ETH zürich

RRE Reliability and Risk Engineering

EPSE Energy & Process Systems Engineering

Introduction to Modeling and Optimization of Sustainable Energy Systems

Introduction

André Bardow & Giovanni Sansavini

Who are we?

Reliability and Risk Engineering
https://rre.ethz.ch/

Prof. Dr. Giovanni Sansavini

Energy and Process Systems Engineering
https://epse.ethz.ch/

Prof. Dr. André Bardow

Administration

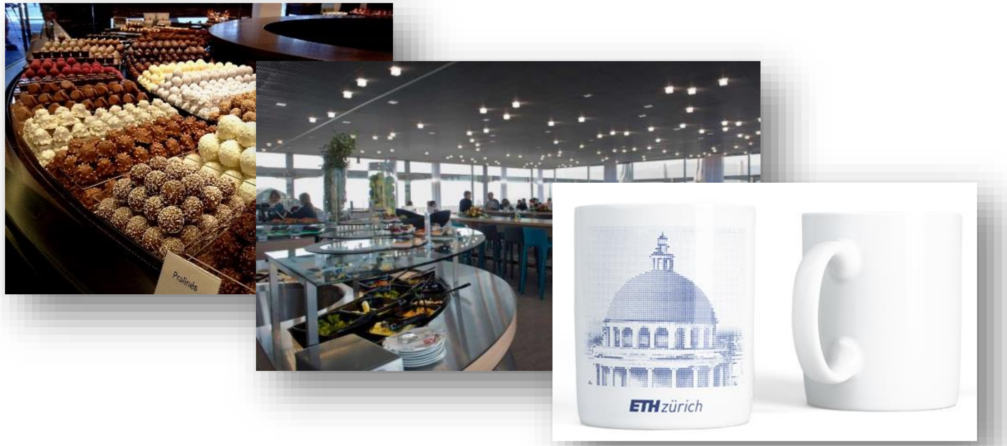
- Course dates
  - Lecture Wed 16:15 p.m. – 18:00 p.m. in HG D 7.1
  - Exercise Thu 13:15 p.m. – 14:00 p.m. in ML F 36
- Course documents
  - Livestream of the Lecture (record provided afterward): https://video.ethz.ch/live/lectures/zentrum/hg/hg-d-7-1.html
  - Slides, recordings, exercises, solutions, and discussion forum are provided via Moodle: https://moodle-app2.let.ethz.ch/course/view.php?id=15661
- Exam
  - Written exam
  - 120 minutes
  - No written aids allowed
  - Session examination
- Office hours: write to moses-edu@ethz.ch
- Exam office hours: 1-2 weeks before the exam (tba)

Found any mistakes?

- *Modeling and Optimization of Sustainable Energy Systems* is a new lecture in an emerging field
  - Lectures and exercise are new at ETH
  - Thus: Mistakes are unavoidable

- If you found any mistakes, please let us know: moses-edu@ethz.ch

- The participant providing the best feedback will receive a prize!



Lecture plan

No.	Date	Content	
1	29.09.	Introduction & Models	
2	06.10.	Heat integration	Applications
3	13.10.	Continuous Optimization	Methods
4	20.10.	Heat exchanger networks	Applications
5	27.10.	Discrete Optimization	Methods
6	03.11.	Life Cycle Assessment (LCA)	Metrics
7	10.11.	Thermoeconomics	Metrics
8	17.11.	Risk Key Performance Indicators for Security	Metrics
9	24.11.	Multi-energy dimension: introduction	Methods & Applications
10	01.12.	Design dimensions: technology modelling	
11	08.12.	Space dimensions: energy networks	
12	15.12.	Uncertainty in energy systems	
13	22.12.	Recap (online)	

ETH zürich

RRE Reliability and Risk Engineering | EPSE Energy & Process Systems Engineering

Introduction to Modeling and Optimization of Sustainable Energy Systems

Introduction

André Bardow & Giovanni Sansavini

After this lecture, you are able to…

✓ plan **your participation** in this course

- explain the **scope of this course**
- recognize tradeoffs in the **energy trilemma**
- classify **mathematical models**

