ETH zürich

RRE
Reliability and Risk Engineering

Introduction to Modeling and Optimization of Sustainable Energy Systems:

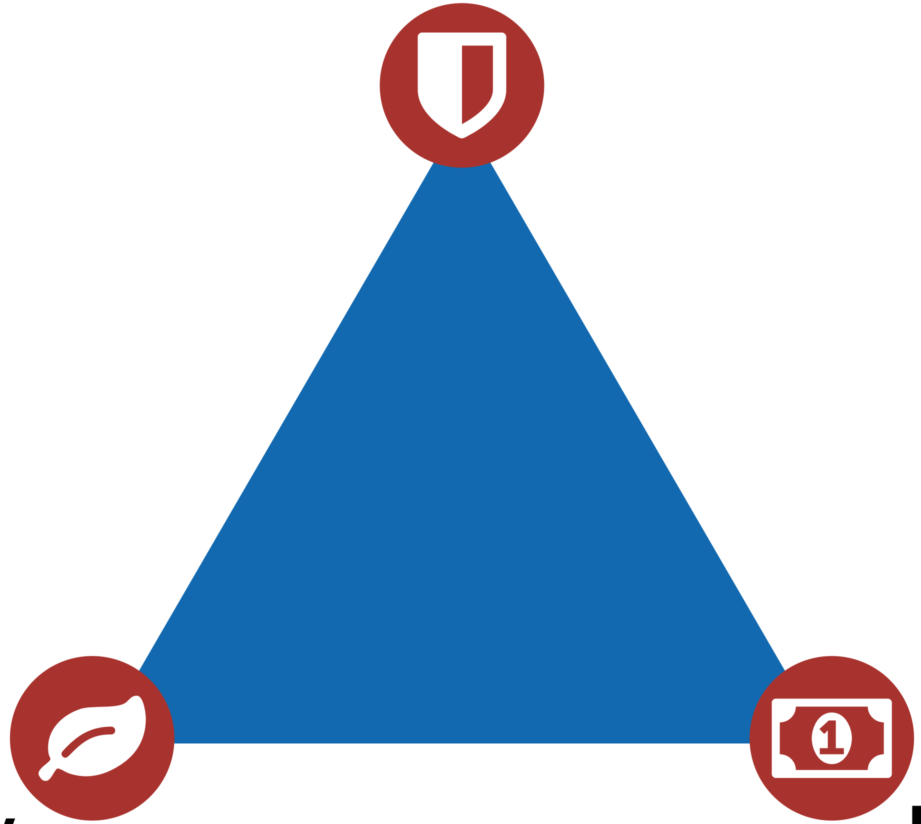
Introduction to multi-energy systems (MES) and time-dependent optimal operation

Prof. Dr. Giovanni Sansavini
Reliability and Risk Engineering

Last lecture: KPIs of energy trilemma and multi-objective optimization

availability of sources
ensuring supply of energy

Security



Sustainability

climate protection
life cycle

Equity

price development
competition

Since the last lecture, you are able to …

- ✓ Define and critically evaluate:
  - ✓ Equity KPIs
  - ✓ Environmental KPIs
  - ✓ Security KPIs:
    - ✓ Reliability indicators
    - ✓ Risk indicators
    - ✓ Resilience indicators
- ✓ Formulate and solve multi-objective optimization problems

After this lecture, you are able to …

- Understand concept, motivation and main design questions of multi-energy systems (MES)
- Understand the different degrees of complexity when optimizing MES
- Formulate time-dependent optimization problem for MES optimal operation

Concept of multi-energy systems (MES)

Multi-energy systems (MES): Definition

- Collection of energy conversion and storage technologies (where the former can be both renewable- or fossil fuel-based), which deals with multiple energy carriers, allows for conversion from one energy carrier to another, can be connected to energy grids, and provides energy carriers to satisfy the energy demands of end-users[1,2,3]
- MES can increase technical, economic and environmental performance relative to “classical” energy systems whose sectors are treated “separately” or “independently”
- The same concept and mathematical formulation can be extended to other sectors, e.g. water-energy nexus, carbon capture and storage (CCS), value chains
- Several other definitions are used depending on the field or on the focus of the analysis: energy hubs[4], smart grids, micro-grids, ...

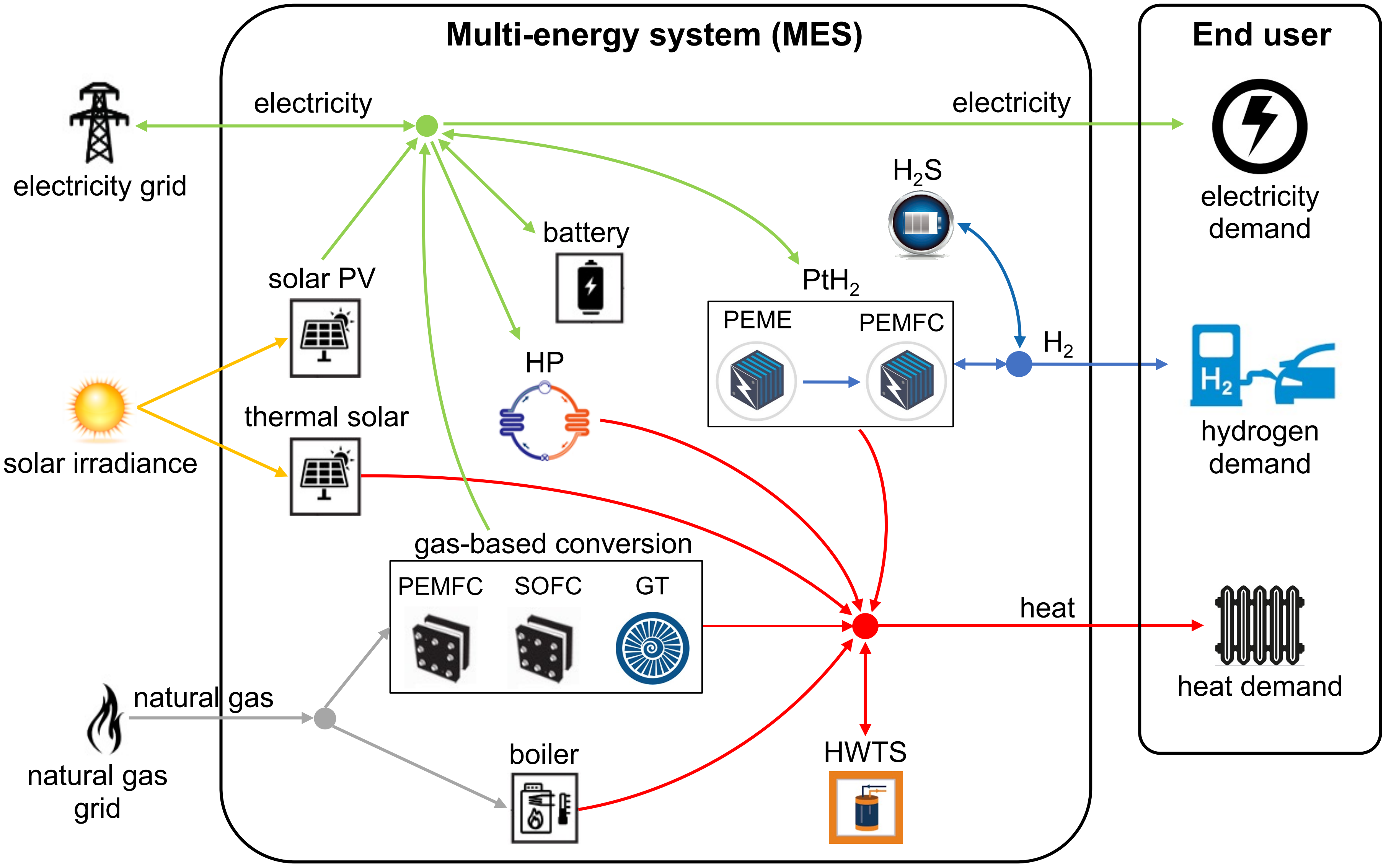
[1] P. Mancarella, Multi-energy systems: an overview of models and evaluation concepts, *Energy*, 2014, **65**, 1-17

[2] D. Grosspietsch, M. Saenger, B. Girod. Matching decentralized energy production and local consumption: A review of renewable energy systems with conversion and storage technologies. *Wiley Interdisciplinary Reviews: Energy and Environment*, 2019, **e336**

[3] P. Gabrielli. Optimal design of multi-energy systems: From technology modeling to system optimization. *PhD Thesis*, ETH Zurich, 2019

[4] M. Geidl et al., Energy hubs for the future, *IEEE Power and Energy Magazine*, 2007, **5(1)**, 24 - 30

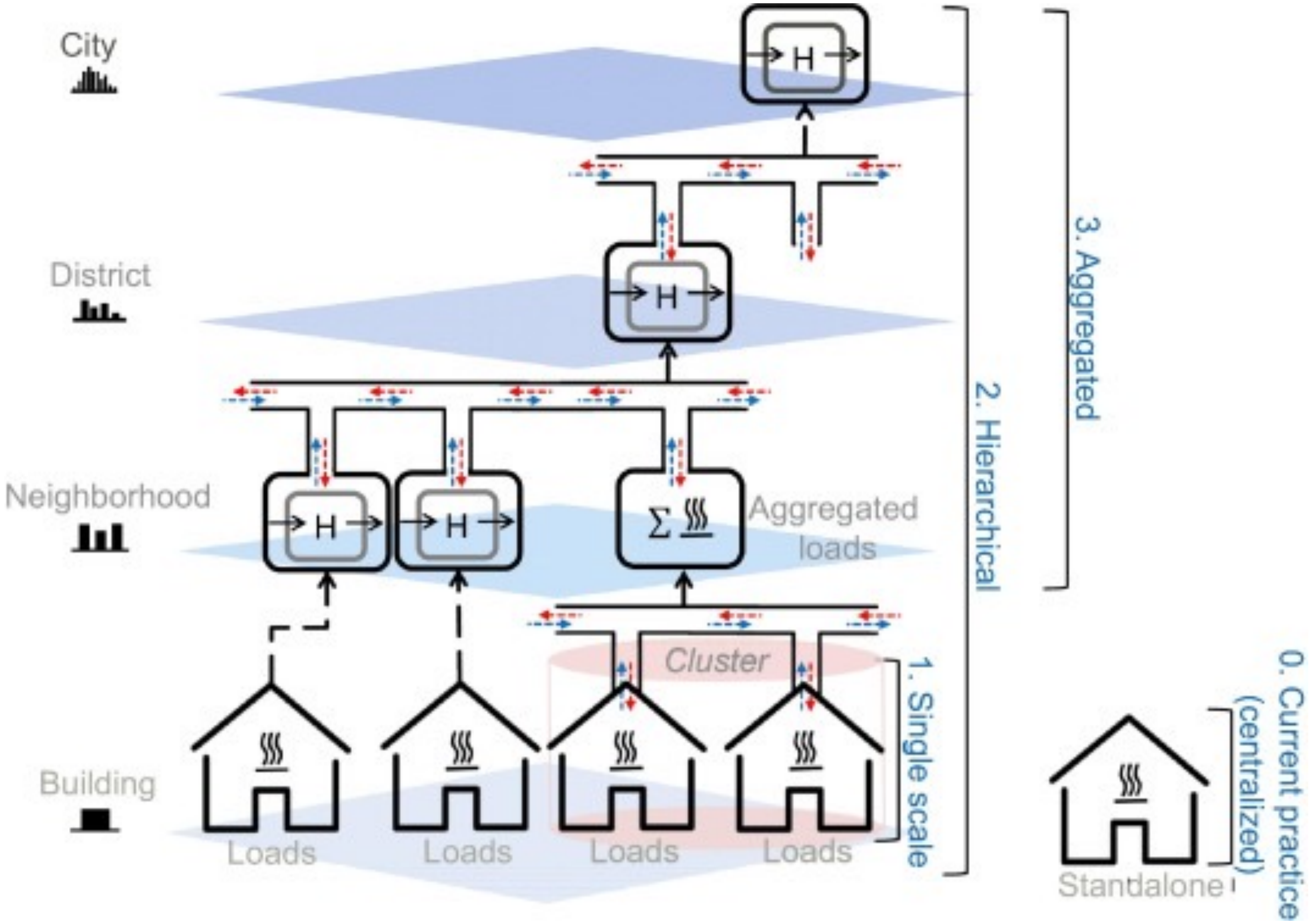
The multi-energy dimension



P. Gabrielli, Optimal design of integrated energy systems: From technology modelling to system optimization, *PhD Thesis*, ETH Zurich, 2019

