Optimizing the Transition Towards Low-Carbon Utility Systems:
Data-Driven Design Optimization for Multi-Objective Industrial Energy System Transformation

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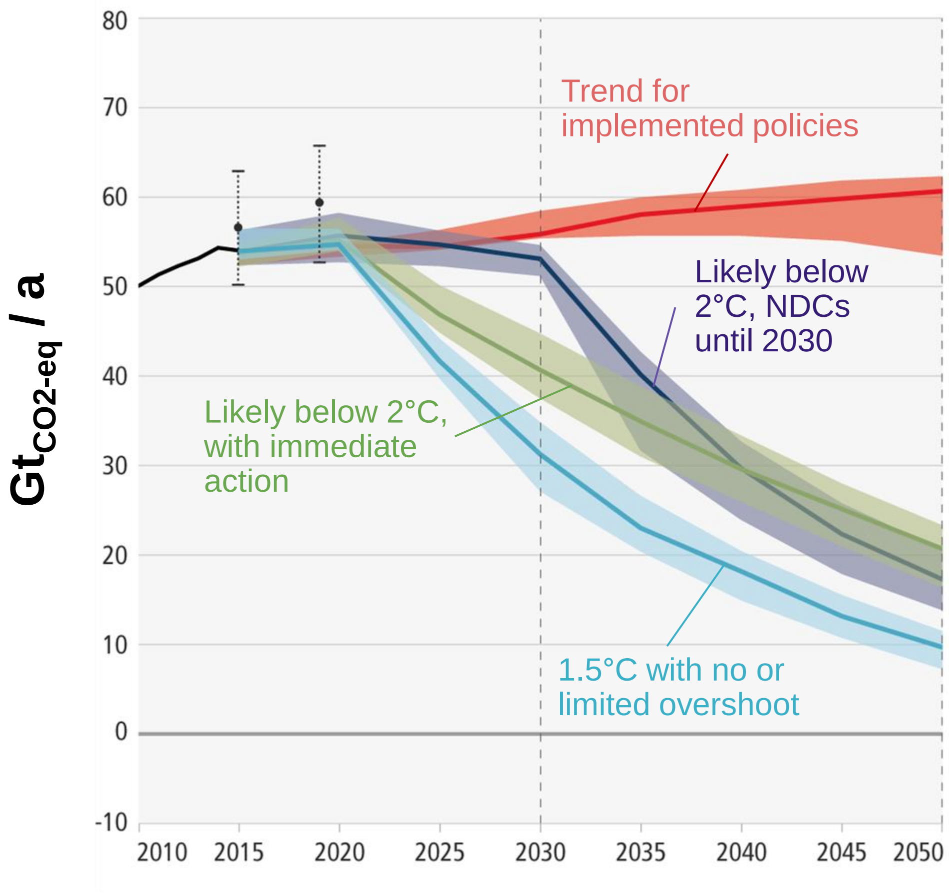
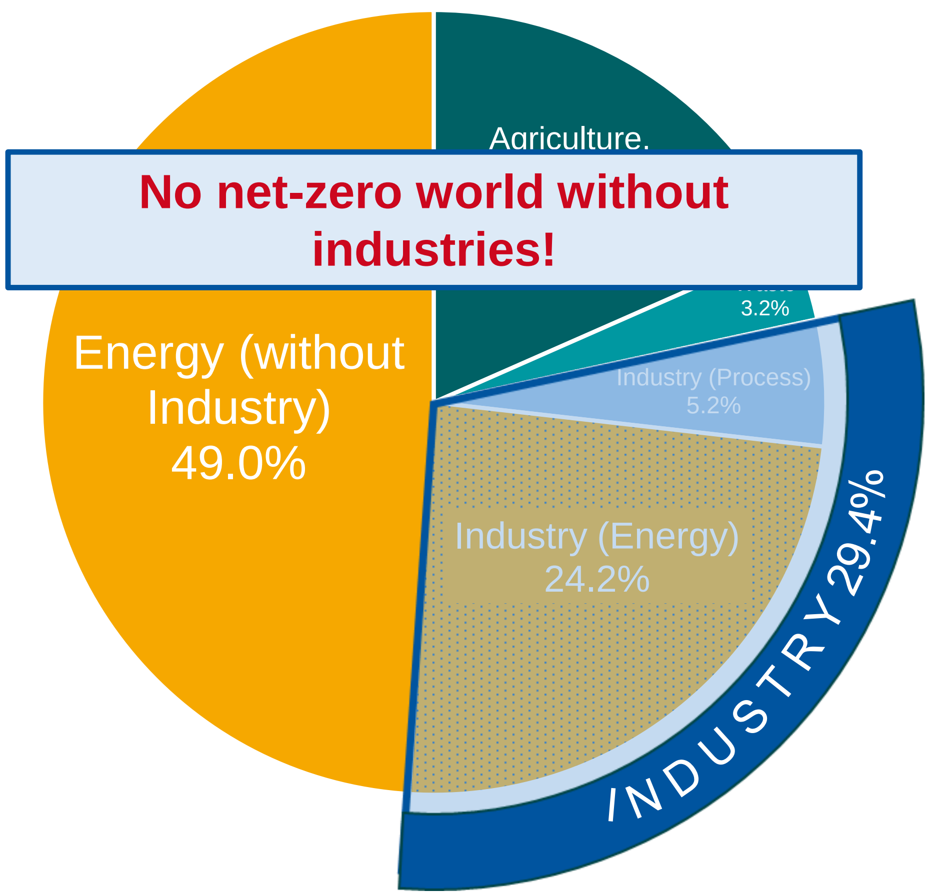
The Global Challenge: Mitigate Climate Change

Projected yearly global GHG emissions[1]

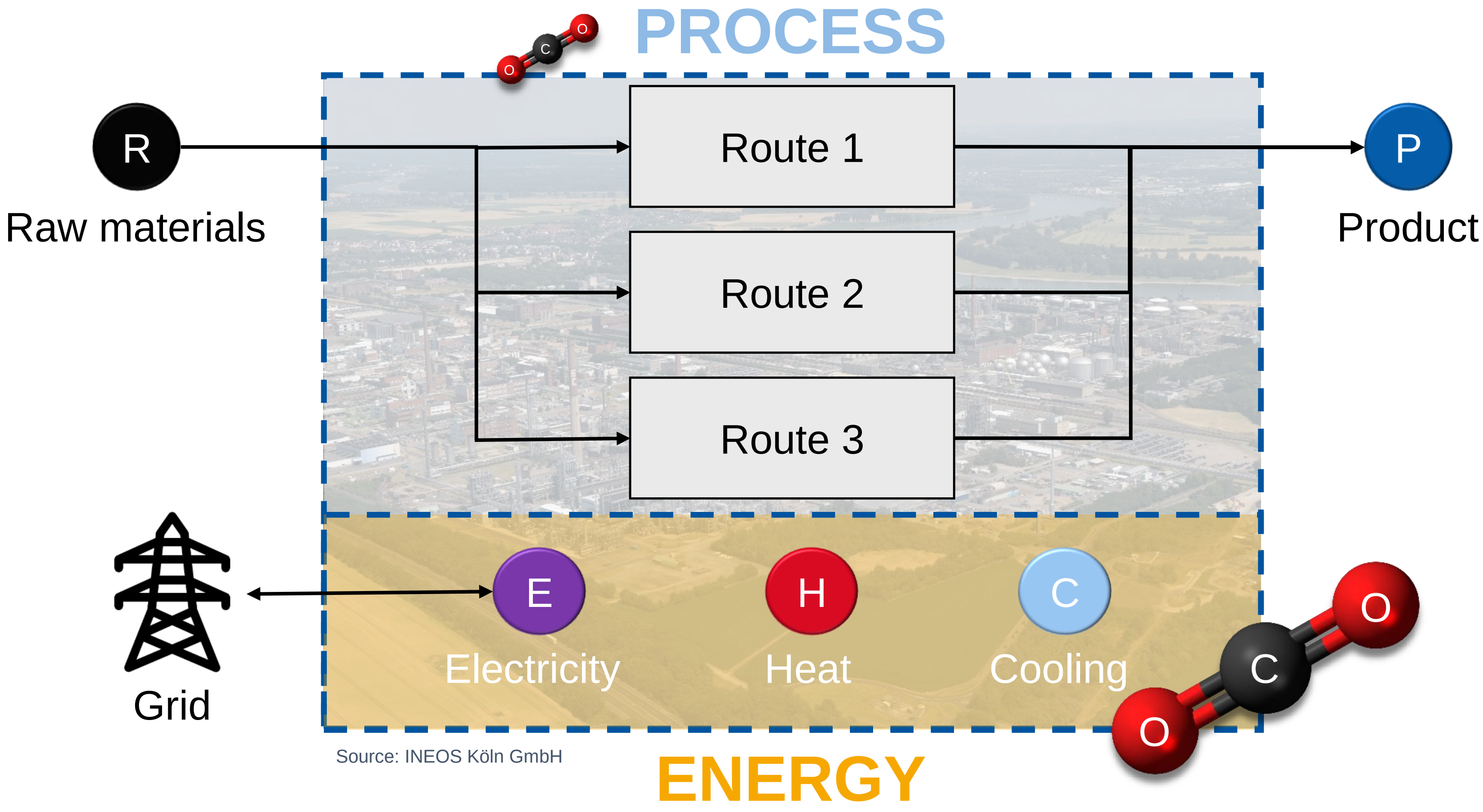


Global GHG emissions by sector²

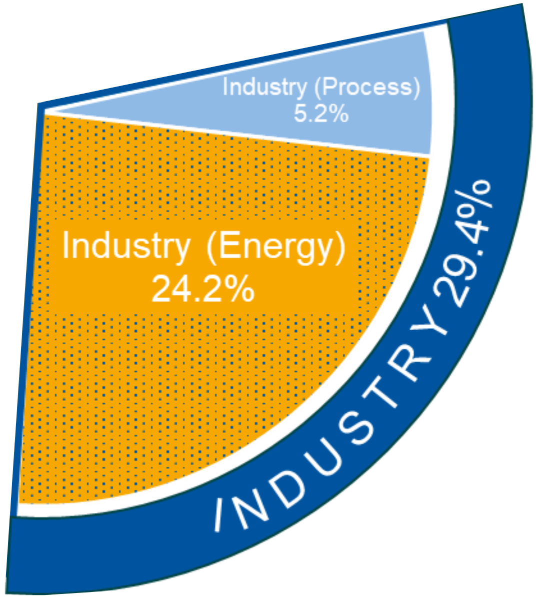


[1] IPCC (2022): Summary for Policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*
[2] Ritchie et al. (2020): CO_2 and Greenhouse Gas Emissions.