ETH zürich

RRE Reliability and Risk Engineering | EPSE Energy & Process Systems Engineering

Introduction to Modeling and Optimization of Sustainable **Energy** Systems

Introduction

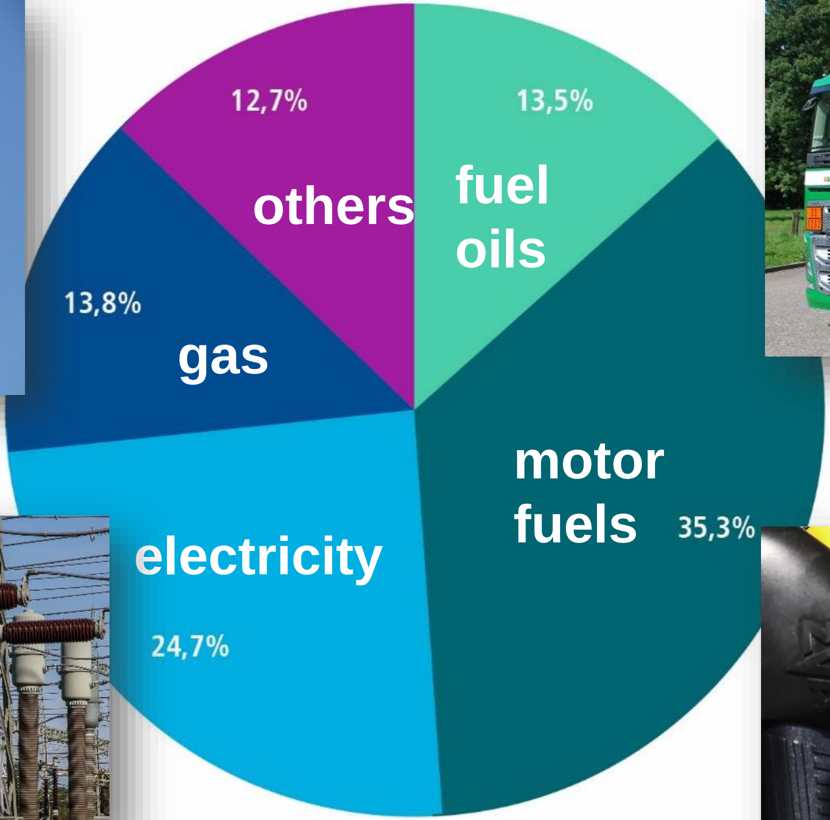
André Bardow & Giovanni Sansavini

Switzerland.

WE ARE FULL OF ENERGY

https://www.eda.admin.ch/

Final energy consumption in Switzerland 2019



www.neftruckcenter.ch

BFE, Schweizerische Gesamtenergiestatistik 2019 (Fig. 2)
OFEN, Statistique globale suisse de l’énergie 2019 (fig. 2)