Spatial perspective: MES exist at various levels (Fractal)

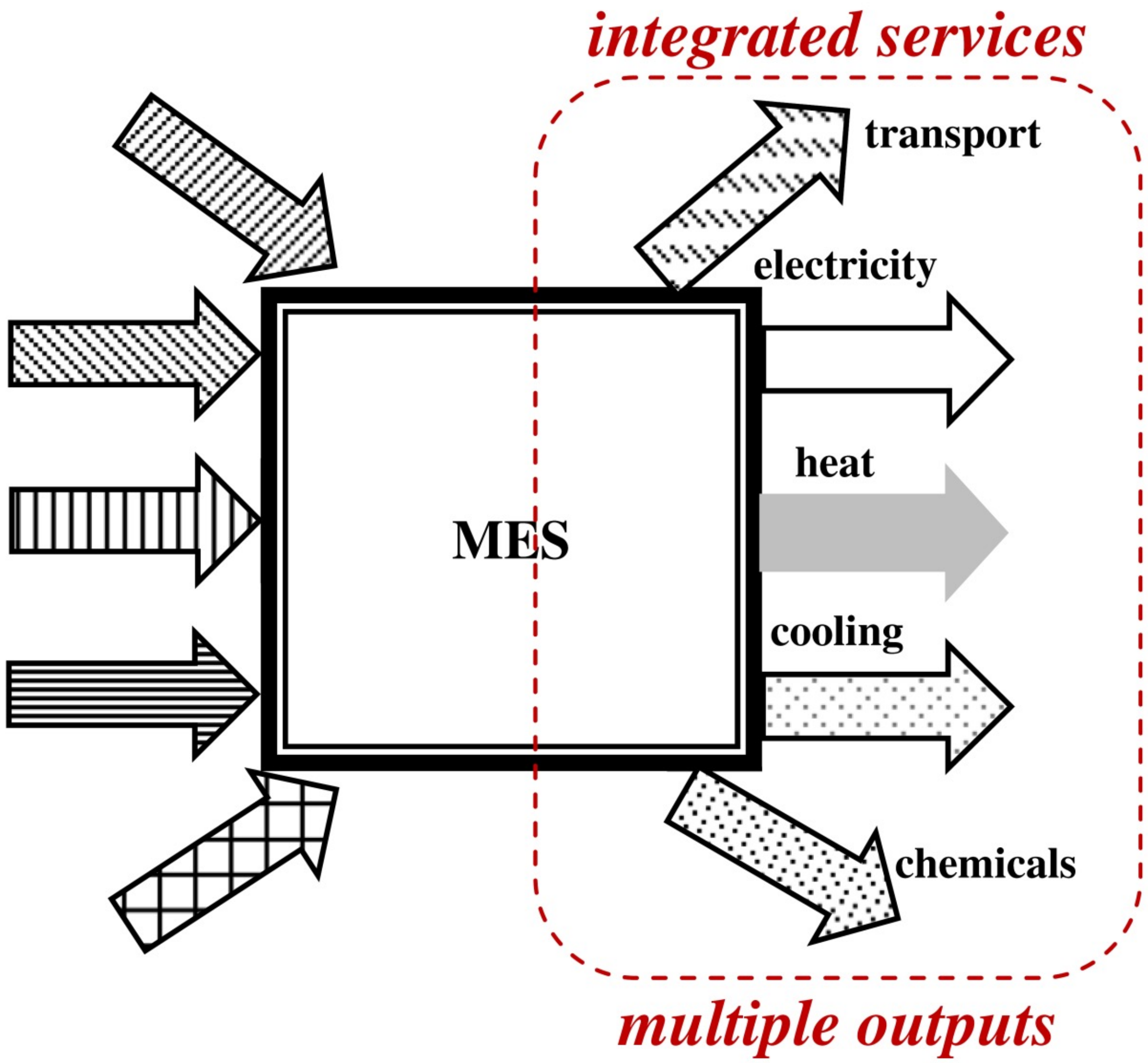
- Multiple energy vectors can be relevant to buildings, districts, city, regions, countries
- Different granularities (i.e. modeling level of detail) are used for different spatial levels
- Often, the broader the scope the lower the modeling level of detail



J.F. Marquant, R. Evins, L.A. Bollinger, J. Carmeliet, A holarchic approach for multi-scale distributed energy system optimization, *Applied Energy*, 2017, **208**, 935-953

Multi-service perspective: From distributed generation to transport

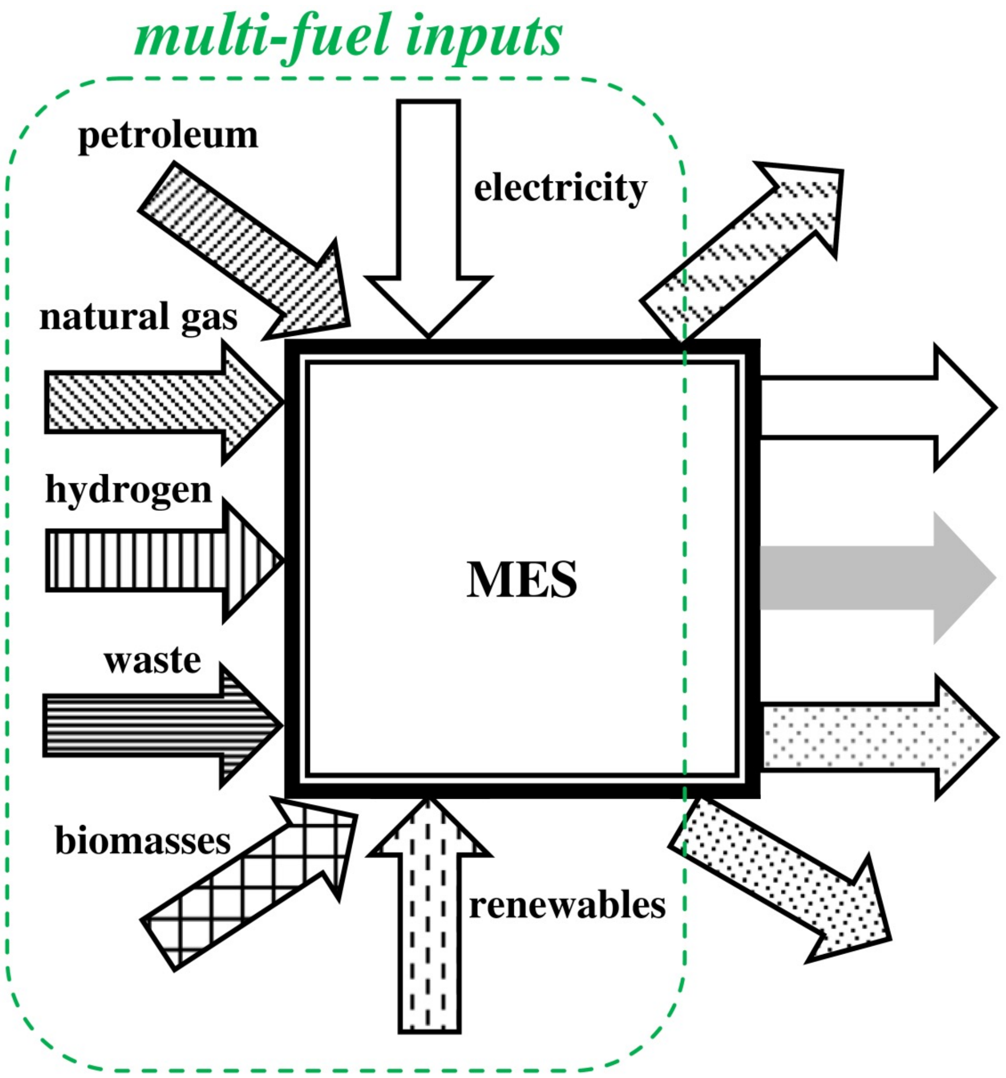
- Different energy vectors can be integrated together for provision of multiple services
- From “classical” electricity and heat to hydrogen and transport
- Improving system performance from techno-economic, energy and environmental perspectives
- Recovering waste heat from combined heat and power (CHP) to supply local thermal demand or cooling demand



P. Mancarella, Multi-energy systems: an overview of models and evaluation concepts, *Energy*, 2014, **65**, 1-17

Multi-fuel perspective: From wind to waste

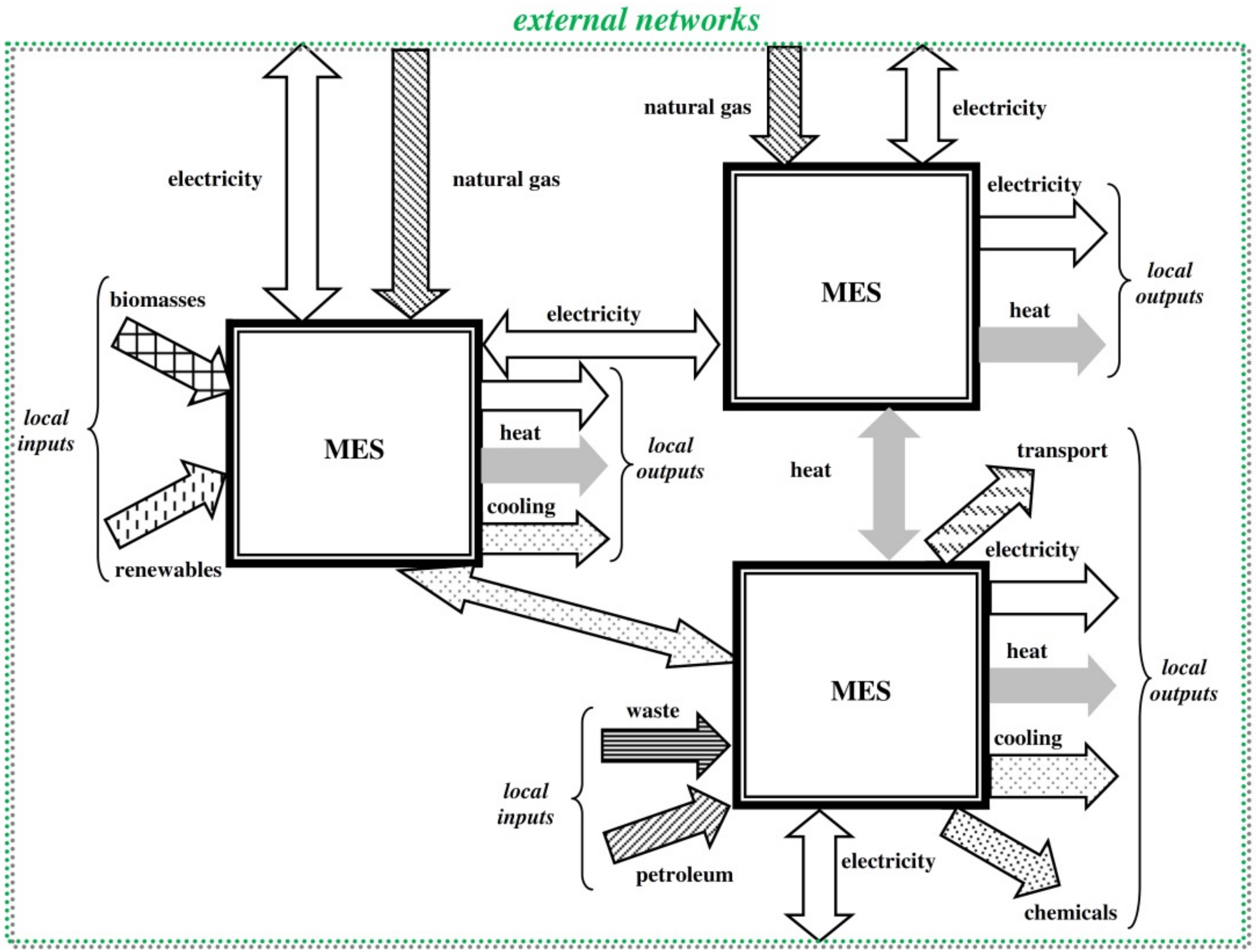
- Demand and supply "balancing" provision: renewable electricity sources (wind and photovoltaic, PV) exhibit high geographical and temporal variability and can be balanced by the MES flexibility
- Interactions with electricity and gas networks and markets
- Increasing interest for MES is the optimal management of waste