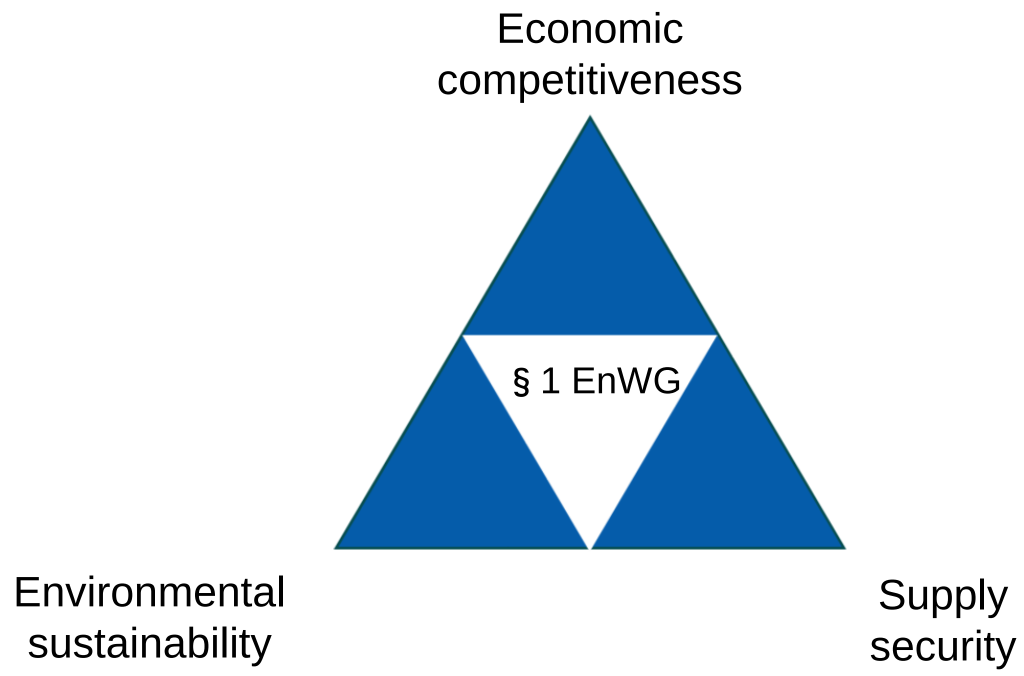
The Industrial Challenge: Decarbonize Process and Energy Systems



Source: INEOS Köln GmbH

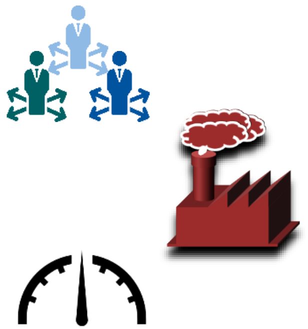


The Industrial Challenge: Decarbonize Energy Systems

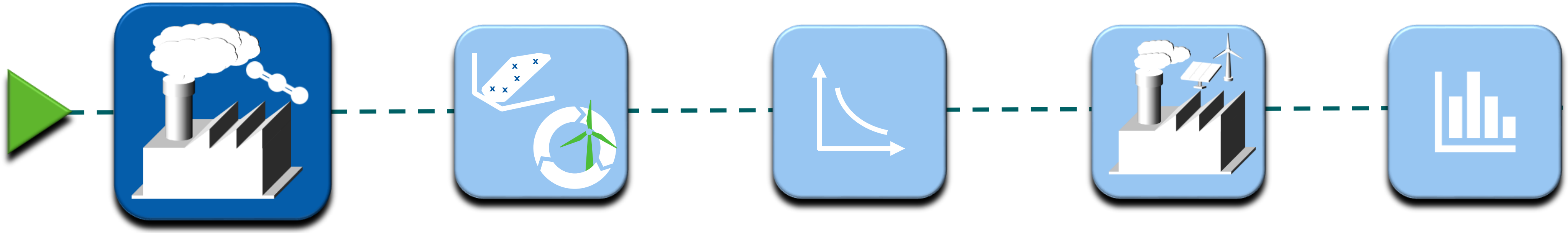


Further Requirements and Difficulties

- Multiple stakeholders with multiple interests and priorities
- Transformation of long-established energy and process systems
- Fast transition

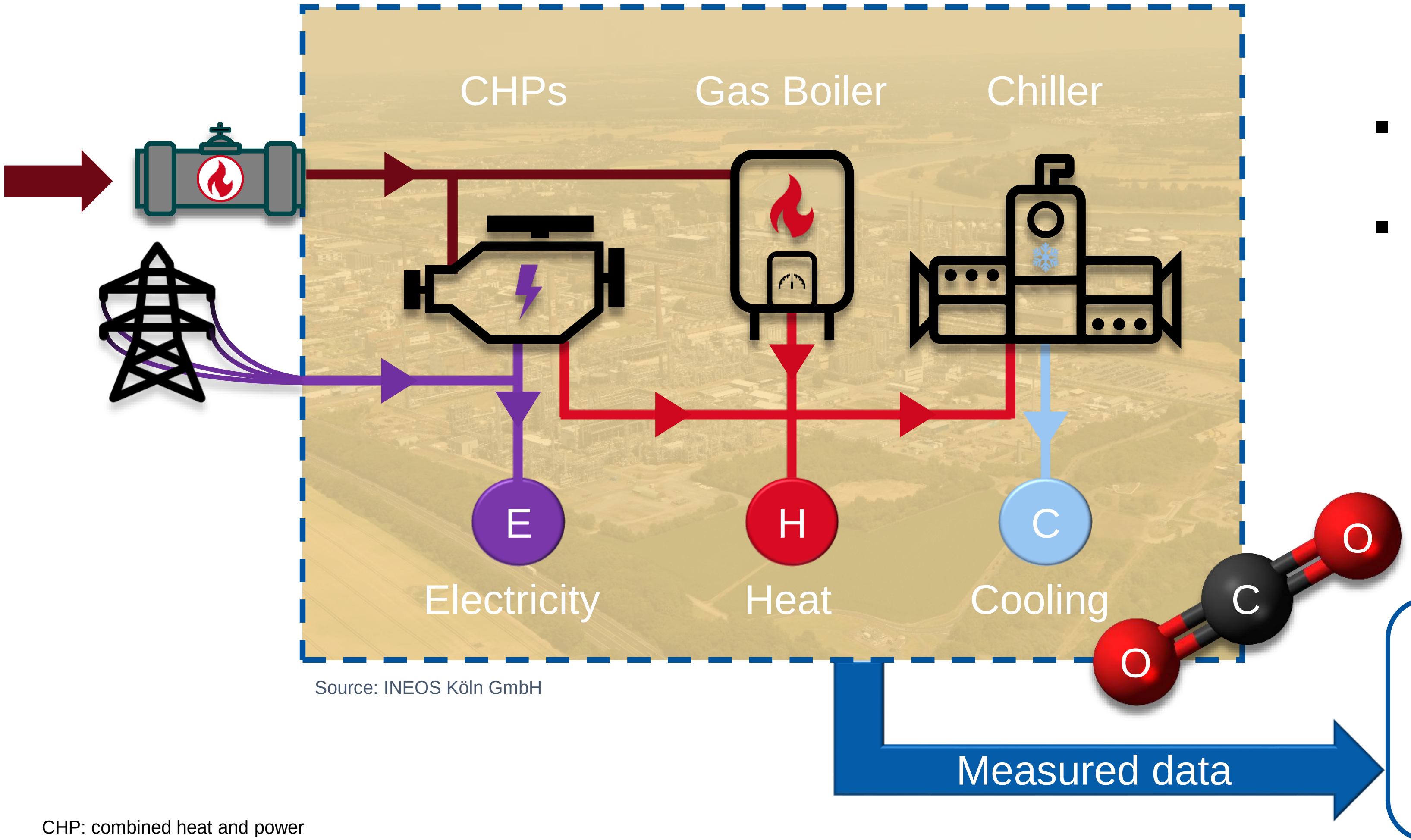


How to best change your energy system now?