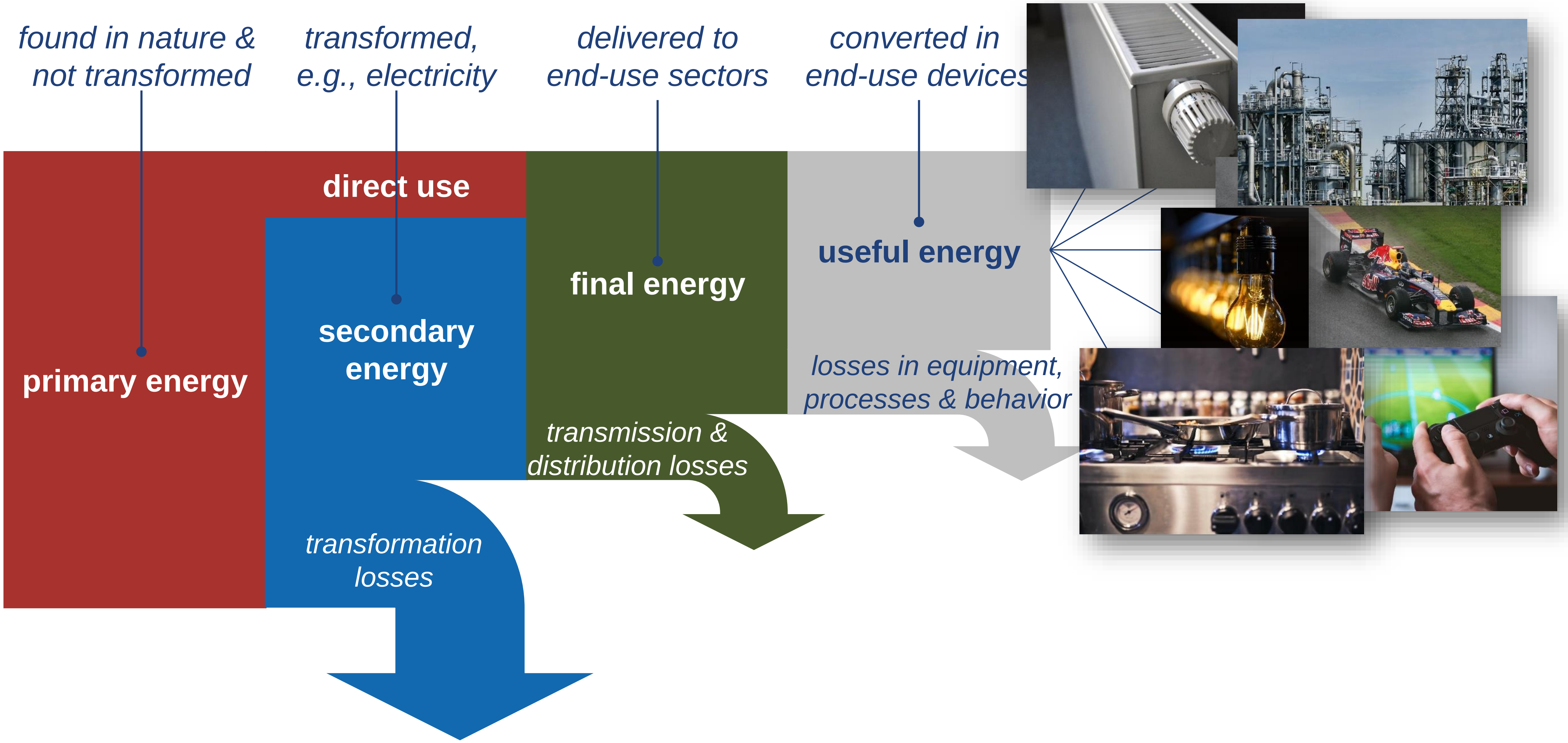
WE ARE FULL OF ENERGY

Final energy consumption in Switzerland 2019

Do we really care about energy ?

BFE, Schweizerische Gesamtenergiestatistik 2019 (Fig. 2)
OFEN, Statistique globale suisse de l'énergie 2019 (fig. 2)

Useful energy, final energy, secondary energy, primary energy



ETH zürich

RRE Reliability and Risk Engineering

EPSE Energy & Process Systems Engineering

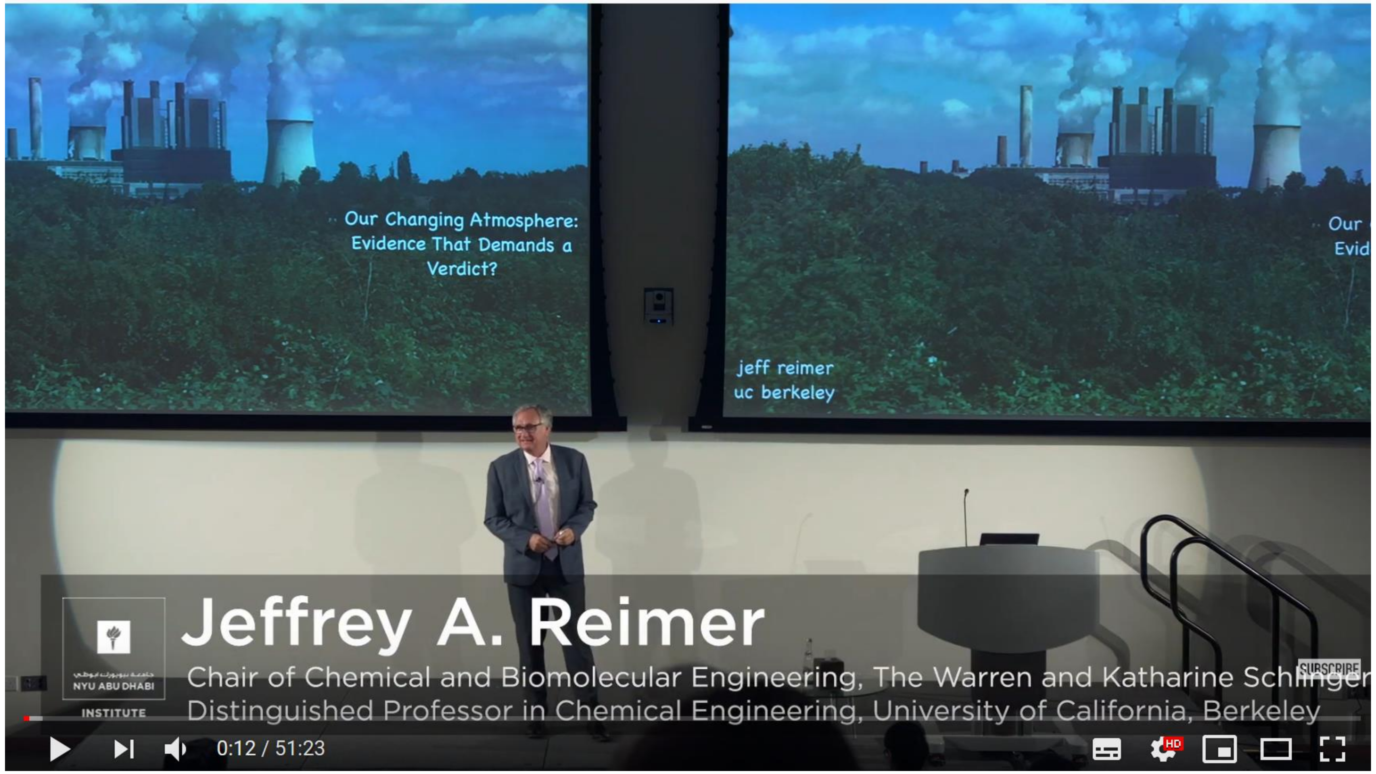
Introduction to Modeling and Optimization of **Sustainable Energy** Systems

