4th International Conference on Smart Energy Systems and 4th Generation District Heating
Aalborg, 13-14 November 2018

Storage Influence in a Combined Biomass/Power-to-Heat Production Plant

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4th International Conference on Smart Energy Systems and 4th Generation District Heating 2018
#SES4DH2018

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4th Generation District Heating Technologies and Systems

French Energy Context

Domestic Hot Water and Space Heating in France:

→ 35% of total energy consumed (665 sur 1900TWh)

[1] Paardekooper, S., Lund, R. S., Mathiesen, B. V., Chang, M., Petersen, U. R., Grundahl, L., ... Persson, U. (2018). Heat Roadmap France: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps.

French Energy Planning (PPE 2016):

→ DHS must deliver 5 times more R&R Energy in 2030 (40TWh)

[2] « Programmation pluriannuelle de l'Energie », République Française, 2016.

Biomass will have a major role:

→ 50% of the energetic mix of DHS by 2030

[2] « Programmation pluriannuelle de l'Energie », République Française, 2016.

BUT Biomass should be considered as a limited resource:

→ Other significant R&R resources must be found

[3] Ericsson K, Nilsson LJ. Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass Bioenergy 2006;30:1-15.

Moreover, increasing amount of renewables on electric grid:

→ Surplus leading to over Voltage

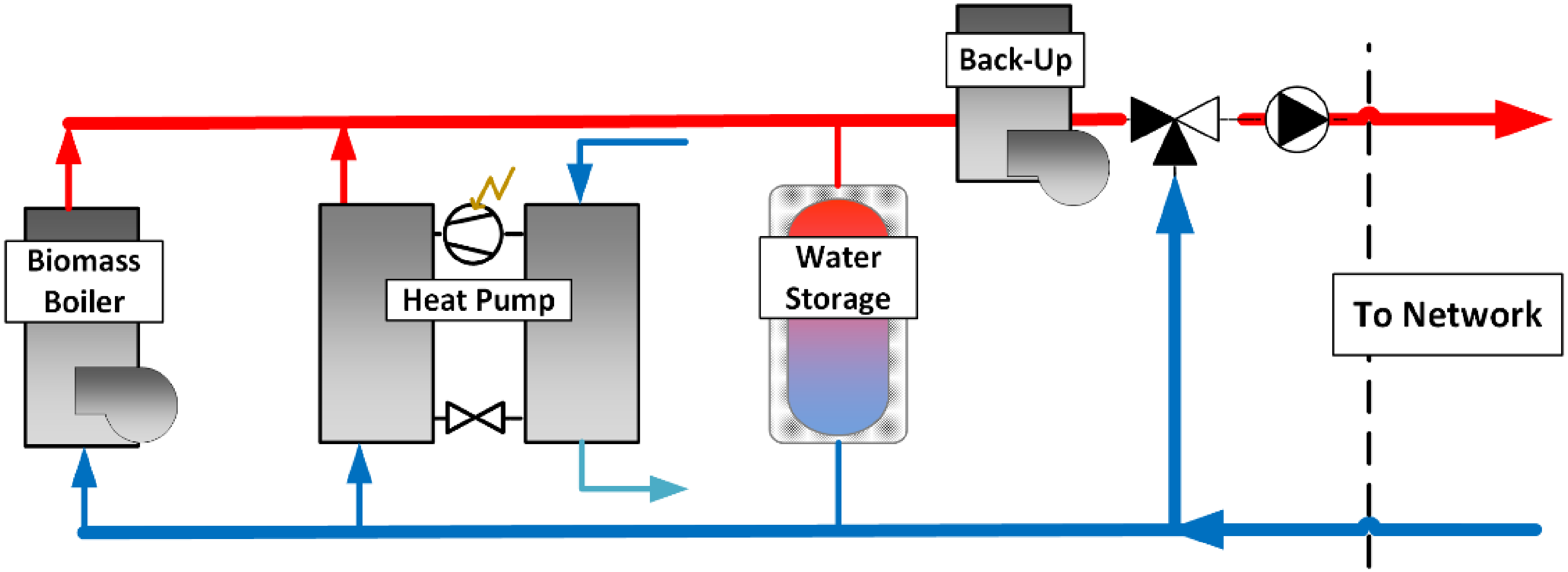
[4] Blarke MB, Jenkins BM. SuperGrid or SmartGrid: Competing strategies for large-scale integration of intermittent renewables? Energy Policy 2013;58:381–90
[5] Nielsen MG, Morales JM, Zugno M, Pedersen TE, Madsen H. Economic valuation of heat pumps and electric boilers in the Danish energy system. Appl Energy 2016;167:189-200

→ Power-to-Heat + Storage

→ **Flexibility to Electric Grid + Additional Significant R&R resources for DHN**

[6] H. Lund, et al. "4th Generation District Heating (4GDH)", Energy, vol. 68, pp. 1–11, 2014.

Production Plant Studied



Outlines

1) Sizing Methodology

2) Sizing Results

3) Operation of the system

1 - Sizing Methodology

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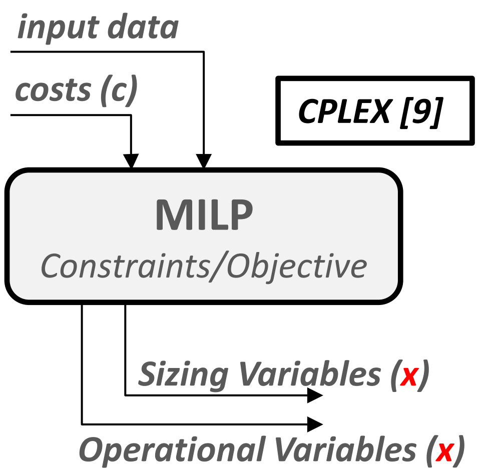
MILP formulation

$$\min_{x} c^T . x$$

$$\begin{cases} A . x = b \\ D . x \geq e \end{cases}$$

MILP and Energy Systems [7]



input data

costs (c)

CPLEX [9]