P. Mancarella, Multi-energy systems: an overview of models and evaluation concepts, *Energy*, 2014, **65**, 1-17

Network perspective: From electricity grid to district pipelines

- MES require interconnections among various multi-energy plant components and multi-energy plants
- Interconnections take place through multi-carrier energy networks, also called smart-energy networks
- Energy networks facilitate possible interactions among MES and between MES and external networks



P. Mancarella, Multi-energy systems: an overview of models and evaluation concepts, *Energy*, 2014, **65**, 1-17

Motivation and design questions for MES

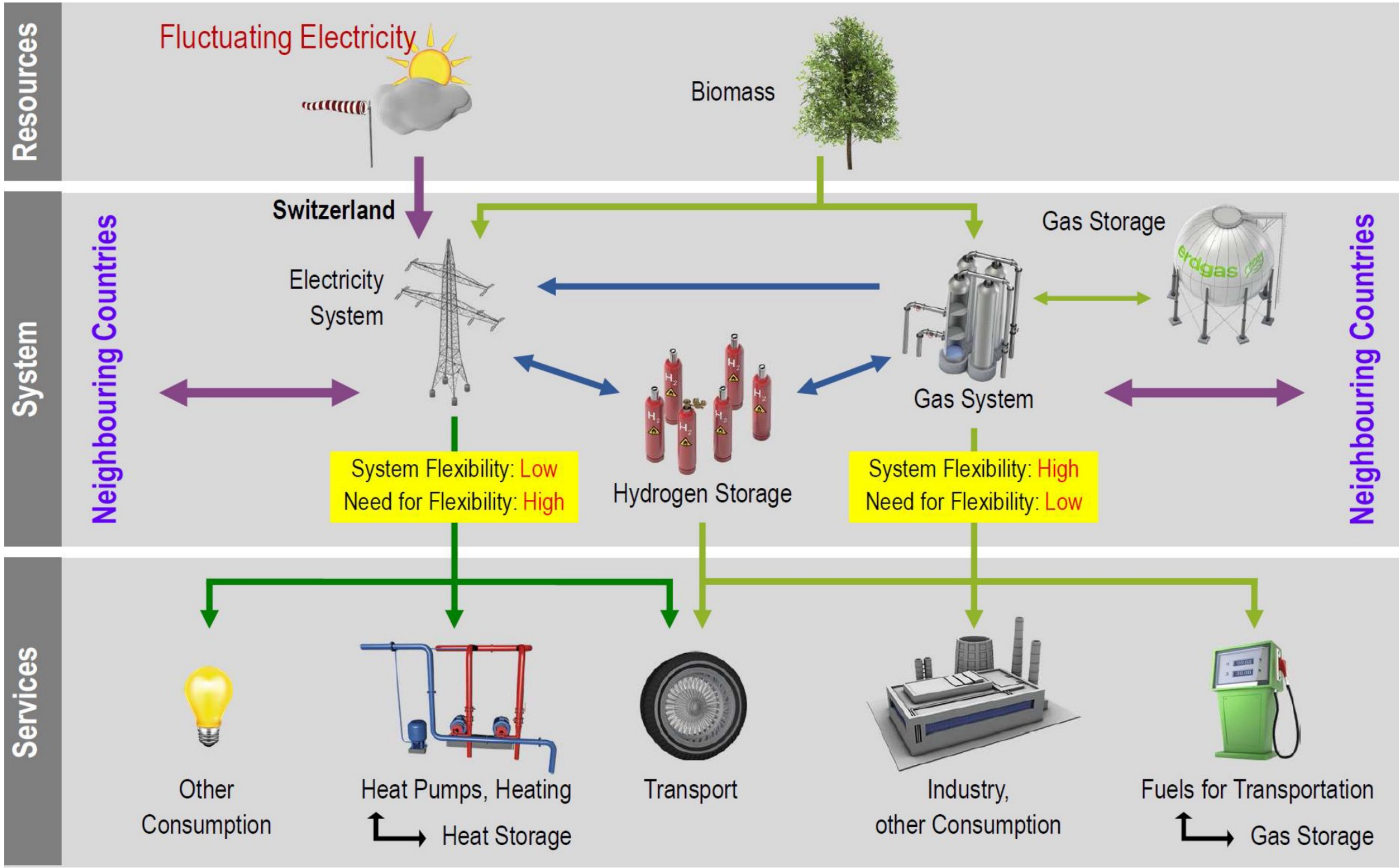
Fundamental questions

- **Design/Dimensioning**: How should the energy conversion and storage technologies be sized, i.e., how much electricity, heat, hydrogen, etc. should the energy system be able to produce?
- **Operation**: How should the energy system be operated, i.e. how much electricity, heat, hydrogen, etc. should be generated at any moment in time depending on the actual energy demands?
- **Storage**: Which and how much of which energy carrier (e.g. electricity, natural gas, heat, hydrogen) should the energy system be able to store at any moment in time?
- **System Impact**: How does a specific energy system influence the overall system performance in terms of costs, energy efficiency, carbon emissions, reliability/availability, power quality?

Benefits of energy systems integration

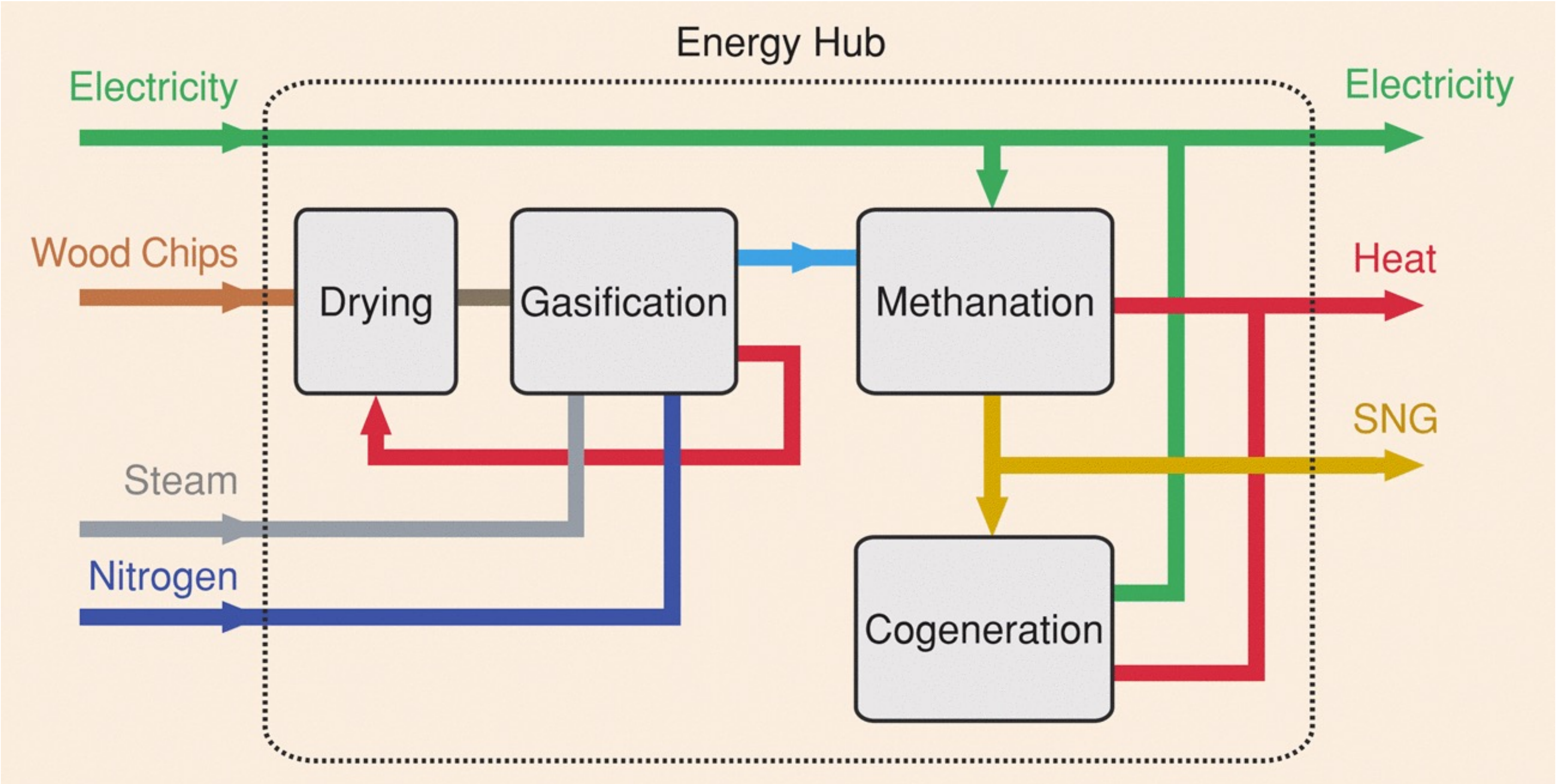
- The MES / energy hub concepts enable new design paradigms for **multiple energy carrier systems**, where the interaction between different energy carriers (and the corresponding infrastructure) is taken into account both at design and operation phase
- MES foster the interplay among **equity, security and sustainability objectives**
- The **flexible** combination of different energy carriers using conversion and storage technologies offers an effective approach for various system improvements
- System **cost** and **emissions** can be reduced, **security and availability of supply** can be increased, **congestion** can be released, and overall energy **efficiency** can be improved

MES help integrating renewables into the energy system



SCCER Heat and Electricity Storage www.sccer-hae.ch, SCCER BIOSWEET Biomass for Swiss Energy Future www.sccer-biosweet.ch

MES in practice: Regionalwerke AG Baden

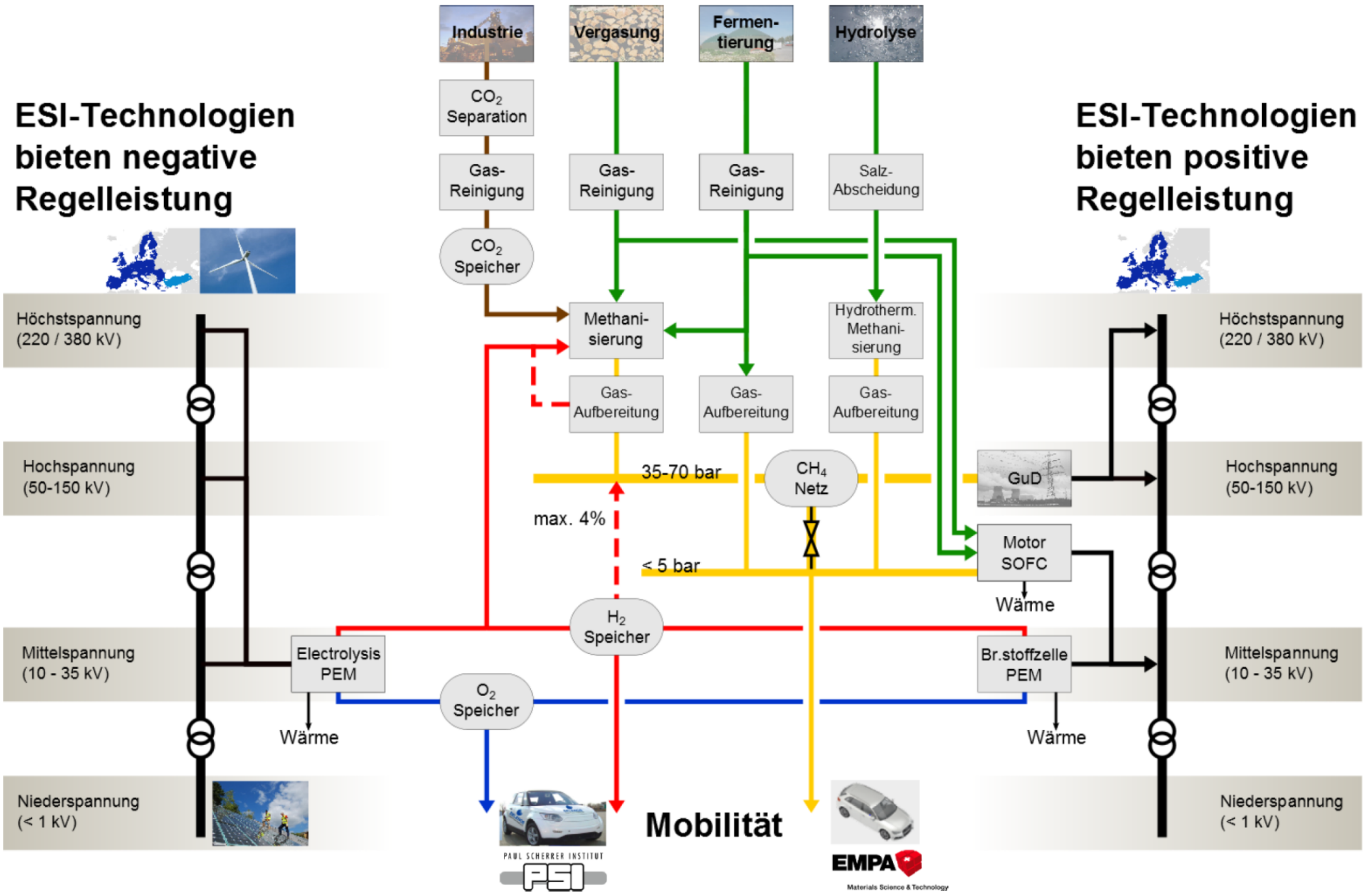


M. Geidl et al., Energy hubs for the future, *IEEE Power and Energy Magazine*, 2007, **5(1)**, 24 - 30

MES in practice: NEST building at EMPA

https://www.empa.ch/web/nest

MES in practice: Energy System Integration (ESI) Platform at PSI



https://www.youtube.com/watch?v=ChyBuKBLqp4

After this lecture, you are able to …

- ✓ Understand concept, motivation and main design questions of multi-energy systems (MES)
- Understand the different degrees of complexity when optimizing MES
- Formulate time-dependent optimization problem for MES optimal operation

