Multi Energy Systems:

Investigating Hidden Flexibilities Provided by Power-to-X Considering Grid Support Strategies

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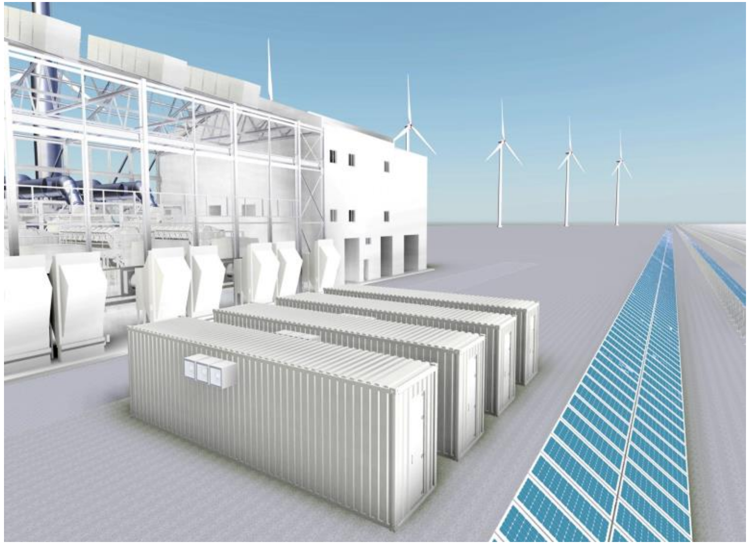

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Content

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Introduction - Research Problem

- Variable nature of renewable energy sources introduces a great challenge for grid operator to balance the electricity supply and demand.

- Replacing production based on fossil fuels in industries, such as chemicals, petrochemicals, food, steel, etc; leads to more sustainable and flexible multi-energy systems.

- Due to approximations made in model formulations (constant / linear relation between power input and energy output), flexibilities provided by PtX to network can be concealed in simulation results. This may lead to increased transmission losses and misinterpretation of MES capacity.

- Existing energy management models for MES do not consider energy cost of production (€/MWh). This results with unnecessary trading of electricity and increase in operational cost.

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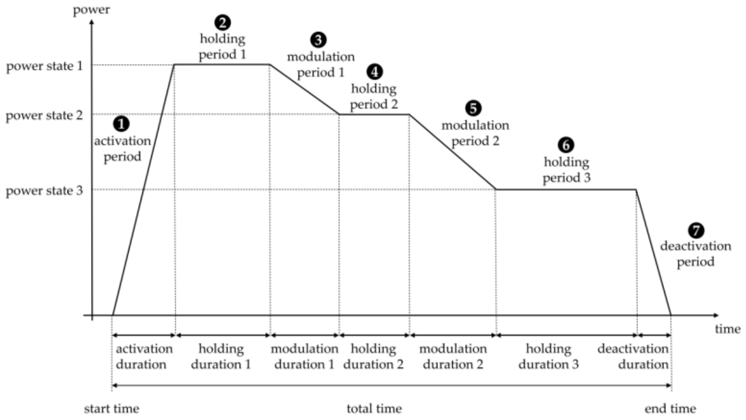
MES: Multi Energy System
PtX: Power-to-X

Introduction - Flexibility

" Flexibility is the ability of a component or a collection of components to respond to power fluctuations in power systems. "

- In this project, PtX devices and the flexibility offered by them to support power system is analyzed.

- PtX technology offers;
  - Larger power balance flexibility for the grid
  - Opportunities for demand flexibility by storage elements



An exemplary flexible load measure with the corresponding parameters [1]

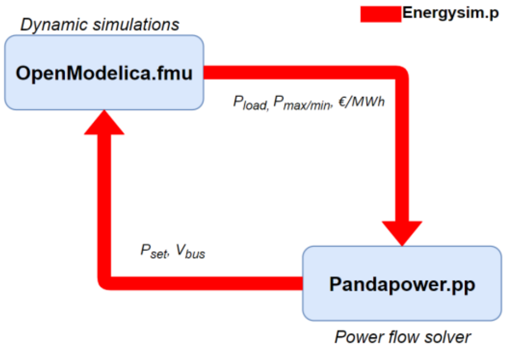
- Additional information obtained from detailed models during flexibility analysis is defined as the hidden flexibility of PtX.

Introduction - Research Questions

1. How to explore multi-energy system flexibility in an industrial area?
   - Which options are available in industrial area?
   - Which technologies have the highest potential to provide flexibility?

2. To what extent does model fidelity impact flexibility analysis?
   - Which assumptions can be made and which physical effects should be considered?

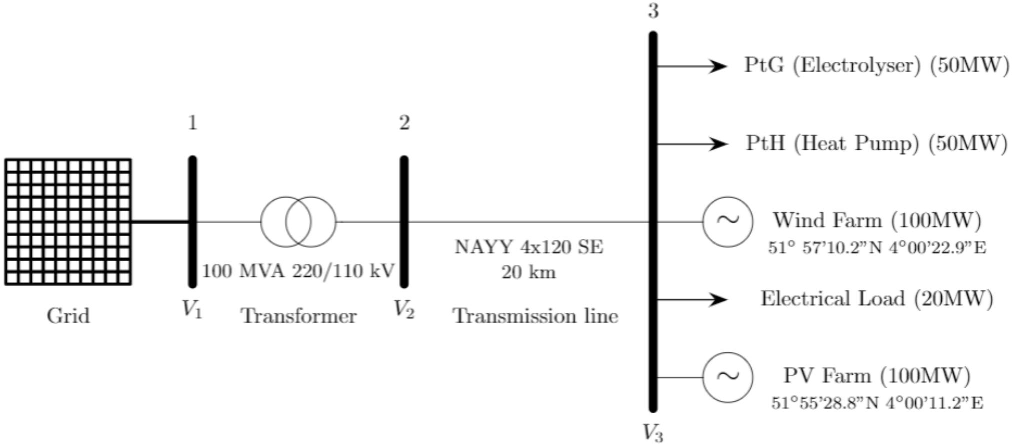
3. How to manage optimal deployment of flexibility considering individual resource constraints?
   - How to control different energy vectors efficiently?
   - How the operation of MES can become economical?