MILP

Constraints/Objective

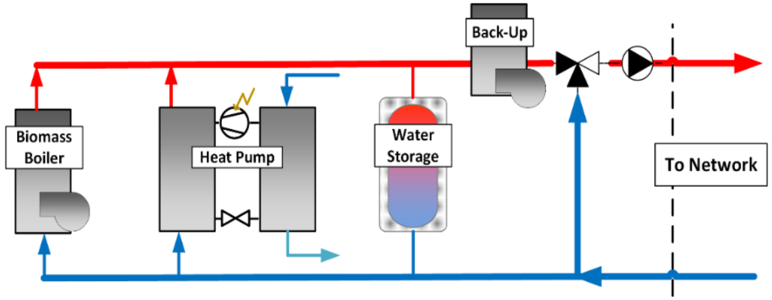
Sizing Variables (x)

Operational Variables (x)

Hypothesis

- No effect of temperature accounted for
- District Heating Operation does not affect costs
- Both sizing and operational optimization

Decision Variables



Var Continuous: 35k
Var Integers: 18k

Operational Variables

$\mathbf{Y}^{\mathbf{i}}(t)$: Back Up / Biomass / HP
$\mathbf{P}^{\mathbf{i}}(t)$: Back Up / Biomass / HP
$\mathbf{Y}^{\mathbf{st}}(t)$: Storage
$\mathbf{P}^{\mathbf{st}}_{\mathbf{ch}}(t)$: Storage
$\mathbf{P}^{\mathbf{st}}_{\mathbf{disch}}(t)$: Storage
$E^{st}(t)$: Storage

Sizing Variables

$\mathbf{P}^{\mathbf{i}}_{max}$: Back Up / Biomass / HP / Storage
E^{st}_{max} : Storage

---

[7] Grossmann Ignacio E. 'Mixed Integer programming for the synthesis of integrated process flowsheets", Comp. Chem. Eng., 1985, 9(5) 463-82.

[8] M. Dahl et al., 'Cost sensitivity of optimal sector-coupled district heating production Systems', Energy, 2019

[9] IBM ILOG CPLEX Optimization Studio V12.7.0 documentation, February 2015

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1 - Sizing Methodology

Equality Constraints

Overall Energy Balance

$$\sum P^i(t) + P^{st}_{disch}(t) = P^{st}_{ch}(t) + P_{load}(t)$$

Storage Energy Balance

$$\frac{E^{st}(t) - E^{st}(t-1)}{\Delta t} = P^{st}_{ch}(t) - P^{st}_{disch}(t) - K_{loss} * E^{st}(t)$$

Boundary Condition Storage

$$E_{st}(t=0) = E_{st}(t=N)$$

Inequality Constraints

Power Limits

$$r^i * P^i_{max} * Y^i(t) \le P^i(t) \le P^i_{max} * Y^i(t)$$

Charging Power Limit

$$0 \le P^{st}_{ch}(t) \le P^{st}_{max} * (1 - Y^{st}(t))$$

Discharging Power Limit

$$0 \le P^{st}_{disch}(t) \le P^{st}_{max} * Y^{st}(t)$$

Energy Storage Limit

$$0 \le E^{st}(t) \le E^{st}_{max}$$

Set of ε-constraints

Minimum REN ratio

$$\sum_{t=1}^{N}\left(P^{bio}(t) + P^{hp}(t) * T^{hp}_{ren}(t)\right) \ge T^{tot}_{ren} * \sum_{t=1}^{N} P_{load}(t)$$

Maximum CO2 content

$$\sum_{t=1}^{N}\sum_{i=1}^{3} CO^i_2 * P^i(t) \le CO^{tot}_2 * \sum_{t=1}^{N} P_{load}(t)$$

Maximum Biomass Available

$$\sum_{t=1}^{N} P^{bio}(t) * \Delta t \le m^{bio}_{max} * PCI^{bio}$$

Constraints: 120k

Objective

$$c_{tot} = c_{invest} + \sum_{n=1}^{T_{am}}\left(\frac{1}{(1+t_{actu})^{n-1}}\left(c_{prod} + c_{start} + c_{maint}\right)\right)$$

$$c_{prod} = \sum_{t=1}^{N}\sum_{i=1}^{3} c^i_{prod} * P^i(t) * \Delta t$$

$$c_{start} = \sum_{t=1}^{N}\sum_{i=1}^{3} c^i_{start} * X^i(t)$$

$$c_{maint} = \sum_{i=1}^{3} c^i_{invest} * P^i_{max} * 0.01$$

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2 - Sizing Results

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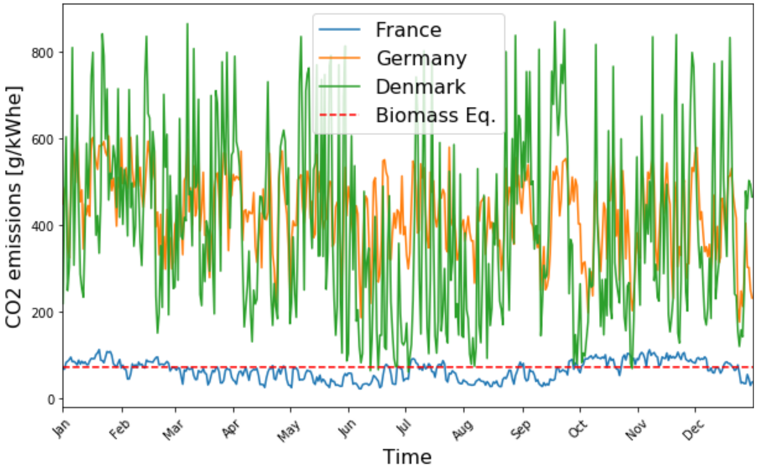
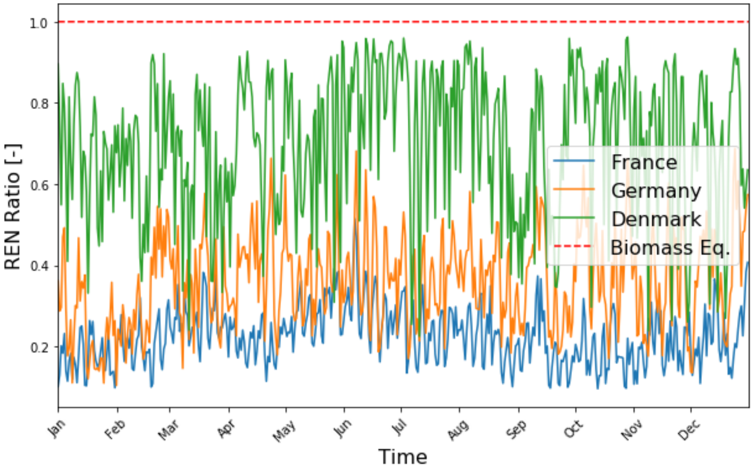
Set of Input Data