Modeling MES:
Complexity of optimization problem and time-dependent optimal operation

The decision-making context determines the optimization problem

	easier	more difficult
Decision variables: Design vs Operation	Technology operation for given technology selection and size	Selection and size of technologies, coupled with their operation
Time dimension	Static	Time-dependent
Space dimension	Single node	Multi-node energy networks
Uncertainty	Deterministic optimization	Robust or stochastic optimization
Objective function	Single objective	Multiple objectives

The optimal operation problem is a special case of the optimal design problem (which requires resolving operation)

Introducing the time dimension

- The time dimension is necessary to model different aspects of MES:
  - Variability of input data, e.g. variable weather conditions, energy prices and demands
  - Common basis to discount costs and to compare design (CAPEX) and operation (OPEX)
  - Energy storage, i.e. connection between consequent time intervals
  - Conversion dynamics, e.g. technology start-up / shut-down, ramp-up / ramp-down
- All aspects of the optimization problem must include a time index, $t \in \{1, \dots, T\}$, which describes the evolution of:
  - Input data, e.g. variable weather conditions, energy prices and demands
  - Objective function, e.g. evaluating a system over a year through total annual cost (TAC)
  - Decision variables, e.g. variable input and output energy of technologies
  - Constraints, e.g. variable scheduling and operation of technologies
- Suited time resolution depends on scope of the optimization problem and on system dynamics

Formulation of the optimization problem: Optimal operation

$$\min_{\boldsymbol{x}} \quad z = f(\boldsymbol{x})$$

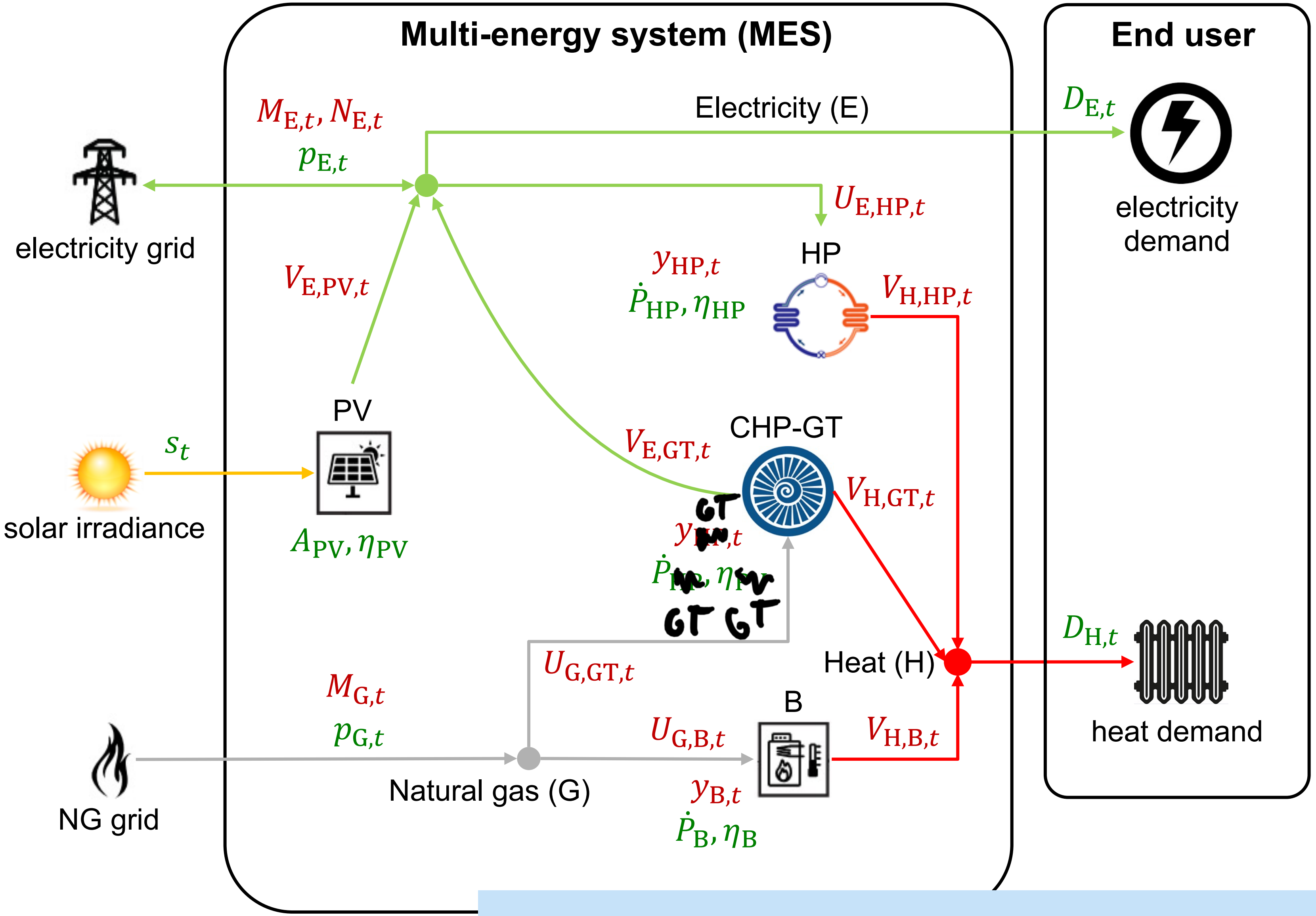
$$\text{s.t.} \quad g_j(\boldsymbol{x}) \leq 0, \qquad j = 1, \dots, n$$
$$h_i(\boldsymbol{x}) = 0, \qquad i = 1, \dots, o$$

"The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle requires creative imagination and marks real advances in science"

Albert Einstein, Léopold Infeld

objective function		z	$\mathbb{R}^{m(T)} \rightarrow \mathbb{R}$	Energy costs (operation)
decision variables		$\boldsymbol{x}$	$\in \mathbb{R}^{m(T)}$	Energy input and output (technology), imported and exported (system)
constraints	equality	$h_i(\boldsymbol{x}) = 0$	$i = 1, \dots, o$	Energy conversion efficiency (typically nonlinear)
	(in)equality	$g_j(\boldsymbol{x}) \leq 0$	$j = 1, \dots, n$	Min/max-power constraints (typically nonlinear)

MES simple case-study: Optimal operation



Decision variables	
Input energy	U
Output energy	V
Imported energy	M
Exported energy	N
ON/OFF scheduling	y

Input data	
Weather conditions (solar)	s
Energy demand	D
Energy price	p
Technology size	P
Technology performance	η

How to minimize operation cost, while satisfying all energy demands?

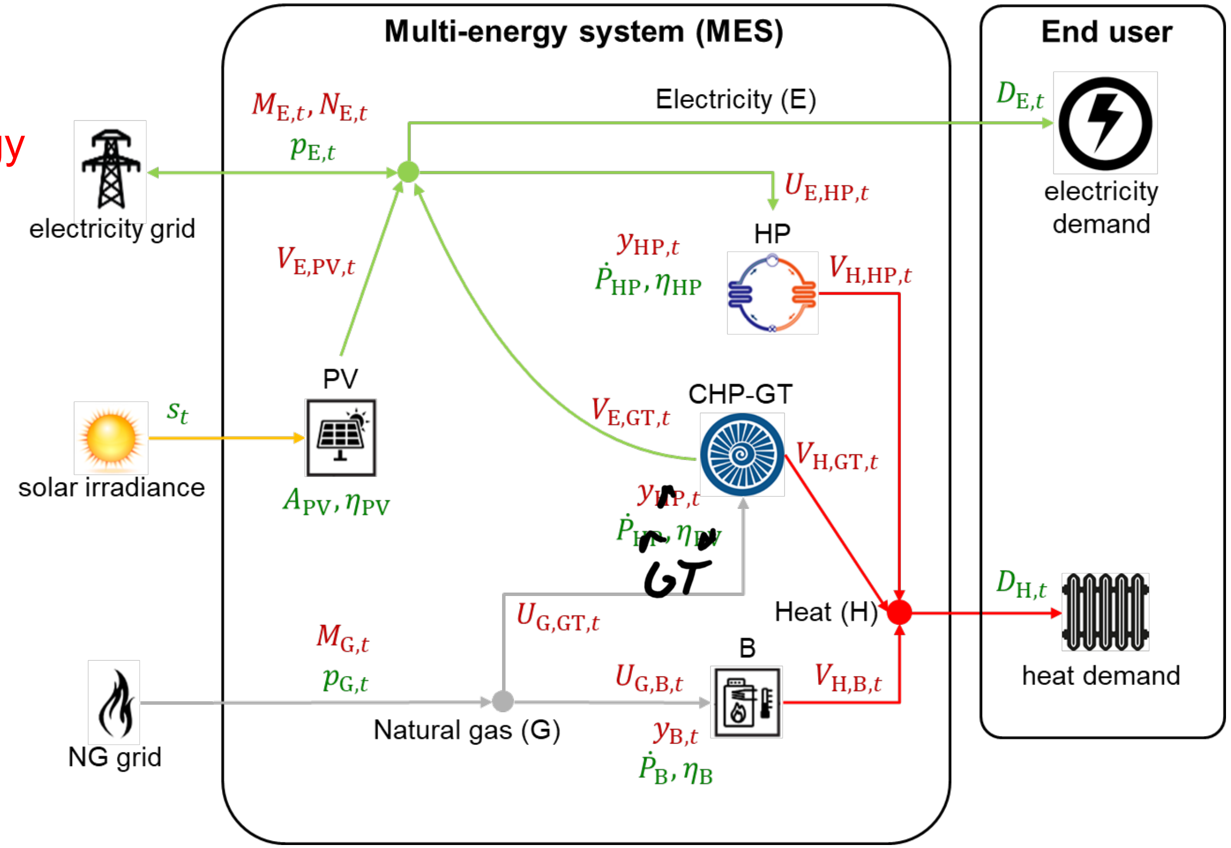
Operation decision variables: Imported, exported, input, output energy

$$\boldsymbol{x} = \left[M_{\mathrm{E},t}, M_{\mathrm{G},t}, N_{\mathrm{E},t}, U_{\mathrm{G,GT},t}, U_{\mathrm{E,HP},t}, U_{\mathrm{G,B},t}, V_{\mathrm{E,GT},t}, V_{\mathrm{H,GT},t}, V_{\mathrm{H,HP},t}, V_{\mathrm{H,B},t}, V_{\mathrm{E,PV},t}, y_{\mathrm{GT},t} y_{\mathrm{HP},t}, y_{\mathrm{B},t}\right]$$

$$\boldsymbol{x} \in \{\mathbb{R} \text{ or } \{0,1\}\}^{m}, m = 14T$$

Function of type and number of available energy grids and technologies

- Operation variables are vectors of dimension T
- Energy variables, $\boldsymbol{x}$, are connected to power variables (e.g. technology size), $\dot{\boldsymbol{x}}$: $\boldsymbol{x} = \dot{\boldsymbol{x}}\Delta t$
- Considering one-year time horizon T:
  - $\Delta t = 1$ year and $T = 1$ (**yearly** resolution)
  - $\Delta t = 1$ hour and $T = 8760$ (**hourly** resolution)
- Technology sizes do not impact the optimization problem, hence are not decision variables