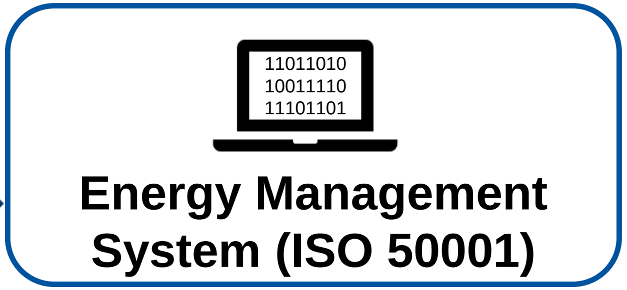
Understand the Decision Problem

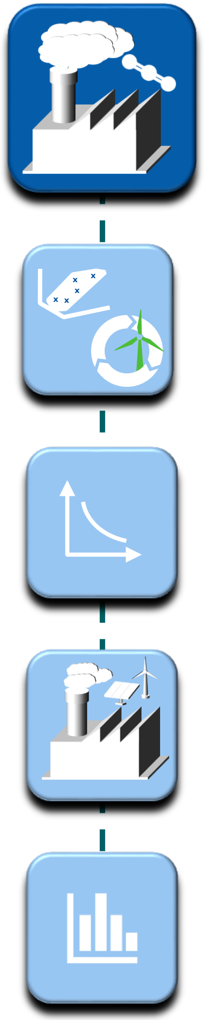
Understand the Existing System



Source: INEOS Köln GmbH

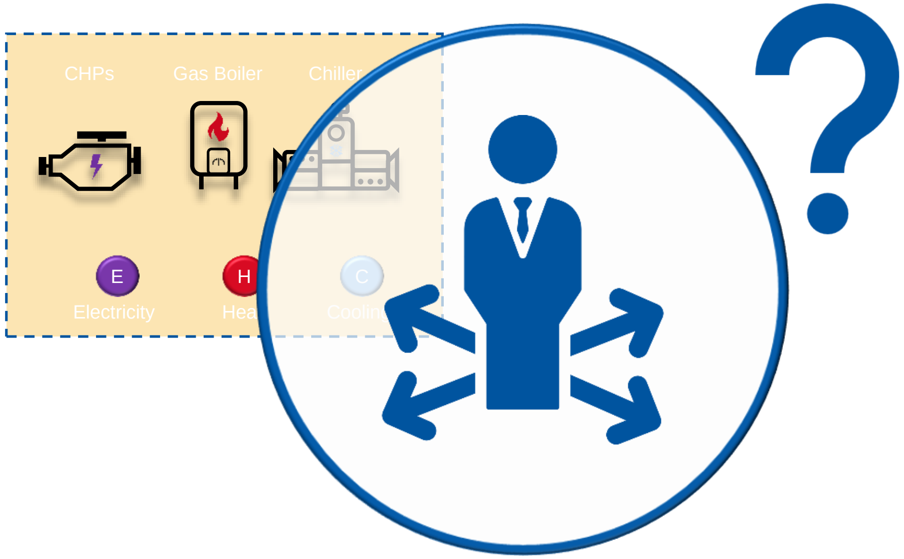
- Product demands
- Existing infrastructre
  - Energy system components
  - Grid infrastructure





CHP: combined heat and power

The Decision Problem: Towards a Fast Redesign of Your Existing Energy System



What do you want?

Targets

- Cost reduction
- Mitigation of environmental impacts
- …

What are your options?

Solution / Technology alternatives

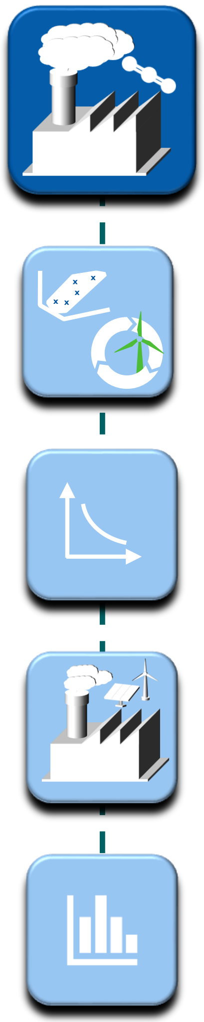
- Fuel switch
- Electrification
- CCU / CCS
- …

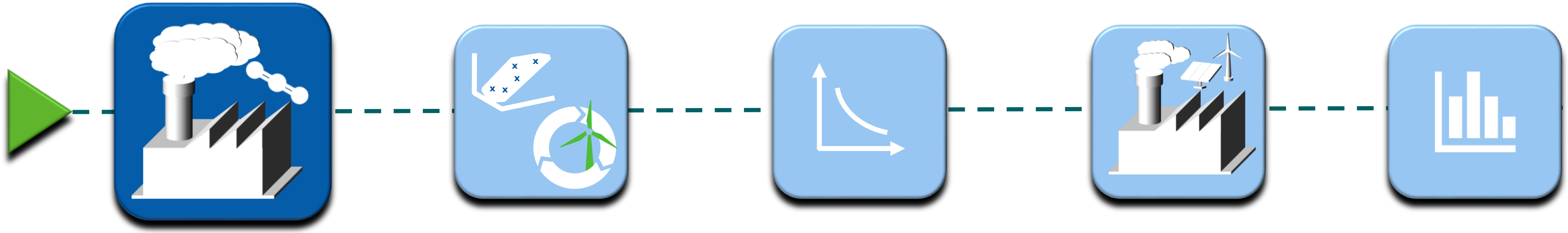
…

What constrains you?

(Technical) constraints

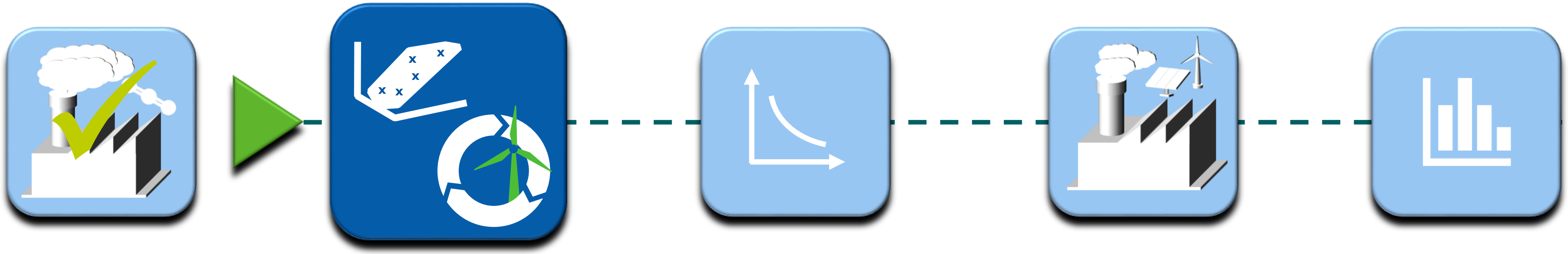
- Product demands
- Existing infrastructure
- Component‘s efficiencies
- Part-load behavior
- …





Understood the Decision Problem ✓

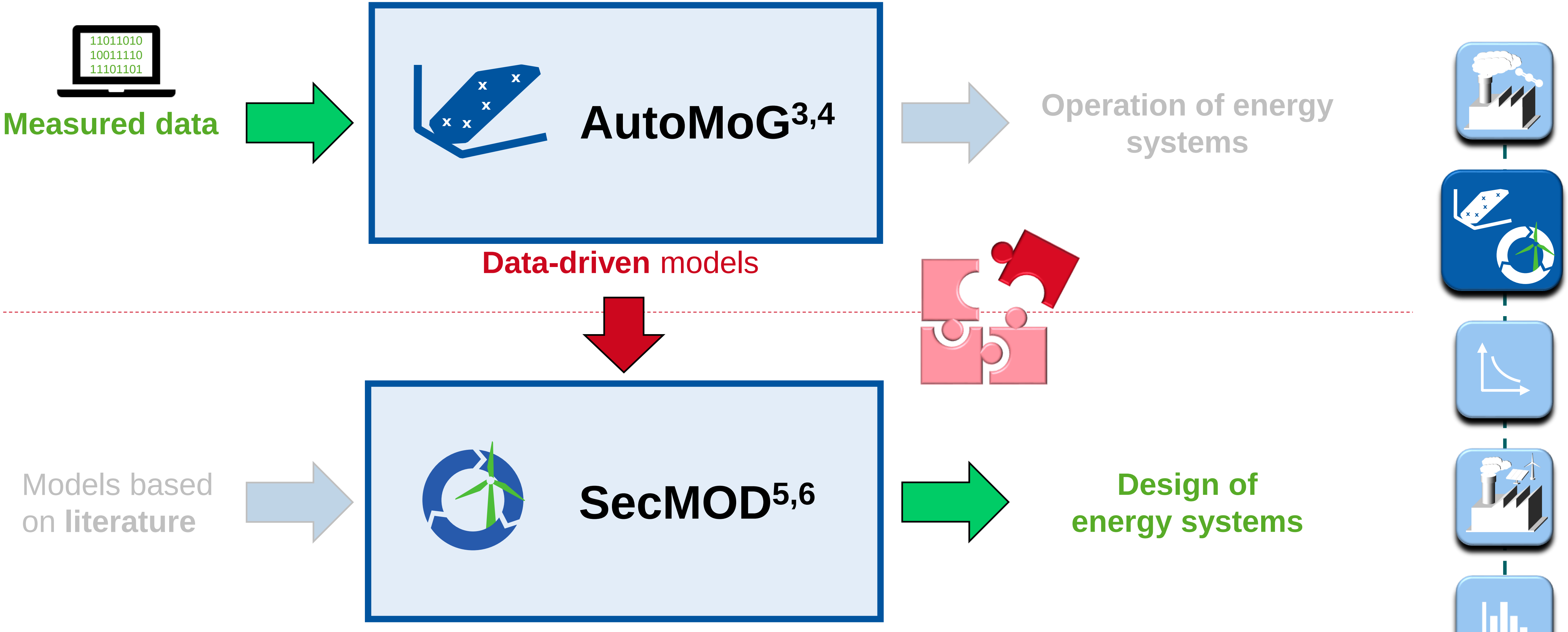
But how to solve it … ?



