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SUPERVISORY CONTROL OF A COMBINED HEAT AND POWER PLANT BY ECONOMIC OPTIMIZATION

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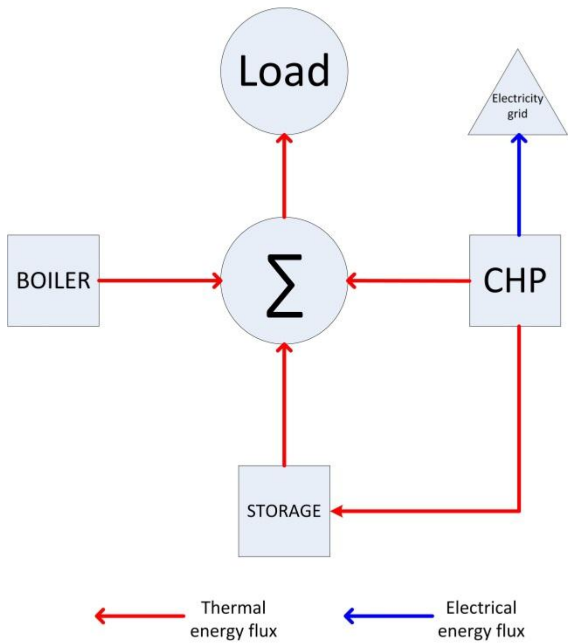
OUTLINE

- SYSTEM
  - System Boundaries
  - Operating States
  - Inputs & Outputs
- COST FUNCTION
  - Constraints
  - Mathematical Formulation
- IMPLEMENTATION
- RESULTS
  - Comparison of Heat-driven & Power-driven operation

SYSTEM

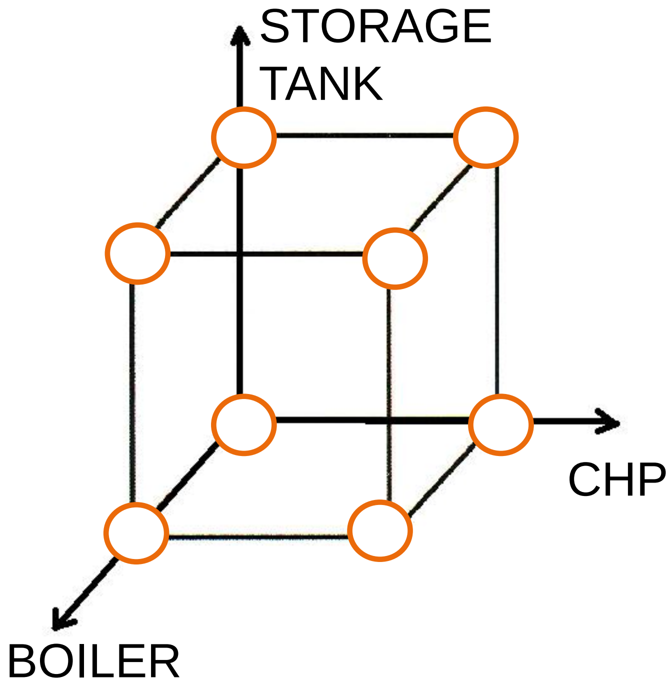
System Boundaries



<u>Assumptions</u>

- Heat Load and Prices are assumed to be perfectly predicted.
- All units may operate throughout a year.
- Electricity is only sold to the grid.
- Investment and maintenance costs are ignored.

Operating States



State 1 : CHP

State 2 : CHP + Boiler

State 3 : CHP + Storage

State 4 : CHP + Boiler + Storage

State 5 : Boiler + Storage

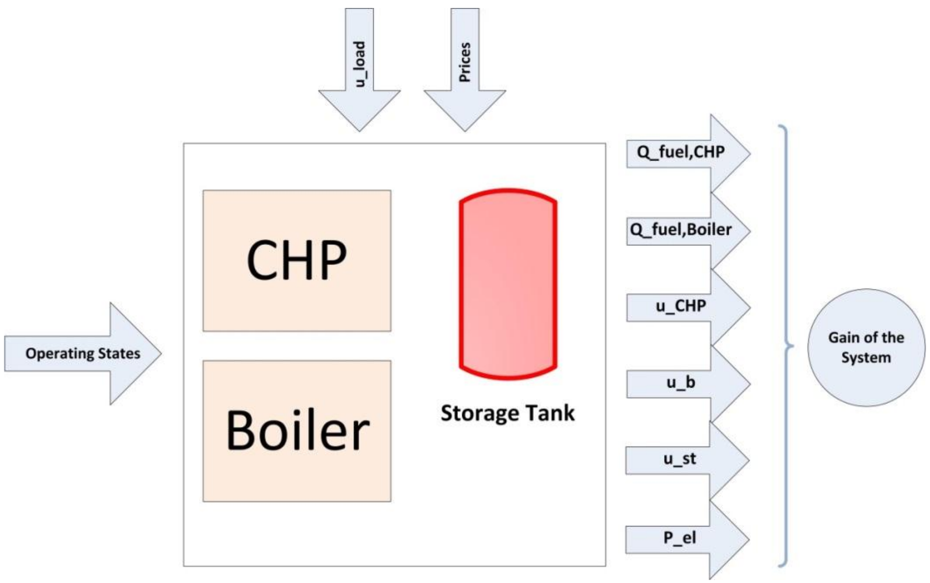
State 6 : Storage

State 7 : Boiler

State 8 : None

*Not all of them are decision variables!

