Hybrid energy systems

Innovate 2022

Day 2 – October 20th , Stockholm

Modelon

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PhD in Controls from Lund University, Sweden (2005)

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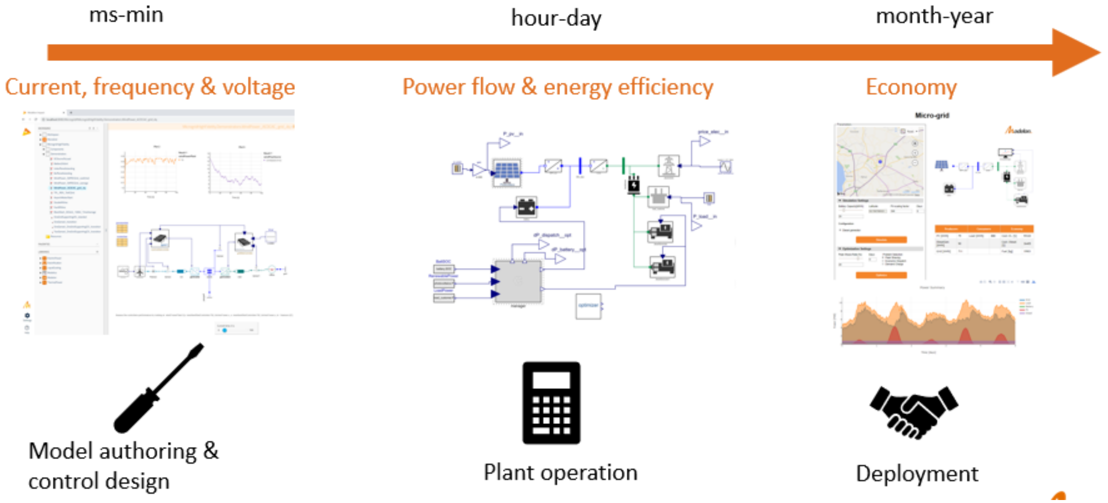
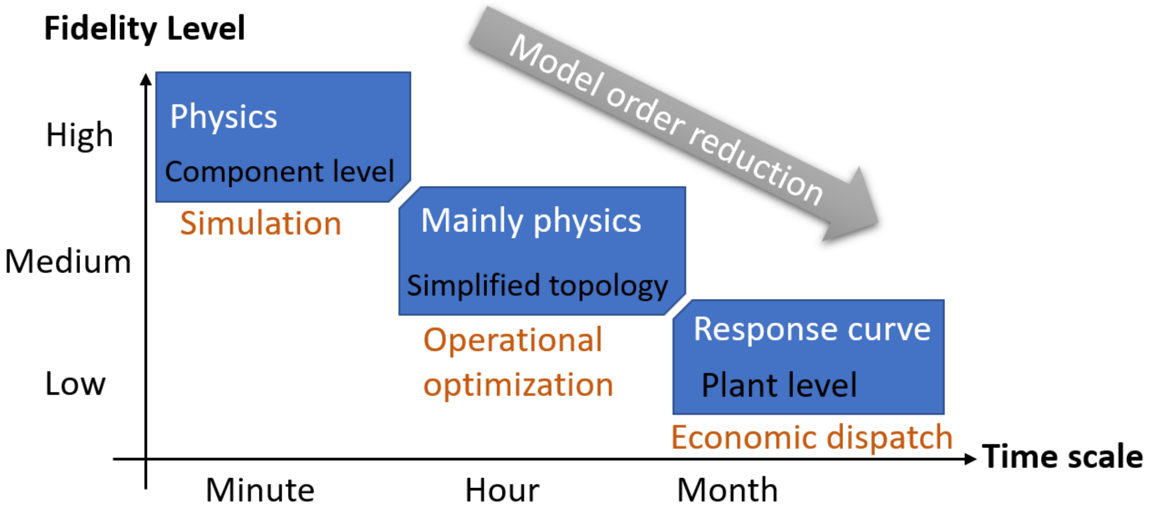
Why hybrid energy systems ?

- Energy transition: large variety of technologies
  - Conventional power plants
  - Renewable energy sources
  - Energy Storage Systems
- Sector coupling: Power-to- (gas, heat, power, X), EV to grid
- Hybrid & complex systems to design, control and integrate
- System simulations can support innovation

FIT FOR PURPOSE MODELLING

Acknowledge the need for models of various fidelity levels





Complex models → **Complex analysis**

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Outline

- Techno-economic assessment of hybrid energy projects
- Integration of renewable energy sources & storage
- Power to heat – heat pump integration

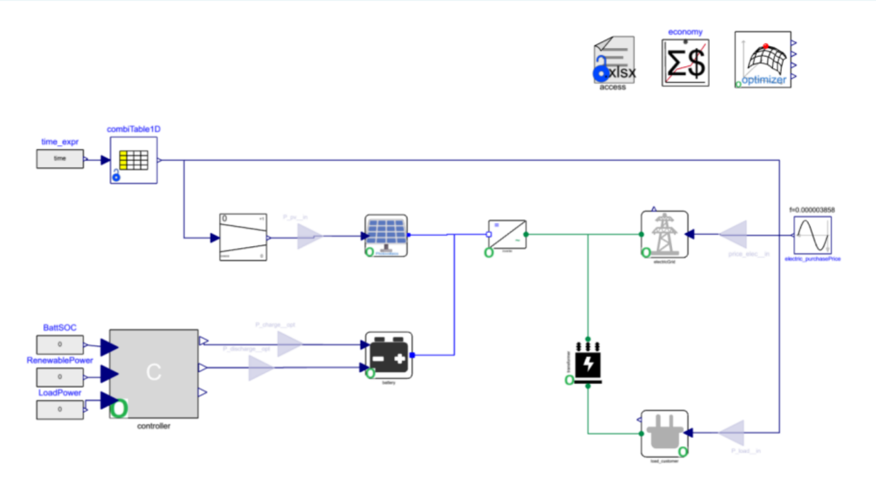
Techno-economic assessment of hybrid energy projects

- Microgrid package
- Optimization workflow
- Sizing and operation of storage
- Complex hybrid energy systems

Early stage development

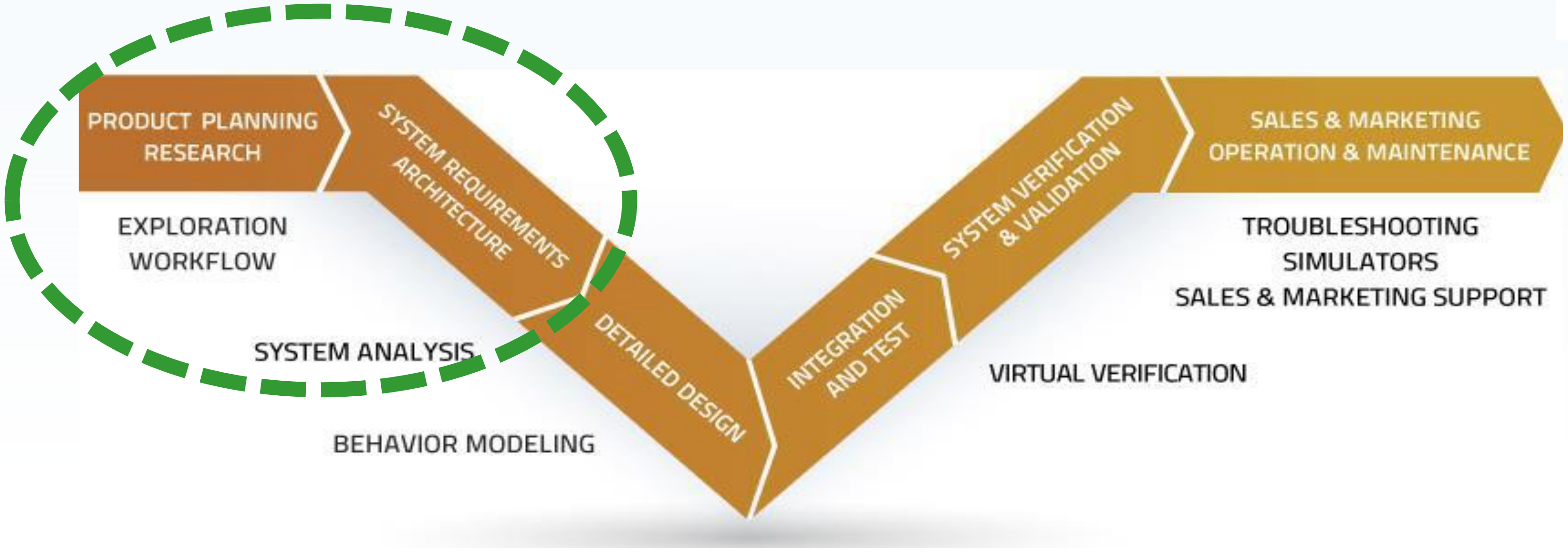
- Topology evaluations
- Achievable performance
- Component sizing
- Component usage

} Component requirements



Model characteristics

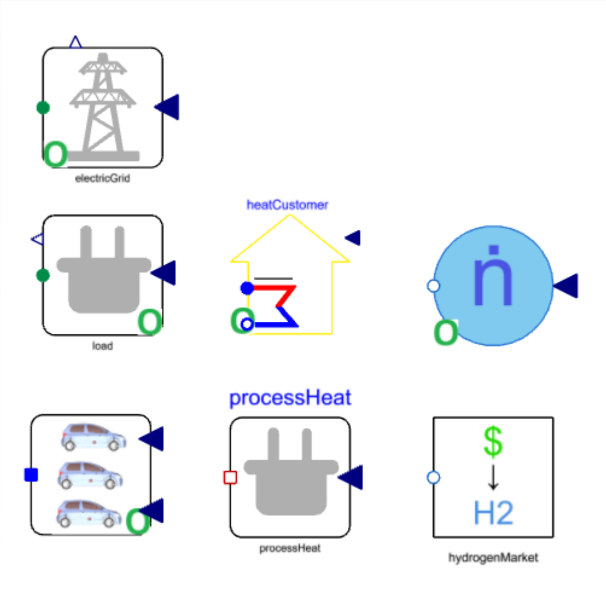
- Power flow
- Efficiency curves
- Dynamics in storage mainly



Microgrid package at a glance

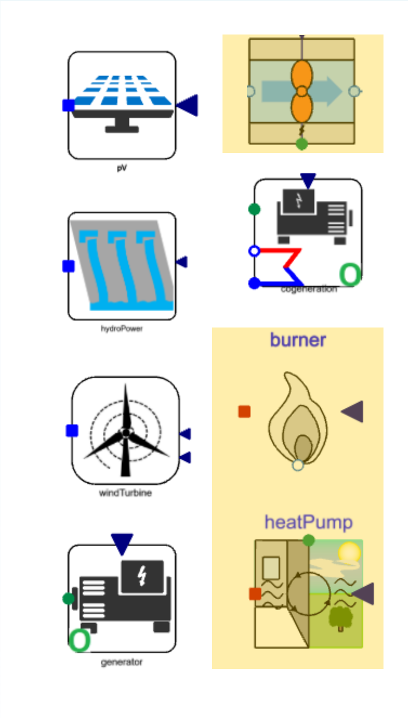
2022.2

2023.1



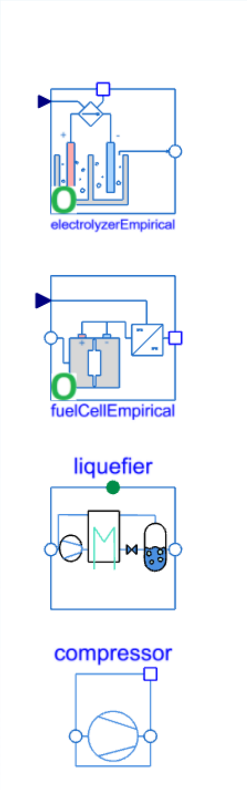
Sources and sinks

Power, heat or hydrogen



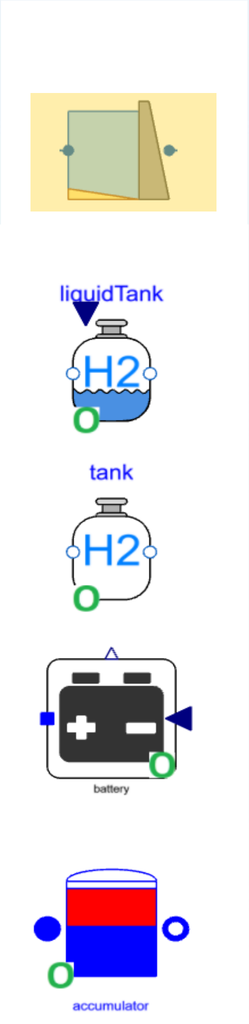
Production & conversion

Power & heat



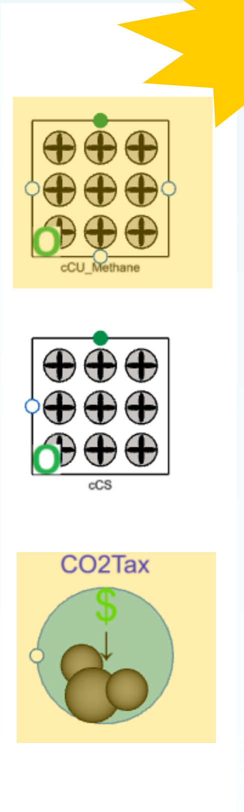
Production & conversion

Hydrogen



Storage

Power, heat or hydrogen



Carbon capture & utilization

Updates since 2022.1

Library scope

- Carbon capture
- Liquid tank H2
- Liquefier
- Gas market
- Electrolyzer and fuel cell with constant efficiency