But how to solve it … ?

Build a Model!

Tools and Models From the Literature



[3] Kämper et al. (2021): AutoMoG: Automated data-driven Model Generation of multi-energy systems using piecewise-linear regression.
[4] Kämper et al. (2021): AutoMoG 3D: Automated Data-Driven Model Generation of Multi-Energy Systems Using Hinging Hyperplanes.
[5] Reinert et al. (2022): SecMOD: An Open-Source Modular Framework Combining Multi-Sector System Optimization and Life-Cycle Assessment.
[6] Baumgärtner et al. (2021): Life-Cycle Assessment of Sector-Coupled National Energy Systems: Environmental Impacts of Electricity, Heat, and Transportation in Germany Till 2050.

Let’s Quantify the Decision Problem…

Decision-maker

Targets
- Cost reduction
- Mitigation of environmental impacts
- …

(Technical) constraints
- Product demands
- Existing infrastructure
- Component‘s efficiencies
- Part-load behavior
- …

Solution / Technology alternatives
- Fuel switch
- Electrification
- CCU / CCS
- …

…

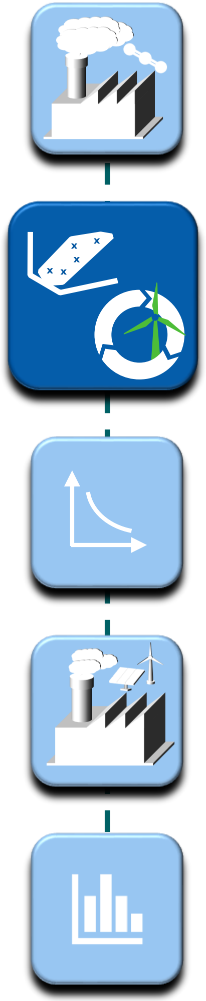
Modeler

Mathematical Optimization

Mixed-**I**nteger **L**inear **P**rogram

Objective function	
$\min_{x,y} \bar{c}^T \cdot \bar{x} + \bar{d}^T \cdot \bar{y}$	CapEx + OpEx
Constraints	
$\text{s.t. } \boldsymbol{A} \cdot \bar{x} + \boldsymbol{B} \cdot \bar{y} \leq \bar{b}$	Demand coverage Existing infrastructure Technical constraints CO_2 limit …
Decision variables	
$\bar{x} \in \mathbb{R}^n, \bar{y} \in \mathbb{Z}^m$	System Design System Operation

SecMOD



Build a Model with SecMOD [5,6]

Energy system optimization

- (MI)LP optimization for transition pathways
- Multi-sector energy demands
- Invest & operation

Life cycle assessment

- Holistic assessment of environmental impacts, e.g., climate change impact
- Full model integration: objective + constraints

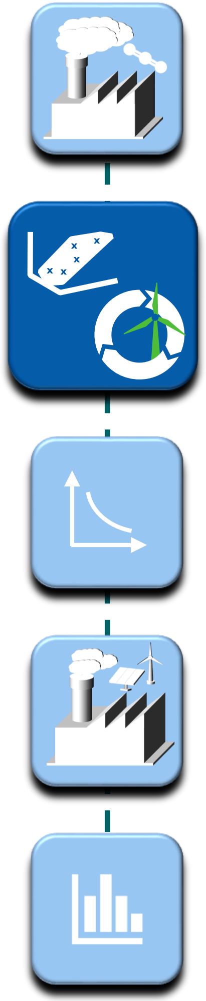
Flexibility

- Modular
- Object-oriented framework
- Build systems based on input data only
- Flexible objective + constraints

Transparency

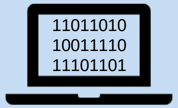
- Python-based
- LP-code: open-source
- MIT license

Open-source code available here:
https://git-ce.rwth-aachen.de/ltt/secmod



How to include our existing infrastructure and its specific technical constraints in our model?

→ With our measured data



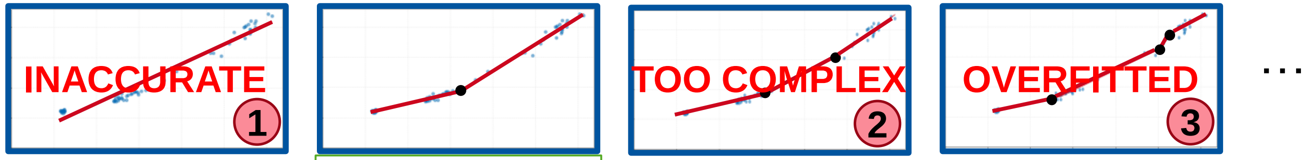
[5] Reinert et al. (2022): SecMOD: An Open-Source Modular Framework Combining Multi-Sector System Optimization and Life-Cycle Assessment.
[6] Baumgärtner et al. (2021): Life-Cycle Assessment of Sector-Coupled National Energy Systems: Environmental Impacts of Electricity, Heat, and Transportation in Germany Till 2050.

Build a Model Based on Measured Data With AutoMoG[3,4]

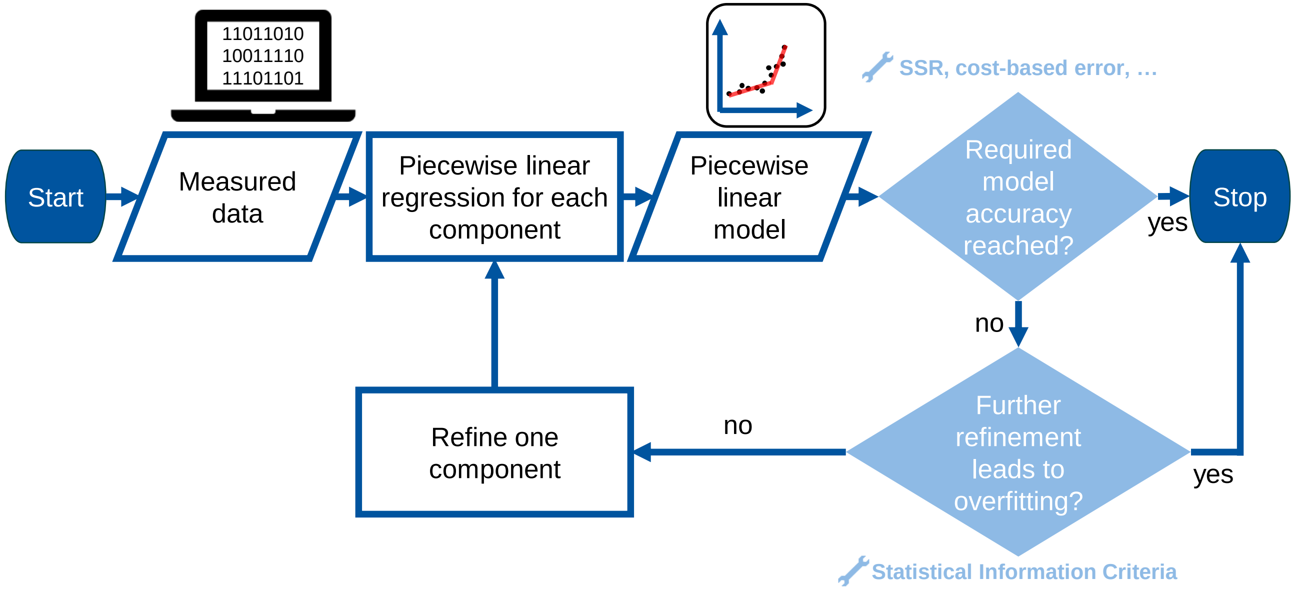
Measured data

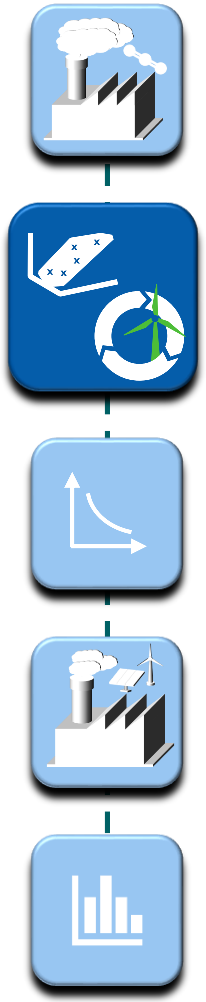
Possible piecewise-linear models

n: number of piecewiese-linear sections



$n = 1$ | BEST MODEL | $n = 3$ | $n = 4$





Model Requirements

1. High accuracy
2. Low complexity
3. No overfitting

Open-source code available here:
https://git-ce.rwth-aachen.de/ltt/automog-3d

[3] Kämper et al. (2021): AutoMoG: Automated data-driven Model Generation of multi-energy systems using piecewise-linear regression.
[4] Kämper et al. (2021): AutoMoG 3D: Automated Data-Driven Model Generation of Multi-Energy Systems Using Hinging Hyperplanes.