Inputs & Outputs



Legend

$Q_{\text{fuel,CHP}}$: Fuel consumption at CHP

$Q_{\text{fuel,Boiler}}$: Fuel consumption at Boiler

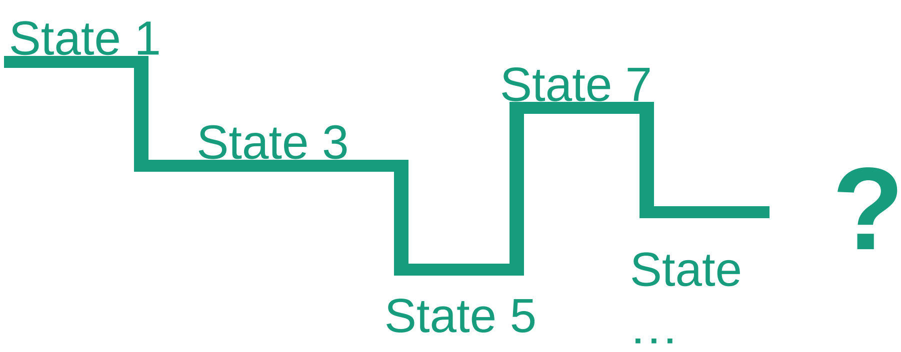
u_{CHP} : Heat supply by CHP

u_{b} : Heat supply by Boiler

u_{st} : Heat supply by Storage

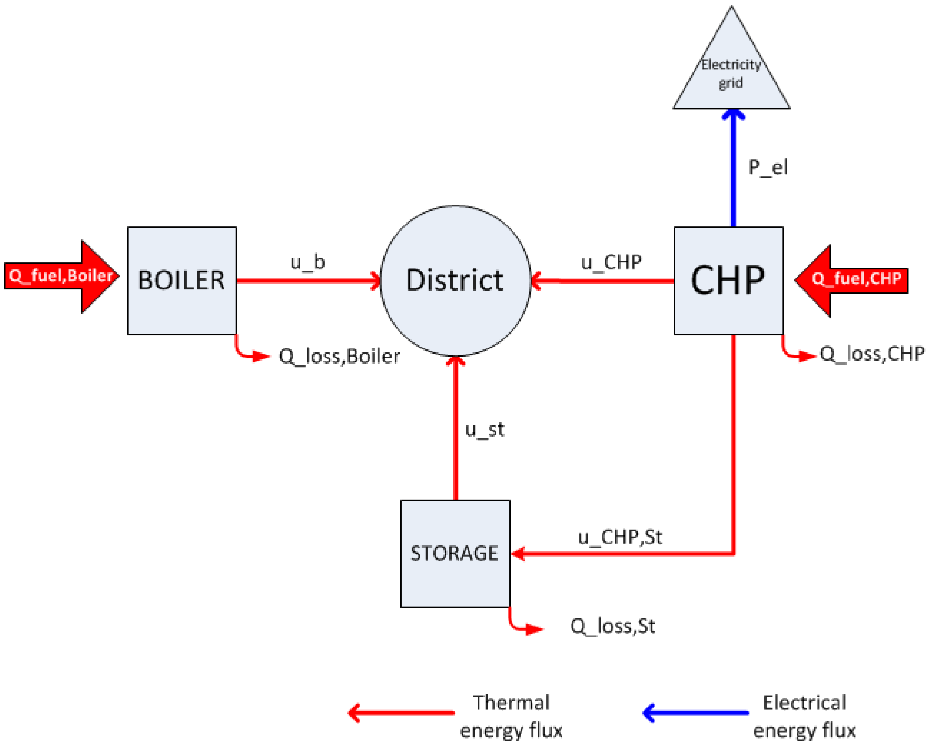
P_{el} : Electricity Production

u_{load} : Heat Load



COST FUNCTION

Gains of units



$$J_{\text{CHP}} = \{ [P_{\text{el}} \cdot c_{\text{el}} + u_{\text{CHP}} \cdot c_{\text{heat}}] - Q_{\text{fuel,CHP}} \cdot c_{\text{gas}} \} \cdot \tau$$

$$J_{\text{Boiler}} = [u_{\text{b}} \cdot c_{\text{heat}} - Q_{\text{fuel,Boiler}} \cdot c_{\text{fuel}}] \cdot \tau$$