Co-simulation Approach

MES: Multi Energy System

Methodolgy – Electrical Energy System



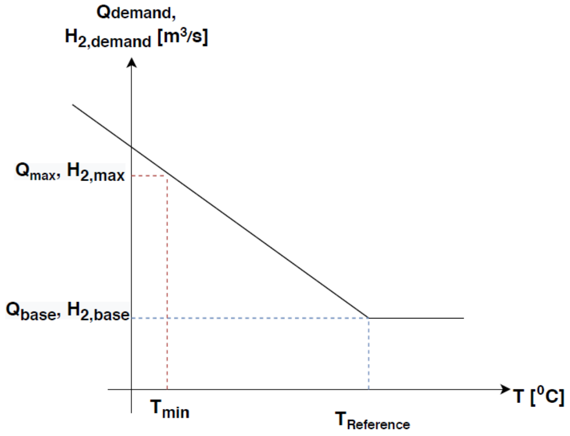
- PEM Electrolyser is one of the most convenient PtX options as a result of hydrogen characteristics.
- Electric heat pumps with auxiliary boilers are commonly recommended for their high efficiencies (Bode & Schmitz, 2018).
- The hourly power output of RES is calculated from Renewables.ninja [2].

PEM: Proton Exchange Membrane
PtG: Power-to-Gas
PtH: Power-to-Heat
RES: Renewable Energy Sources

Methodolgy – Energy Demand Profiles

- Mathematical formulation of Felten, Baginski, and Weber (2017) model:

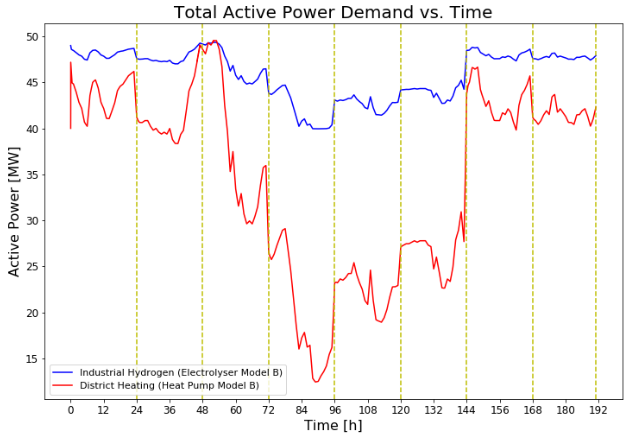
$$Q_{demand}(t) = Q_{base} + \frac{Q_{max} - Q_{base}}{T_{Reference} - T_{min}} \cdot max(0,\ T_{Reference} - T(t))$$



The relation between ambient temperature and hydrogen & heat demand [1]

- Historical local ambient temperature data is used for the calculation of energy demand profiles.

	T_R [ºC]	T_{min} [ºC]	Q_{base}, $H_{2,base}$ [m³/s]	Q_{max}, $H_{2,max}$ [m³/s]
Industrial PtG	25	5	3.14e-03	3.85e-03
District Heating PtH	25	5	3	4



PtG: Power-to-Gas
PtH: Power-to-Heat

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Modelling – PEM Electrolyser

- Temperature dependency of electrolyser efficiency is considered.
- Electrolyser performance is calculated considering operational conditions (temperature, pressure, cell current effects).
- Balance of plant elements are considered for temperature evolution.

Model	Physical Domains	Modelling Approach	Dynamic Behaviour	Modelling Scale
A	Electrochemical Electrical	Analytic + Empirical	Static	Cell/Stack
B	Electrochemical Electrical Thermal	Analytic + Empirical	Static + Dynamic (ODE)	Cell/Stack + BOP

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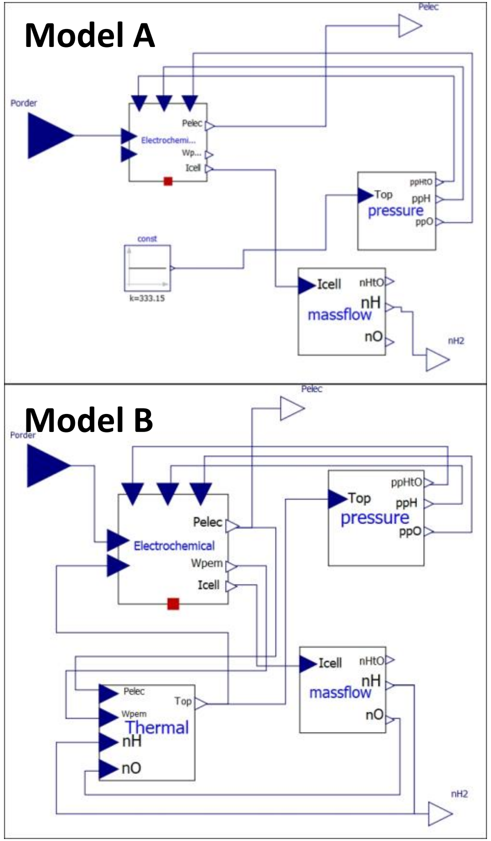
MES: Multi Energy System
ODE: Ordinary Differential Equation
BOP: Balance of Plant

Modelling – PEM Electrolyser



Electrochemical: $V_{cell}(T) = V_{ocv}(T,p) + V_{act}(T) + V_{ohm}(T) \ [V]$

Pressure: $pp_{H2O} = 6.1078.10^{-3}.exp\left(17.2694 . \frac{T-273.15}{T-34.85}\right) \ [bar]$