Workflow

- Unique model for
  - Initial simulation
  - Optimization
- Automatic summation of costs
- Excel file import for forecast (load, prices, renewable power)

Performance

- Full year optimization with 1h sampling in 3-15 min

Physical modelling

- Efficiency-based
  - Constant
  - Load dependent
- Static components – except for storage!
- Simpler media models
  - Constant properties
  - Heating value, density, heat capicity, carbon content,...
- Nonlinearities from loss, compression, efficiency map, enthalpy flow

Electrolyzer

$$V_{cell,el} = E_{rev} + (r_1 + r_2 T_{el}) i_{el} + s\, log_{10}\left((t_1 + t_2 T_{el} + t_3 T_{el}^2) i_{el} + 1\right)$$

$$n_{\dot{H_2},el} = \eta_F \frac{n_{el} i_{el} A_{el}}{zF}$$

$$\eta_F = \frac{i_{el}^2}{f_1 + i_{el}^2} f_2$$

Battery

$$C \frac{dSOC}{dt} = P \cdot \begin{cases} \eta & \text{if P>0} \\ \frac{1}{\eta} & \text{if P<0} \end{cases}$$

Compressor

$$P = \dot{m} \frac{RT}{M} \log\left(\frac{p_{in}}{p_{out}}\right)$$

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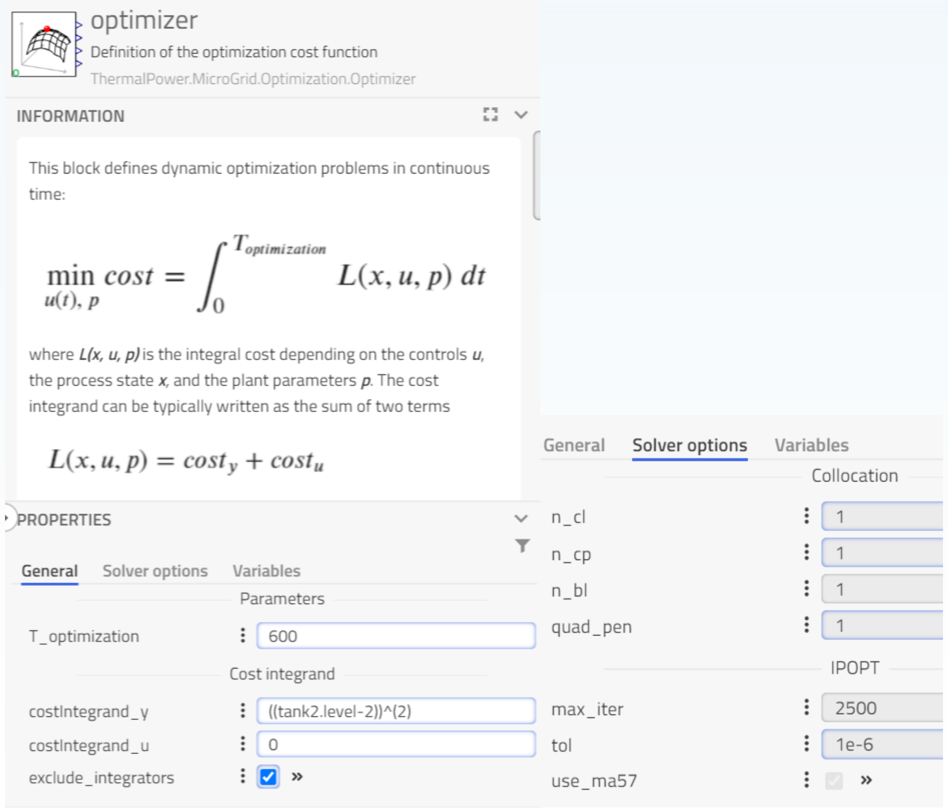
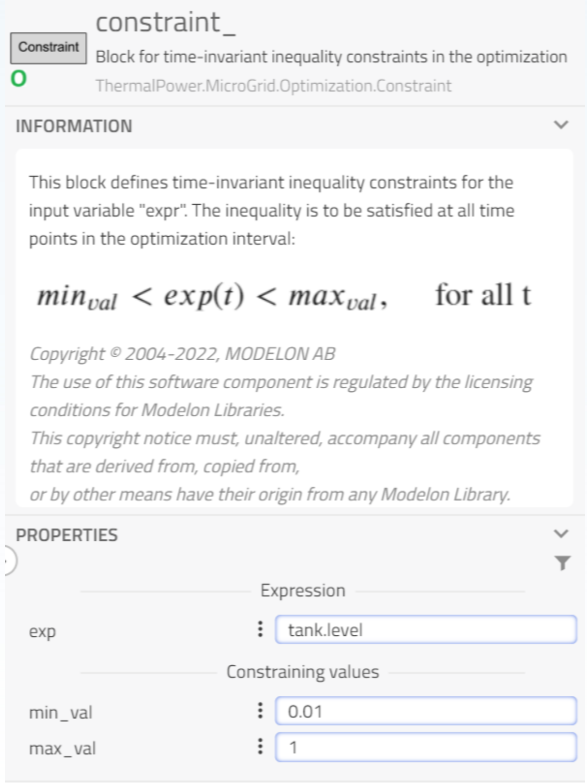
Optimization components

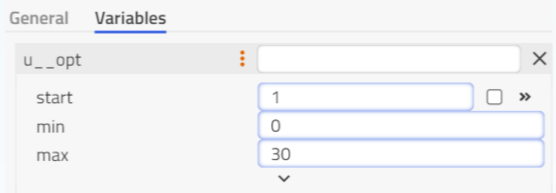
Optimizer for cost & solver settings



Inequality constraint block



Any variable bound is interpreted as optimization constraint



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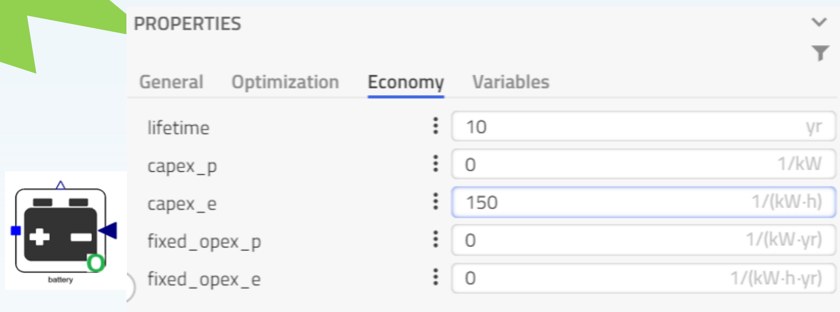
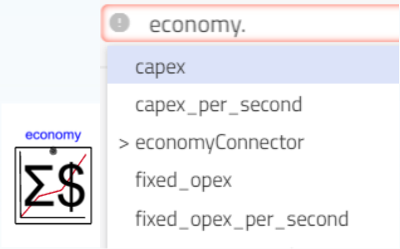
Economy modelling

2022.2

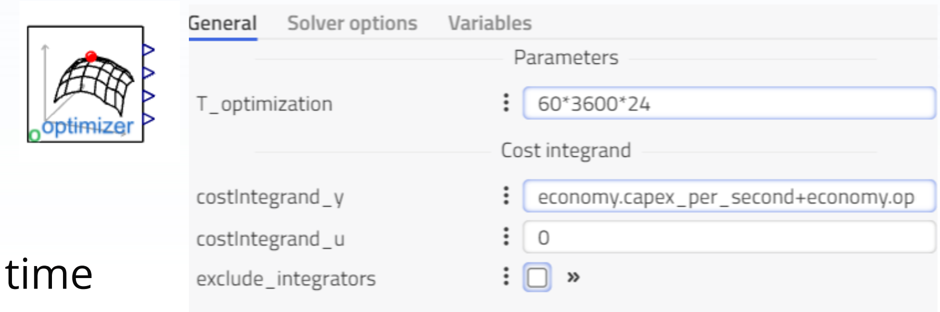
- CapEx and OpEx added to all components
  - Economy Tab
  - CapEx assumed to scale linearly with component capacity
  - Fixed or varying operational costs



- Automatic summation of all costs in *Economy* component
  - Cost normalized by life-time – to be included as integrand term in optimization
  - Capex_per_second, opex_per_second



- Allows technology assessment *w.r.t.* various KPIs
  - CapEx, OpEx, Total Cost of Ownership, Net Present Value, pay-back time

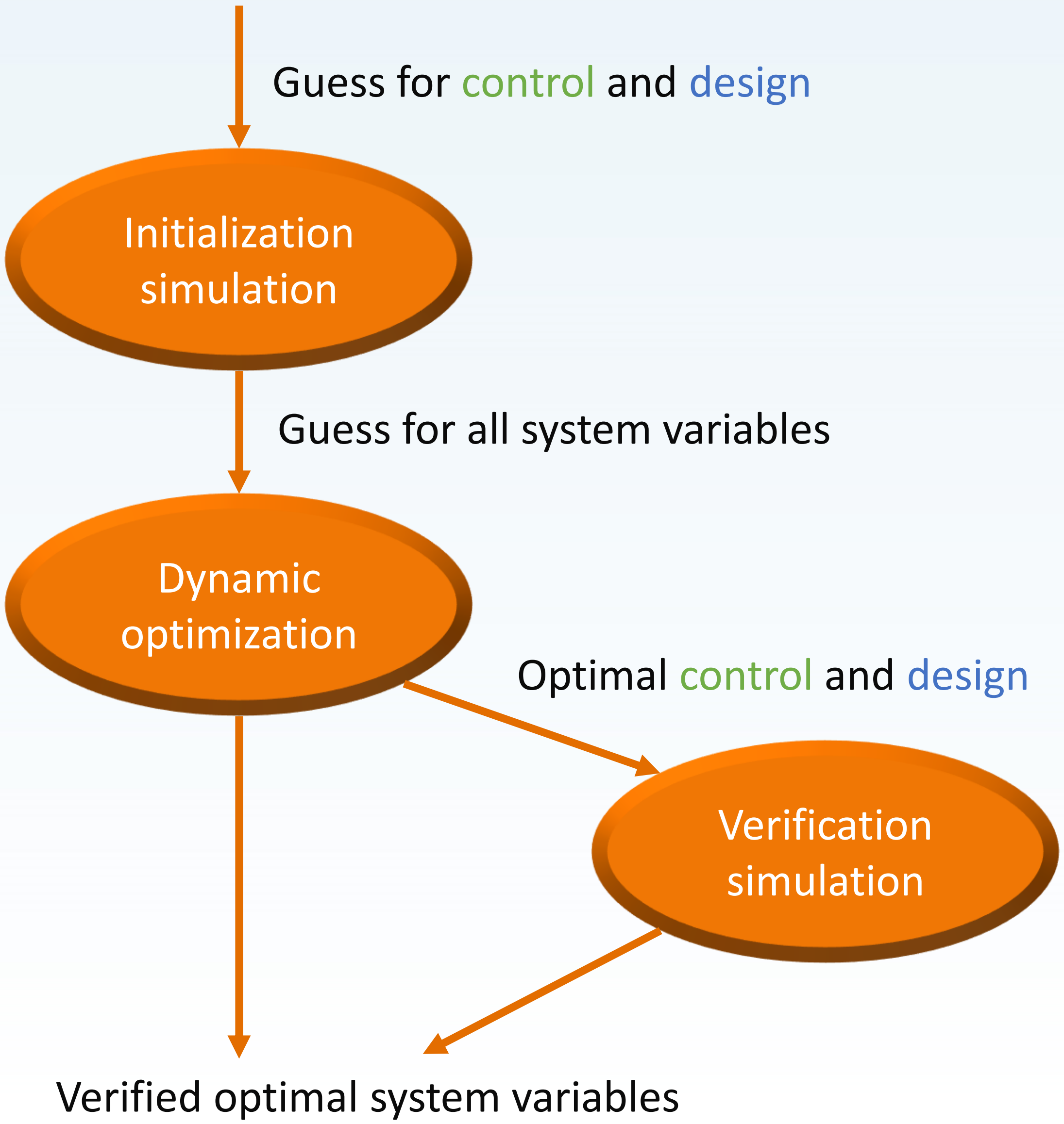


Techno-economic assessment

- Microgrid package
- Optimization workflow
- Sizing and operation of storage
- Complex hybrid energy systems