$$J_{\text{Storage}} = [u_{\text{st}} \cdot c_{\text{heat}}] \cdot \tau$$

$$J_T = J_{\text{CHP}} + J_{\text{Boiler}} + J_{\text{Storage}}$$

Legend

$Q_{\text{fuel,CHP}}$: Fuel consumption at CHP

$Q_{\text{fuel,Boiler}}$: Fuel consumption at Boiler

u_{CHP} : Heat supply by CHP

u_{b} : Heat supply by Boiler

u_{st} : Heat supply by Storage

P_{el} : Electricity Production

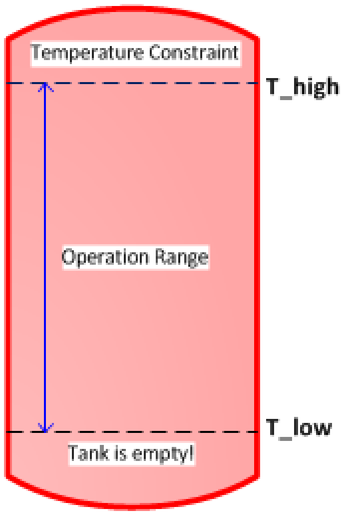
c_{el} , c_{heat} , c_{gas} : Prices

J_{CHP} , J_{Boiler} , J_{Storage} : Gains

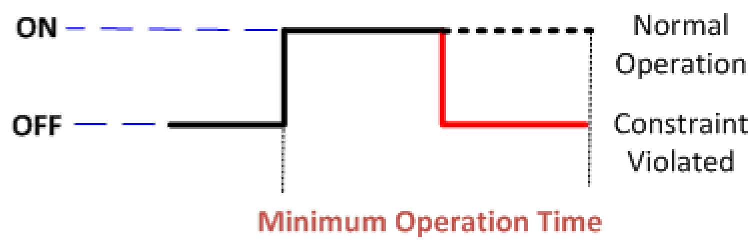
$Q_{\text{loss,CHP}}$, $Q_{\text{loss,Boiler}}$, $Q_{\text{loss,St}}$: Losses

Constraints

Temperature Constraint



Minimum Operation Time Constraint at CHP



Mathematical Formulation of the Cost Function

$$J_{\mathrm{T}} = max \sum_{t=1}^{H_p} \left(J_{\mathrm{CHP}}^{(t)} \cdot b_1^{(t)} + J_{\mathrm{Storage}}^{(t)} \cdot b_2^{(t)} + J_{\mathrm{Boiler}}^{(t)} \cdot b_3^{(t)} \right)$$

$$subject\ to \qquad T_{\mathrm{s}}^{(t)} < T_{\mathrm{high}}$$

(Temperature Constraint)

$$when\ \ b_1^{(t)} - b_1^{(t-1)} \neq 0, \qquad then \sum_{k=t}^{(t+t_{min})} \left\| b_1^{(k)} - b_1^{(k-1)} \right\| = 0$$

(Minimum Operation Time Constraint)

Table 1. Operating States based on binary variables

States	b_1	b_2	b_3
1	1	0	0
2	1	0	1
3	1	1	0
4	1	1	1
5	0	1	1
6	0	1	0
7	0	0	1
8	0	0	0

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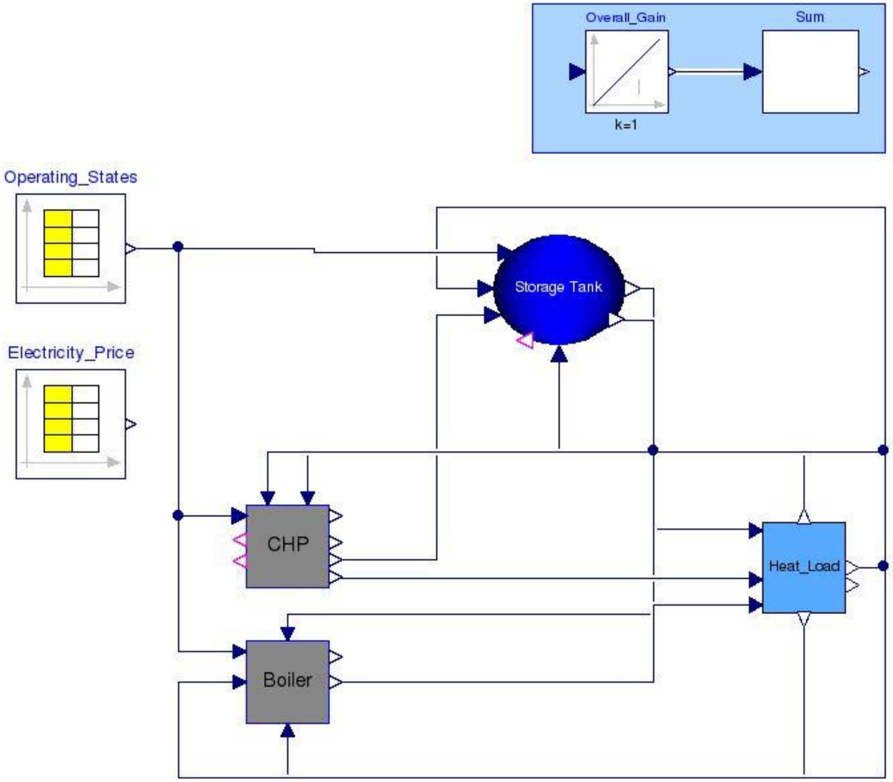
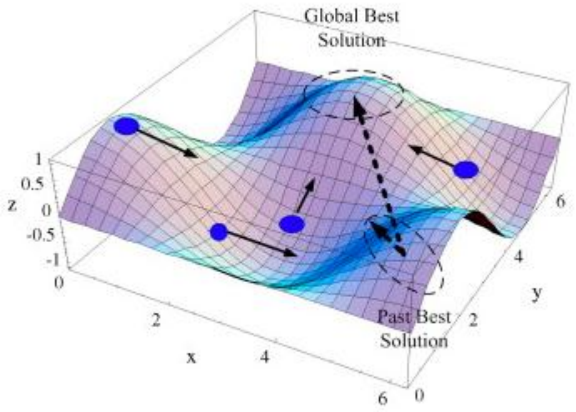
IMPLEMENTATION