Molar Massflow: $\dot{n}_{H_2} = \frac{n_{cells} . I}{2 .F}\eta_f \ [mol/s]$

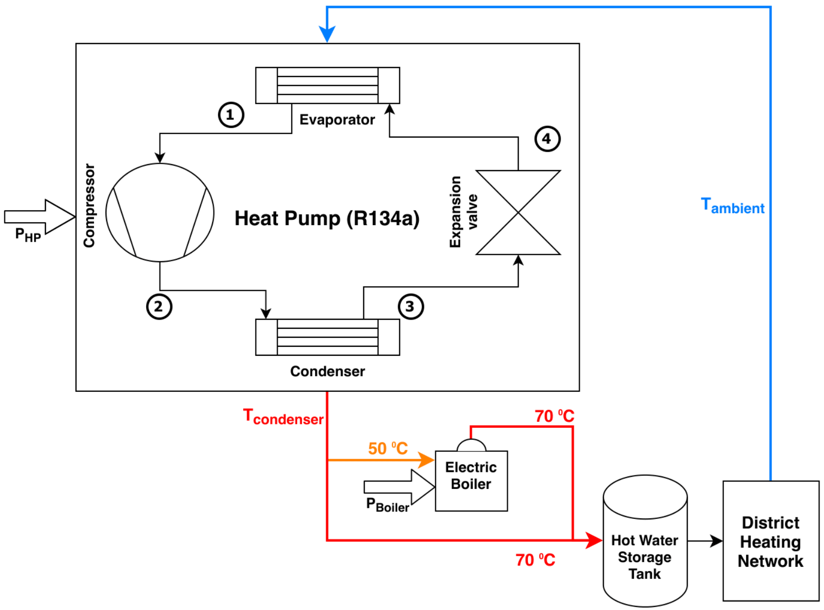
Thermal:

$$C_{th}\frac{dT}{dt} = \dot{Q}_{electrolysis,heat}(V,I) + \dot{W}_{pump,loss} - \dot{Q}_{cooling}(P) - \dot{Q}_{loss}(T) - \sum_j \dot{n}_j.\Delta h_j$$

- Thermal submodel
  - BOP: circulation pump, cooling system
  - Static vs. first order dynamics

BOP: Balance of Plant

Modelling – Electric Heat Pump



Model A:

$$P_t = \frac{\dot{Q}_t^{HP}}{COP^{average}} \quad \forall\, t$$

Model B & C:

$$P_t = \frac{\dot{Q}_t^{HP}}{COP_t^{real}(T_{inlet}, T_{outlet})} \quad \forall\, t$$

Plus for Model C:

$$if\ T_{amb} < 15^{0}C\ then\ T_{cond} = 50^{0}C$$

$$Q_{boiler} = \dot{m}.c.\Delta T, \qquad \eta_{boiler} = 0.99$$

Model	Modelling Approach	Ambient Temperature	Modelling Scale
A	Regression	Daily Average	Heat Pump
B	Regression	Hourly Measured	Heat Pump
C	Regression	Hourly Measured	Heat Pump with Auxiliary E-Boiler

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COP: Co-efficient of Performance

Modelling – Electric Heat Pump

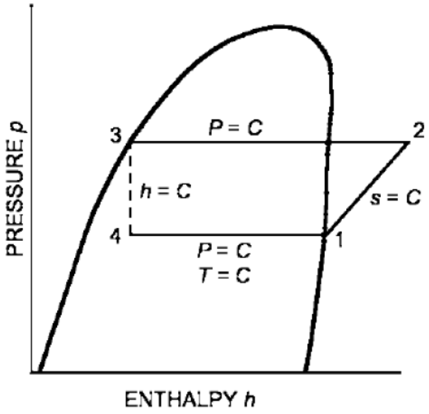

Figure: Theoretical Single-Stage Vapor Compression Refrigeration Cycle (C:Constant)

- Pressure – Enthalpy table of refrigerant R-134a is used for COP calculation with the assumptions shown in the figure.

$$COP = \frac{Q_{produced}}{P_{consumed}} = \frac{Q_{condenser}}{W_{compressor}} = \frac{h_2 - h_3}{h_2 - h_1}$$

COP results for various ambient and condenser temperatures:

$T_{ambient}$	-20	-16	-12	-8	-4	0	4
COP @ $T_{cond} = 50°C$	3.3931	3.6429	3.9268	4.2500	4.6251	5.0604	5.5750
COP @ $T_{cond} = 70°C$	2.4174	2.5586	2.7150	2.8887	3.0837	3.3013	3.5476
$T_{ambient}$	8	12	16	20	24	28	32
COP @ $T_{cond} = 50°C$	6.1957	6.9452	7.8660	9.0564	10.5899	12.7115	15.7889
COP @ $T_{cond} = 70°C$	3.8298	4.1514	4.5195	4.9559	5.4618	6.0736	6.8178

$$COP(T_{amb}) = a_1 T_{amb}^5 + a_2 T_{amb}^4 + a_3 T_{amb}^3 + a_4 T_{amb}^2 + a_5 T_{amb} + a_6$$

5th order polynomial function parameters for $T_{condenser}$ = 50,70 °C:

$T_{condenser}(°C)$	a_1	a_2	a_3	a_4	a_5	a_6
50	3.46e-8	1.29e-6	4.35e-5	2.387e-3	1.186e-1	5.063
70	1.46e-8	-9.66e-8	6.61e-6	1.01e-3	5.864e-2	3.295