Optimization workflow

- Optimization solver needs reasonable initial guess of solution for reliable convergence
- Generated by specifying degrees of freedom
  - Component sizes
  - Control laws

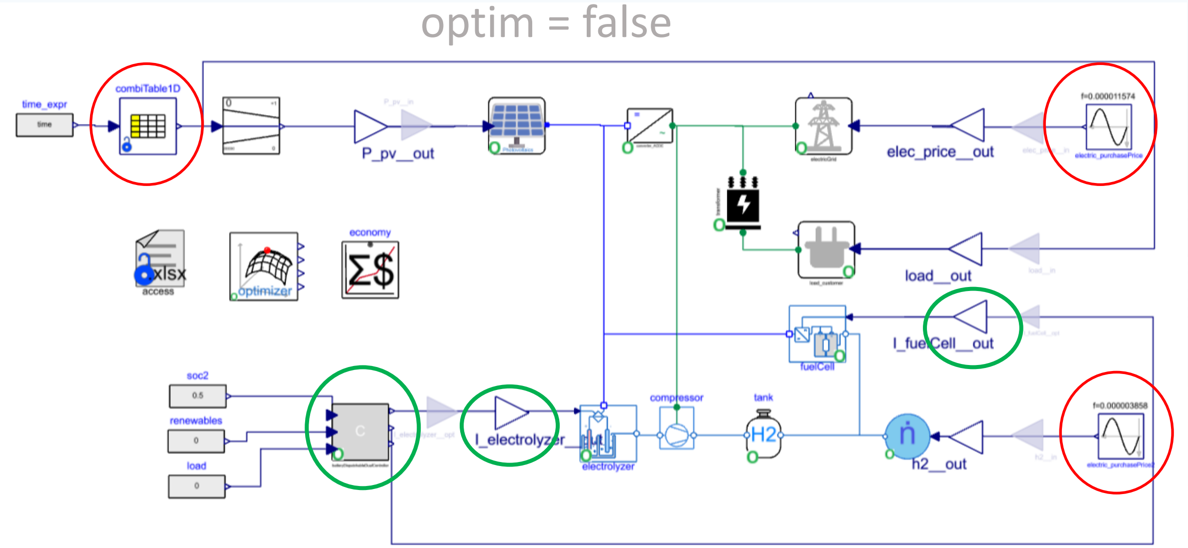


Initialization versus optimization models

Simulation model

Boundary conditions assigned by blocks

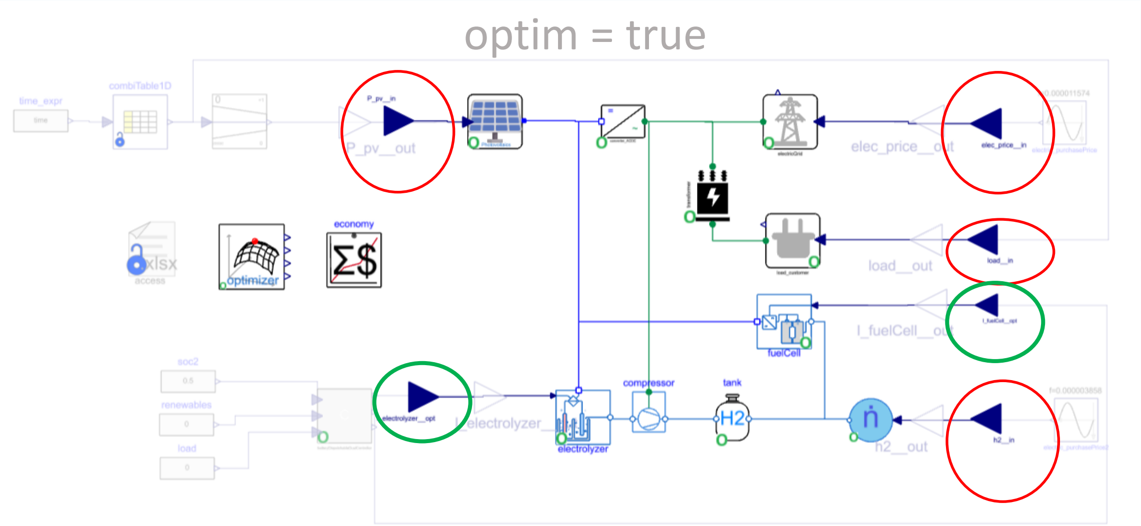
Controller for electrolyzer & fuel cell



Optimization model

Boundary conditions set by inputs

Control signals set by inputs



Custom function

- Custom function runs the entire optimization workflow and returns the results
- Found in the Resources folder of Thermal Power Library
- To be placed
    - Local install: C:\Users\UserName\impact\custom_functions
    - Server install: /home/jovyan/impact/custom_functions
- All settings read from optimizer block

Import methods for compilation and fmu loading

```
from pymodelica import compile_fmu
from pyfmi import load_fmu
from pyjmi import transfer_optimization_problem
```

Compilation & loading of the model for initialization

```
# Compile the optimization initialization model
init_sim_fmu = compile_fmu("CSTR.CSTR_Init_Optimization", "CSTR.mop")

# Load the model
init_sim_model = load_fmu(init_sim_fmu)
```

Initial simulation

```
# Simulate with constant input Tc
init_res = init_sim_model.simulate(start_time=0., final_time=150.)
```

Compilation of the optimica code

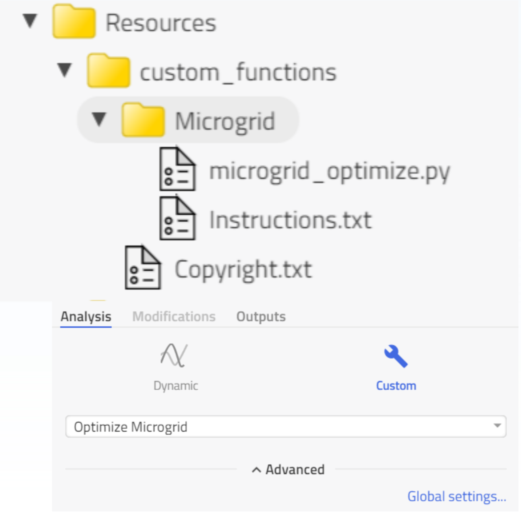
```
# Compile and load optimization problem
op = transfer_optimization_problem("CSTR.CSTR_Opt2", "CSTR.mop")
```

Optimization options

```
# Set options
opt_opts = op.optimize_options()
opt_opts['n_e'] = 19 # Number of elements
opt_opts['init_traj'] = init_res
opt_opts['nominal_traj'] = init_res
opt_opts['IPOPT_options']['tol'] = 1e-10
```

Optimization

```
# Solve the optimal control problem
res = op.optimize(options=opt_opts)
```



Techno-economic assessment

- Microgrid package
- Optimization workflow
- Sizing and operation of storage

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Storage – design, operation and integration

- Storage to mitigate impact of variability and uncertainty of renewables
  - Decoupling of demand & production
  - Sector decoupling

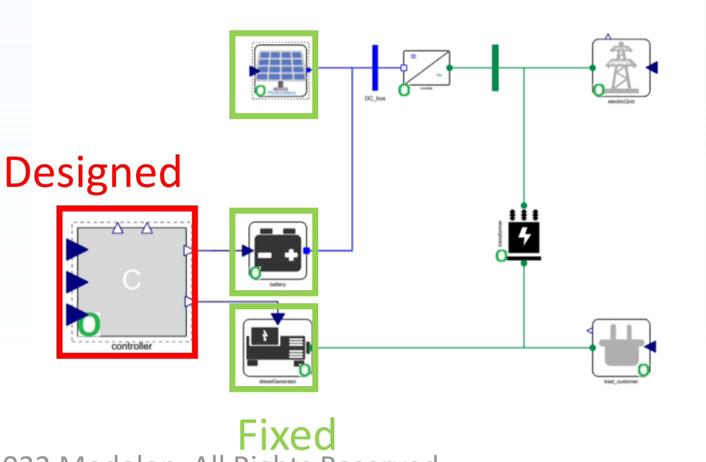
- Significant research to develop new storage systems
  - Cheap, scalable (capacity & power), dispatchable, efficient, sustainable
  - Electrical, thermal, thermal electrical, potential, chemical

- Investors & innovators need a tool for early assessment

Typical approach – Sizing and controls done separately

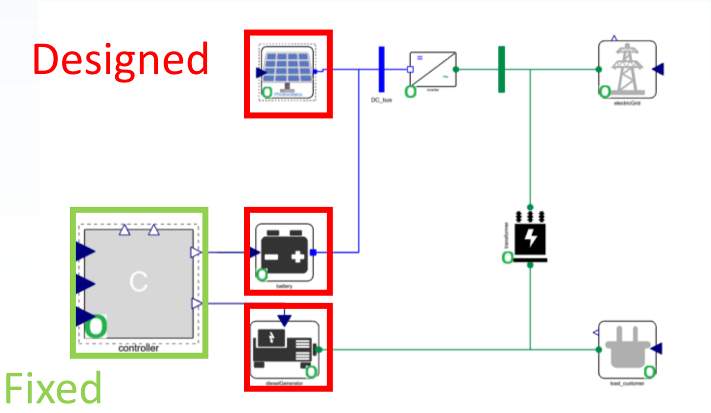
Control

- When designing a control strategy, the assets' size is normally considered fixed
- Control aims at operating the assets for a minimal operational cost while fulfilling operational constraints – not easy!
- Focus is on OPEX
- Mathematically, it is about optimization of time-trajectories
  - Ex: battery charging rate

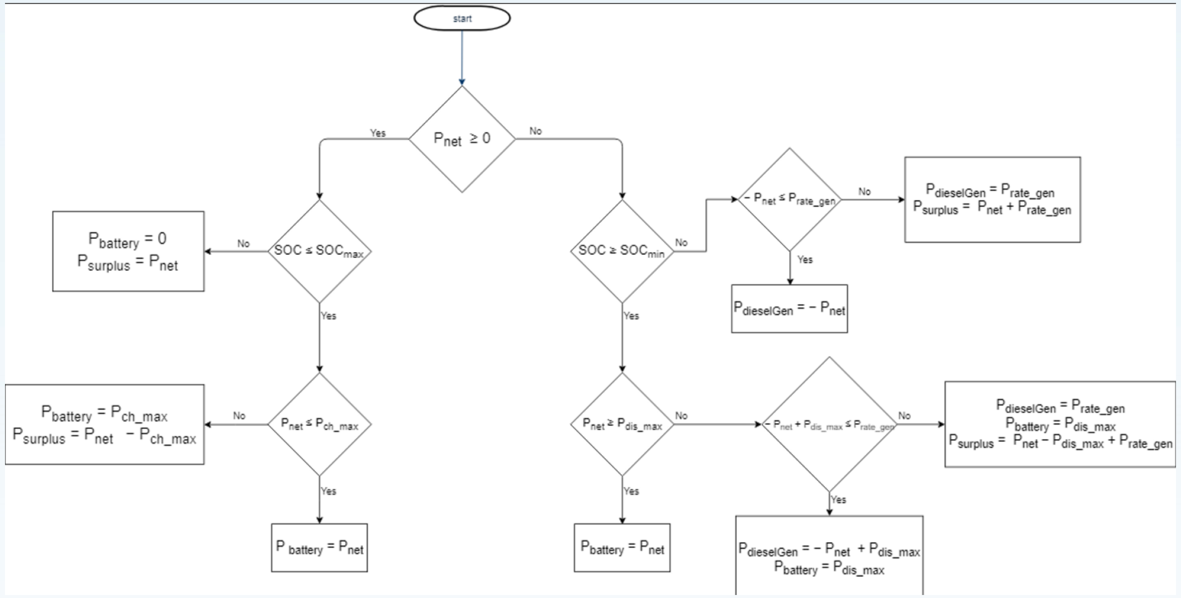


Sizing

- When sizing, the control strategy is normally fixed
- Sizing aims at finding the size of all assets for a minimal overall cost while fulfilling operational constraints
- Focus is on CAPEX
- Mathematically, it is about parameter optimization
  - Ex: battery capacity



Simple storage control



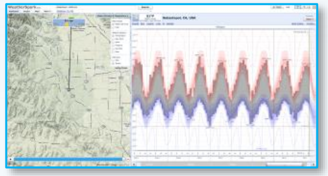
- Simple approach
  - If energy surplus => battery is charged
  - If energy missing => battery is discharged

- No usage of forecast for price, load and weather

- Best control strategy depends on system configuration & boundary conditions
- Difficult to systematically derive control strategy for every considered system