- Modelica/Dymola for Modeling & Simulation
- GenOpt (Generic Optimization Program) with Particle Swarm Optimization (PSO) Algorithm

PSO

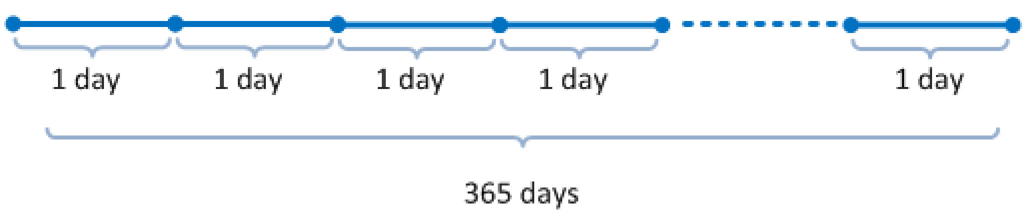
- Population based stochastic algorithm
- Inspired by swarm intelligence (bird flocks, fish schools etc.)
- particle best position & global best position



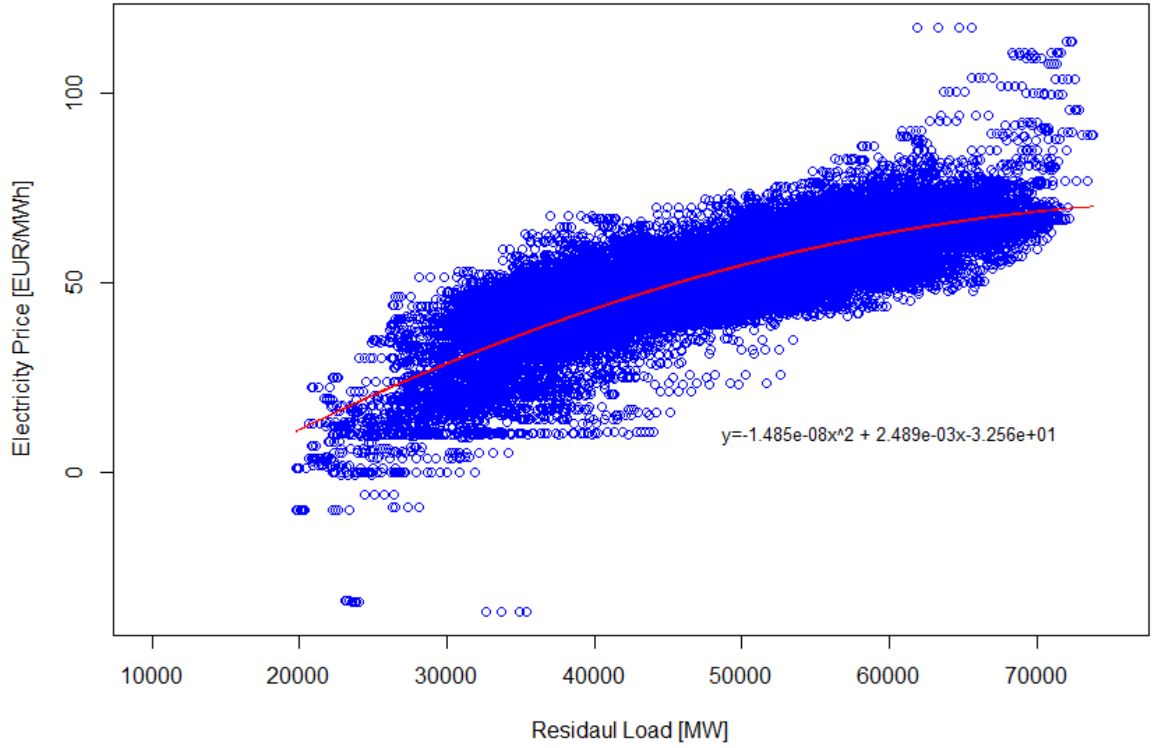
Particle velocity vectors in PSO [1]