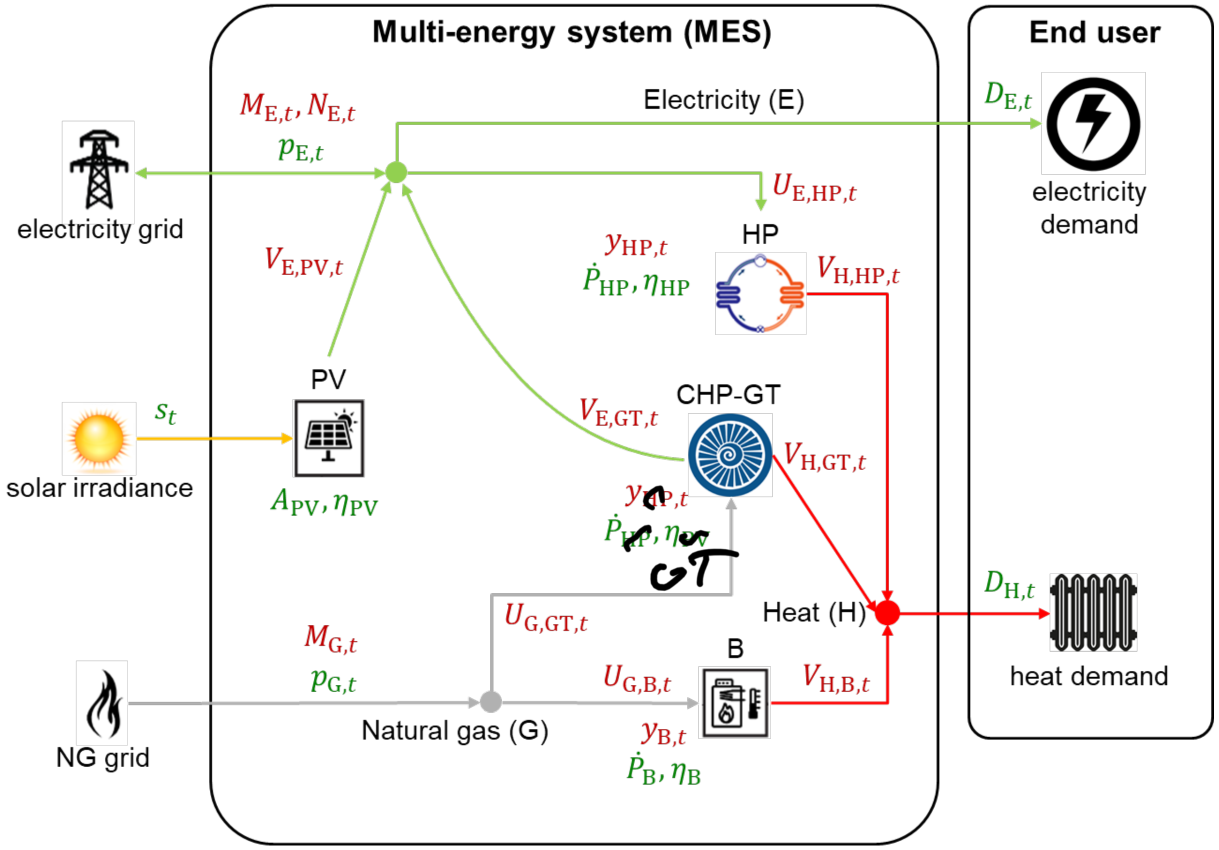


Operation objective function: Energy costs

LP

$$z_{\text{cost}} = \sum_{t=1}^{T} \left(\underbrace{p_{\mathrm{G},t} M_{\mathrm{G},t}}_{\text{Fuel expenditure}} + \underbrace{p_{\mathrm{E},t} M_{\mathrm{E},t}}_{\text{Electricity expenditure}} - \overbrace{p_{\mathrm{E},t} N_{\mathrm{E},t}}^{\text{Electricity revenue}} \right)$$

- The energy cost depends on the time-dependent cost of natural gas, $p_{\mathrm{G},t}$, and electricity, $p_{\mathrm{E},t}$
- z is a linear function of the imported ($M_{\mathrm{G},t}$, $M_{\mathrm{E},t}$) and exported ($N_{\mathrm{E},t}$) energy
- Only operation costs are considered, since installation costs are known as input data through the installed sizes



Constraints (1): Energy balances for electricity (E)

LP

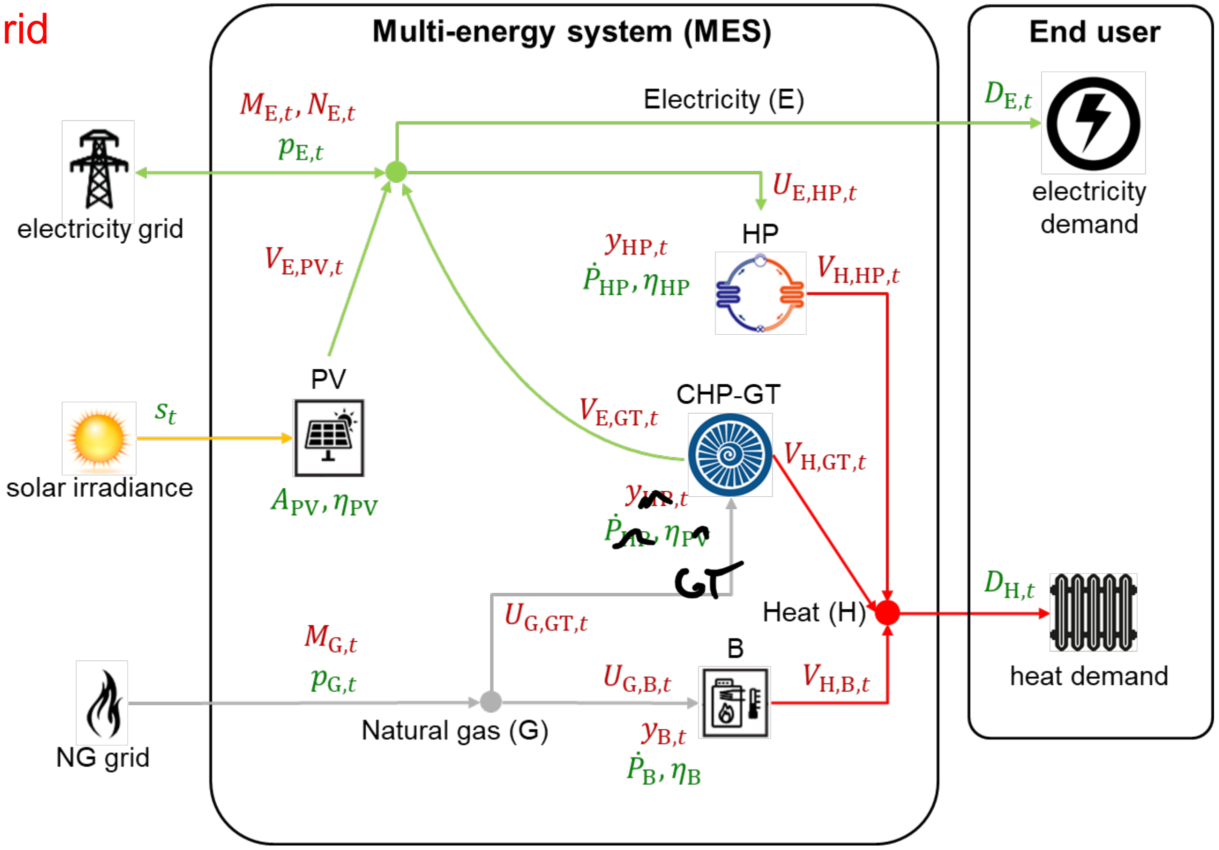
ti amo 233 ♡

Boundary condition = tu pure devi amarmi $\forall\, t > 0$

$$\underbrace{V_{\mathrm{E,GT},t} + V_{\mathrm{E,PV},t}}_{\text{Output energy by technologies}} - \underbrace{U_{\mathrm{E,HP},t}}_{\text{Input energy by technologies}} + \overbrace{M_{\mathrm{E},t}}^{\text{Imported energy from grid}} - \overbrace{N_{\mathrm{E},t}}^{\text{Exported energy to grid}} = \underbrace{D_{\mathrm{E},t}}_{\text{Energy demand}}$$

$$0 \le M_{\mathrm{E},t} \le \underbrace{M_{\mathrm{E,max}}}_{\text{Maximum energy imported from grid}}, \qquad 0 \le N_{\mathrm{E},t} \le \underbrace{N_{\mathrm{E,max}}}_{\text{Maximum energy exported to grid}}$$

Energy carriers are written for all time intervals and (in their simplest form) are linear constraints



Constraints (1): Energy balances for all energy carriers

LP

Electricity (E)

$$V_{\mathrm{E,GT},t} + V_{\mathrm{E,PV},t} - U_{\mathrm{E,HP},t} + M_{\mathrm{E},t} - N_{\mathrm{E},t} = D_{\mathrm{E},t}$$

$$0 \le M_{\mathrm{E},t} \le M_{\mathrm{E,max}}, \qquad 0 \le N_{\mathrm{E},t} \le N_{\mathrm{E,max}}$$

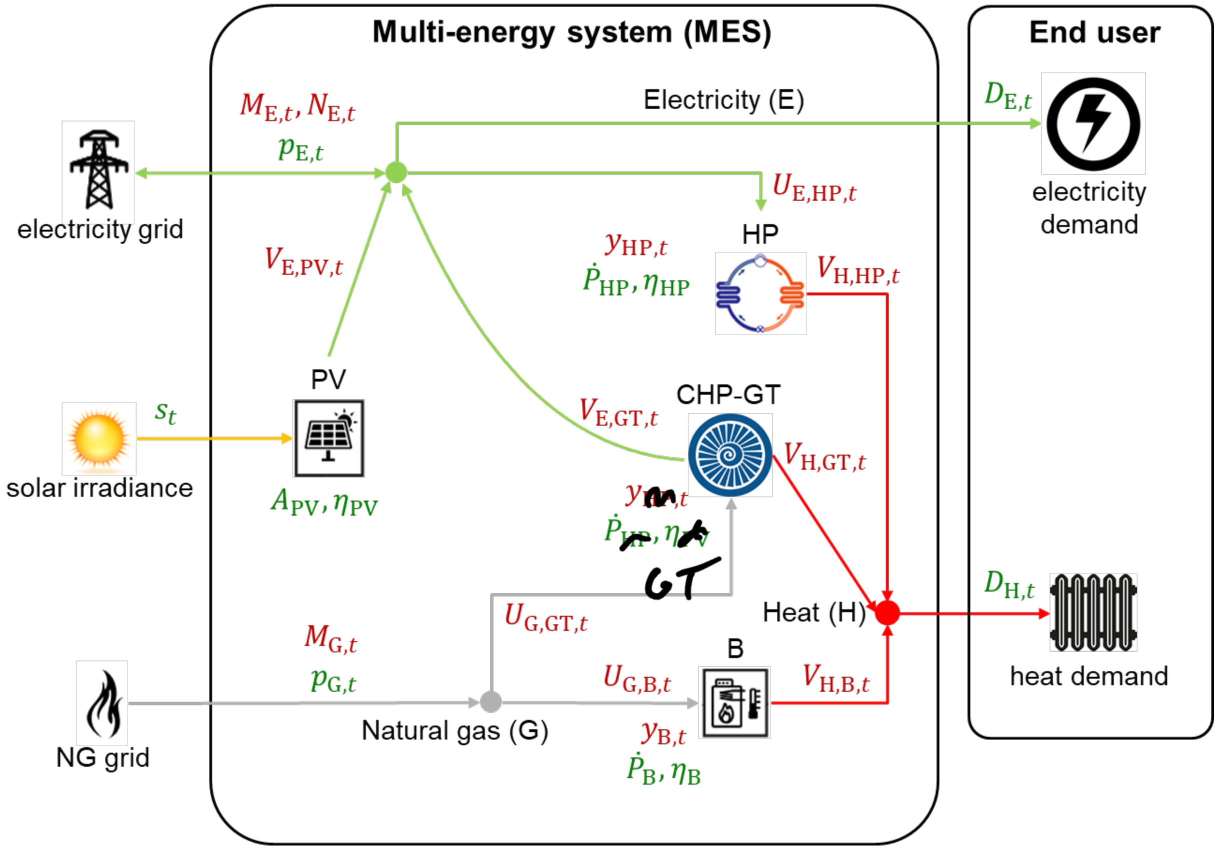
Heat (H)

$$V_{\mathrm{H,GT},t} + V_{\mathrm{H,HP},t} + V_{\mathrm{H,B},t} = D_{\mathrm{H},t}$$