Proposed approach: Control co-design

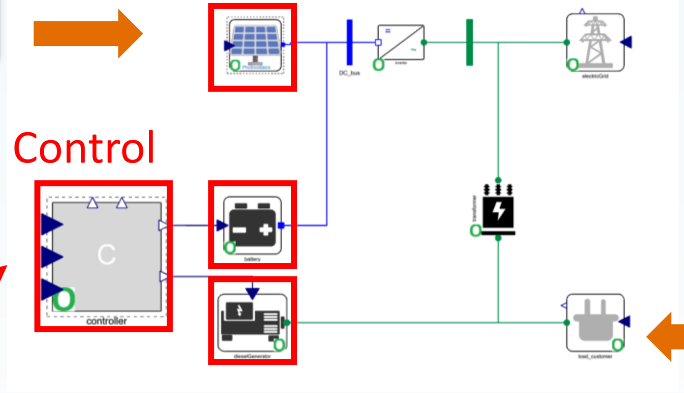
Solve simultaneously for optimal control and optimal sizing while exploiting forecast



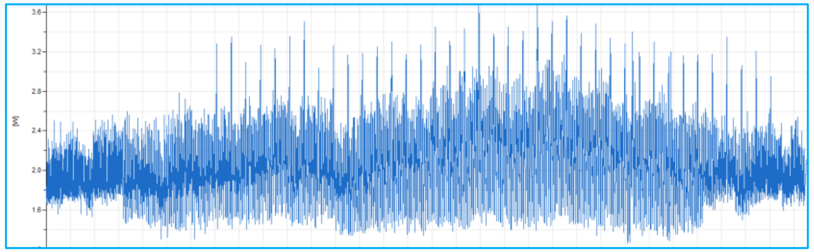
Weather

Design

Control



Electricity price



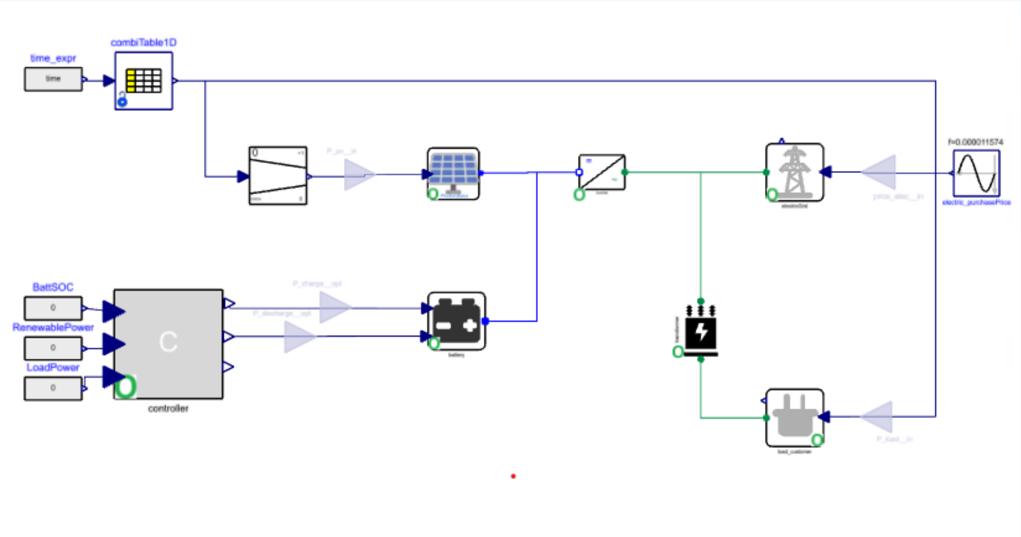
Load

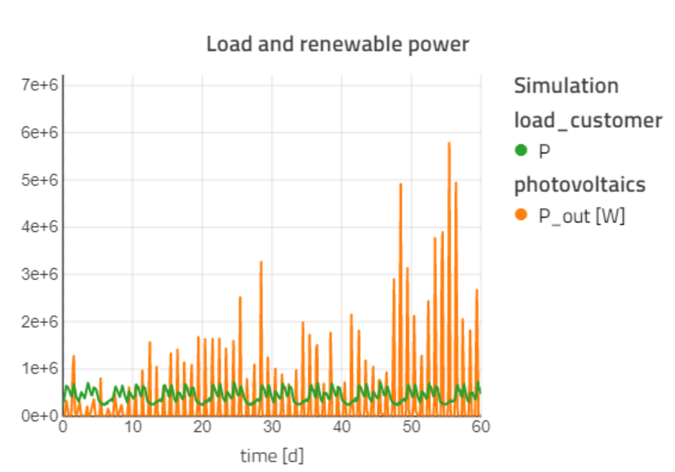
Most critical component:

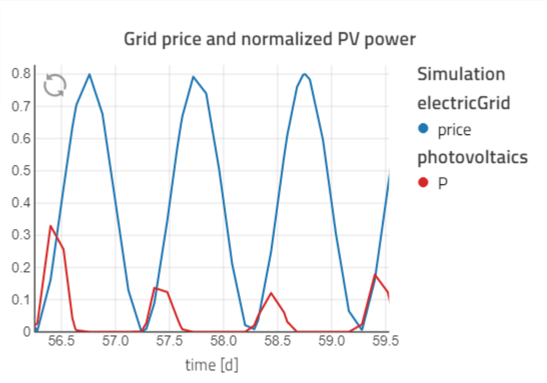
- No need to derive empirical controllers
- Constraint handling
- Forecast exploitation
- Interacting control loops

Battery sizing – Problem Description

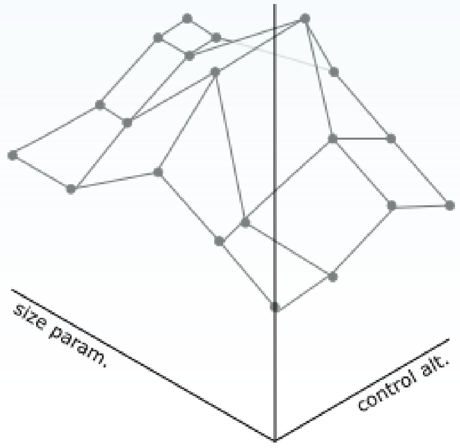
- Given expected profiles over 3 months for
  - Electricity price
  - Load
  - Renewable power
- Find the battery size & operation
- To minimize the total cost of ownership (opex+capex)





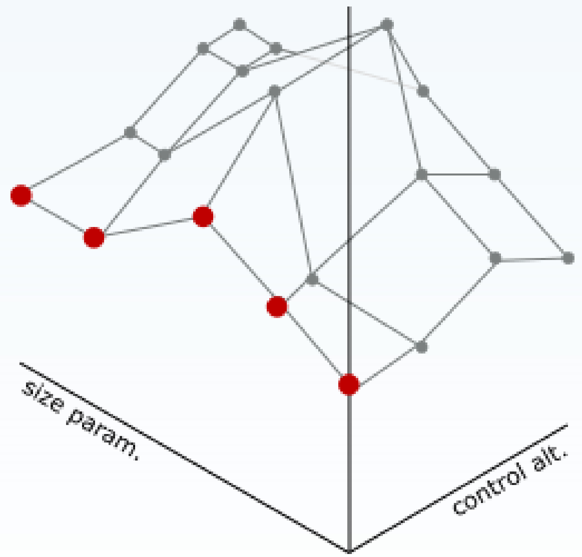


Grid price does not peak at the same time as PV power



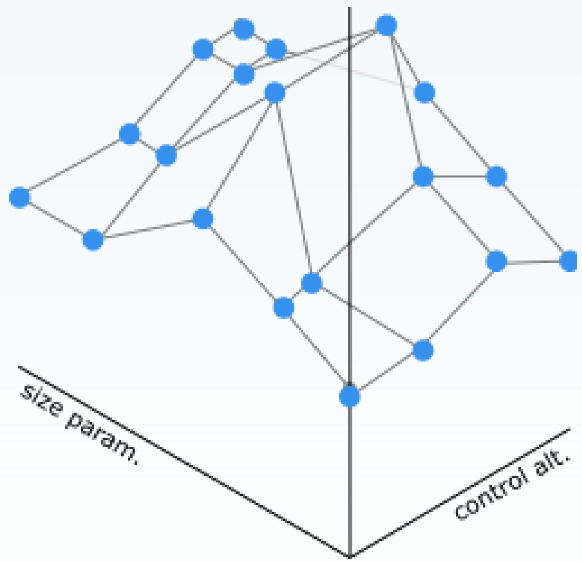
Evaluation of three strategies

Fixed controller + capacity sweep



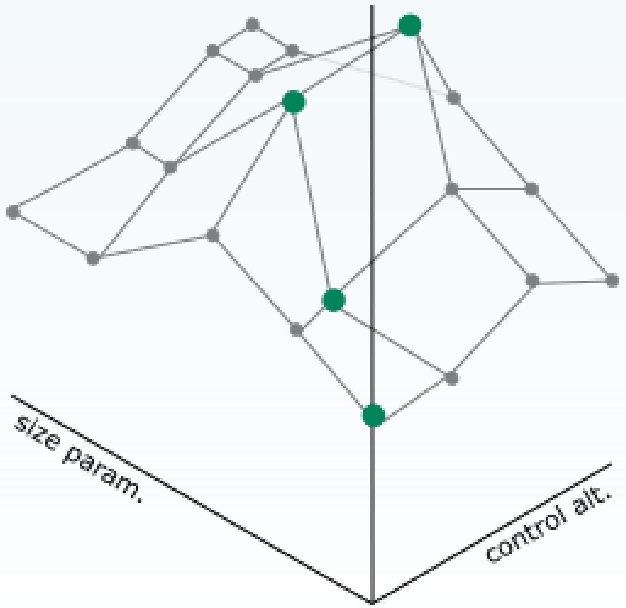
Batch of simulations

Optimal dispatch + capacity sweep



Batch of optimizations

Control co-design



Single optimization

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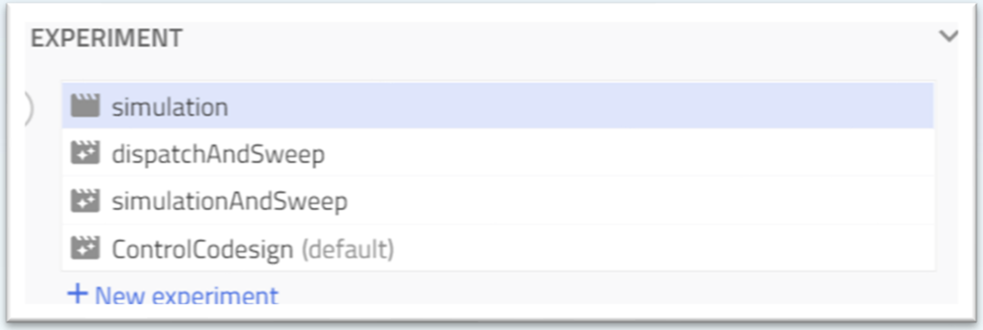
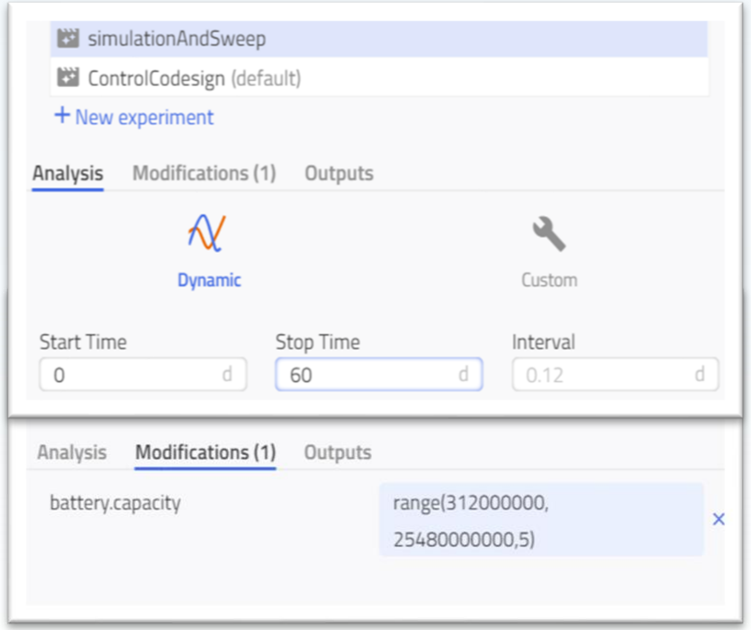
Experiments in Modelon Impact