RESULTS

- A Future Scenario (2023) is approximated for comparison.
- A heat-driven operation is chosen as a reference operation mode.
- Overall gains of heat-driven and power-driven operations for 1 year are compared. (365 sequential optimizations with prediction horizon of 1 day)



Residual Load & Electricity Prices (2011)



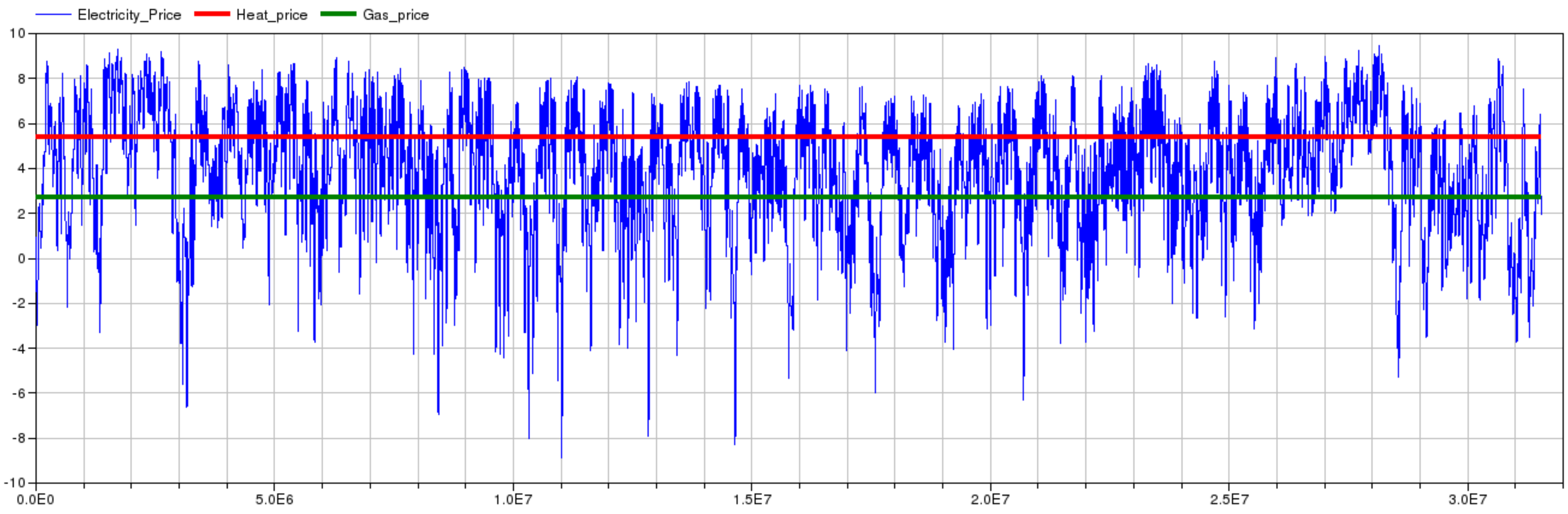
Electricity Prices (2023)