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Build a Model with SecMOD and AutoMoG

Measured data

AutoMoG[3,4]

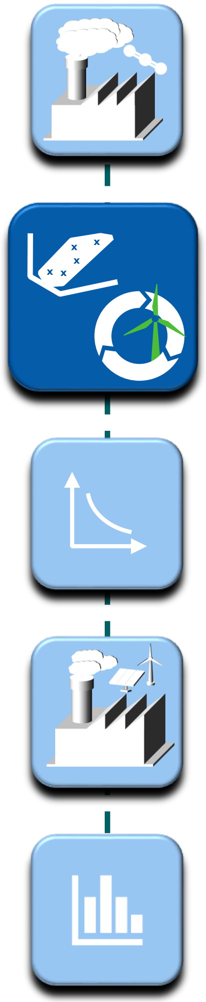
- Automated model generation from measured data
- Balances model accuracy and complexity

Data-driven models

SecMOD[5,6]

- (MI)LP framework for design optimizations
- Highly configurable to address specific decision-making case

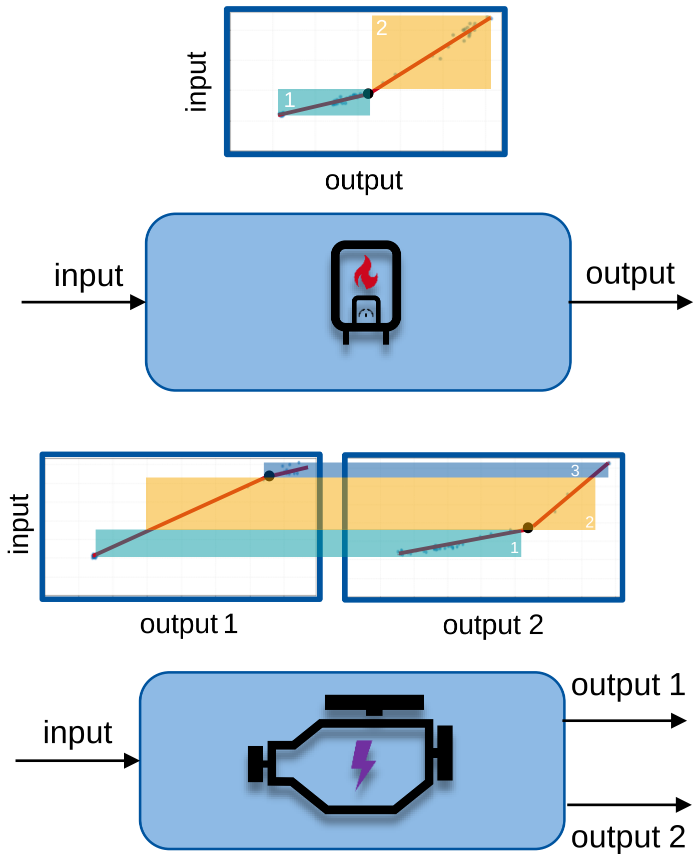
Design Optimization



[3] Kämper et al. (2021): AutoMoG: Automated data-driven Model Generation of multi-energy systems using piecewise-linear regression.
[4] Kämper et al. (2021): AutoMoG 3D: Automated Data-Driven Model Generation of Multi-Energy Systems Using Hinging Hyperplanes.
[5] Reinert et al. (2022): SecMOD: An Open-Source Modular Framework Combining Multi-Sector System Optimization and Life-Cycle Assessment.
[6] Baumgärtner et al. (2021): Life-Cycle Assessment of Sector-Coupled National Energy Systems: Environmental Impacts of Electricity, Heat, and Transportation in Germany Till 2050.

How To Combine AutoMoG and SecMOD?

AutoMoG



System Operation

$\overline{PF}$: product flow – which outputs result, which inputs are needed?

$\overline{s}$:To which extent are the components used?

$$\overline{PF} = f(\overline{s}),$$

f : Piecewise-linear function
→ Mixed-integer linear constraints

$$\text{e.g.,} \begin{bmatrix} - & \mathbf{GAS} \\ + & \mathbf{ELECTRICITY} \\ + & \mathbf{HEAT} \end{bmatrix} = f(\overline{s}_{\mathrm{CHP}})$$

System Design

$$\overline{s} \leq \mathit{EXISTING\_CAPACITY} + \mathit{NEW\_CAPACITY}$$

SecMOD

min CapEx + OpEx

s.t.

- Demand coverage
- Existing infrastructure
- Technical constraints
- CO_2 limit

Decisions

- System Operation
- System Design

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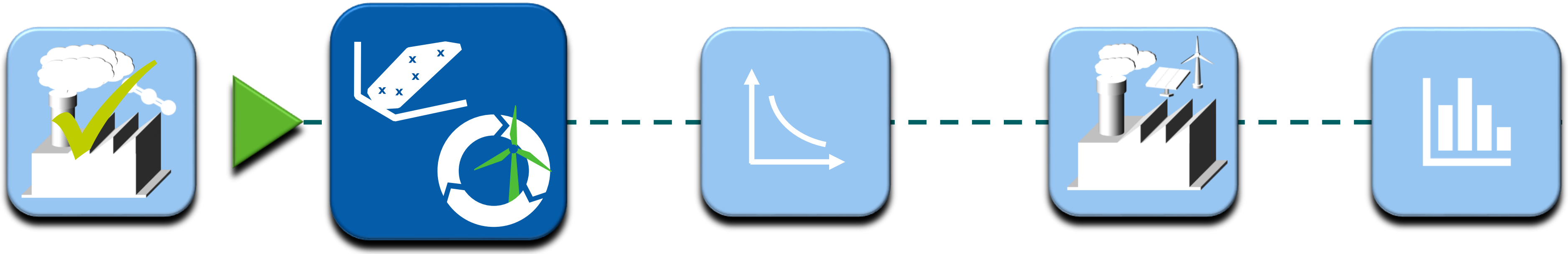

Built a Model ✓

Analyse Trade-Offs

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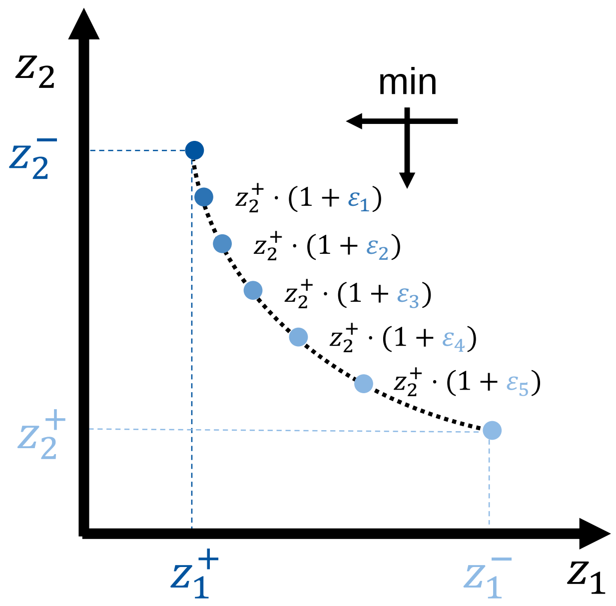
Analyse Trade-Offs for the Bi-Objective Case

$$\min_{\overline{x},\overline{y}\in\mathcal{F}} \left(z_1(\overline{x},\overline{y}), z_2(\overline{x},\overline{y}) \right)$$

$\mathcal{F}$: feasible solution space



ε-constraint method[7]

1. $z_1^+ = \min_{\overline{x},\overline{y}\in\mathcal{F}} z_1(\overline{x},\overline{y})$

2. $z_2^+ = \min_{\overline{x},\overline{y}\in\mathcal{F}} z_2(\overline{x},\overline{y})$

3. For $i = 1 \ldots 5$

$$z_1^{(i)} = \min_{\overline{x},\overline{y}\in\mathcal{F}} z_1(\overline{x},\overline{y})$$

$$\text{s.t.} \quad z_2(\overline{x},\overline{y}) \leq z_2^{(2)} = z_2^+ \cdot (1+\varepsilon_i)$$

Set of Pareto-optimal alternatives $\mathcal{A} = \left\{ (z_1^+, z_2^-), \ldots, \left(z_1^{(i)}, z_2^{(i)}\right), \ldots, (z_1^-, z_2^+) \right\}$

[7] Chankong and Haimes (1983): Multiobjective Decision Making: Theory and Methodology.

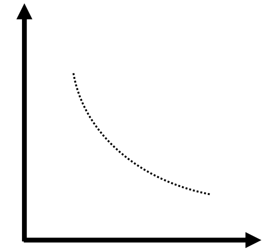
Analysed Trade-Offs ✓

Select a Solution

Select the Best Solution by Multi-Criteria Decision Making Methods

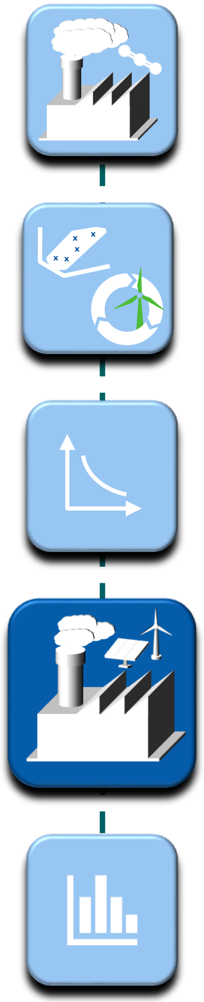
Solution Generation

ε-Constraint method



Multi-Criteria Decision Making (MCDM)

Ranking of targets: Weighting[8]	Ranking of alternatives: Scoring[9]
Entropy Method	TOPSIS



Set of pareto-optimal alternatives $\mathcal{A}$

$$\mathcal{A} = \left\{ (z_1^+, z_2^-), \dots, \left(z_1^{(i)}, z_2^{(i)}\right), \dots, (z_1^-, z_2^+) \right\}$$

Decision matrix X

$$\boldsymbol{X} = \left(x_{ij}\right)_{i=1,\dots,|\mathcal{A}|;j=1,2} = \begin{bmatrix} z_1^+ & z_2^- \\ \vdots & \vdots \\ z_1^{(i)} & z_2^{(i)} \\ \vdots & \vdots \\ z_1^- & z_2^+ \end{bmatrix} \in \mathbb{R}^{|\mathcal{A}|\text{x}2}$$

[8] Odu (2019): Weighting Methods for Multi-Criteria Decision Making Technique.
[9] Zanakis et al. (1998): Multi-attribute decision making: A simulation comparison of select methods.

