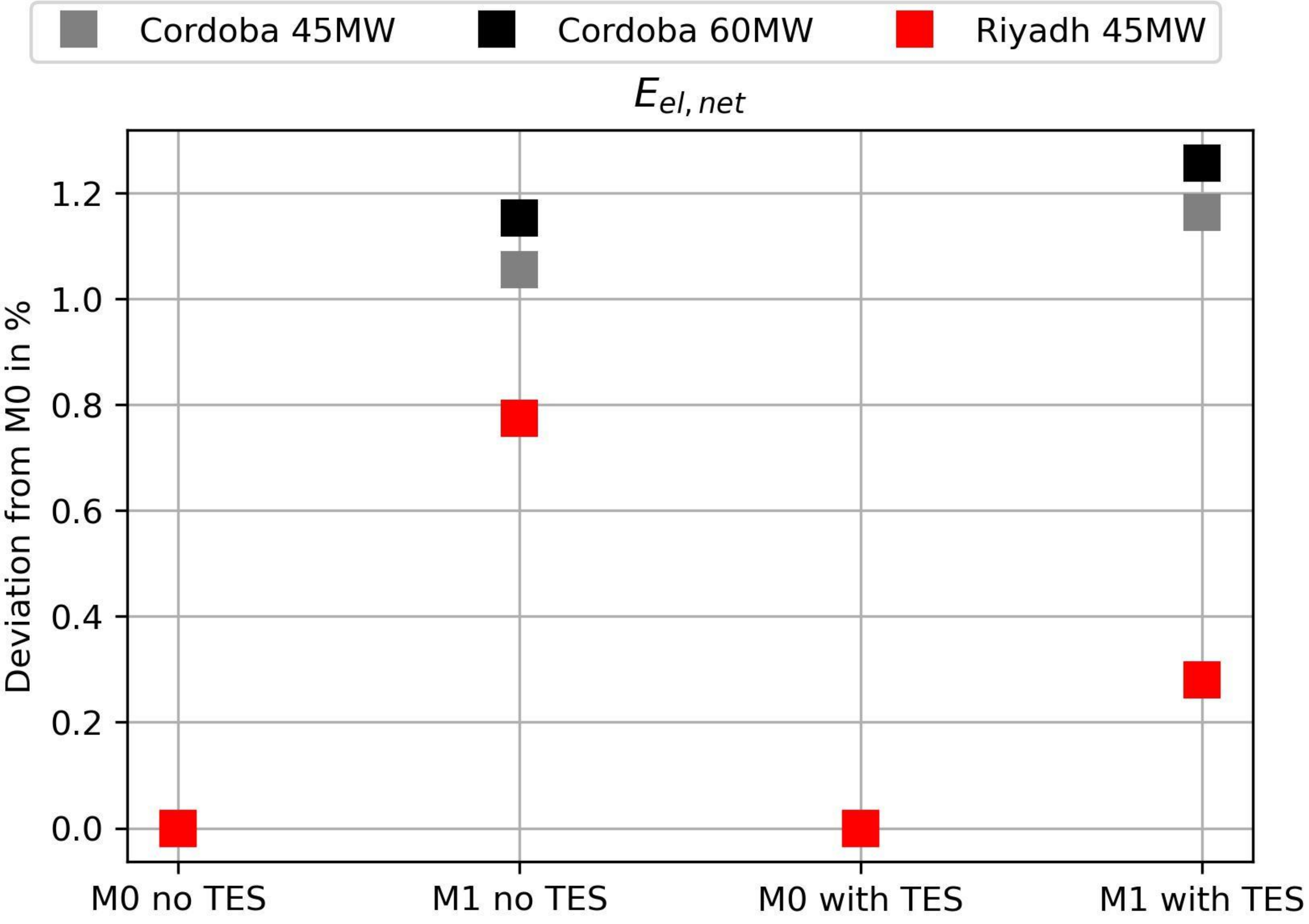
M3	M4	M5	M6
energy based model	energy based model	energy based model	energy based model
60 min time steps	60 min time steps	60 min time steps	60 min time steps
	power block neglects ambient conditions	power block neglects ambient conditions	power block neglects ambient conditions
		power block uses piecewise linear approximation	power block efficiency constant