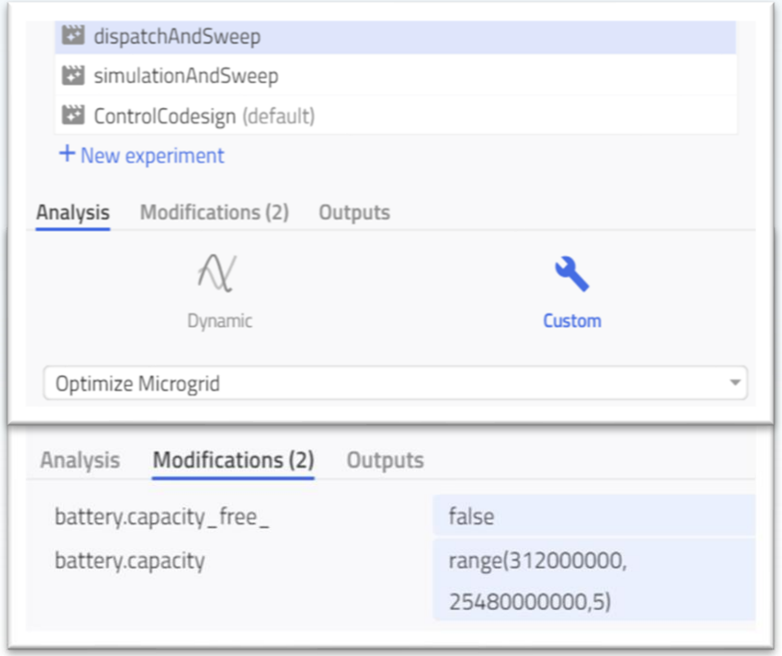


Fixed controller + capacity sweep



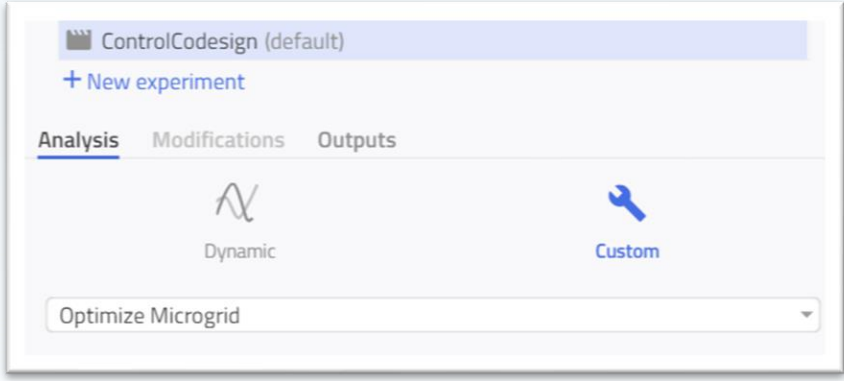
Batch of simulations

Optimal dispatch + capacity sweep



Batch of optimizations

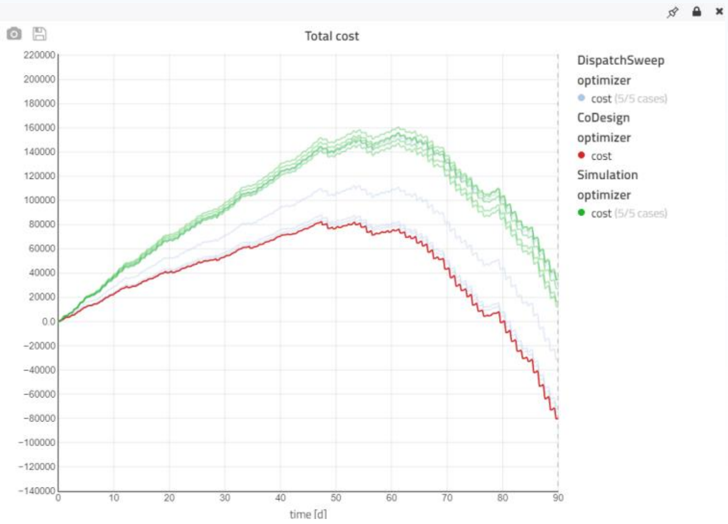
Control co-design

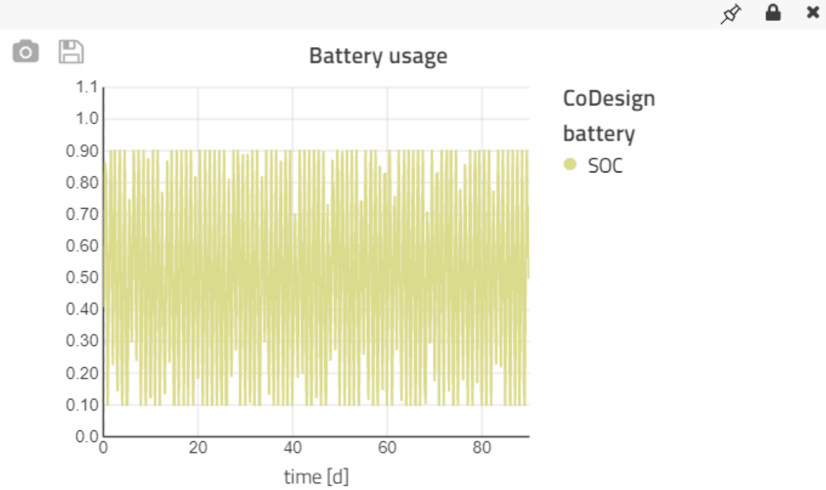


Single optimization

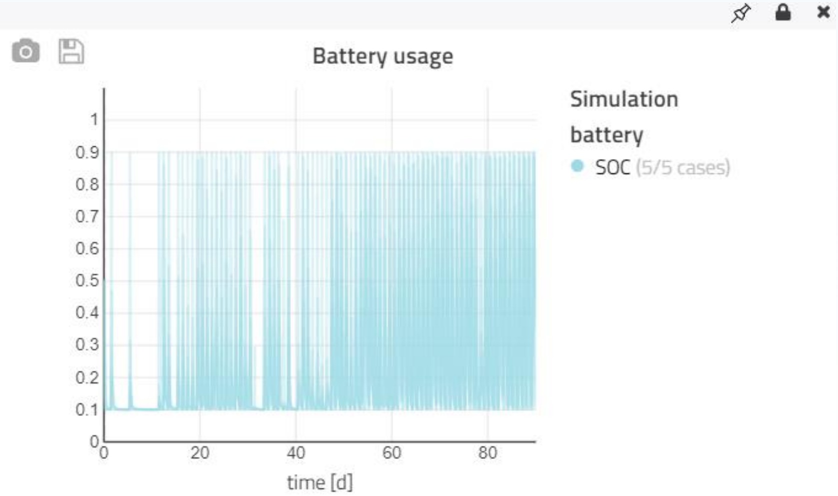
Results

Strategy	Lowest cost [kEUR]	Optimal storage size [MWh]	Cost at small battery [kWh]	Computation time [s]
Simulation + sweep	12.3 [cost]	2.1 (case 2)	35.5	5s (~5*1)
Optimal dispatch + sweep	-101.3 [benefit]	6.2 (case 4)	32.3	100s (~5*20)
Co-design	-101.4 [benefit]	6.0	-	23s





Fully exploited storage



Poorly exploited storage

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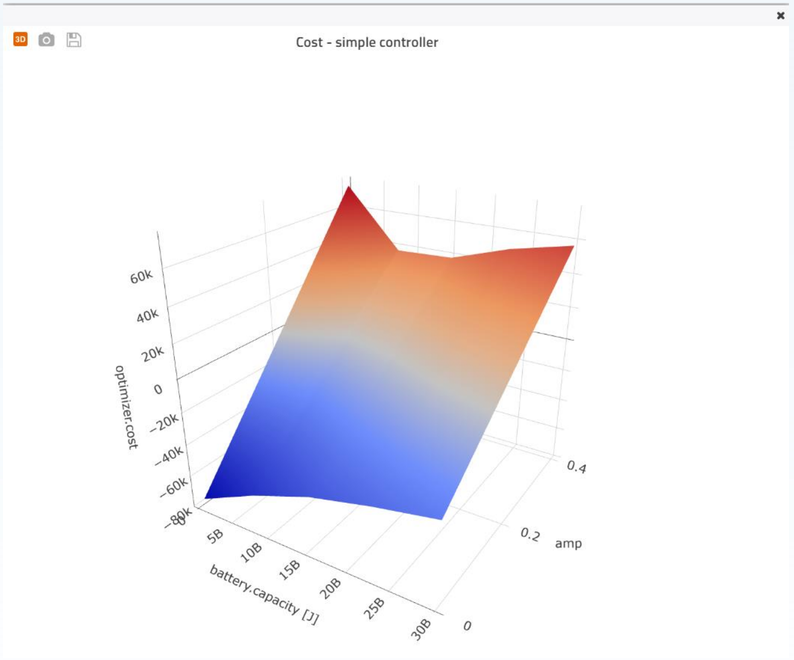
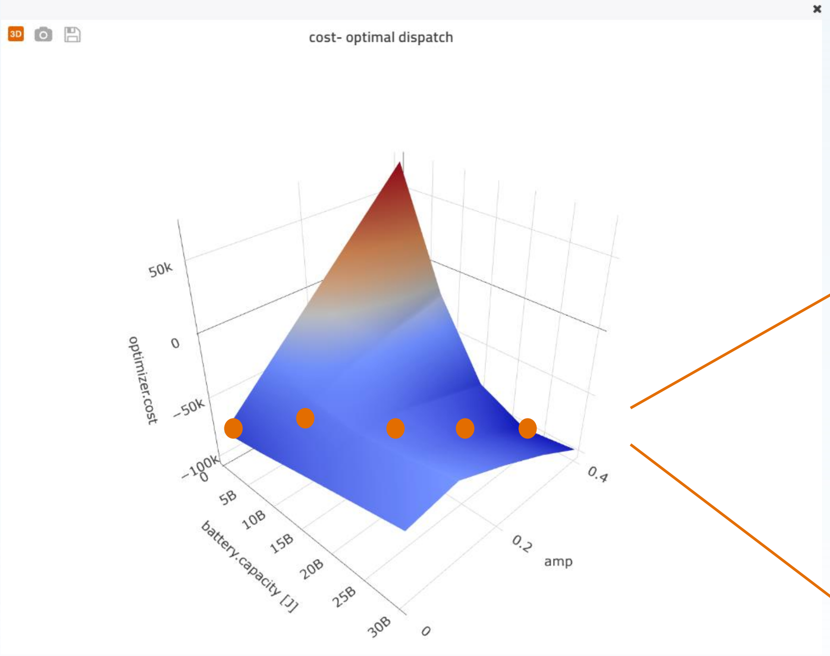
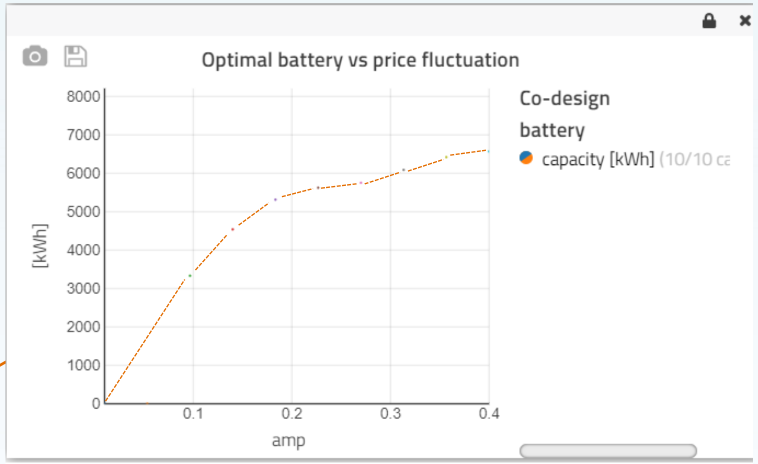
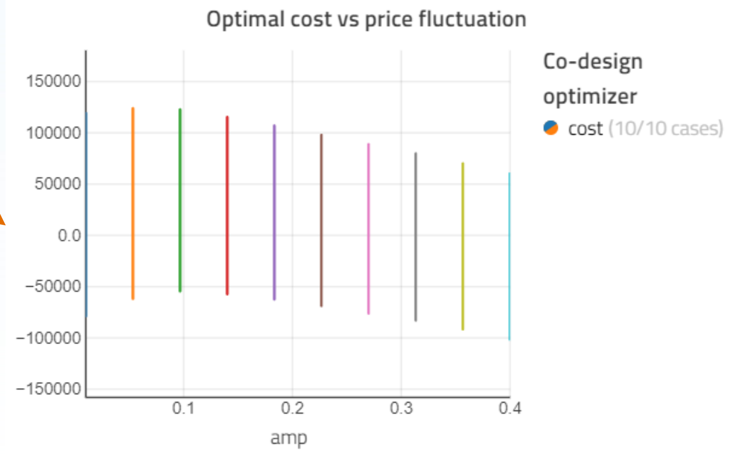
DEMO