Weight Your Objectives

Alternative Generation | **Weighting** | Scoring

ε-Constraint method | **Entropy Method** | TOPSIS

Normalized decision matrix $\boldsymbol{P}$

$$\boldsymbol{P} = \left(p_{ij}\right)_{i=1,\ldots,|\mathcal{A}|;j=1,2} = \left(\frac{x_{ij}}{\sum_{i=1}^{|\mathcal{A}|} x_{ij}}\right)$$

(Shannon) entropy vector $\overline{\boldsymbol{e}}$

$$e_j = -\frac{1}{\ln|\mathcal{A}|} \cdot \sum_{i=1,\ldots,|\mathcal{A}|} p_{ij} \cdot \ln\left(p_{ij}\right) \in [0,1]$$

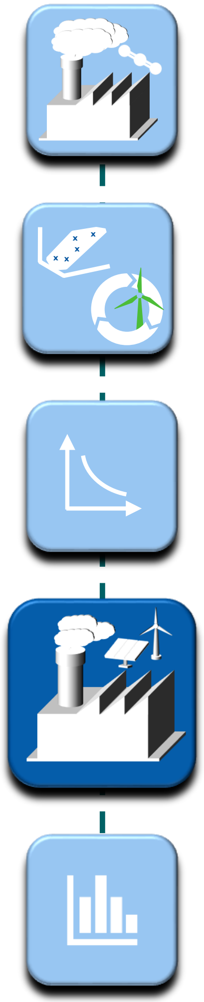
Weight vector $\overline{\boldsymbol{w}}$

$$w_j = \frac{1-e_j}{\sum_{i=1,2} 1-e_j}$$

[10]

$1 - e_j$: **How much information can be derived from criterion j?**

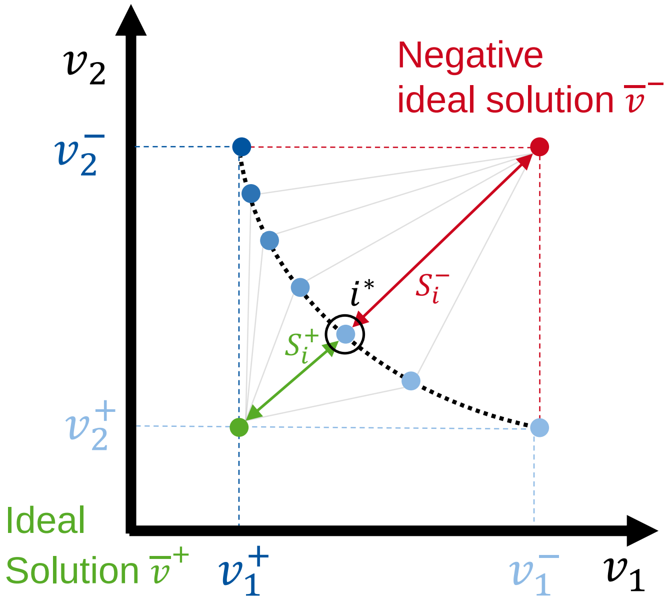
More information ⇔ More weight



[10] Shanon, Cllaude E. (1948): A Mathematical Theory of Communication, Bell System Technical Journal.

Score Alternatives

Alternative Generation	Weighting	**Scoring**
ε-Constraint method	Entropy Method	**TOPSIS**



Technique for Order Preference by Similarity to Ideal Solution

Weighted normalized decision matrix V

$$V = (v_{ij}) = (w_j \cdot p_{ij}) \in \mathbb{R}^{|\mathcal{A}| \times 2}$$

Ideal / negative ideal solution $\overline{v}^{+/-}$

$$\overline{v}^{+/-} = \left(v_1^{+/-}, v_2^{+/-}\right)^{\mathrm{T}}$$

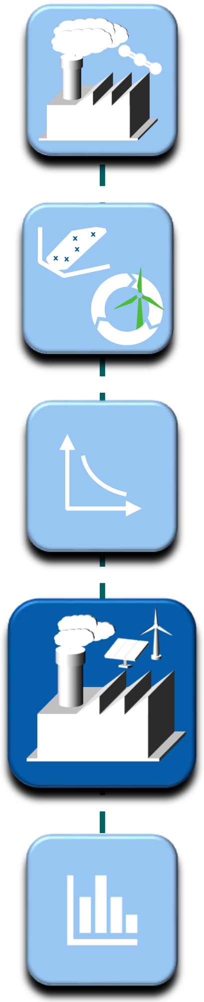
Distance to ideal / negative ideal solution $S_i^{+/-}$

$$S_i^{+/-} = \left\| \overline{v}^{(i)} - \overline{v}^{+/-} \right\|_2$$

Choose alternative i^*

$$i^* = \operatorname{argmax}_{i=1,\dots,|\mathcal{A}|} \left(\frac{S_i^-}{S_i^- + S_i^+} \right)$$

[11]

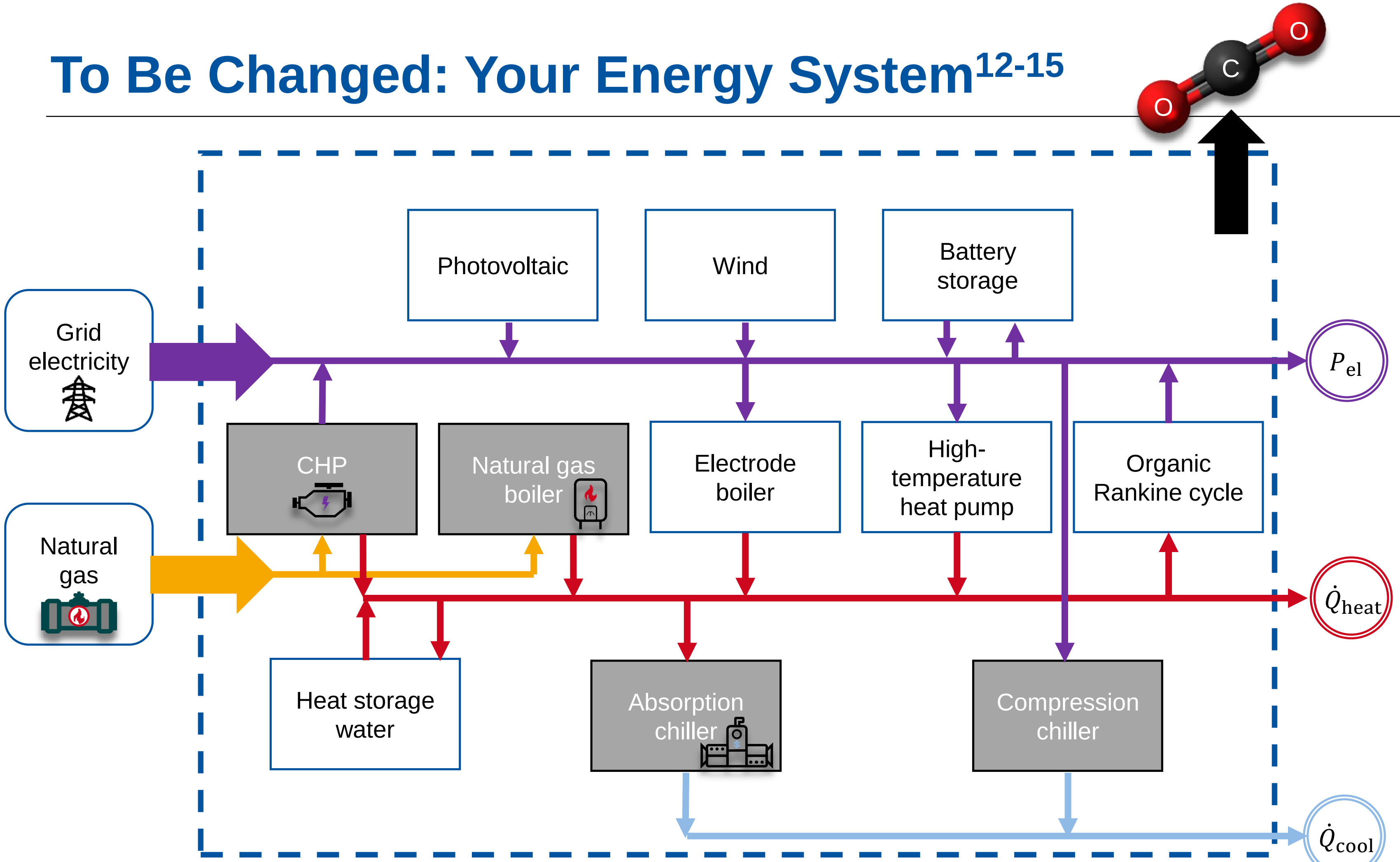


[11] Shih et al. (2007): An extension of TOPSIS for group decision making.