IMPACT OF MODEL SIMPLIFICATIONS

https://paintingvalley.com/sketches/desktop-computer-sketch-10.png

Impact of Time Step Size

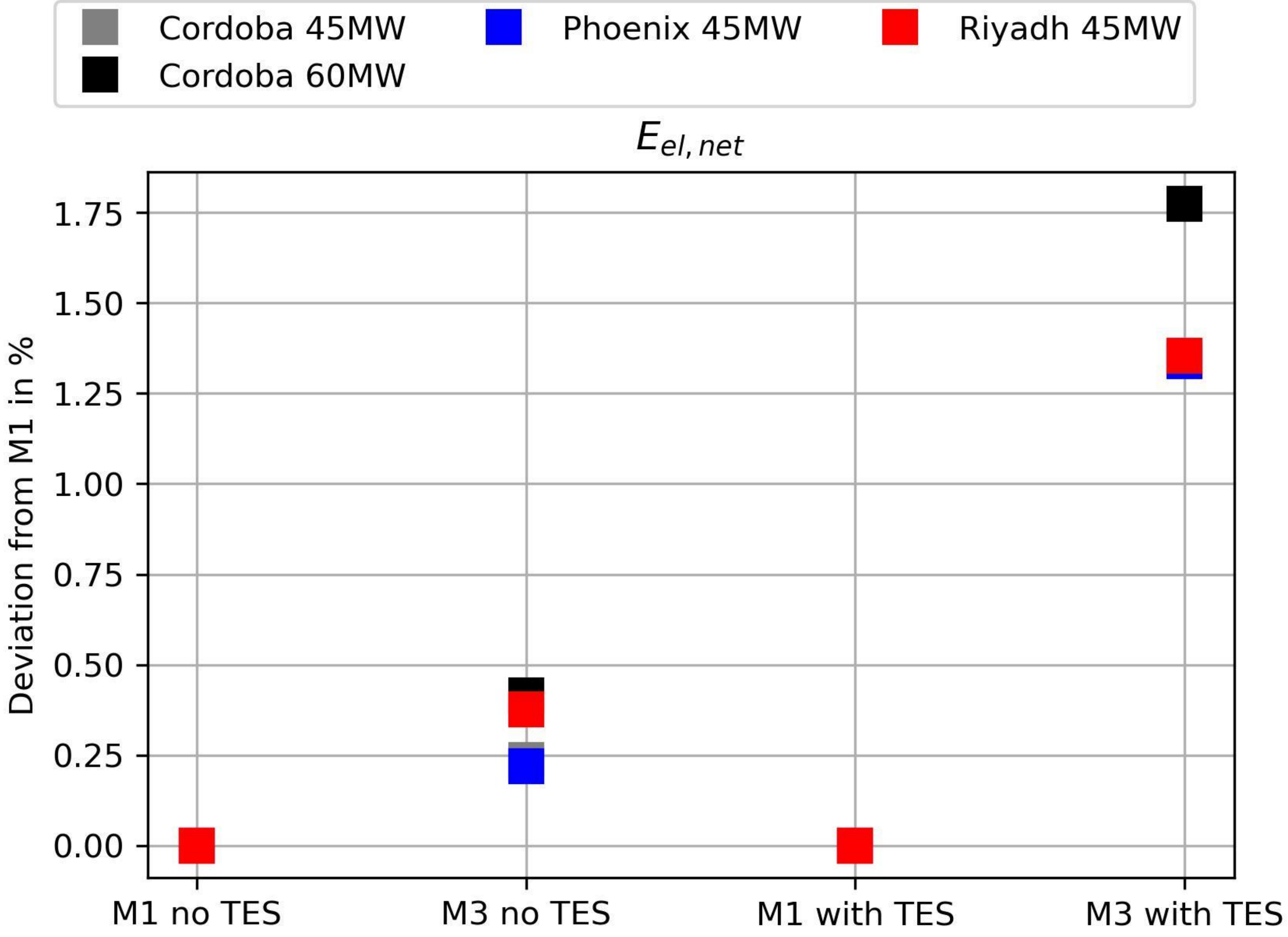


larger time steps lead to a slight overestimation of annual electrical yield

- increase in time of operation due to larger time steps
- neglection of short radiation dips
- similar trend with and without TES