Weather:	In-Situ measurements from year 2017 in Grenoble
Network Load:	3000 dwelling equivalent [10] + Internal tool CEA for hourly profile
Electricity Cost:	Day-Ahead prices (EPEX-SPOT and ENTSO-E)
Investment/Operational Costs:	Literature [11, 12, 13, 14]
REN Ratio and CO2 Content:	Eco2mix (RTE Database) + CITEPA

*[10] A.-S. Provent et al., « Livrable 1.1.1 Rapport d'étude sur les réseaux de chaleur existants et les réseaux adaptés aux Eco-quartiers », **ADEME**, p. 109, 2013.*
*[11] J.-M. Servant, « EVALUATION DES COUTS D'EXPLOITATION ASSOCIES AUX CHAUFFERIES BIOMASSE », **ADEME**, nov. 2010.*
*[12] « Renewable Energy in District Heating and Cooling, A sector roadmap for REmap », **IRENA**, p. 112, 2017.*
*[13] « Etude des coûts d'investissement et d'exploitation associés aux installations biomasse énergie des secteurs collectifs et industriels », **ADEME**, mai 2015.*
*[14] H. Lund et al., « Energy Storage and Smart Energy Systems », **International Journal of Sustainable Energy Planning and Management**, Vol 11 (2016), oct. 2016.*

CO2 Content and REN Ratio of Electricity





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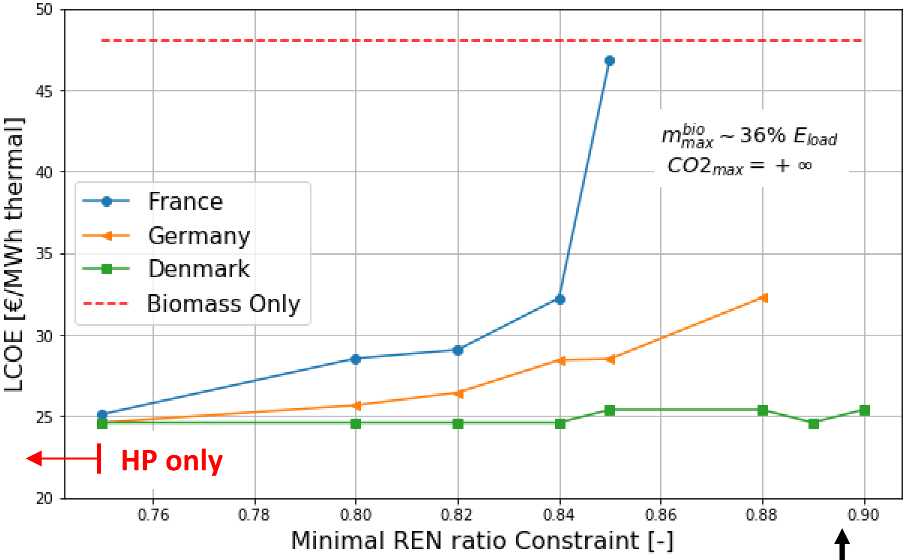
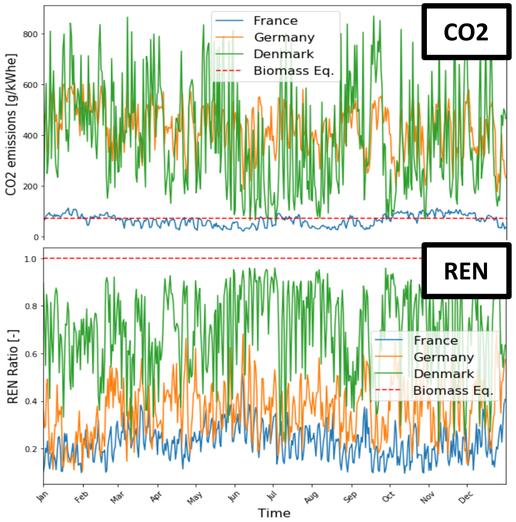
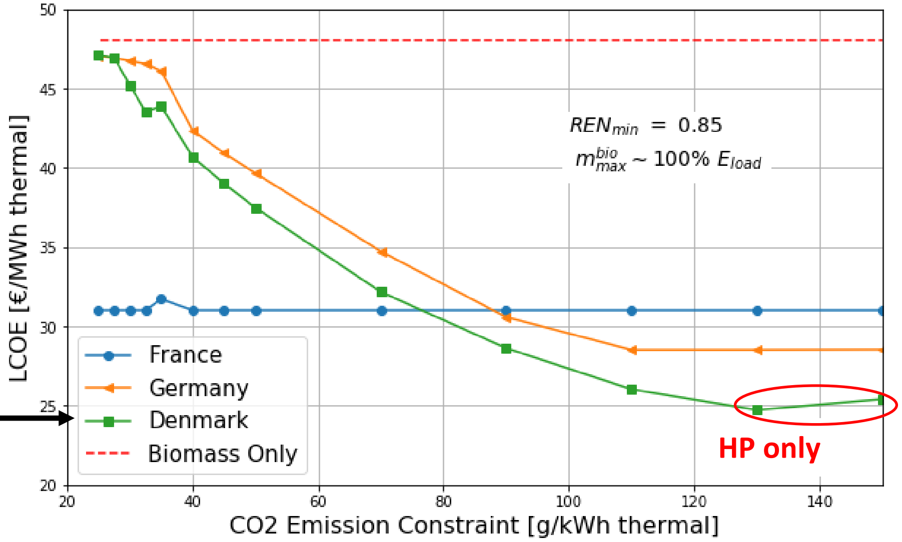
2 - Sizing Results