Selected a Solution ✓

Case Study Analysis

To Be Changed: Your Energy System[12-15]

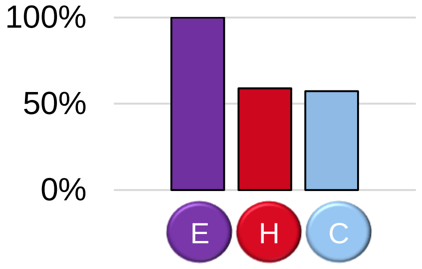


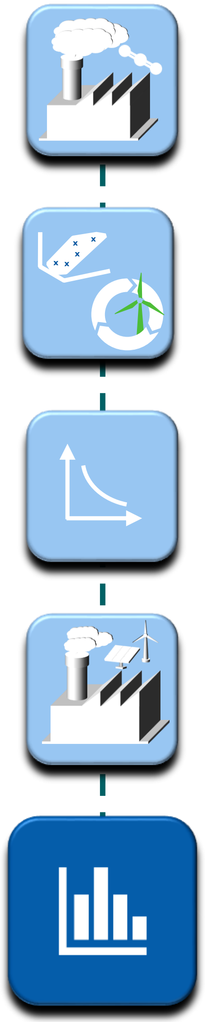
: Existing infrastructure with synthetically generated measured data from [13]

Targets

- ↓ Total Annualized Costs (TAC)
- ↓ Global Warming Impact (GWI)

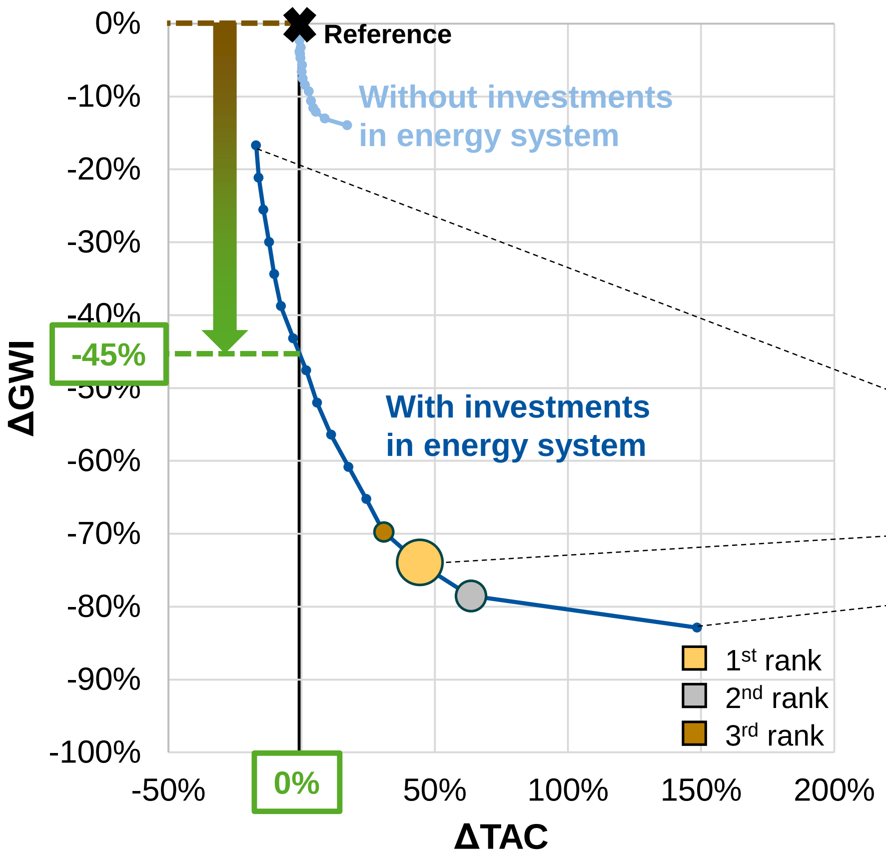
Ø Demand structure

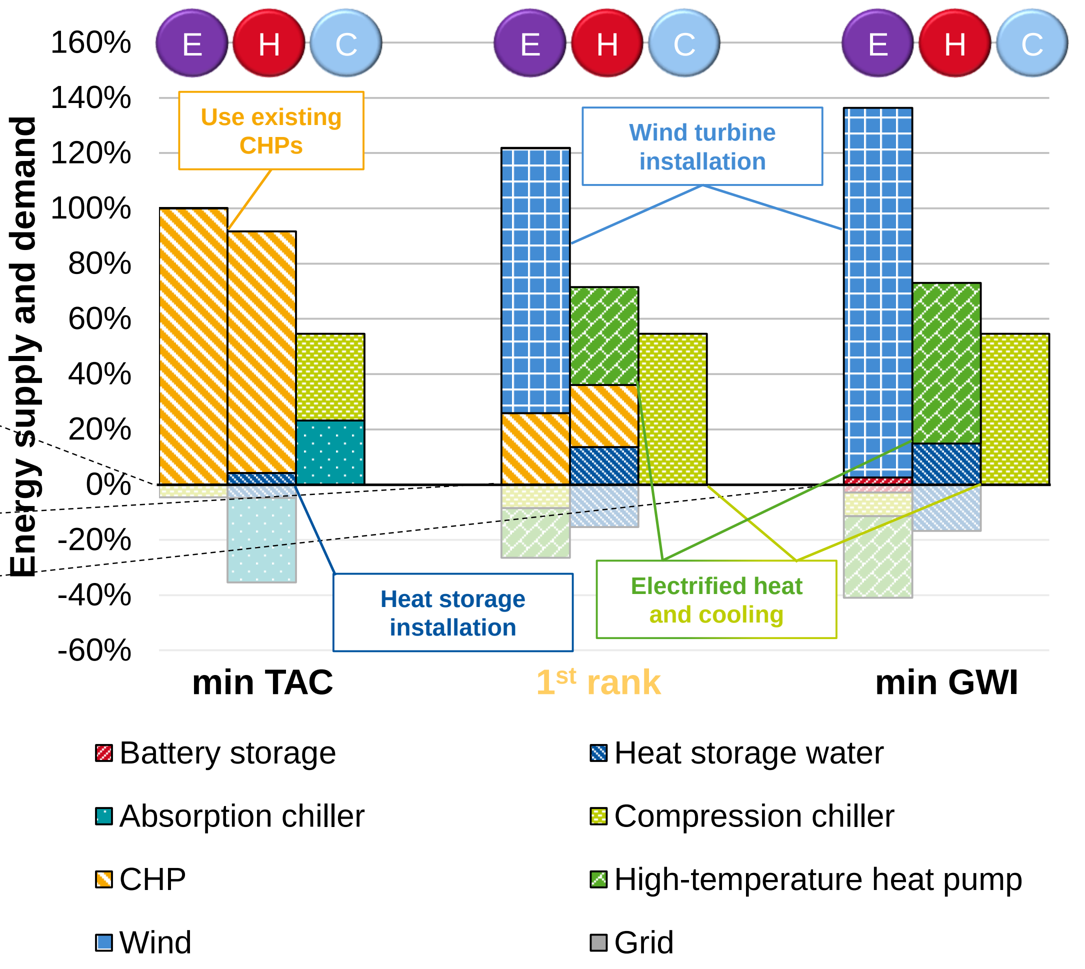


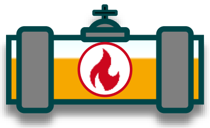


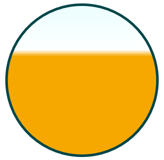
[12] Reinert et al. (2022): Combining optimization and life cycle assessment: Design of low-carbon multi-energy systems in the SecMOD framework.
[13] Goderbauer et al. (2016): An adaptive discretization MINLP algorithm for optimal synthesis of decentralized energy supply systems.