Sensitivity *w.r.t.* fluctuations in grid price







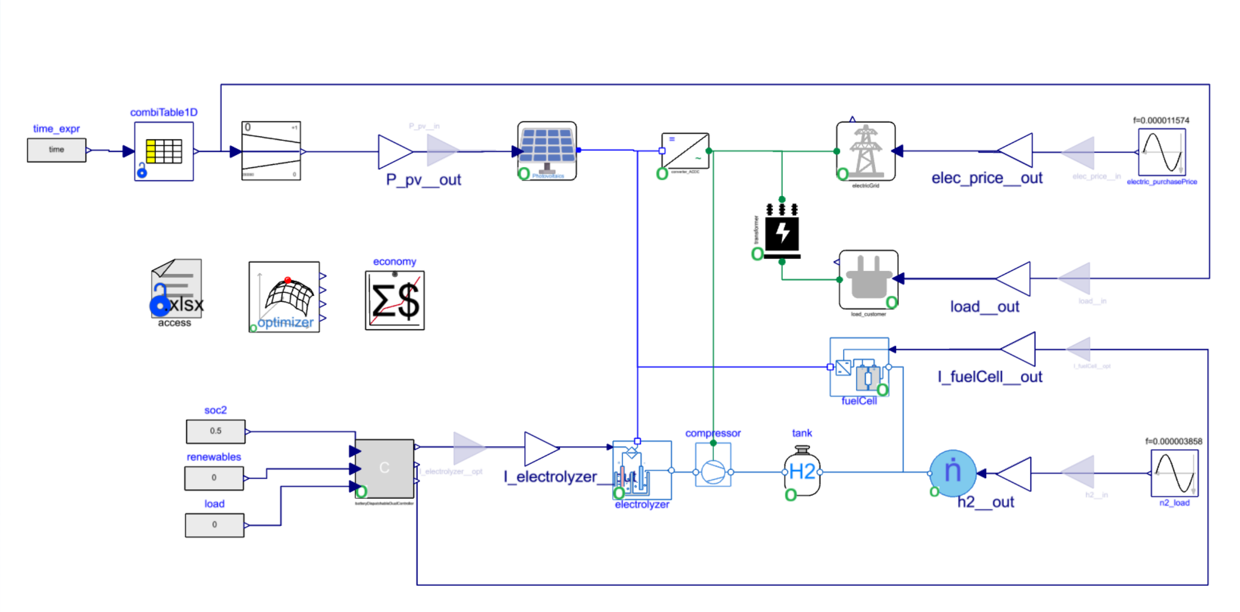


Large area in the red (no benefit)
Optimal storage size at high fluctuations
No battery best when constant grid price

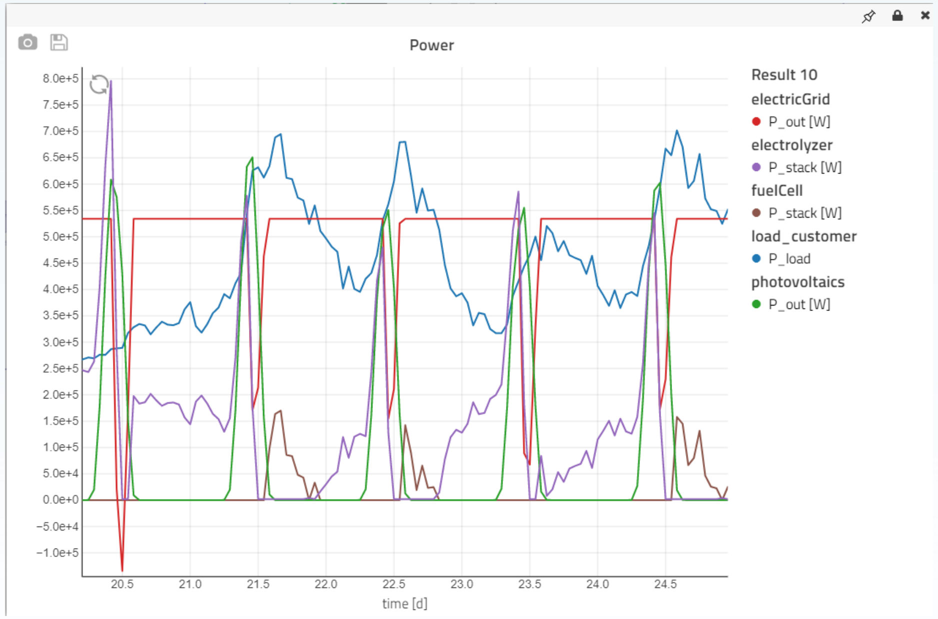
Small area in the red (no benefit)
Best profit when large battery & fluctuation
No battery best when constant grid price

Optimal operation of a hydrogen system

Minimize the operational cost = demand charge + grid energy



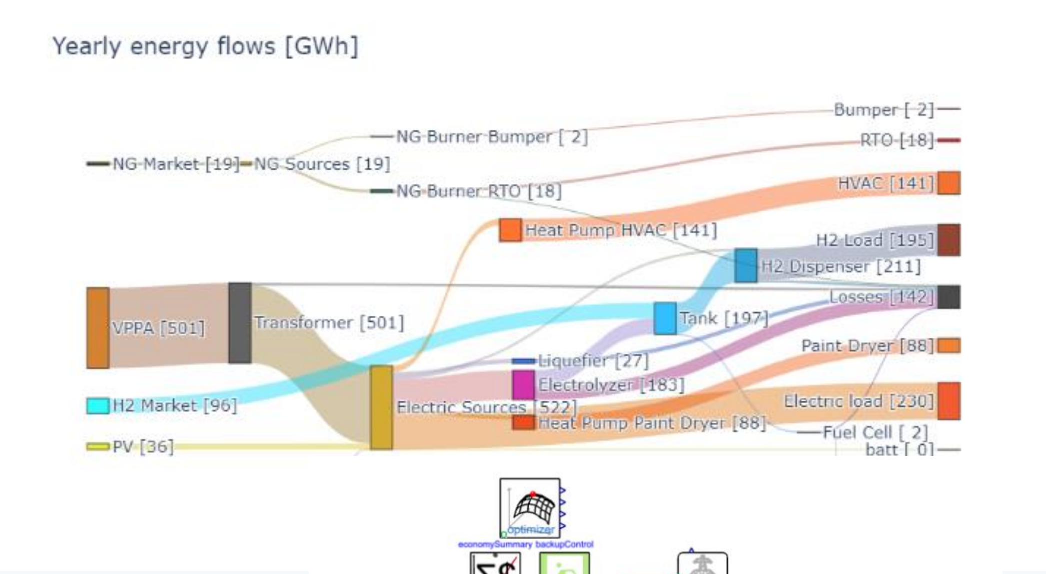
ThermalPower.MicroGrid.Examples.Simulation.EconomicDispatchHydrogen

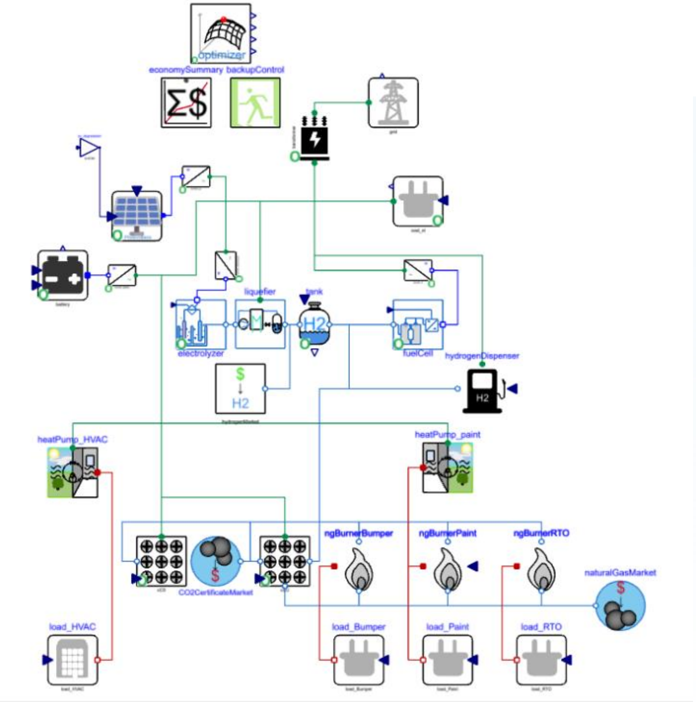


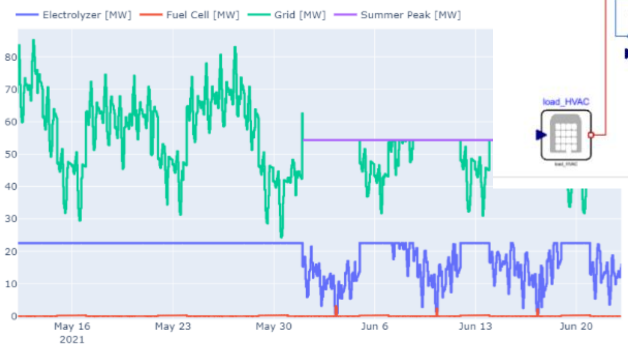
- Grid import shaved to minimize demand charge
- Electrolyzer mainly driven by PV
- Fuel cell used to shave load peaks when no PV output

Complex energy system

- Car manufacturing company
- Use case to be published at upcoming Asian Modelica conference
- TCO minimization, targeting carbon neutrality
- Technology options
    1. *Import versus on-site generation* for hydrogen and power
    2. *Fuel cell versus battery* for backup-power and peak shaving
    3. *CCS vs. CCUS vs. carbon tax* to deal with the emissions from the combustion processes
    4. *Conventional burner versus heat pump* for drying process



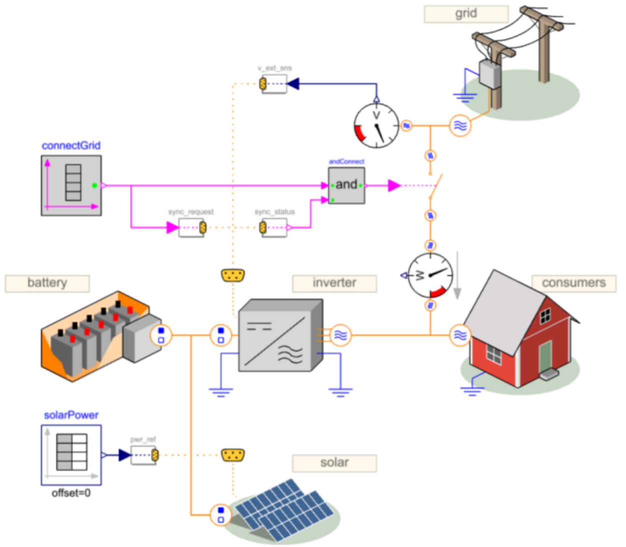


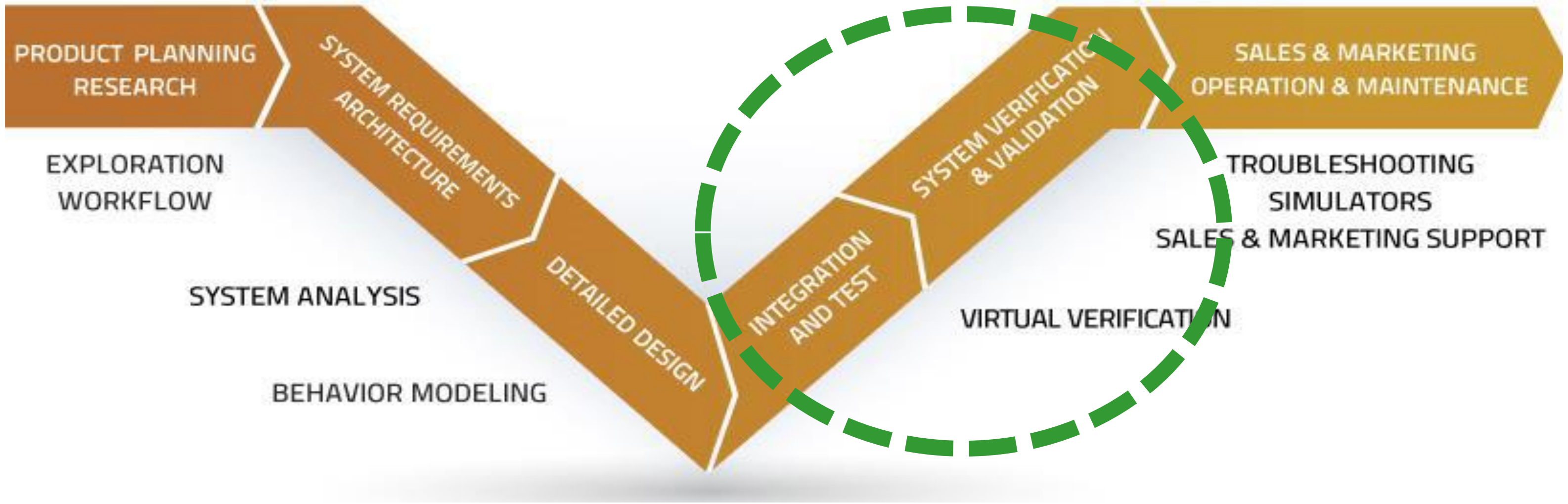


Renewables integration and control

LATE STAGE DEVELOPMENT

- Virtual design verification
- Implementation optimization
- Software verification
- Customer issue analysis