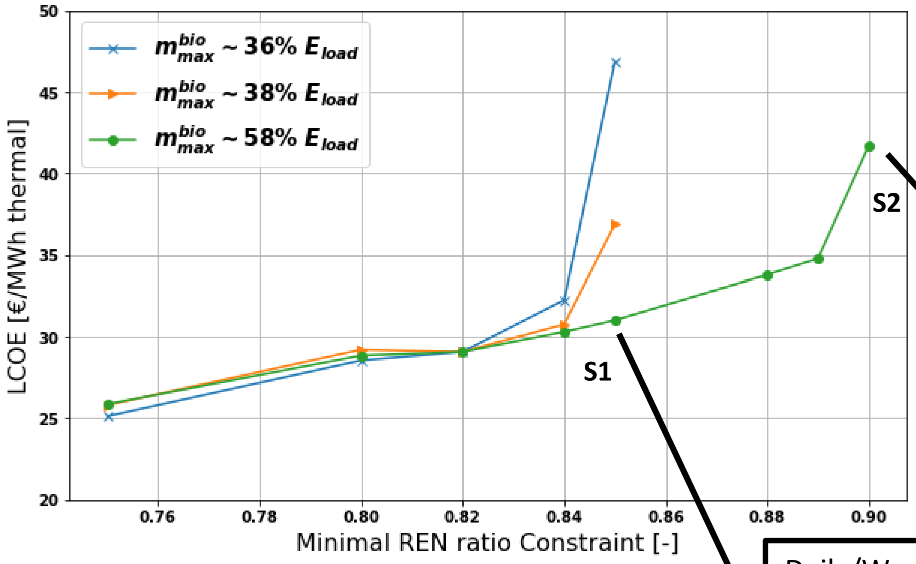
The less renewable is the electricity and the more we need to invest in Biomass (and Storage) to satisfy the REN constraint

The higher is the CO2 content of the electricity and the more we need to invest in Biomass (and Storage) to satisfy the CO2 constraint



2 - Sizing Results

Focus on French Context



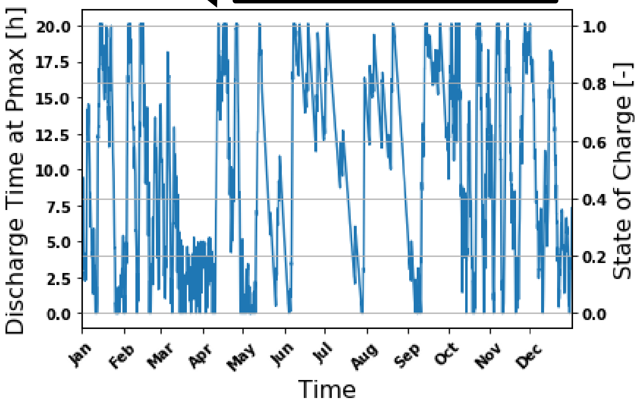
- Increase of Available Biomass → Increase of the reachable REN Constraint
- Increase of REN Constraint → Increase of LCOE mostly because of Storage size increase

	S1	S2
Vol^{st} $[m^3]$	6.5k	155k
$Cycles^{st}$ $[-]$	48	2
τ^{st} $[h]$	20	537
P^{st}_{max} [-]	0.49	0.74
E^{st}_{max} [-]	1	40

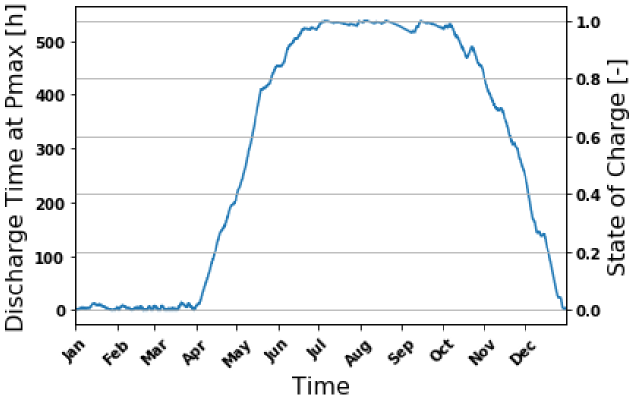
P^{load}_{max} ~ 18MW

	S1	S2
P^{bio}_{max} [-]	0.34	0.44
P^{HP}_{max} [-]	0.46	0.40

Daily/Weekly Storage

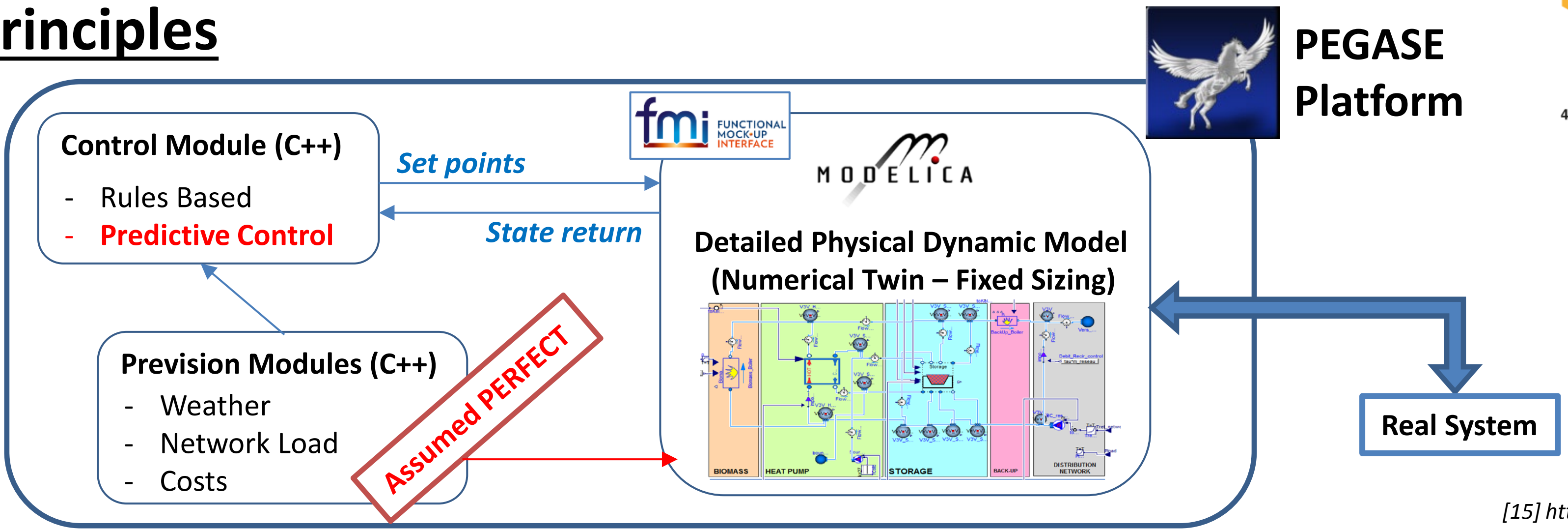


Inter-Seasonal Storage



3 – MILP Operation

Principles



PEGASE Platform

Control Module (C++)
- Rules Based
- **Predictive Control**

Set points

State return

Prevision Modules (C++)
- Weather
- Network Load
- Costs

Assumed PERFECT

Detailed Physical Dynamic Model (Numerical Twin – Fixed Sizing)