$$c_{\text{heat}} = 5{,}4\ \frac{ct.}{kWh}$$

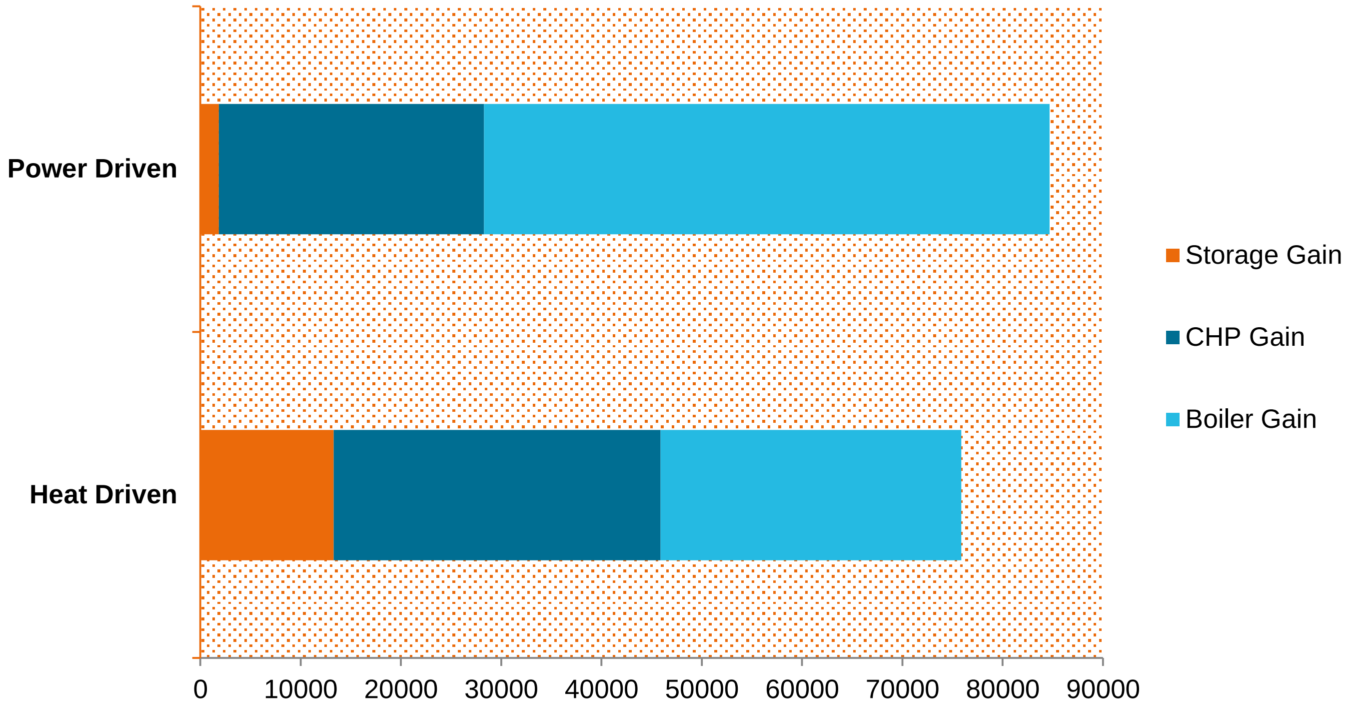
$$c_{\text{gas}} = 2{,}7\ \frac{ct.}{kWh}$$

Table 2. Power Capacities for the simulation scenario. [2]

Technology	Power Capacity [GW]
PV	61.3
Wind onshore	49.3
Wind offshore	14.1



Comparison of gains of two operations



	Heat Driven	Power Driven
Storage Gain	**13278**	**1831**
CHP Gain	**32623**	**26433**
Boiler Gain	**29977**	**56410**

Gains [€/year]

- **11 % increase in overall gains**

Comparison of CHP gains

Table 3. Comparison with respect to specific gains of the CHP

Operation Mode	CHP Gain	Operation Hours	Specific Gain
Heat Driven	32623 €/year	6210 hours	5,28 € / hour
Power Driven	26433 €/year	2300 hours	11,49 € / hour

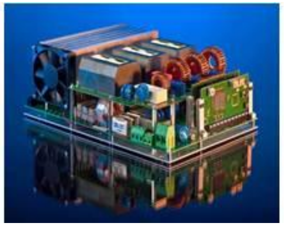
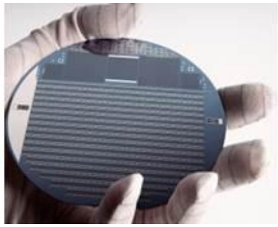
References

[1] Varadi, D., (2013) *Social learning algorithms : Particle Swarm Optimization (PSO)*

[2] Elci, M., & Oliva, A., & Herkel, S., & Klein, K., & Ripka, A. (2015) *Grid Interactivity of a Solar Combined Heat and Power District Heating System.* International Conference on Solar Heating and Cooling for Buildings and Industry, SHC 2014.