M0	MFB	15 min
M1	MFB	60 min

Impact of Energy Based Modeling

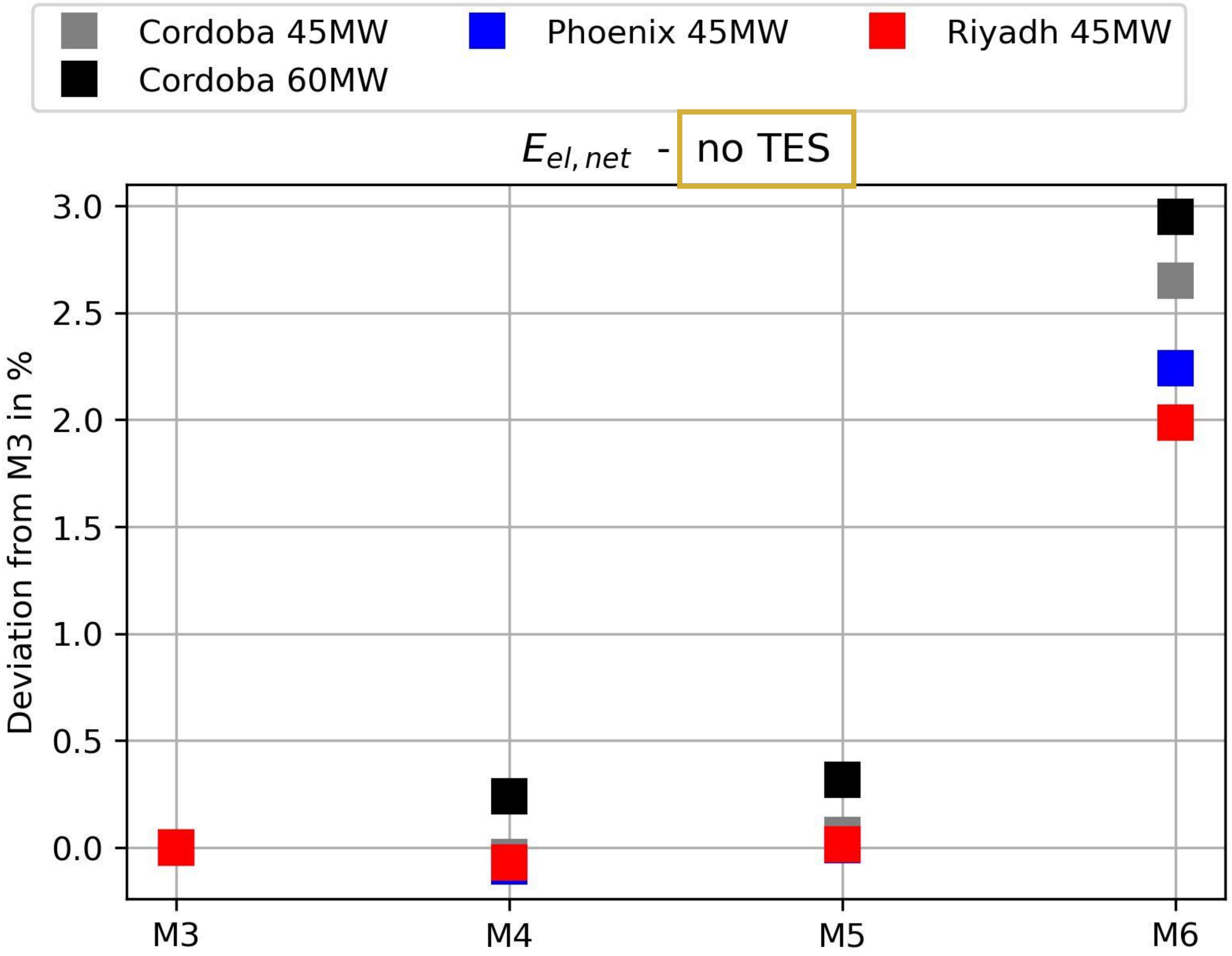


energy based modeling leads to an overestimation of annual electrical yield for models with TES