Real System

[15] http://fmi-standard.org/

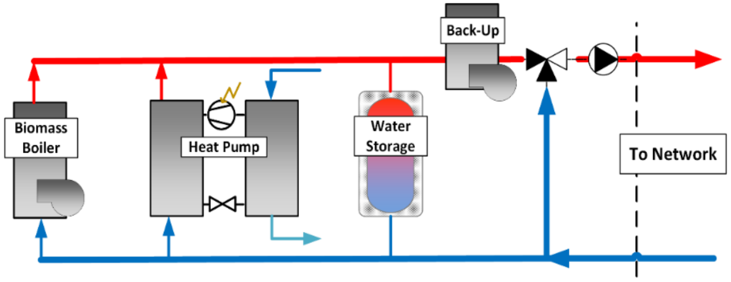
Operational Predictive MILP modifications

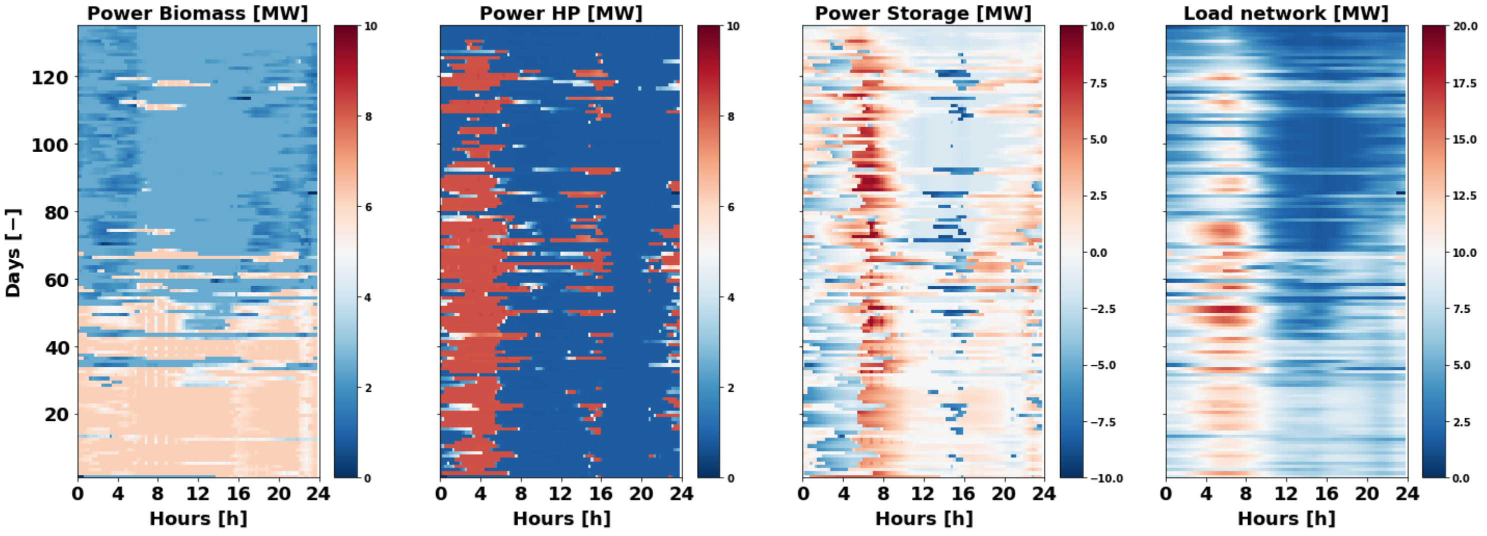
	Sizing	**Operation**
Optimization Horizon	1 year	24 h (receding)
N° of Simulations	1	8760
Decision Variables	Sizing + Operational	Operational only
Objective function	$c_{invest} + c_{prod} + c_{dem} + c_{maint}$	$c_{prod} + c_{dem}$

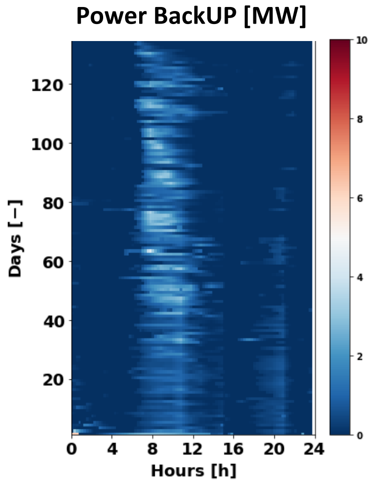
3 – MILP Operation

Results – S1

- Receding Horizon of 24h
- Optimization performed every hour
- Time Step of Simulation of 15 minutes
- 5 first months shown







- Biomass as Based Load
- Heat Pump and then Storage used for peaks (due to cost of electricity)

Back-Up Usage of 4.4% only → Validating the design and the Operational MILP

Conclusion and Perspectives

Sizing Methodology

- Traditional Methods limited
- 'Power fluxes' type MILP problem

→ **Appropriate Physico-Mathematical Approach**

In France, Power-to-Heat with inter-seasonal storage is necessary only to reach very high REN ratio

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MILP based operation required only 4.4% of the back up

Comparison with Rule Based Logic Control is beneficial to MILP

Validation through Operation

- Testing Co-simulation Platform PEGASE
- Comparison of different Control strategies

→ **Setting up control strategies prior field operation**

What to do next ?