Thanks for your attention

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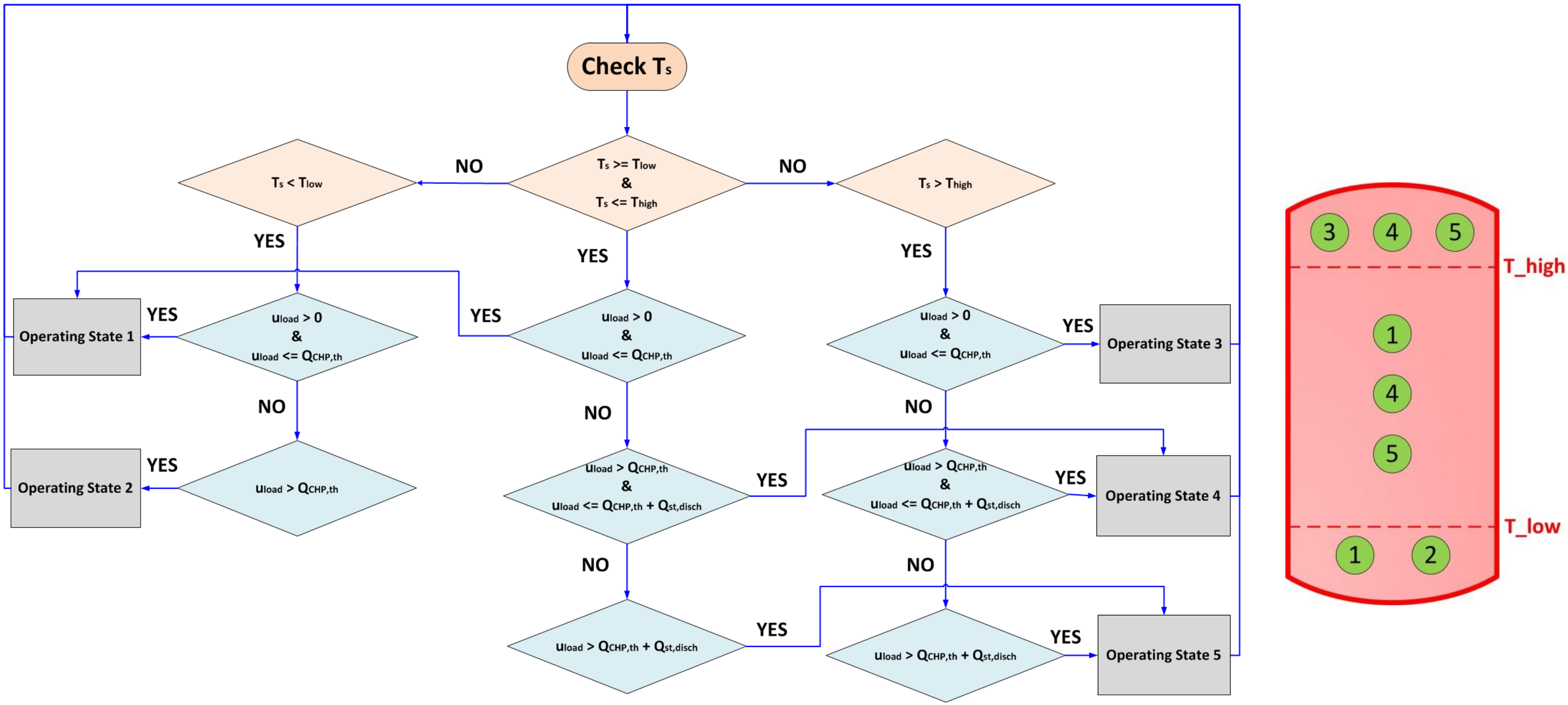
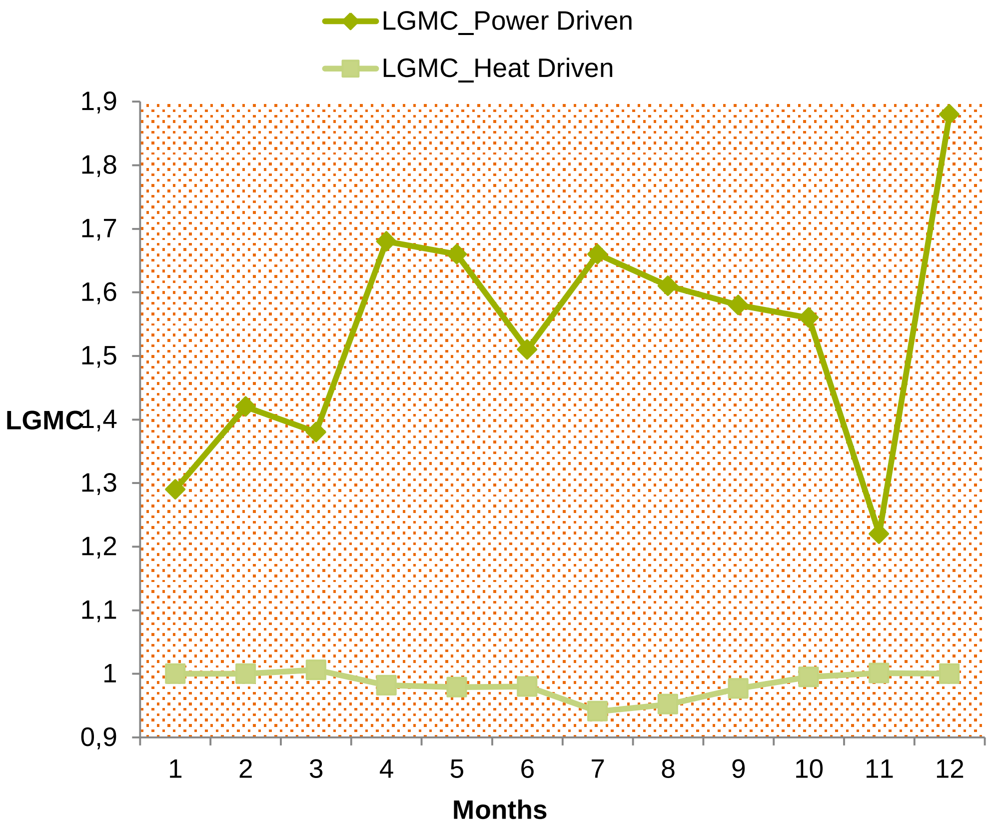
Heat Driven Model (Reference Model)