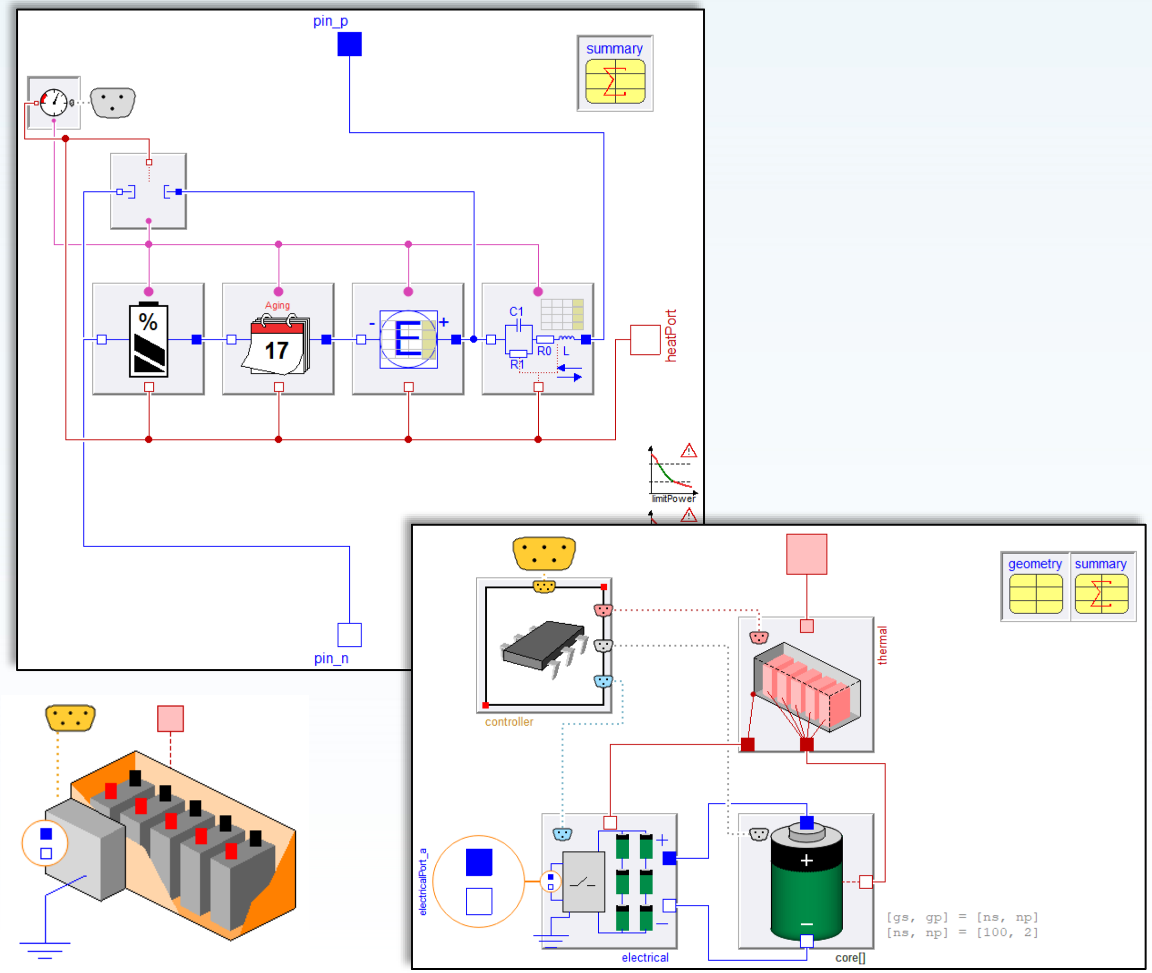


Model characteristics

- Detailed 3 phase AC representation
- Current, voltage & frequency
- Grid feeding & grid forming controller
- Synchronization algorithm

Electrification Library – Battery model

- From battery cell to module to pack
- Scalable fidelity: from lumped packs to individual cells
- Separate scaling of physical domains: core battery, thermal dynamics, electrical connections, controls
- Modular core battery models
    - Charge capacity
    - Voltage
    - Impedance
    - Self discharge
    - Aging
- Battery management control
- Cell imbalances



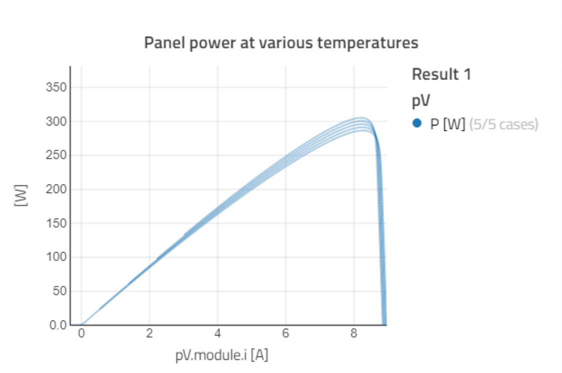
Component architecture with separation of domains

Thermal Power Library – Photovoltaic panel models

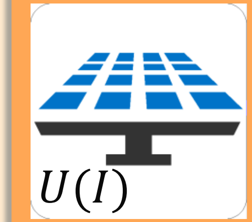
$$P = \eta P_{rat} \frac{irr}{irr_{ref}} (1 + \alpha(T - T_{ref}))$$

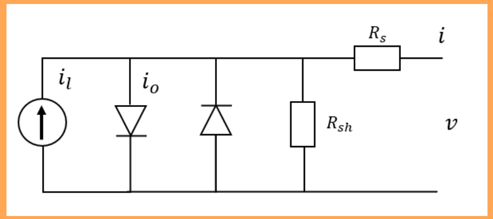
- Simple efficiency model
- Low-fidelity
- Targeting energy management
- Power source for the whole PV plant

ThermalPower.MicroGrid.RenewableEnergy.PhotoVoltaics.PhotoVoltaics_efficiency



Reference conditions			
S_ref	1000	W/m²	
T_c_ref	25	°C	
AM_ref	1.5		
Geometry and configuration			
A	1.95624	m²	
n_cells	72		
n_modules	1		
Five parameter			
i_mp_ref	8.26	A	
i_sc_ref	8.95	A	
v_oc_ref	45.1	V	
v_mp_ref	35.7	V	
alpha_sc_ref	0.066/(100)*i_sc_ref		
beta_oc_ref	-0.33/(100)*v_oc_ref		





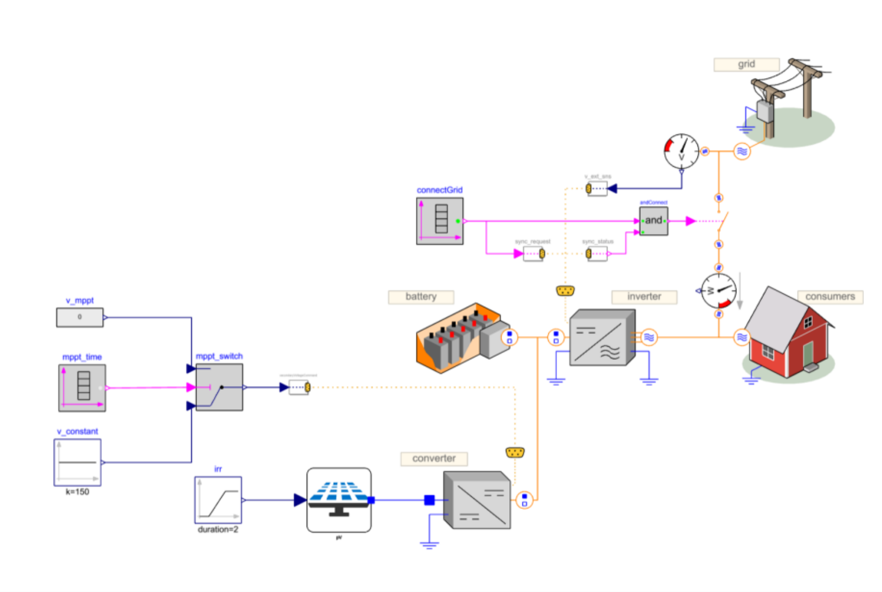
$$i = i_L - i_o\left(e^{\frac{v+R_s i}{a}} - 1\right) - \frac{v + R_s i}{R_{sh}}$$

- Single-diode 5 parameters model
- Current/voltage map
- Optional Maximal Power Point Tracking
- Suitable for inverter control
- By-pass diode around every module
- Prepared for advanced heat transfer
- Blocking diode in every string
- Hierarchical model from cell to array

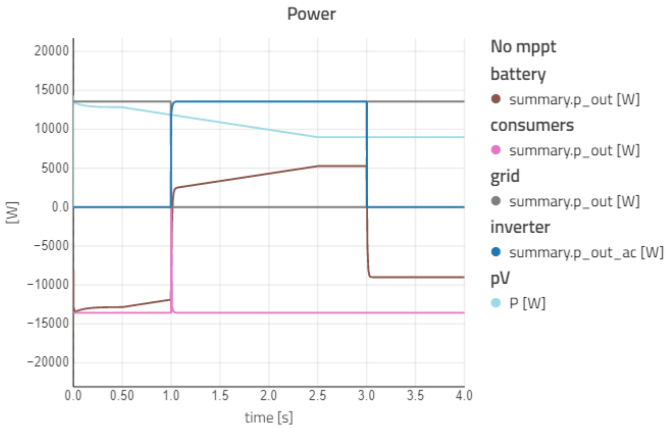
ThermalPower.MicroGrid.RenewableEnergy.PhotoVoltaics.Array

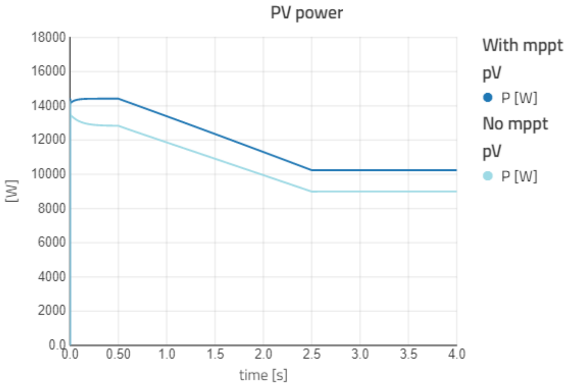
DEMO

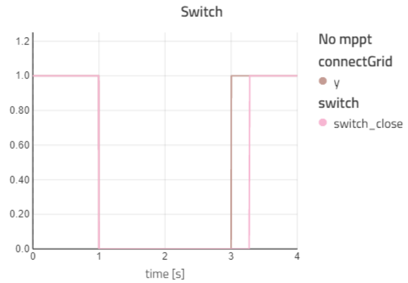
Renewable and battery integration

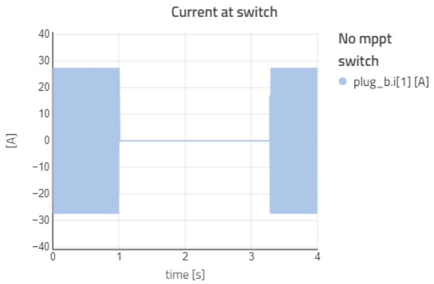


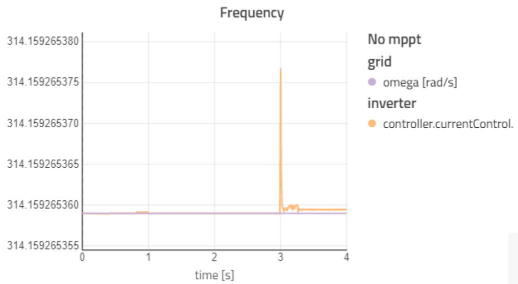
Time [s]	Event	Inverter	Battery
0-1		Grid feeding, P_ref=0	Being charged by PV
1	Power outage		
1-3		Grid forming, voltage & frequency control	Being discharged to replace grid and meet the load demand
3.0	Connection request	Synchronizing with grid	
3.4-	Grid connected	Grid feeding, P_ref=0	Being charged by PV