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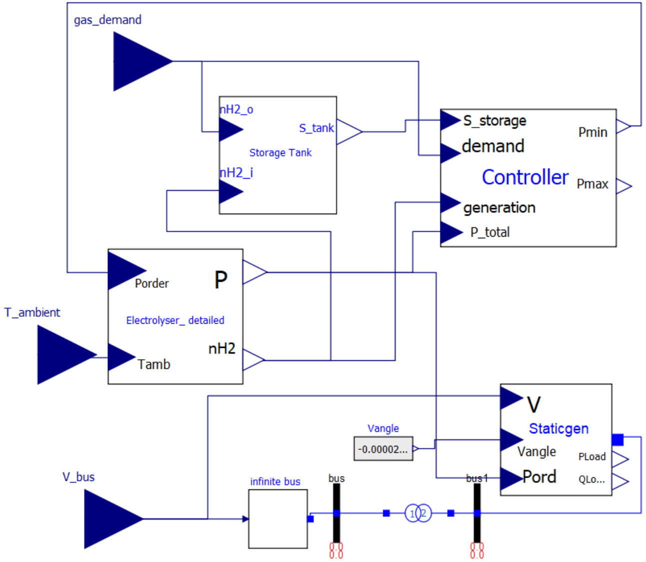
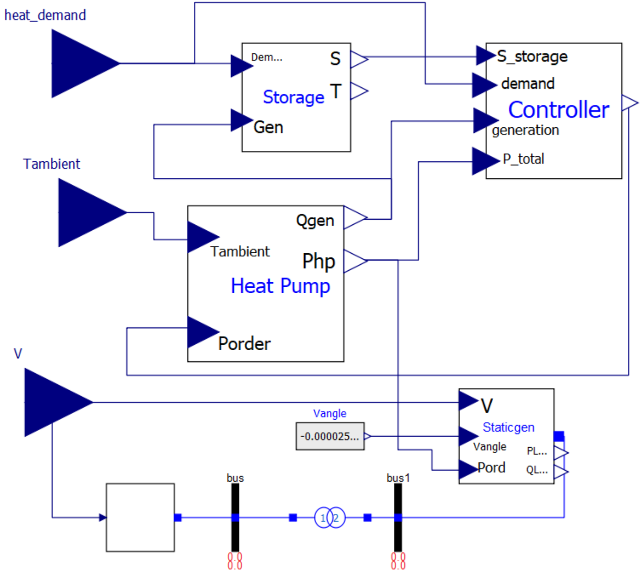
COP: Co-efficient of Performance

Modelling - Power-to-X Models

Power-to-Gas



Power-to-Heat



- **Electrolyser & Heat Pump,** calculate energy output based on power input and operating conditions.
- **Controller,** calculates P_{min}, P_{max} constraints for Pandapower.
- **Storage,** calculates amount of stored energy in m^3.
- **StaticGenerator,** provides electrical interface and controls Q_{load}.

Case Study

1. **Multi-Energy System Analysis:**
   - It is carried out in order to investigate the seasonal weather behaviour in the area and flexible capacity of MES.
2. **Power-to-X Analysis:**
   - Efficiency characters of different models compared in order to investigate the effect of temperature evolution on device performance.
3. **Power System Analysis:**
   - **Base case**: None of the PtX is available for flexibility service. Without any flexibility service, measuring the flexible demand of MES.

$$P_{demand,flexible} = P_{demand,PtG} + P_{demand,PtH} - P_{gen,WF} - P_{gen,PV}$$

   - **First case:** Only one PtX is available for flexibility service. Comparing both PtX options with respect to reduction in flexible demand of MES during flexibility service and analyzing the energy output of PtX models A, B, C for the same flexibility service.

   - **Second case**: Both PtXs are available for flexibility service. Considering cost signals, analyzing the deployment of flexibility between PtG & PtH and quantifying the savings in total operational cost.

$$C_{total} = \sum_{i=0}^{95} \left(\int_{t_i}^{t_{i+1}} P_{PtX} \cdot C_{PtX,i} \, dt \right)$$

MES: Multi Energy System
PtG: Power-to-Gas
PtH: Power-to-Heat
PtX: Power-to-X

Co-Simulation - Optimal Deployment of Flexibility

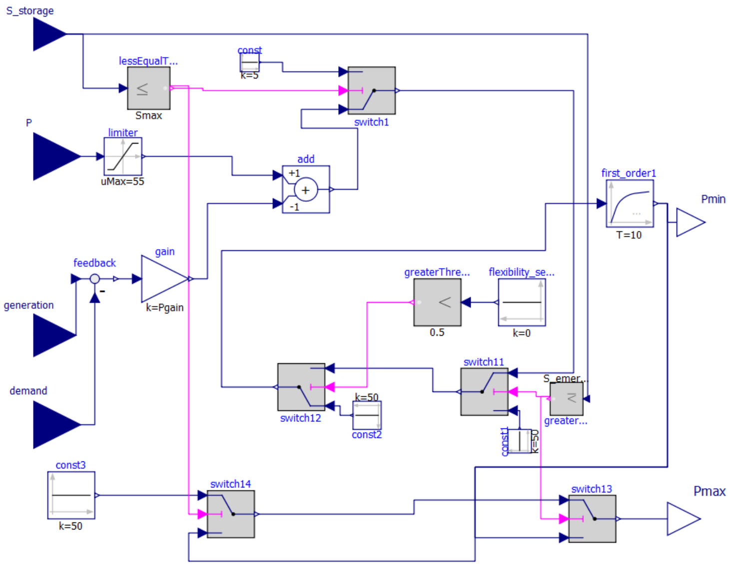
Objective function: $$\min \sum_{i\,\epsilon\,PtX} f_i(P_i)$$

Cost function: $$f_{pol}(P) = c_1 P$$

Constraints:

Element	Constraint	Remark
Power-to-X (Load) **RES (Static Generator)**	$P_{min,i} \le P_i \le P_{max,i}$ $Q_{min,i} \le Q_i \le Q_{max,i}$ (fixed)	Operational power constraints (Device flexibility)
Transformer	$L_i \le L_{max,i}$ (fixed)	Branch constraint (Maximum loading percentage)
Line	$L_i \le L_{max,i}$ (fixed)	Branch constraint (Maximum loading percentage)
Bus	$V_{min,i} \le V_i \le V_{max,i}$ (fixed)	Network constraint

Co-Simulation – Adjustable Power Level Controller



Constraint decision making:

$$P_{min} = \begin{cases} 0.1\ p.u. & S_{storage}(t) > S_{max} \\ P(t) - (\dot{n}_{H_2,prod} - \dot{n}_{H_2,demand}) \times K_{gain} & S_{emergency} \leq S_{storage}(t) \leq S_{max} \\ 1.0\ p.u. & S_{storage}(t) < S_{emergency} \end{cases}$$

$$P_{max} = \begin{cases} 1.0\ p.u. & if\ S_{emergency} \leq S_{storage}(t) \leq S_{max} \\ P_{min} & else \end{cases}$$

Co-Simulation - Levelized Cost of Energy

- Cost function: $f_{pol}(P) = c_1 P$
- Calculates c_1 $[EUR/MWh]$ in cost function

	Electrolyser	Electric Heat Pump	Electric Boiler
CAPEX(C_{CAP}) [€$/kW$]	200	1000	70
O & M(C_{OM}) [€$/kW$]	8	35.5	1.4
Lifetime (LT) [a]	20	20	15
Carbon emission factor($CO_{2,EF}$) [gCO_2/kWh]	16.6	62.3	-
Carbon penalty(C_{PEN}) [€$/kW$]	16.6	62.3	-
Carbon price (CP) [€$/gCO_2$]	1	1	1

$$C_{PtG}(t) = \frac{\left(\frac{C_{CAP}+C_{OM}}{LT}\right)_{Electrolyser} + C_{PEN}}{\eta_{electrolyser}(t)}$$

$$C_{PtH}(t) = \frac{\left(\frac{C_{CAP}+C_{OM}}{LT}\right)_{HP} + \left(\frac{C_{CAP}+C_{OM}}{LT}\right)_{Boiler} + C_{PEN}}{COP_{HP}(t)}$$

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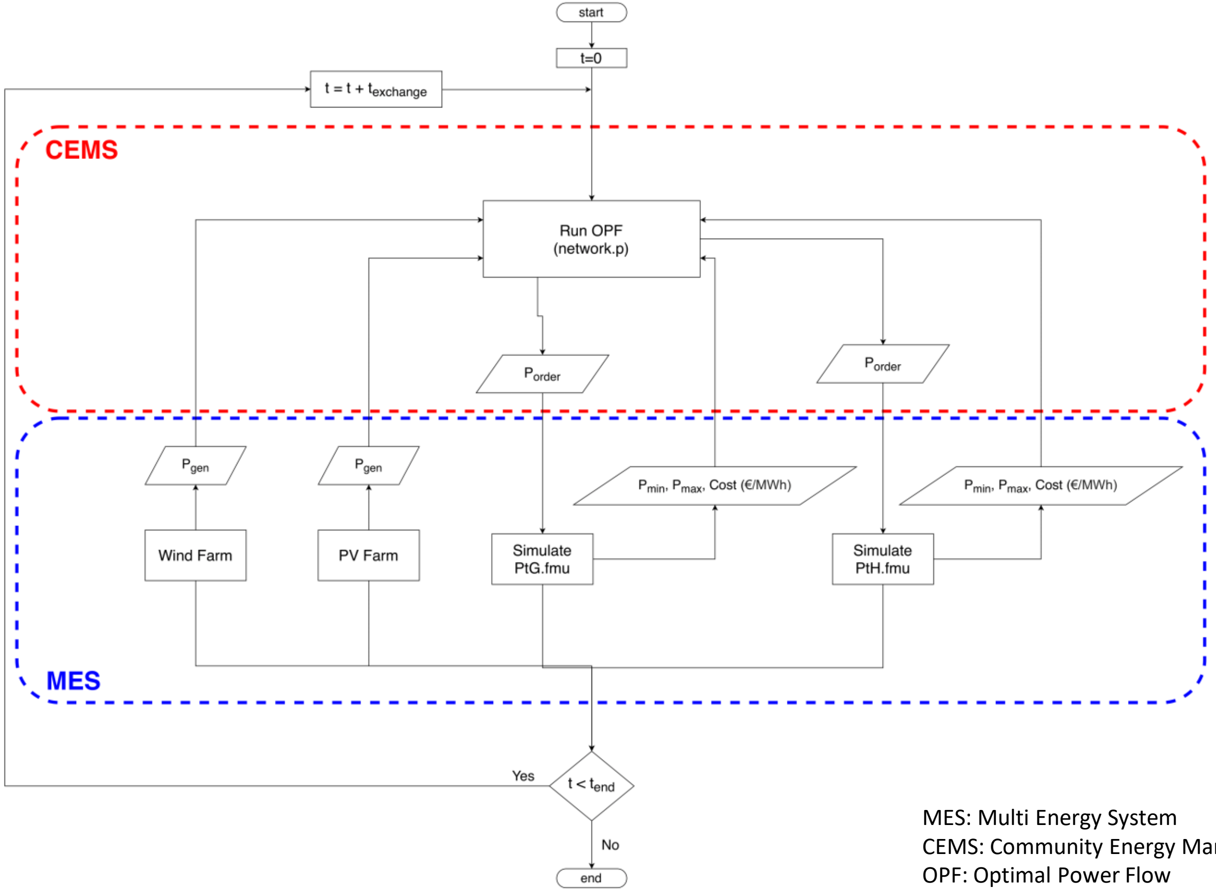
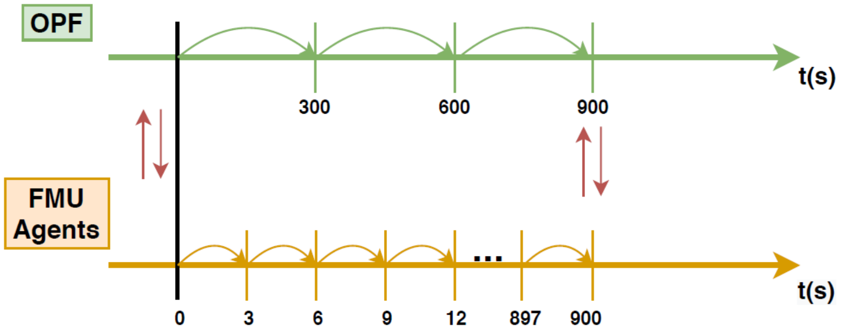
Co-simulation Flow Chart