- *Add a cogeneration plant to the studied system*
- *Multi-Period in Operation (inter-seasonal storage)*
- *Temperature effect in Operational MILP*

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THANK YOU

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1 - Sizing Methodology

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$$\min_{x} c^T . x$$

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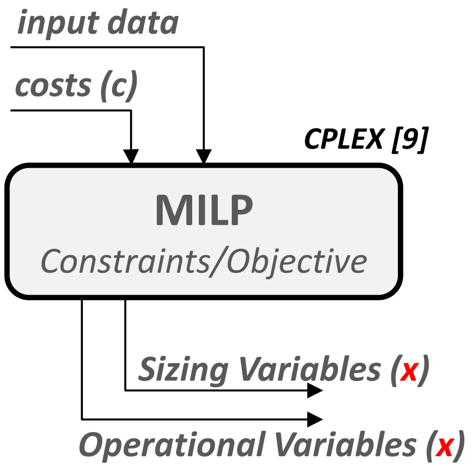
MILP and Energy Systems [7]



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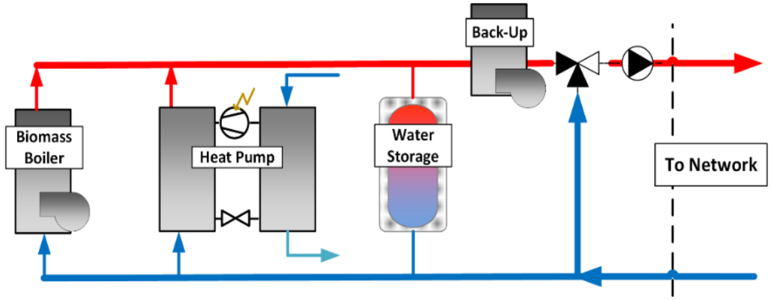
Hypothesis

- No effect of temperature accounted for
- District Heating Operation does not affect costs
- Both sizing and operational optimization

Decision Variables



Var Continuous: 35k
Var Integers: 18k

Operational Variables

$\mathbf{Y}^{\mathbf{i}}(t)$: Back Up / Biomass / HP
$\mathbf{P}^{\mathbf{i}}(t)$: Back Up / Biomass / HP
$\mathbf{Y}^{\mathbf{st}}(t)$: Storage
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Sizing Variables

$\mathbf{P}^{\mathbf{i}}_{max}$: Back Up / Biomass / HP / Storage
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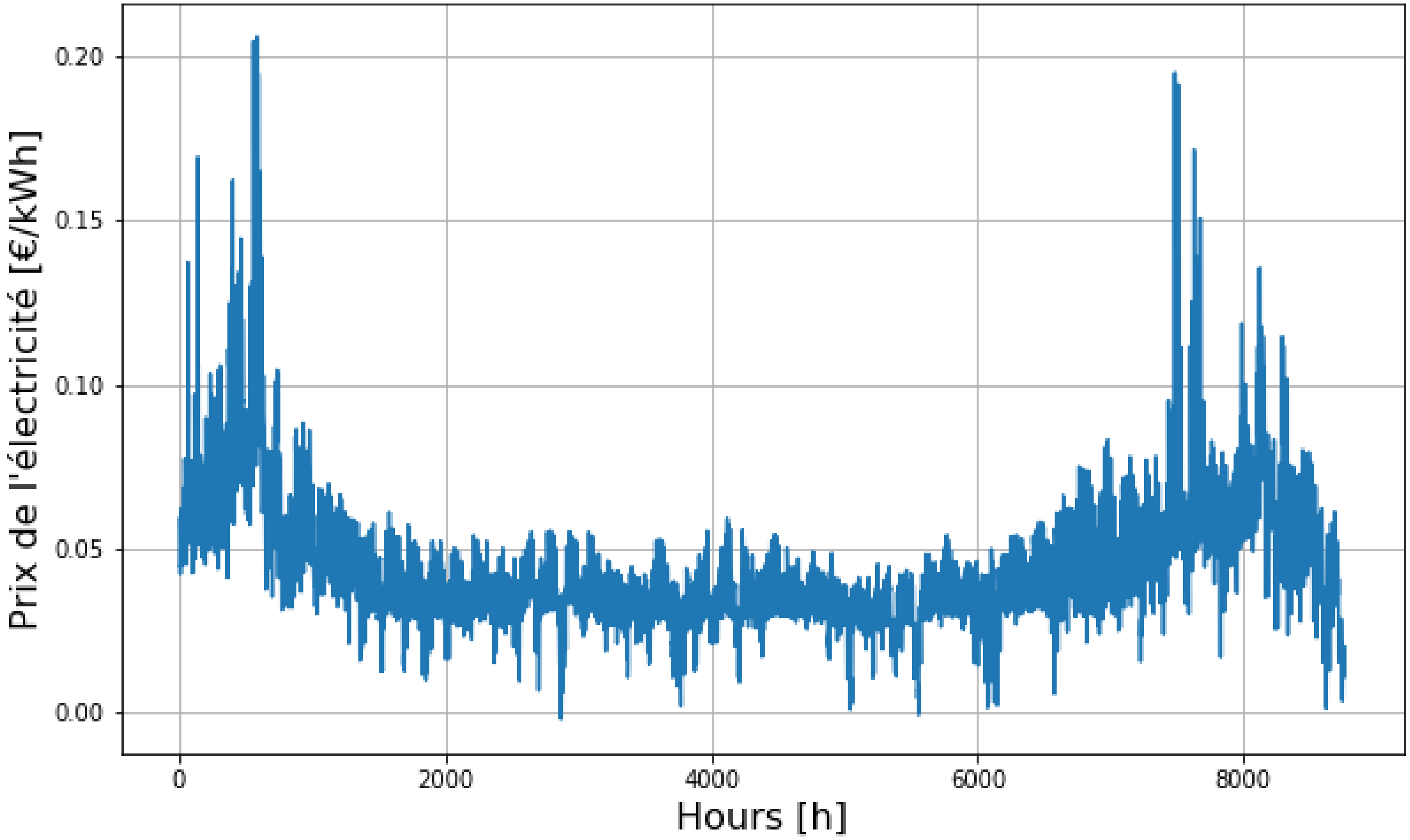
Back Up


Prix de l'électricité [€/kWh]
0.20
0.15
0.10
0.05
0.00
0
2000
4000
6000
8000
Hours [h]

1 - Sizing Methodology

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Equality Constraints

Overall Energy Balance

$$\sum P^i(t) + P^{st}_{disch}(t) = P^{st}_{ch}(t) + P_{load}(t)$$

Storage Energy Balance

$$\frac{E^{st}(t) - E^{st}(t-1)}{\Delta t} = P^{st}_{ch}(t) - P^{st}_{disch}(t) - K_{loss} * E^{st}(t)$$