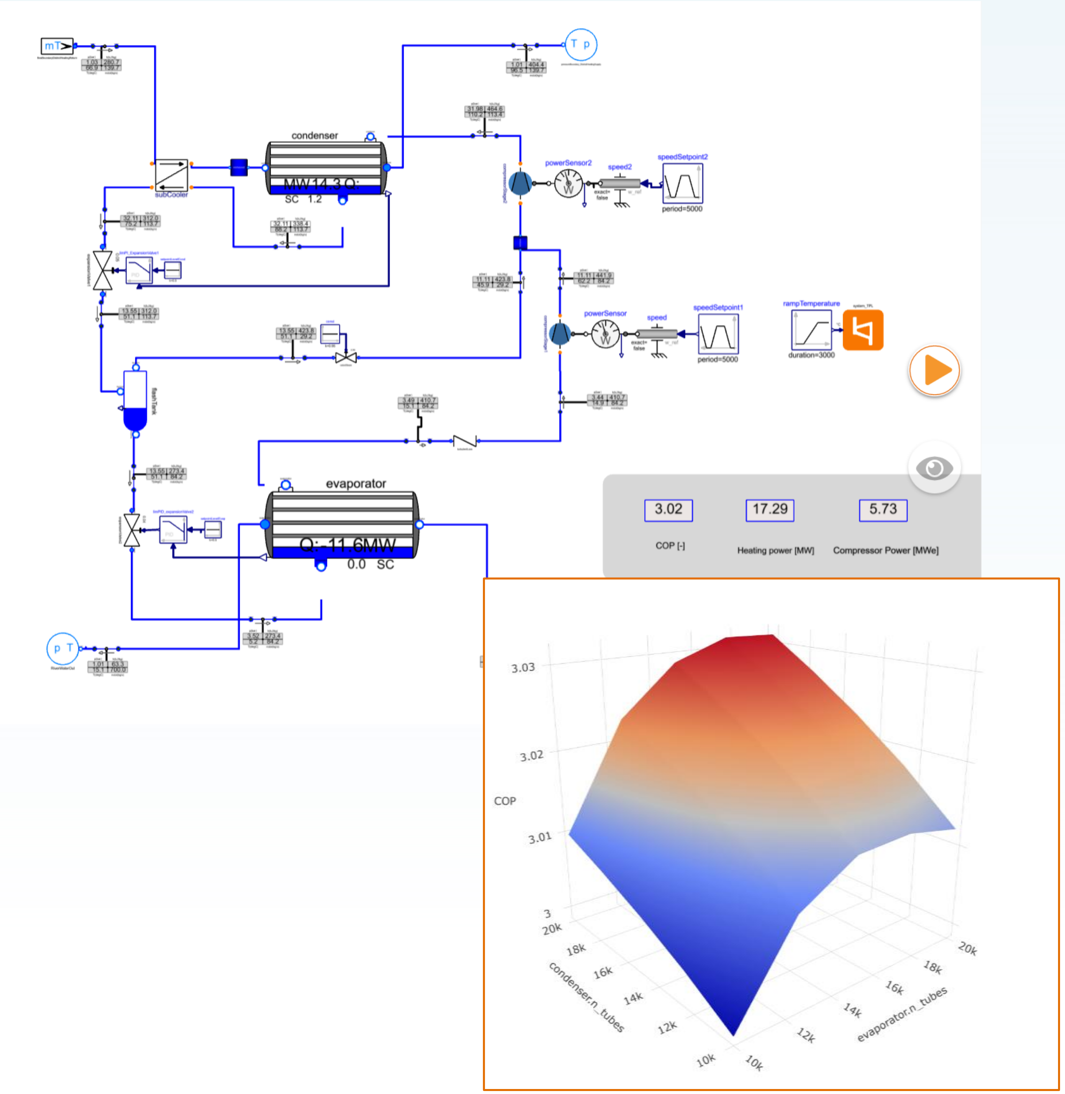
Modelon

Power to heat – Heat pump integration

- Detailed heat pump model Siemens SHP-600 added in 2022.2 release
- New design approach in realistic environment with closed loop system feedback!
- Allows heat pump and control strategy design for new electricity market grid services for heat pumps

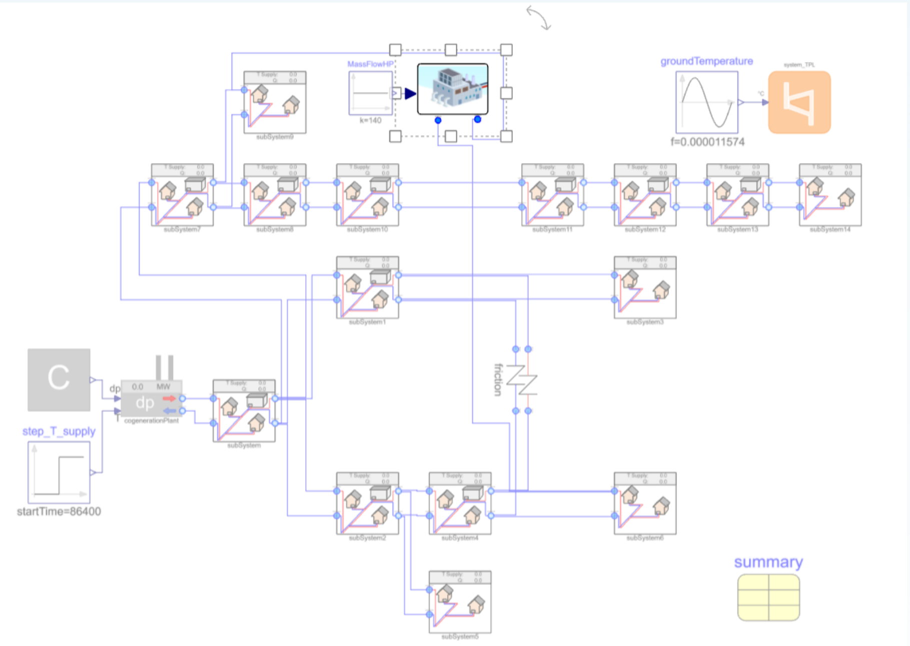
New heat pump model Siemens SHP-600

- High-fidelity heat pump based on existing Thermal Power Library components useful for:
  - Basic design studies (heat exchanger geometry, compressor maps)
  - Working fluid studies
  - Basic control design
- Constant or varying boundary conditions without direct feedback – as state of the art for design workflows



Heat pump integration for design verification

- Integration of the heat pump into a district heating system impacts heat pump performance and control stability:
    - Changing COP when change of network temperature.
    - Possible feedback of heat pump output provides additional challenges for heat pump control design!
- Not state of art for design but significant reduction of risk and effort for commission and field testing through coupled dynamic simulation



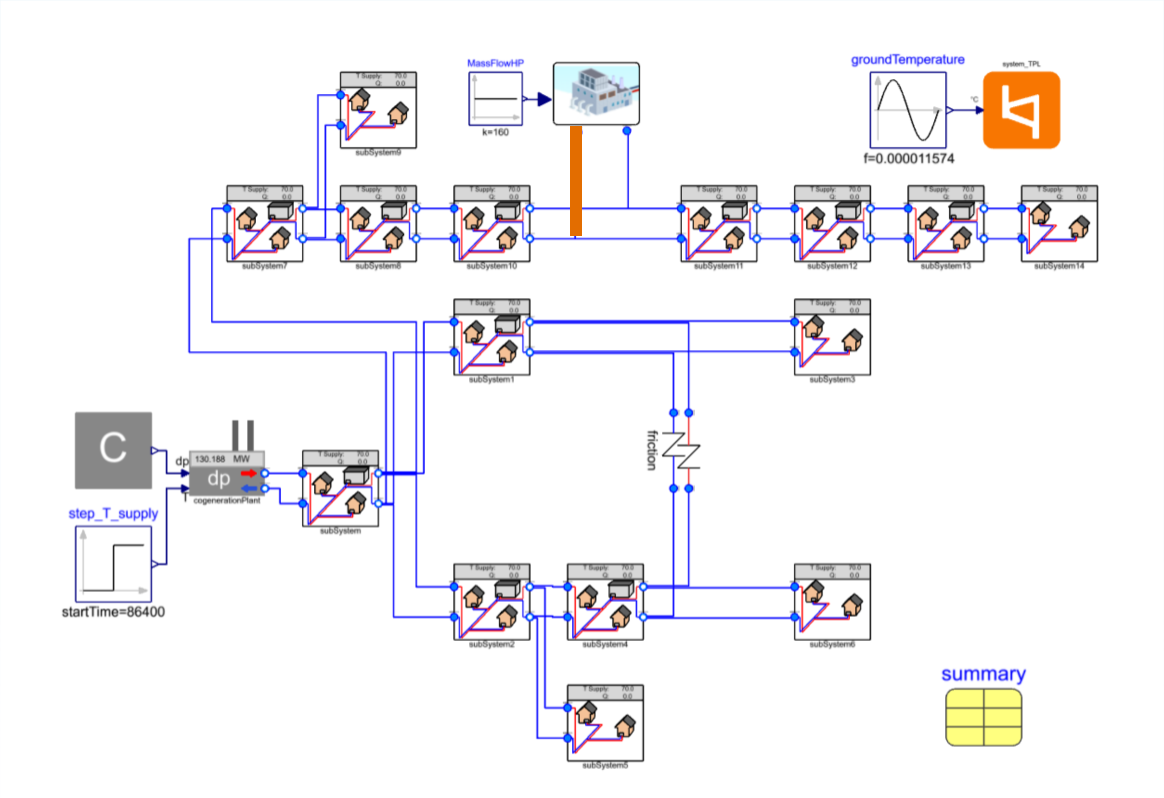
Modelon

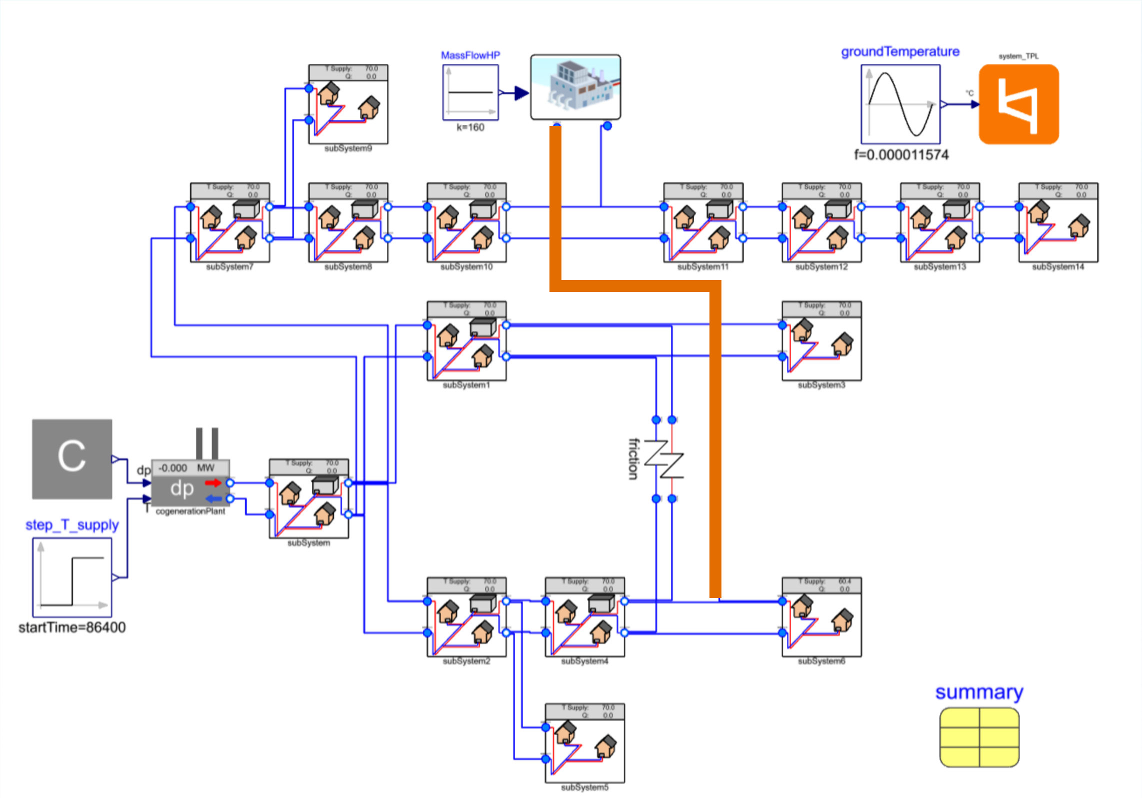
Heat pump integration for studying electric grid services

- Heat pumps are preferably operated at times of low electricity prices - typically high renewables share, fewer stabilizing conventional units
- Heat pumps compressor can be used for demand side electricity reduction because heating systems provide high thermal inertia and potentially storage capacity.
- Effects on consumers while providing primary frequency control with heat pump compressor can be studied

DEMO

Heat pump integration for studying electric grid services





Config1: Heat pump inlet is connected with return flow (30°C)

Config2: Heat pump inlet is connected with remote feed (60°C)

Conclusion

- Challenging engineering problems related to the energy transition
  - Large variety of technologies
  - Sector coupling
  - Design, controls & integration challenges
- Through various examples, we could should how system simulation & Modelon Impact can be used to address these challenges:
  - Feasibility assessment of hybrid energy projects
  - Integration of storage and renewables to the grid
  - Power-to-heat