Natural gas (G)

$$-U_{\mathrm{G,GT},t} - U_{\mathrm{G,B},t} + M_{\mathrm{G},t} = 0$$

$$0 \le M_{\mathrm{G},t} \le M_{\mathrm{G,max}}$$



Energy balances are written for all time intervals and for all energy carriers

Constraints (2): Conventional technology performance

Heat pump (HP)

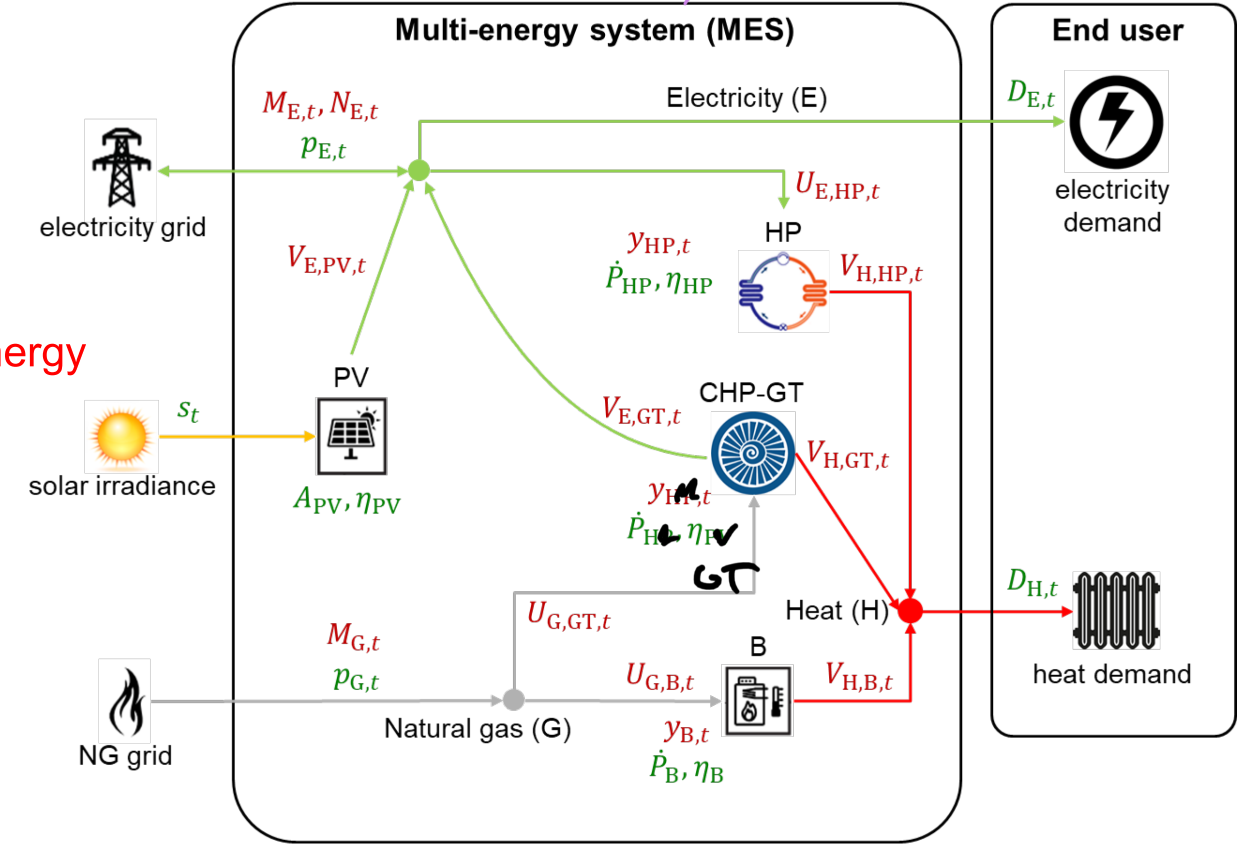
MINLP

HP conversion efficiency

$$V_{\mathrm{H,HP},t} = \overbrace{\eta_{\mathrm{HP}}\left(U_{\mathrm{E,HP},t}\right)}$$

ti amo 233 ♥

this is stricky



$$\text{if ON } (y_{\mathrm{HP},t} = 1): \quad L_{\mathrm{HP}} y_{\mathrm{HP},t} \leq U_{\mathrm{E,HP},t} \leq P_{\mathrm{HP}} y_{\mathrm{HP},t}$$

HP minimum energy — HP maximum energy

$$\text{if OFF} (y_{\mathrm{HP},t} = 0): \quad 0 \leq U_{\mathrm{E,HP},t} \leq 0$$

nastiest form

- $\eta(U)$ is generally nonlinear
- ON/OFF behavior can be described via binary variable y (i.e. MILP or MINLP)
- Minimum and maximum energy can refer to both rated input or output energy

Constraints (2): Conventional technology performance

MINLP

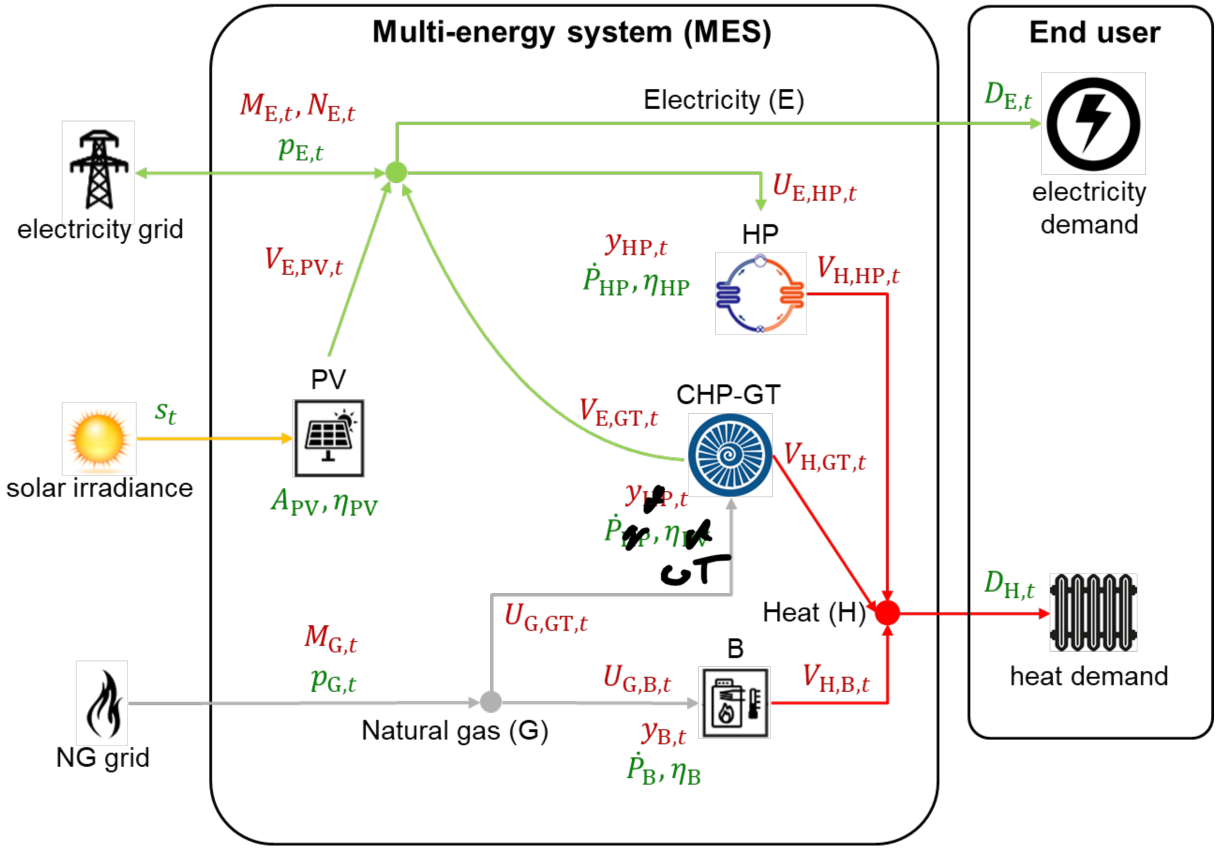
Boiler (B)

$$V_{\mathrm{H,B},t} = \overbrace{\eta_{\mathrm{B}}\big(U_{\mathrm{G,B},t}\big)}^{\text{B conversion efficiency}}$$

$$\text{if ON } (y_{\mathrm{B},t} = 1): \quad \underbrace{L_{\mathrm{B}}}_{\text{B minimum energy}} y_{\mathrm{B},t} \le U_{\mathrm{G,B},t} \le \underbrace{P_{\mathrm{B}}}_{\text{B maximum energy}} y_{\mathrm{B},t}$$

$$\text{if OFF} (y_{\mathrm{B},t} = 0): \quad 0 \le U_{\mathrm{G,B},t} \le 0$$

- $\eta(U)$ is generally nonlinear
- ON/OFF behavior can be described via binary variable y (i.e. MILP or MINLP)
- Minimum and maximum energy can refer to both rated input or output energy



Constraints (2): CHP technology performance

Gas turbine (GT)

GT electrical efficiency: from gas to electricity (GE)

MINLP

$$V_{\mathrm{E,GT},t} = \eta_{\mathrm{GE,GT}}\left(U_{\mathrm{G,GT},t}\right)$$

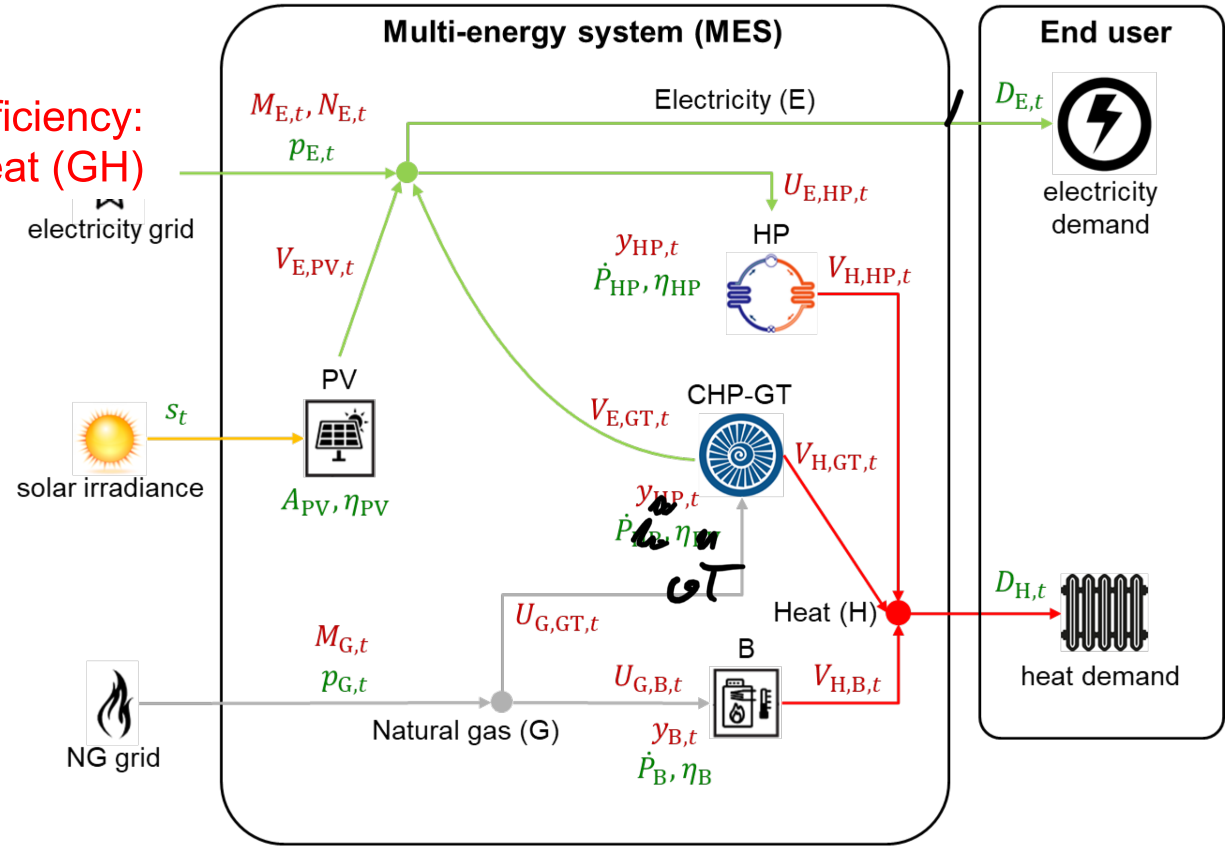
GT thermal efficiency: from gas to heat (GH)

$$V_{\mathrm{H,GT},t} = \eta_{\mathrm{GH,GT}}\left(U_{\mathrm{G,GT},t}\right)$$

$$\text{if ON}(y_{\mathrm{GT},t} = 1): \quad L_{\mathrm{GT}} y_{\mathrm{GT},t} \leq U_{\mathrm{G,GT},t} \leq P_{\mathrm{GT}} y_{\mathrm{GT},t}$$

$$\text{if OFF}(y_{\mathrm{GT},t} = 1): \quad 0 \leq U_{\mathrm{G,GT},t} \leq 0$$