Boundary Condition Storage

$$E_{st}(t=0) = E_{st}(t=N)$$

Biomass Maintenance

$$Y^{Bio}(t \in I) = 0$$

Inequality Constraints

Power Limits

$$r^i * P^i_{max} * Y^i(t) \le P^i(t) \le P^i_{max} * Y^i(t)$$

Charging Power Limit

$$0 \le P^{st}_{ch}(t) \le P^{st}_{max} * (1 - Y^{st}(t))$$

Discharging Power Limit

$$0 \le P^{st}_{disch}(t) \le P^{st}_{max} * Y^{st}(t)$$

Energy Storage Limit

$$0 \le E^{st}(t) \le E^{st}_{max}$$

Minimum ON Time

$$T^i_{on} * X^i(t) \le \sum_{j=1}^{T^i_{on}} Y^i(t+j-1)$$

Constraints: 120k

Set of ε-constraints

Minimum REN ratio

$$\sum_{t=1}^{N} \left(P^{bio}(t) + P^{hp}(t) * T^{hp}_{ren}(t)\right) \ge T^{tot}_{ren} * \sum_{t=1}^{N} P_{load}(t)$$

Maximum CO2 content

$$\sum_{t=1}^{N} \sum_{i=1}^{3} CO_2^i * P^i(t) \le CO_2^{tot} * \sum_{t=1}^{N} P_{load}(t)$$

Maximum Biomass Available

$$\sum_{t=1}^{N} P^{bio}(t) * \Delta t \le m^{bio}_{max} * PCI^{bio}$$

Objective

$$c_{tot} = c_{invest} + \sum_{n=1}^{T_{am}} \left(\frac{1}{(1 + t_{actu})^{n-1}} \left(c_{prod} + c_{start} + c_{maint}\right) \right)$$

$$c_{prod} = \sum_{t=1}^{N} \sum_{i=1}^{3} c^i_{prod} * P^i(t) * \Delta t$$

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$$c_{maint} = \sum_{i=1}^{3} c^i_{invest} * P^i_{max} * 0.01$$

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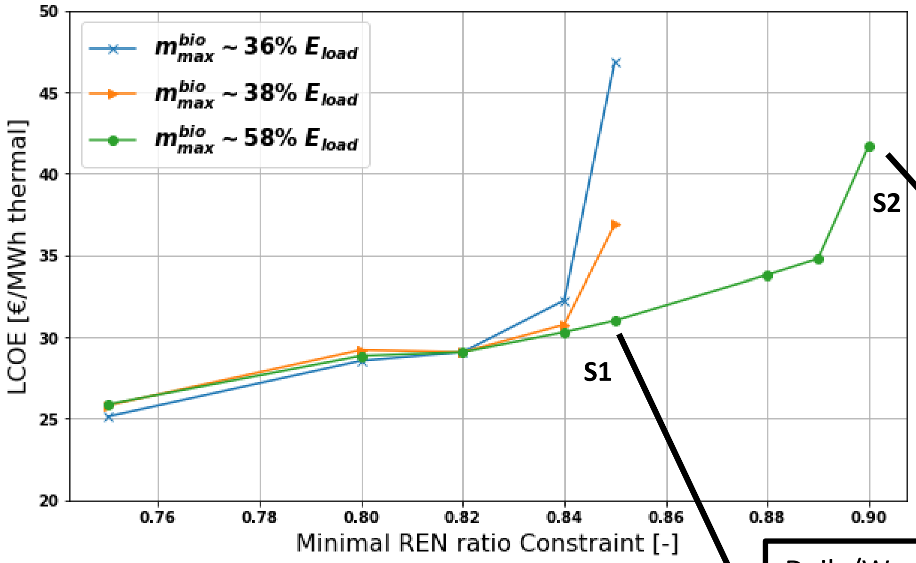
2 - Sizing Results

Focus on French Context



- No Impact of CO2 in French Case
- Increase of Available Biomass → Increase of the reachable REN Constraint
- Increase of REN Constraint → Increase of LCOE mostly because of Storage size increase

	S1	S2
m^{bio} used [tons]	~5k	7k
P_{max}^{bio} [-]	0.34	0.44
P_{max}^{HP} [-]	0.46	0.40
P_{max}^{st} [-]	0.49	0.74
E_{max}^{st} [-]	1	40

$P_{\max}^{load}$ ~ 18MW

	S1	S2
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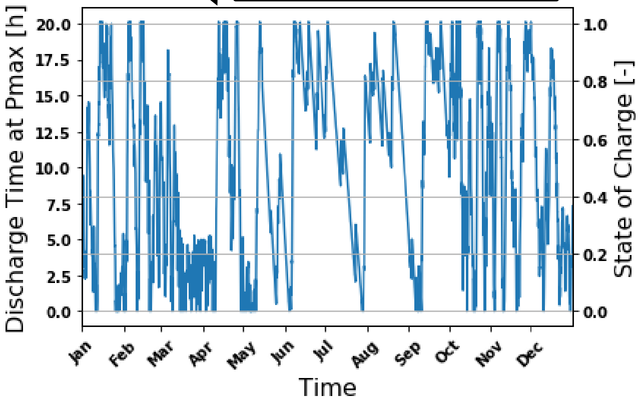
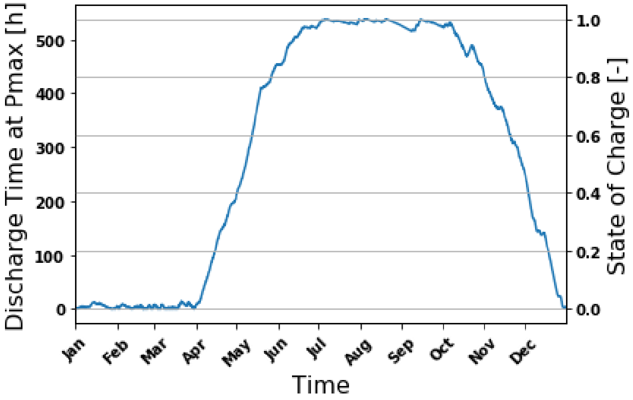
Daily/Weekly Storage