Trade-Off Analysis and Product Balances for Base Scenario

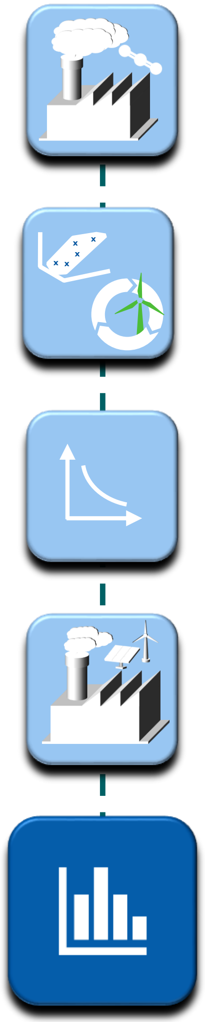






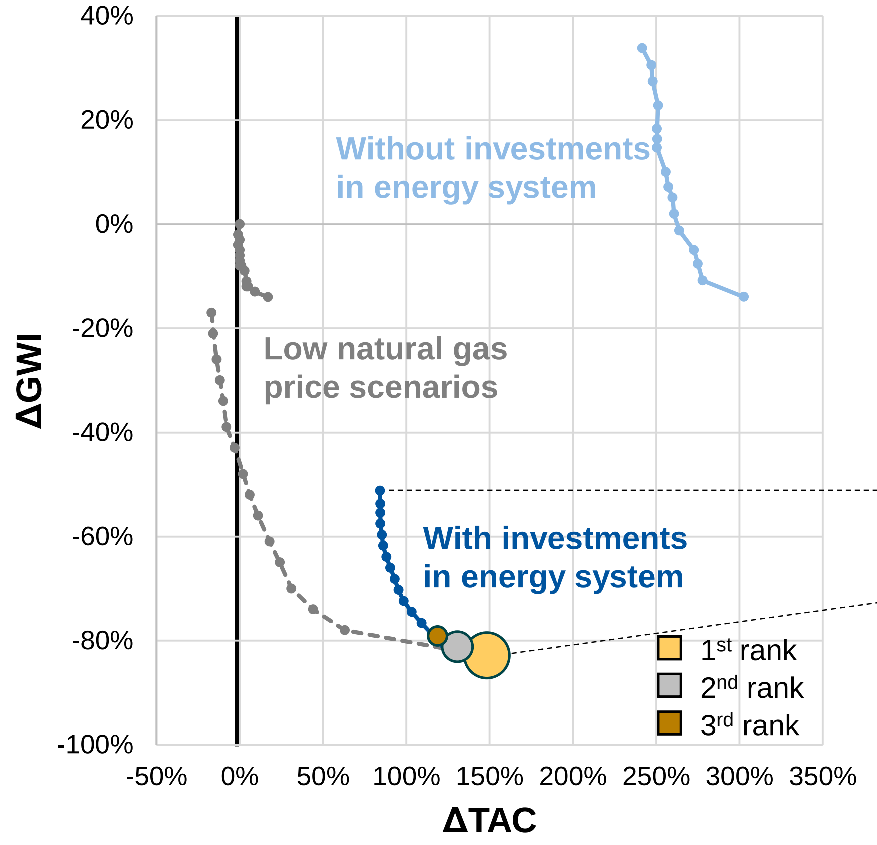


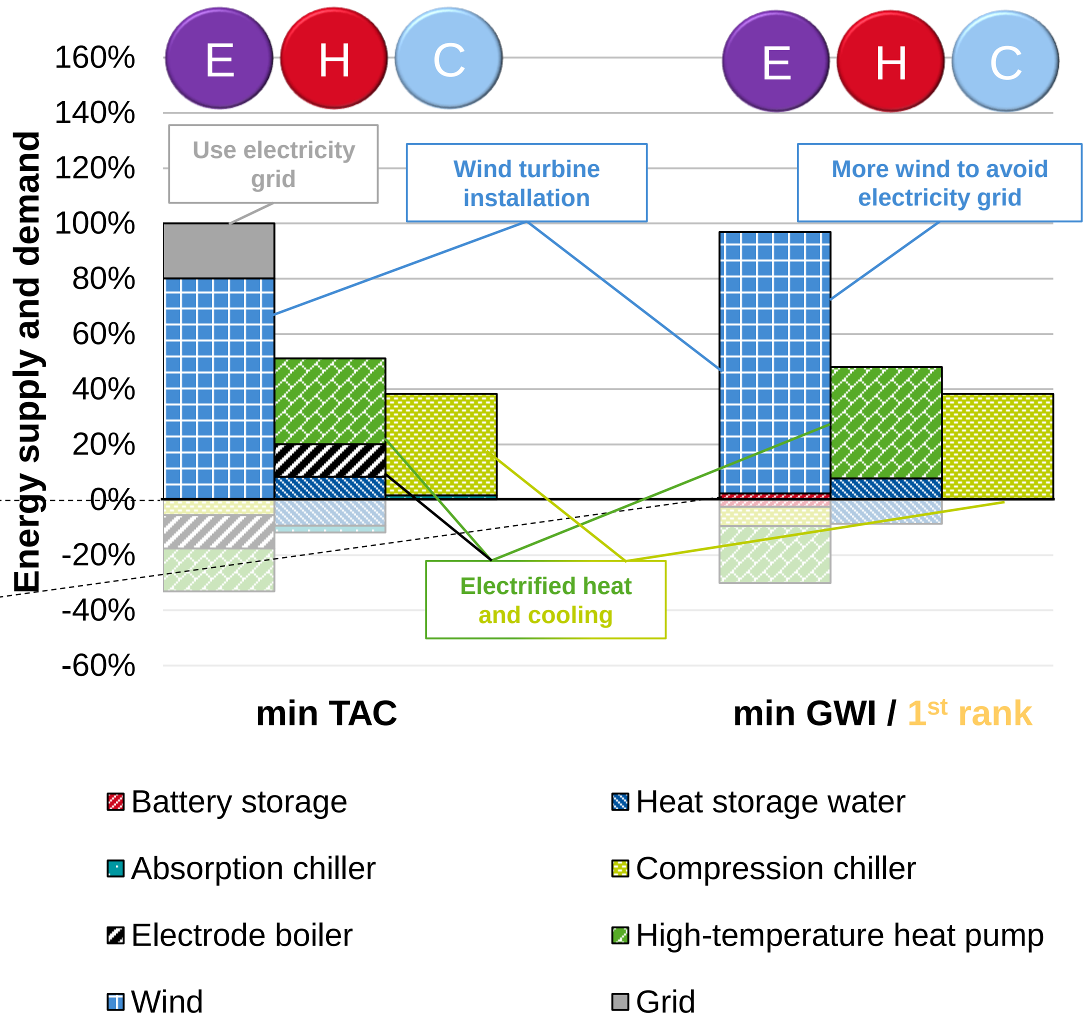
Ø 2,86 ct/kWh[14]

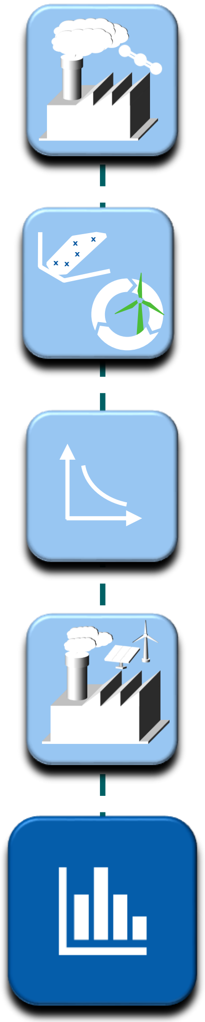


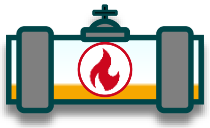
[14] Bundesnetzagentur and Bundeskartellamt (2020): Monitoringbericht 2019.

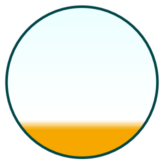
Scenario: Increased Natural Gas Prices (End of 07/2022)











Ø 20,54 ct/kWh[15]

[15] EEX (2022): spot market prices THE.

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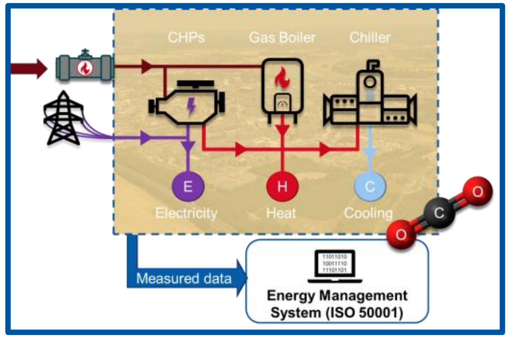
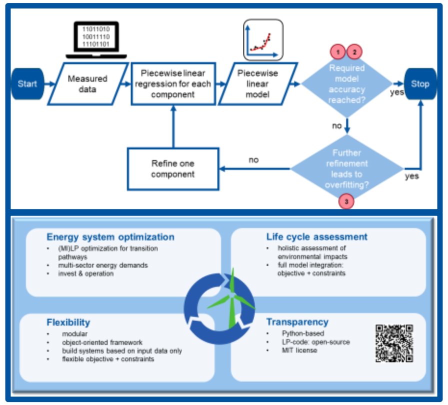
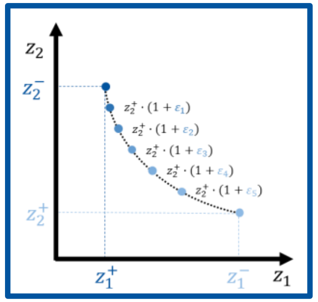
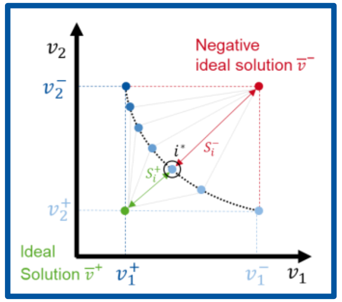
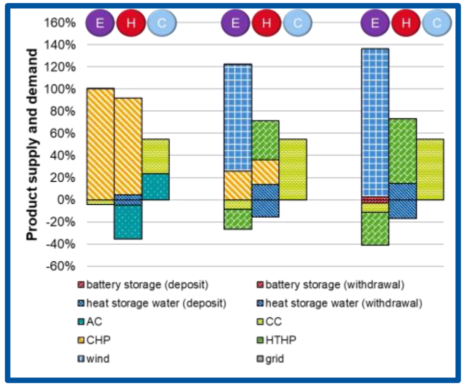
How-To: Change Your Energy System Now!











Understand the decision problem

… by collecting data from existing system

Build a model

…by applying AutoMoG and SecMOD

Analyse Trade-offs

… with the ε-constraint method

Select a solution

… by MCDM weighting and scoring methods

Case Study Analysis

… of your running system

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Open-source code available here:

SecMOD
https://git-ce.rwth-aachen.de/ltt/secmod

AutoMoG
https://git-ce.rwth-aachen.de/ltt/automog-3d

Thank you for your attention!

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