MES: Multi Energy System
CEMS: Community Energy Management System
OPF: Optimal Power Flow

Simulation Tools

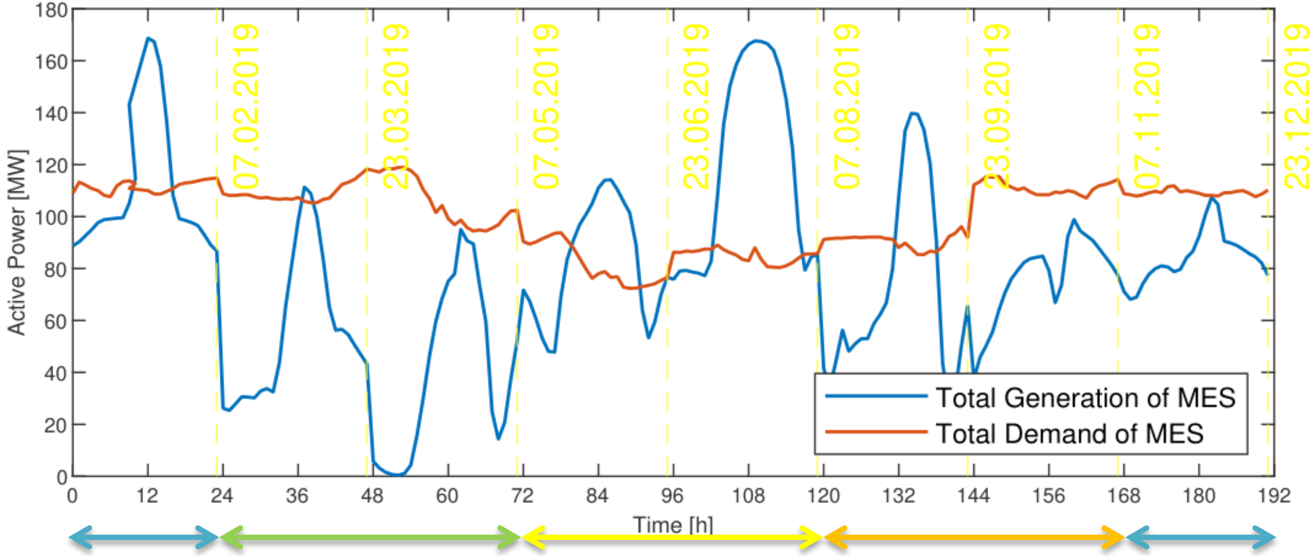
1. OpenModelica
   - For fast simulation of complex dynamics from different energy domains, using object-oriented programming language
   - To export FMU's for co-simulation
2. Pandapower
   - Optimal power flow solver
   - Used for the energy management of MES for various co-simulation cases
3. Energysim (Co-simulation)
   - Allows to implement complex simulations with reduced computational burden by exchanging only necessary variables



Co-simulation step and exchange times

FMU: Functional Mock-up Unit
OPF: Optimal Power Flow

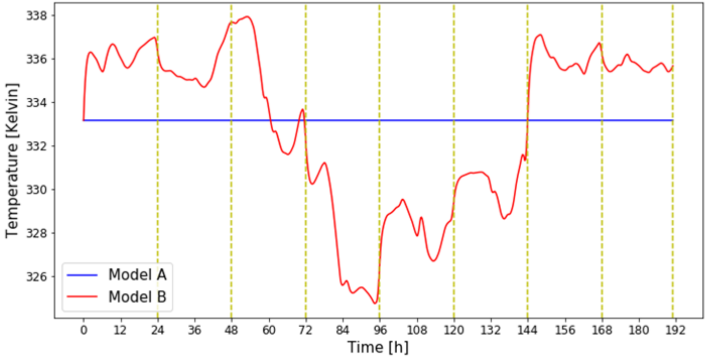
Results - MES Analysis

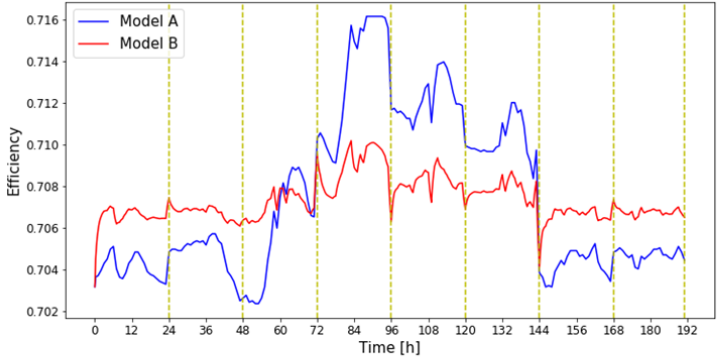


Results – PtX Analysis

Power-to-Gas (Electrolyser)