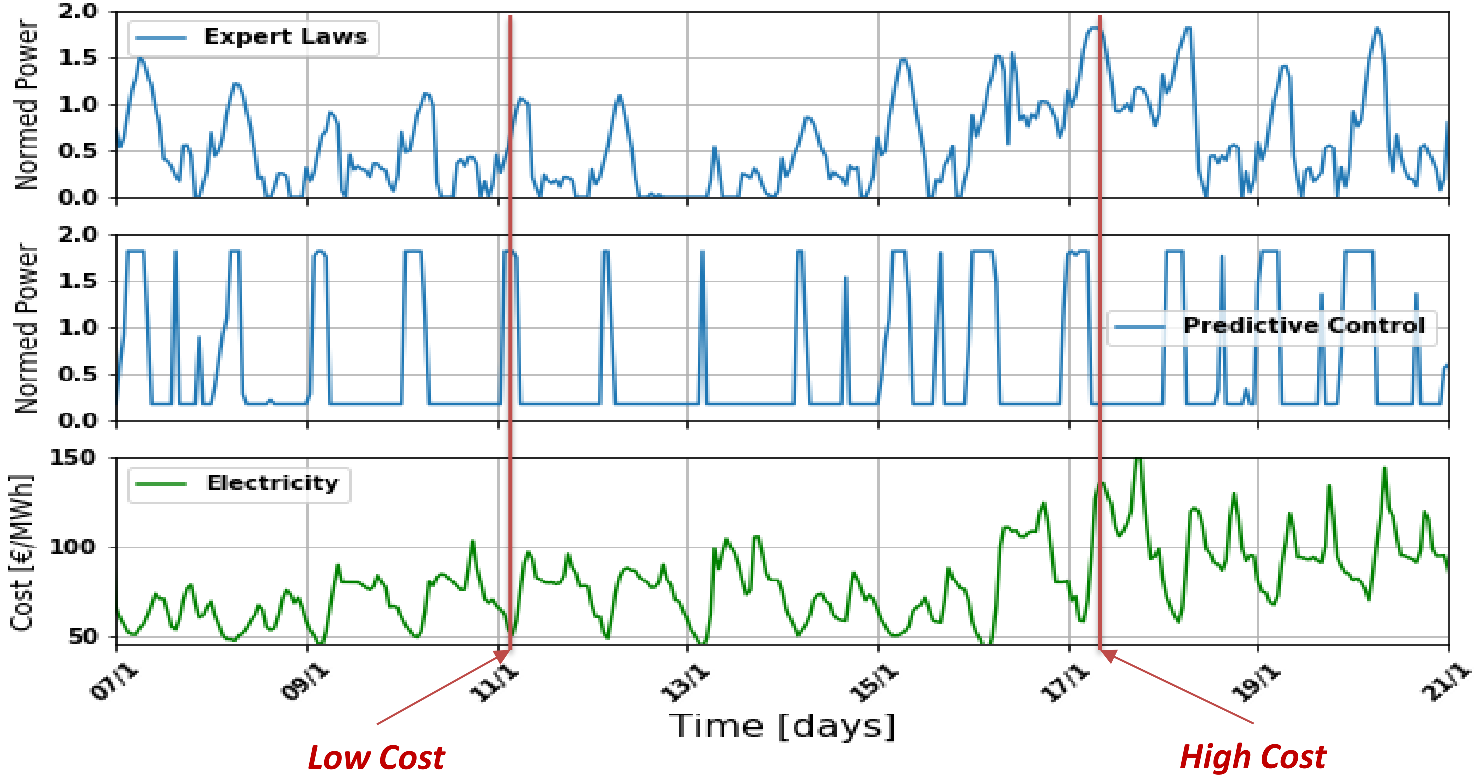


Inter-Seasonal Storage



3 – MILP Operation

Comparison with usual Rules Based Control



- Reduced Operational Cost
- Optimal use of the synergy between low electricity costs and available storage

3 – MILP Operation

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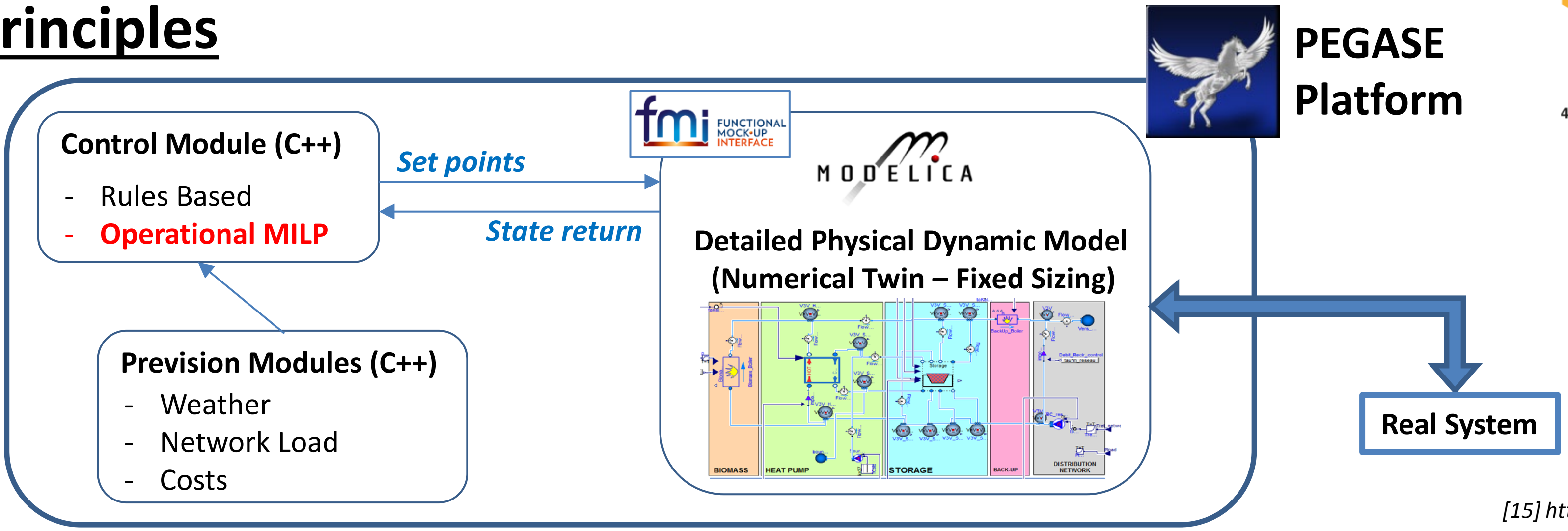
Principles



Control Module (C++)
- Rules Based
- Operational MILP

Prevision Modules (C++)
- Weather
- Network Load
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Set points

State return

Detailed Physical Dynamic Model (Numerical Twin – Fixed Sizing)

PEGASE Platform

Real System

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Decision Variables	Sizing + Operational	Operational only
Costs	$c_{invest} + c_{prod} + c_{dem} + c_{maint}$	$c_{prod} + c_{dem}$
N° of Simulations	1	8760
System State Return	No	Every hour