- overestimation of PB efficiency due to loss of exergy information in the PB
- higher PB operation time due to loss of exergy information in the storage
- underestimation of parasitics due to loss of control variables

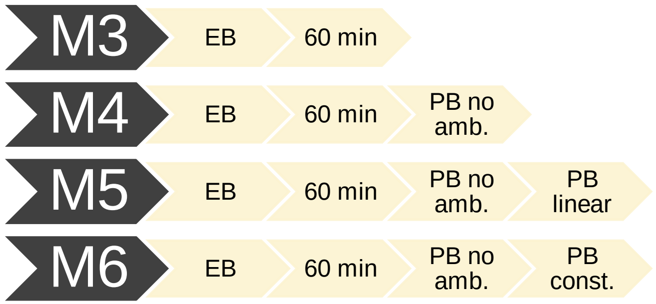
M1	MFB	60 min
M3	EB	60 min

Impact of Power Block Simplifications

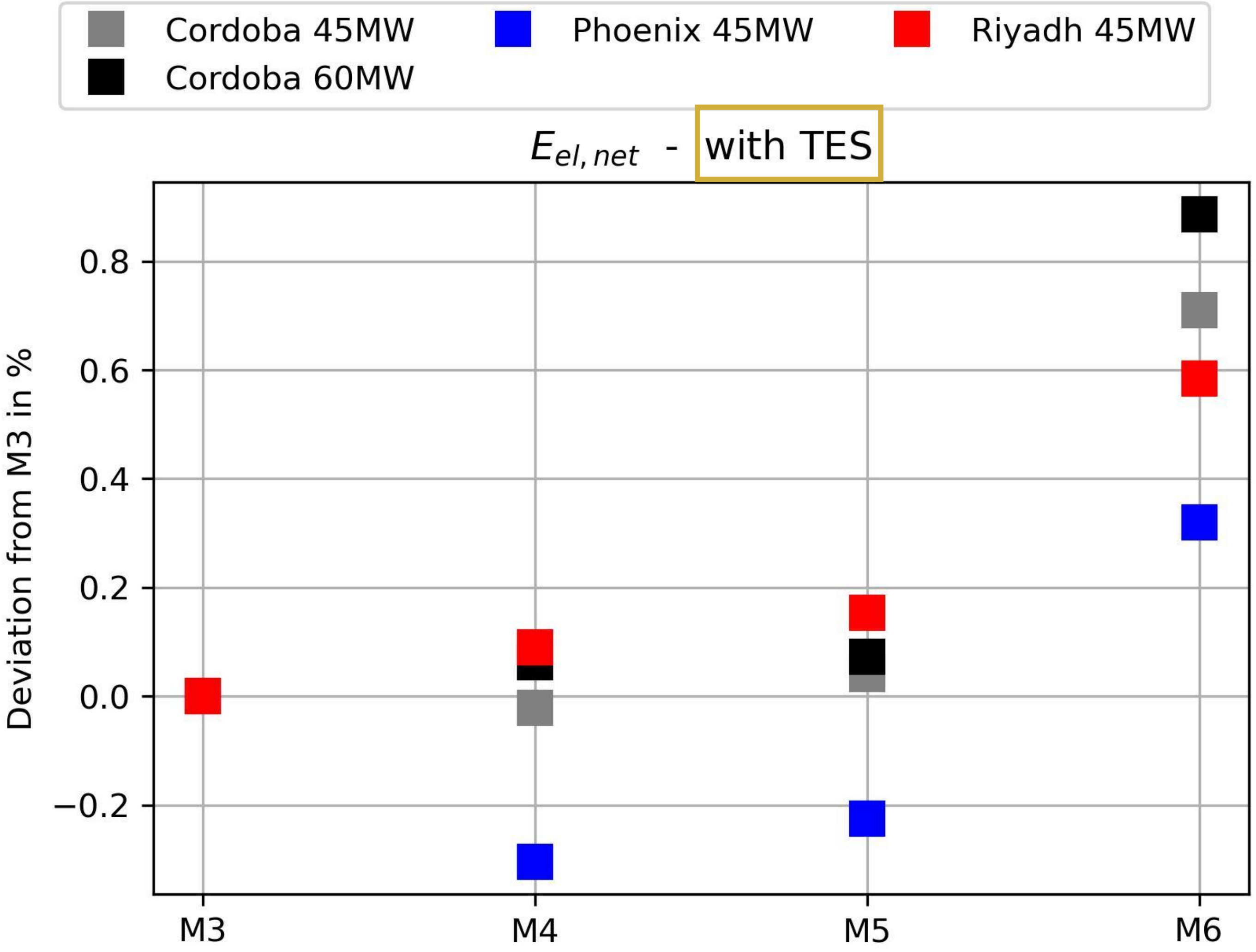


electrical yield increases with degree of PB simplification

- ambient conditions and linearization have little impact
- constant PB efficiency leads to a significant increase