Max ΔT = 13

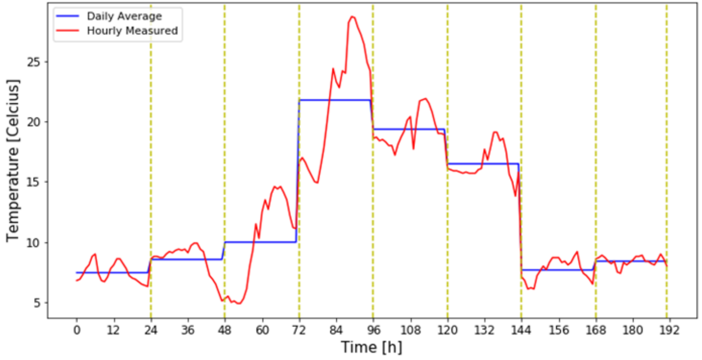


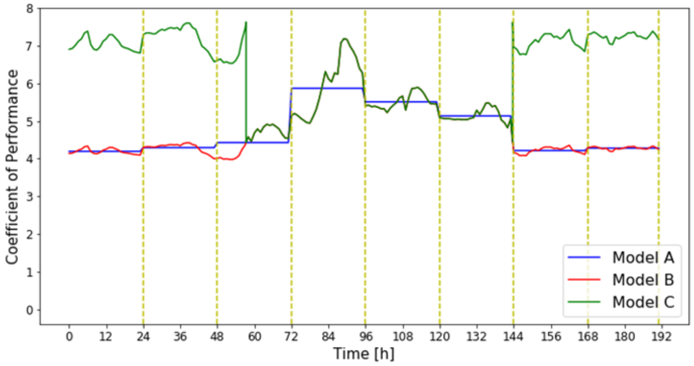


Max Δη = 0.6%

Power-to-Heat (Heat Pump)

Max ΔT = 7



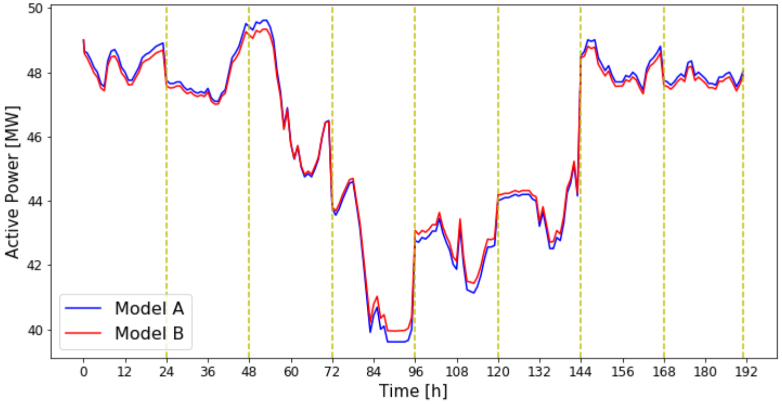


Max ΔCOP_{AB} = 1.4

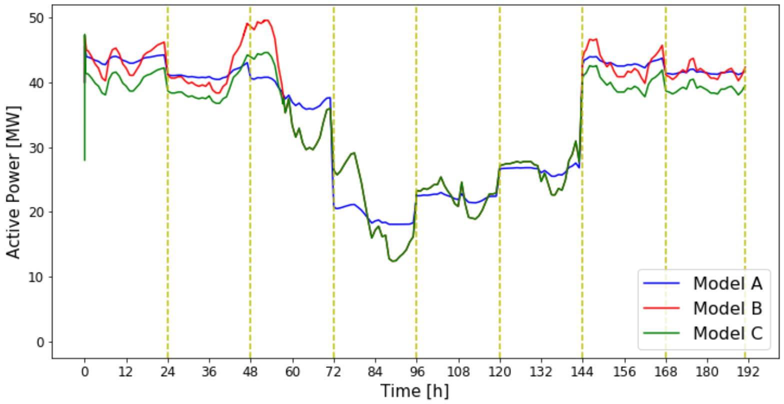
Max ΔCOP_{BC} = 3

Results – PtX Analysis

Power-to-Gas (Electrolyser)
Max ΔP = 0.4 MW



Power-to-Heat (Heat Pump)
Max ΔP_{AB} = 1.4 MW
Max ΔP_{BC} = 5 MW



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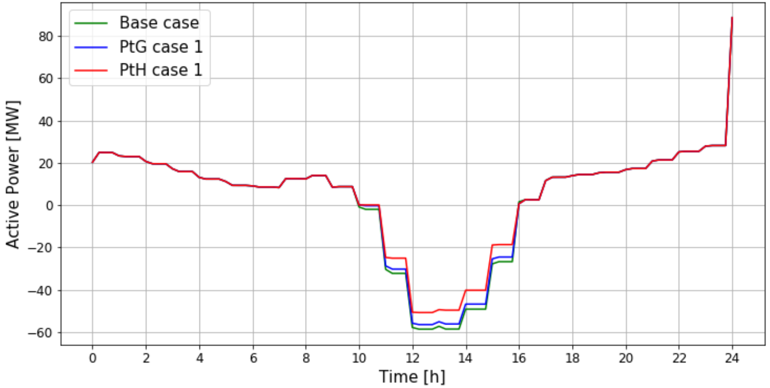
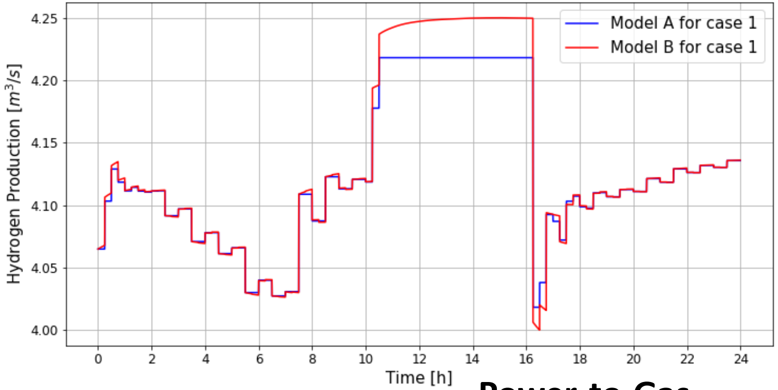
Results – Power System Analysis, Case 1