u_{load} = Heat load

$Q_{\text{CHP,th}}$ = CHP nominal thermal power

$Q_{\text{St,disch}}$ = Storage tank nominal discharge power



LGMC = Load-Grid Matching Coefficient

$$LGMC_{abs}(G) := \frac{\int P_{el}(\tau)\cdot G(\tau)\cdot d\tau}{W_{el}\cdot \bar{G}} \ [-]$$

$$where \quad W_{el} := \int P_{el}(\tau)\cdot d\tau \ [\mathrm{kWh}]$$

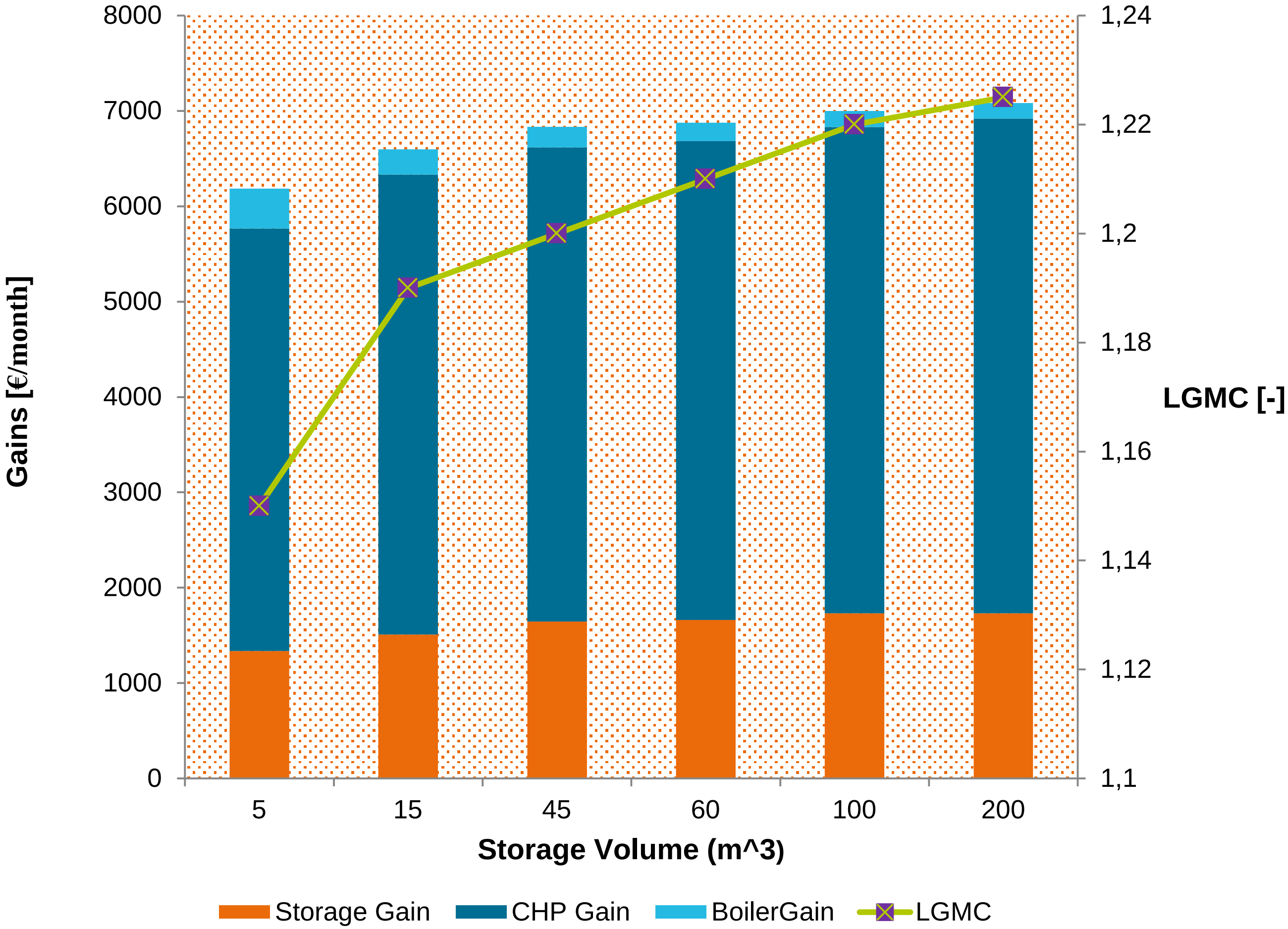
P_{el} : Electricity Production

G : Residual Load

LGMC > 1 : Grid favorable Production

LGMC < 1 : Grid adverse Production

LGMC = 1 : Grid-neutral behavior



Volume	CHP Operation Hours
5m3	417h
15m3	447h
45m3	458h
60m3	463h
100m3	467h
200m3	469h