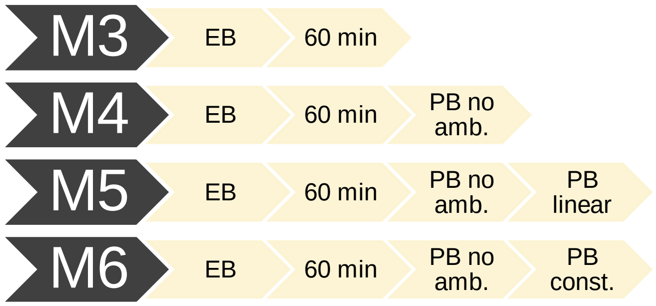


Impact of Power Block Simplifications

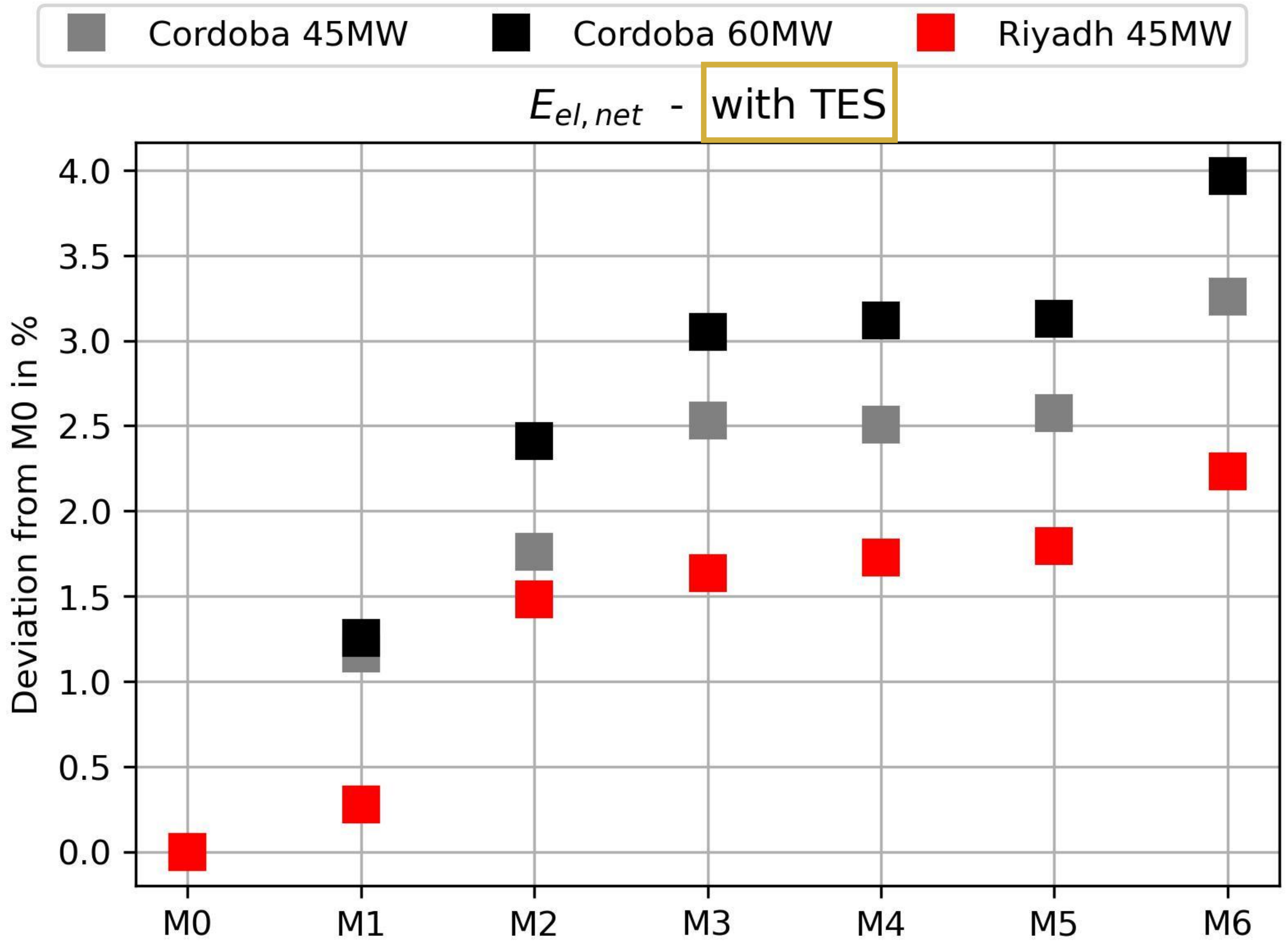


TES smoothes out impact of PB simplifications on electrical yield

- more operation close to design point due to larger solar field
- PB not designed for Phoenix