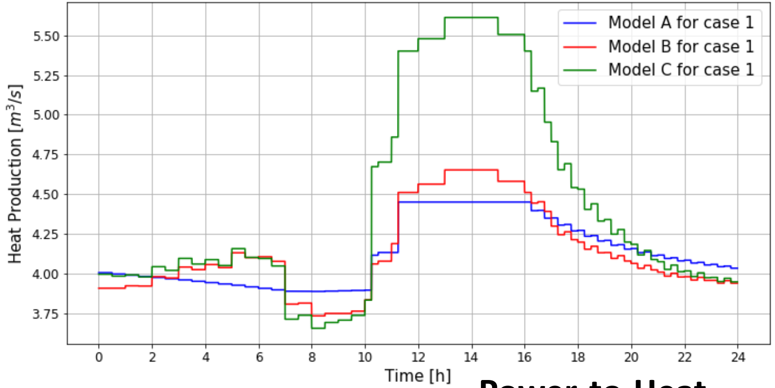
Max $\Delta P_{base\text{-}PtG}$ = 2 MW

Max $\Delta P_{base\text{-}PtH}$ = 10 MW



Power-to-Gas

Max ΔH_2 = 0.032 m^3/s



Power-to-Heat

Max $\Delta Q_{A\text{-}B}$ = 0.20 m^3/s

Max $\Delta Q_{B\text{-}C}$ = 0.96 m^3/s

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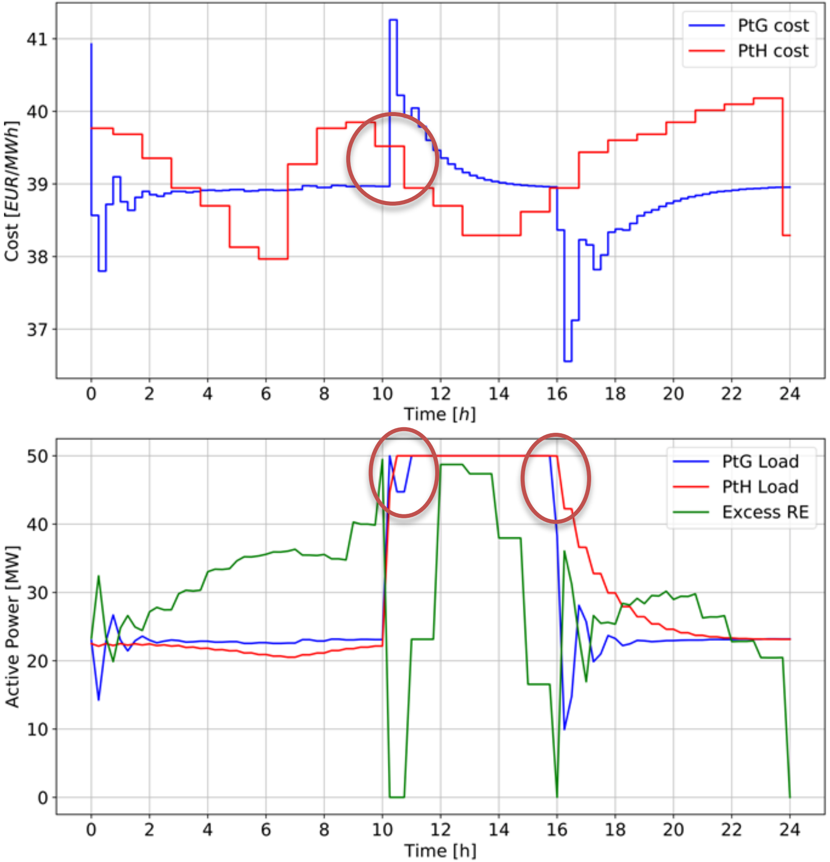
Results – Power System Analysis, Case 2



Time	Optimal Deployment		50% Equal Priority		100% PtG Priority	
	PtG [MW]	PtH [MW]	PtG [MW]	PtH [MW]	PtG [MW]	PtH [MW]
10:00	23.10	22.15	23.09	22.15	23.10	22.15
10:15	50.00	44.74	47.37	47.37	50.00	44.74
10:30	44.74	50.00	47.37	47.37	50.00	44.74
10:45	44.74	50.00	47.37	47.37	50.00	44.74
11:00	50.00	50.00	50.00	50.00	50.00	50.00
—						
16:00	38.27	49.98	44.13	44.13	49.98	38.27

- From 10:00 to 16:00, optimal deployment of flexibility was able to save 2.75€ with respect to 100% PtG priority and 0.99€ with respect to 50% equal deployment

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PtG: Power-to-Gas

Conclusion

1. Precision of flexibility analysis is bounded by the efficiency characterization of PtX and correct efficiency characterization of PtX highly depends on operating temperature conditions.

   - ➢ Case study results showed that 0.6% efficiency(PtG) & 1.4 - 3.0 COP(PtH) deviation is observed due to operational temperature evolution.

2. Comprehensive control approach can be achieved by agent-based hierarchical energy management system. This new understanding may help to improve predictions of the optimum operation point of MES.

   - ➢ In case study, optimal dispatch was able to save 2.75 € in one hour.

3. The relevance of co-simulation and Energysim for flexibility analysis of multi-energy systems is clearly supported by the current methodology.

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MES: Multi Energy System
PtX: Power-to-X

References

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