- CHP technologies have two energy outputs
- The conversion efficiency must be specified in terms of input-to-output energy

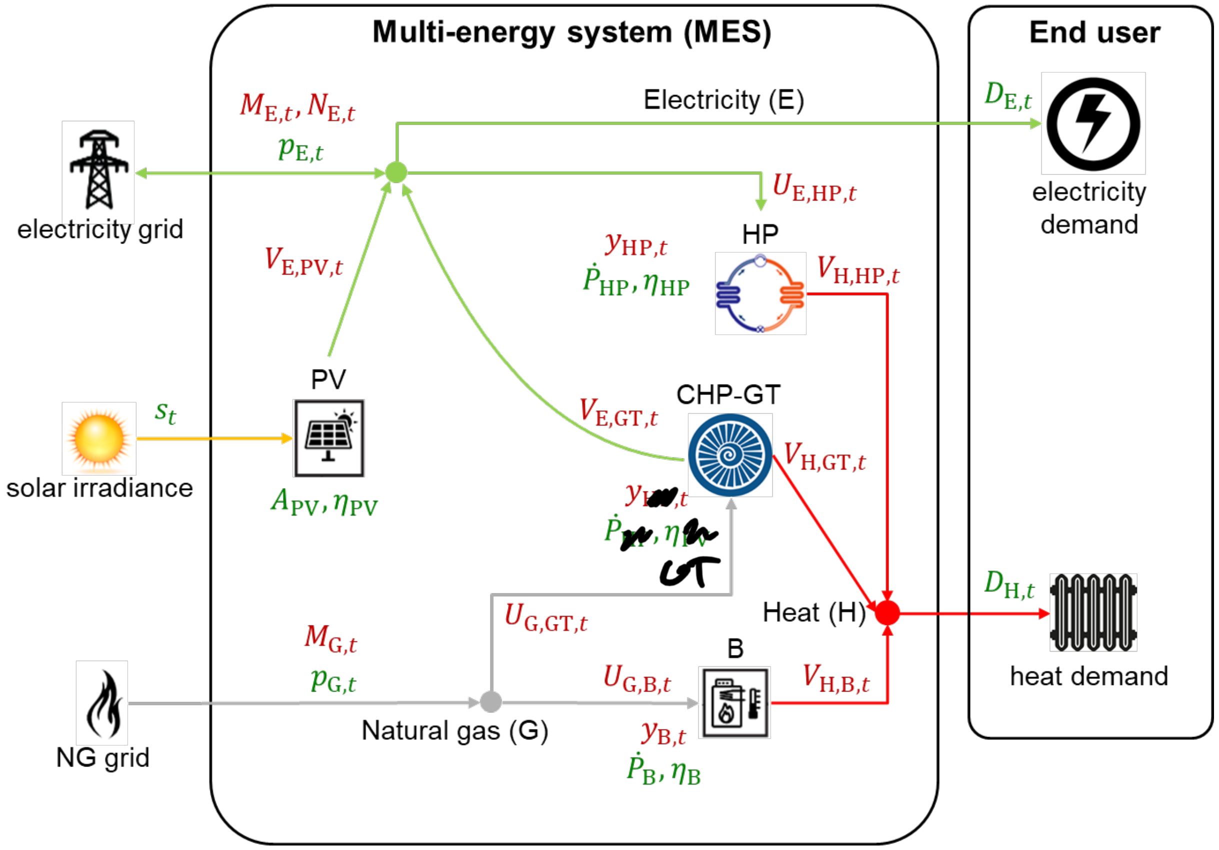


Constraints (2): Renewable energy technology performance

LP

Photovoltaic (PV) panels

$$V_{\mathrm{E,PV},t} = \underbrace{\eta_{\mathrm{PV}}(\overset{\text{solar irradiance}}{s_t})}_{\text{PV conversion efficiency}} \underset{\text{PV installed area}}{A_{\mathrm{PV}}}, \qquad \forall t \in \{1, \dots T\}$$



- $\eta_{PV}(s)$ nonlinear function of solar irradiance, s; since s is an input parameter, this is still a LP
- The same applies when the efficiency is a function of generic weather conditions, w_t:

$$V_{\mathrm{E,PV}} = \eta_{\mathrm{PV}}(w_t) A_{\mathrm{PV}}$$

- Capacity of RE technologies often related to area or number of units (e.g. wind turbines)

General MILP formulation: Optimal operation

Objective function

$$\min_{M_j, N_j,\, j \in \mathcal{J}} z_{\text{cost}} = \sum_{t=1}^{T} \sum_{j \in \mathcal{J}} p_{j,t} \left(M_{j,t} - N_{j,t} \right)$$

s. t.

Energy balances

$$\sum_{k \in \mathcal{K}} \left(V_{j,k,t} - U_{j,k,t} \right) + M_{j,t} - N_{j,t} = D_{j,t}$$

$$0 \leq M_{j,t} \leq M_{j,\max}, \quad 0 \leq N_{j,t} \leq N_{j,\max} \qquad \forall j \in \mathcal{J}, \forall t = \{1, \ldots, T\}$$

Dispatchable technologies

$$V_{\bar{j},k} = \eta_{\underline{j}\bar{j},k} \left(U_{\underline{j},k,t} \right) \qquad \forall \bar{j} \in \bar{\mathcal{J}}_k, \underline{j} \in \underline{\mathcal{J}}_k, k \in \mathcal{K}_{\text{C}}, \forall t = \{1, \ldots, T\}$$

RE technologies

$$V_{\bar{j},k,t} = \eta_k(w_t)\, A_k \qquad \forall \bar{j} \in \bar{\mathcal{J}}_k, k \in \mathcal{K}_{\text{R}}, t \in \{1, \ldots, T\}$$

MES structure

$\mathcal{J}$ = Set of energy carriers, $\{\text{E}, \text{G}, \text{H}\}$

$\mathcal{K}$ = Set of technologies, $\{\text{GT}, \text{HP}, \text{B}, \text{PV}\}$

$\mathcal{K}_{\text{R}}$ = Set of renewable energy technologies, $\{\text{PV}\}$

$\mathcal{K}_{\text{C}}$ = Set of dispatachable technologies, $\{\text{HP}, \text{B}, \text{GT}\}$

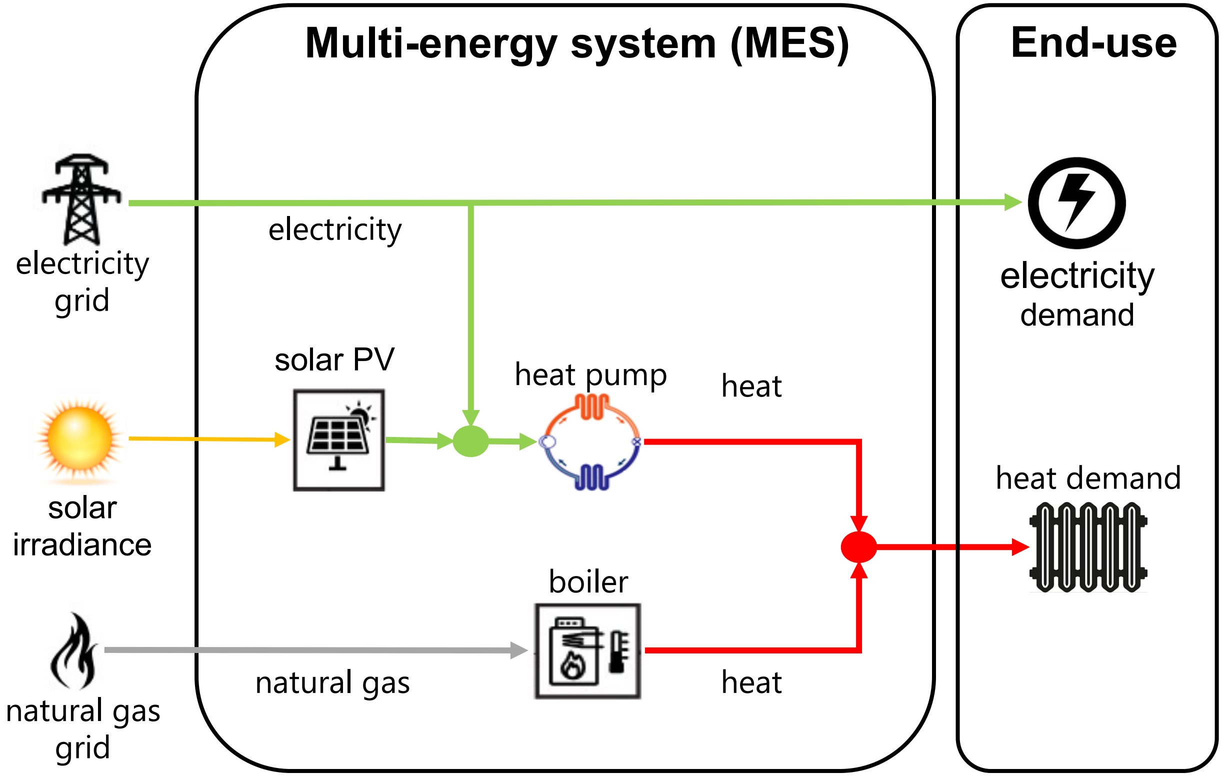
$\bar{\mathcal{J}}_k$ = Set of output carriers for technology k

$\underline{\mathcal{J}}_k$ = Set of input carriers for technology k

T = Length of the time horizon

More complex energy systems are defined by wider sets of energy carriers and technologies, but from the same set of equations