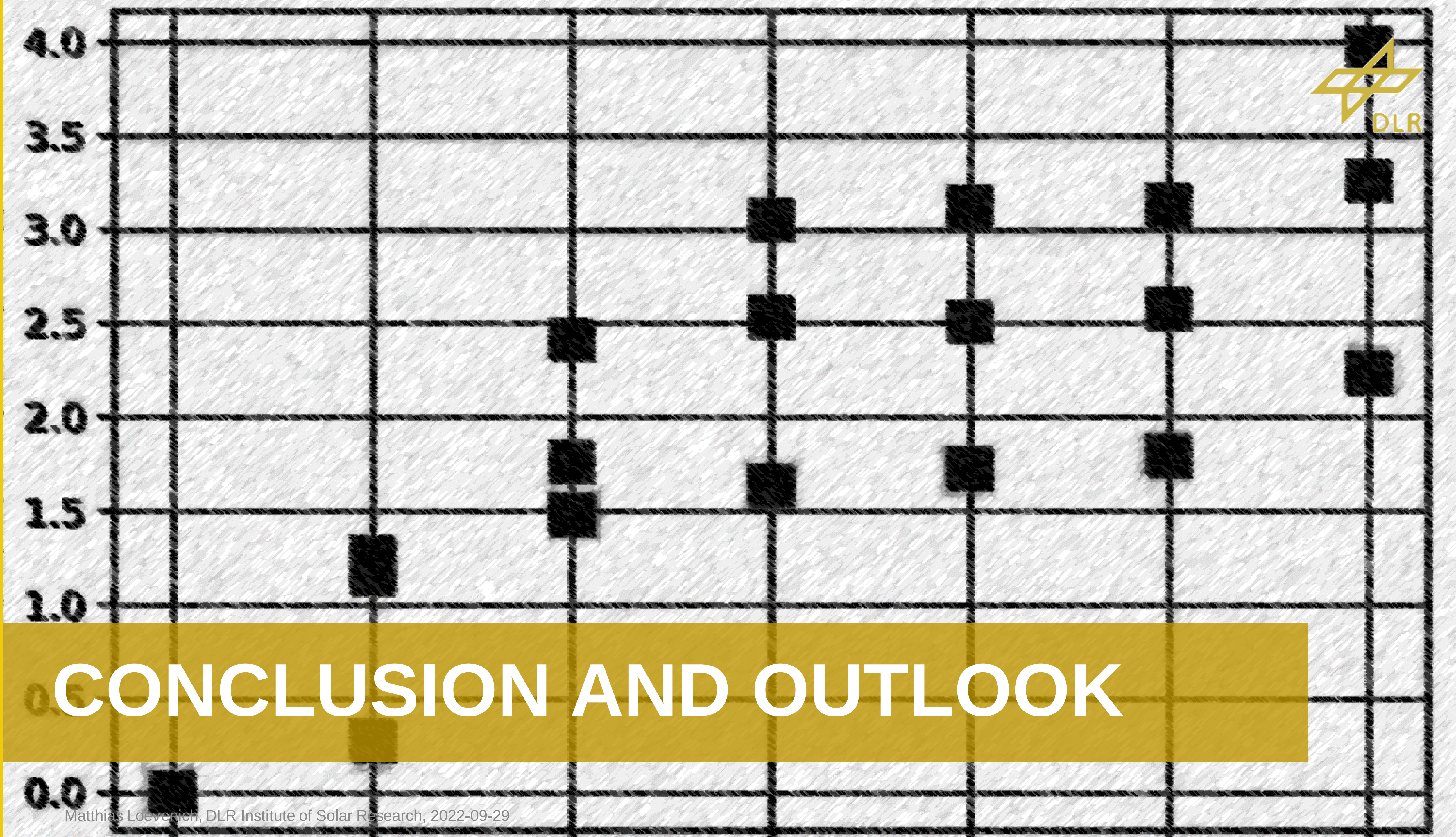
Classification of the Results



deviations in annual electrical yield do not exceed 4 %

- moderate value for annual yield assessment

M0	MFB	15 min		
M1	MFB	60 min		
M2	EB	15 min		
M3	EB	60 min		
M4	EB	60 min	PB no amb.	
M5	EB	60 min	PB no amb.	PB linear
M6	EB	60 min	PB no amb.	PB const.



CONCLUSION AND OUTLOOK

Conclusion

impact of model simplifications investigated on exemplary CSP trough plant

- time step size
- mass flow based vs. energy based modeling
- power block model simplifications

investigated simplifications have only a moderate influence on the annual electrical yield (< 4%)

time steps of 60 min lead to an overestimation of around 1 % compared to 15 min

energy based modeling leads to an overestimation of up to 2 % for models with indirect thermal energy storage

influence of heat input on the power block performance should be considered in annual yield assessment models

Outlook

enlarge the study for other CSP configurations and sites	how representative are the results obtained so far?
continue the study for CSP hybrid configurations	does the hybrid character induce more deviations?
investigate impact of simplifications on accuracy and performance of optimization algorithms	what error and direction of error can be expected from different optimization algorithms?

essentially,
all models are wrong,
but some are useful

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THANK YOU FOR YOUR ATTENTION!

https://freshspectrum.com/simulation/

Impressum

Topic: **Impact of Model Simplifications on the Annual Yield of CSP Systems**

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Author: Matthias Loevenich, PhD Student at DLR Institute of Solar Research

Supervisor: Robert Pitz-Paal, Jürgen Dersch

Institute: DLR Institute of Solar Research

Credits: SolarPACES Banner from https://www.solarpaces-conference.org/
Solar Energy System Images by DLR SF STS
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Cartoon Cite G. E. P. Box from https://freshspectrum.com/simulation
Two-Stage Optimization picture from Langiu et al., COMANDO: A Next-Generation Open-Source Framework for Energy Systems Optimization, Computers and Chemical Engineering 2021
Cartoon Tower-PC from https://paintingvalley.com/sketches/desktop-computer-sketch-10.png