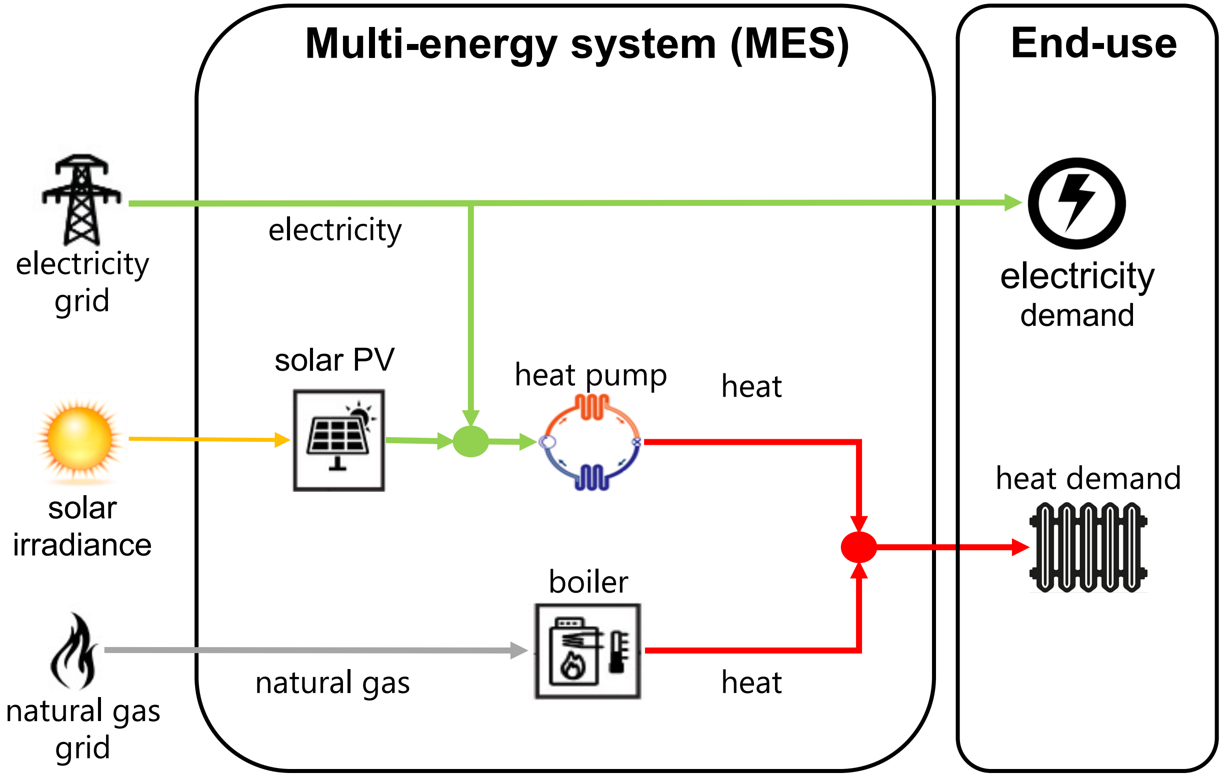
MES optimal operation example



Input data			
Electricity demand	$\boldsymbol{D}_{\mathbf{E}}$	$\boldsymbol{D}_{\mathbf{E},t}$	kWh
Heat demand	$\boldsymbol{D}_{\mathbf{H}}$	$\boldsymbol{D}_{\mathbf{H},t}$	kWh
Electricity price	p_{E}	0.15	CHF/kWh
Natural gas price	p_{G}	0.03	CHF/kWh
Electricity grid carbon footprint	γ_{E}	100	gCO_2/kWh
Natural gas grid carbon footprint	γ_{G}	230	gCO_2/kWh
Technology sizes	P	2000	kW
Boiler efficiency	η_{B}	0.95	-
Heat pump efficiency	η_{HP}	4	-
Solar PV	$\boldsymbol{\eta}_{\mathbf{PV}}$	$\boldsymbol{\eta}_{\mathbf{PV}}(\boldsymbol{w}_t)$	-

One week time horizon T with hourly resolution t

MES optimal operation example



Input data			
Electricity demand	$\boldsymbol{D}_{\mathbf{E}}$	$\boldsymbol{D}_{\mathbf{E},t}$	kWh
Heat demand	$\boldsymbol{D}_{\mathbf{H}}$	$\boldsymbol{D}_{\mathbf{H},t}$	kWh
Electricity price	p_{E}	0.15	CHF/kWh
Natural gas price	p_{G}	0.05	CHF/kWh
Electricity grid carbon footprint	γ_{E}	100	gCO_2/kWh
Natural gas grid carbon footprint	γ_{G}	230	gCO_2/kWh
Technology sizes	P	2000	kW
Boiler efficiency	η_{B}	0.95	-
Heat pump efficiency	η_{HP}	4	-
Solar PV	$\boldsymbol{\eta}_{\mathbf{PV}}$	$\boldsymbol{\eta}_{\mathbf{PV}}(\boldsymbol{w}_t)$	-

Decision variables (minimum-cost optimization)			
Heat pump heat output	$V_{\mathrm{H,HP}}$	?	kWh
Boiler heat output	$V_{\mathrm{H,B}}$	?	kWh
Imported electricity	M_{E}	?	kWh
Imported natural gas	M_{G}	?	kWh
Exported electricity	N_{E}	?	kWh

MES optimal operation example

Objective function

$$\min_{M_{E,t}, M_{G,t}} \quad z_{\text{cost}} = \sum_{t=1}^{T} p_{E,t}\,(M_{E,t} - N_{E,t}) + p_{G,t}\, M_{G,t}$$

s.t.

Energy balances

$$V_{H,HP,t} + V_{H,G,t} = D_{H,t}$$

$$V_{E,PV,t} + M_{E,t} = D_{E,t}$$

$$-U_{E,HP,t} - N_{E,t} + V_{E,PV,t} = M_{E,t}$$

$$M_{E,t}, M_{G,t}, N_{E,t} \geq 0 \qquad \forall t = \{1, \ldots, 168\}$$

Dispatchable technologies

$$V_{H,HP,t} = \text{COP}\, U_{E,HP,t}$$

$$V_{H,G,t} = \eta_G\, M_{G,t}$$

$$\forall t = \{1, \ldots, 168\}$$

RE technologies

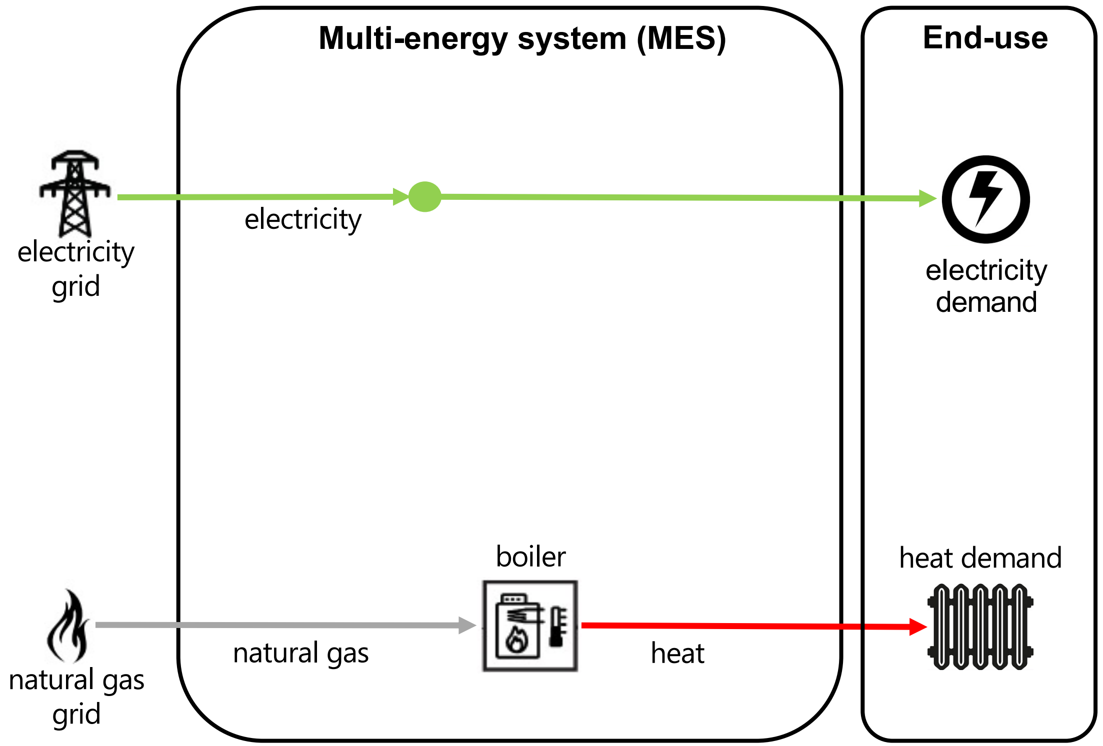
$$V_{E,PV,t} = \eta_{PV}(w_t)\, A_{PV}$$

$$\forall t \in \{1, \ldots, 168\}$$

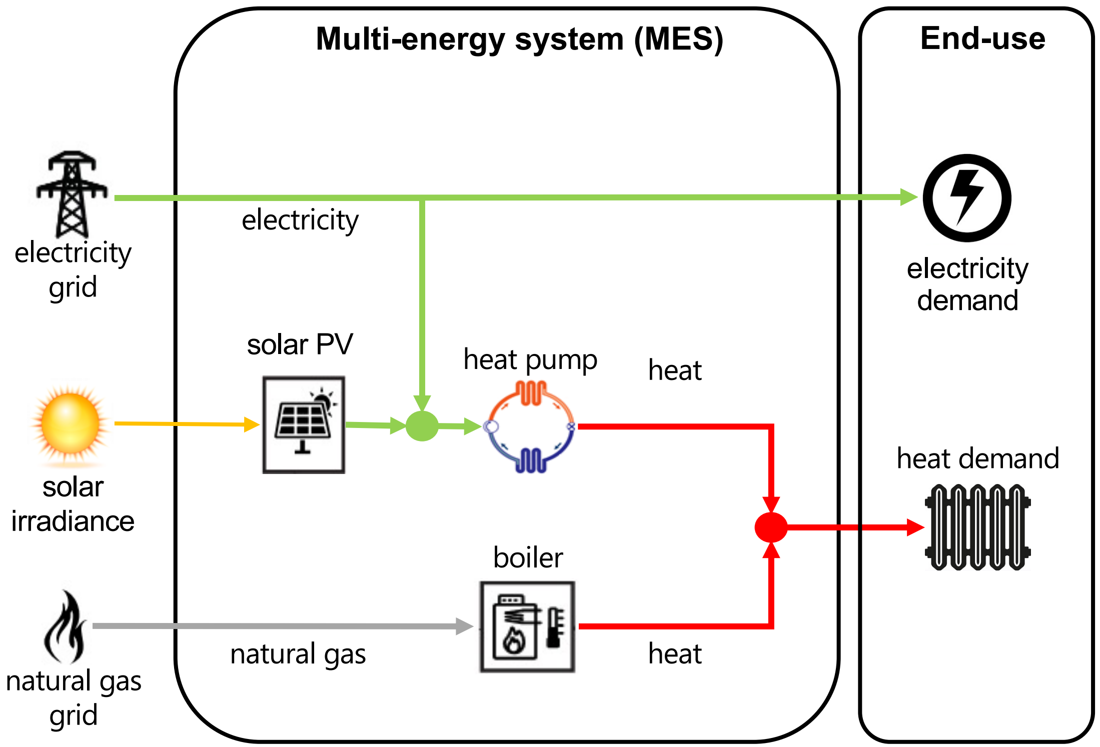
Input data			
Electricity demand	$\boldsymbol{D_E}$	$\boldsymbol{D_{E,t}}$	kWh
Heat demand	$\boldsymbol{D_H}$	$\boldsymbol{D_{H,t}}$	kWh
Electricity price	p_E	0.15	CHF/kWh
Natural gas price	p_G	0.05	CHF/kWh
Electricity grid carbon footprint	γ_E	100	gCO_2/kWh
Natural gas grid carbon footprint	γ_G	230	gCO_2/kWh
Technology sizes	P	2000	kW
Boiler efficiency	η_B	0.95	-
Heat pump efficiency	η_{HP}	4	-
Solar PV	$\boldsymbol{\eta_{PV}}$	$\boldsymbol{\eta_{PV}(w_t)}$	-

Decision variables (minimum-cost optimization)			
Heat pump heat output	$V_{H,HP}$	?	kWh
Boiler heat output	$V_{H,B}$	?	kWh
Imported electricity	M_E	?	kWh
Imported natural gas	M_G	?	kWh
Exported electricity	N_E	?	kWh

MES optimal operation example: Comparison with conventional system



Objective function			
Minimum-cost optimization	z_{cost}	230	CHF/week
Minimum-emissions optimization	z_{CO2}	467	$kgCO_2$/week



Objective function			
Minimum-cost optimization	z_{cost}	**122**	CHF/week
Minimum-emissions optimization	z_{CO2}	**126**	$kgCO_2$/week

After this lecture, you are able to …

- ✓ Understand concept, motivation and main design questions of multi-energy systems (MES)
- ✓ Understand the different degrees of complexity when optimizing MES
- ✓ Formulate time-dependent optimization problem for MES optimal operation

- Next lectures:
  - Optimal design
  - Space dimension: energy networks
  - Uncertainty dimension: uncertainty associated with input data