Introduction

André Bardow & Giovanni Sansavini

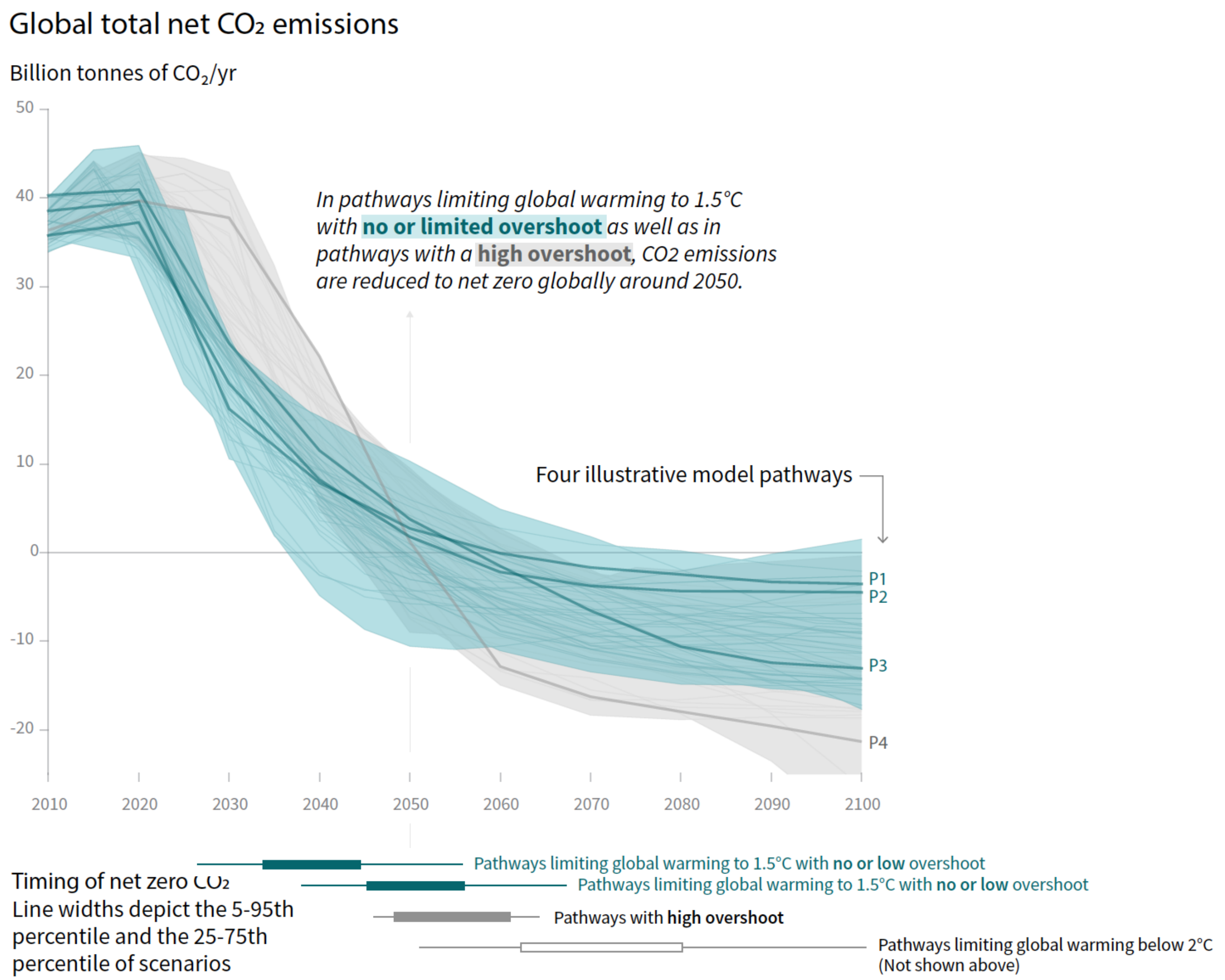
Climate change ! Recommended video by Jeff Reimer

Jeff Reimer: **Our Changing Atmosphere - Evidence That Demands a Verdict**



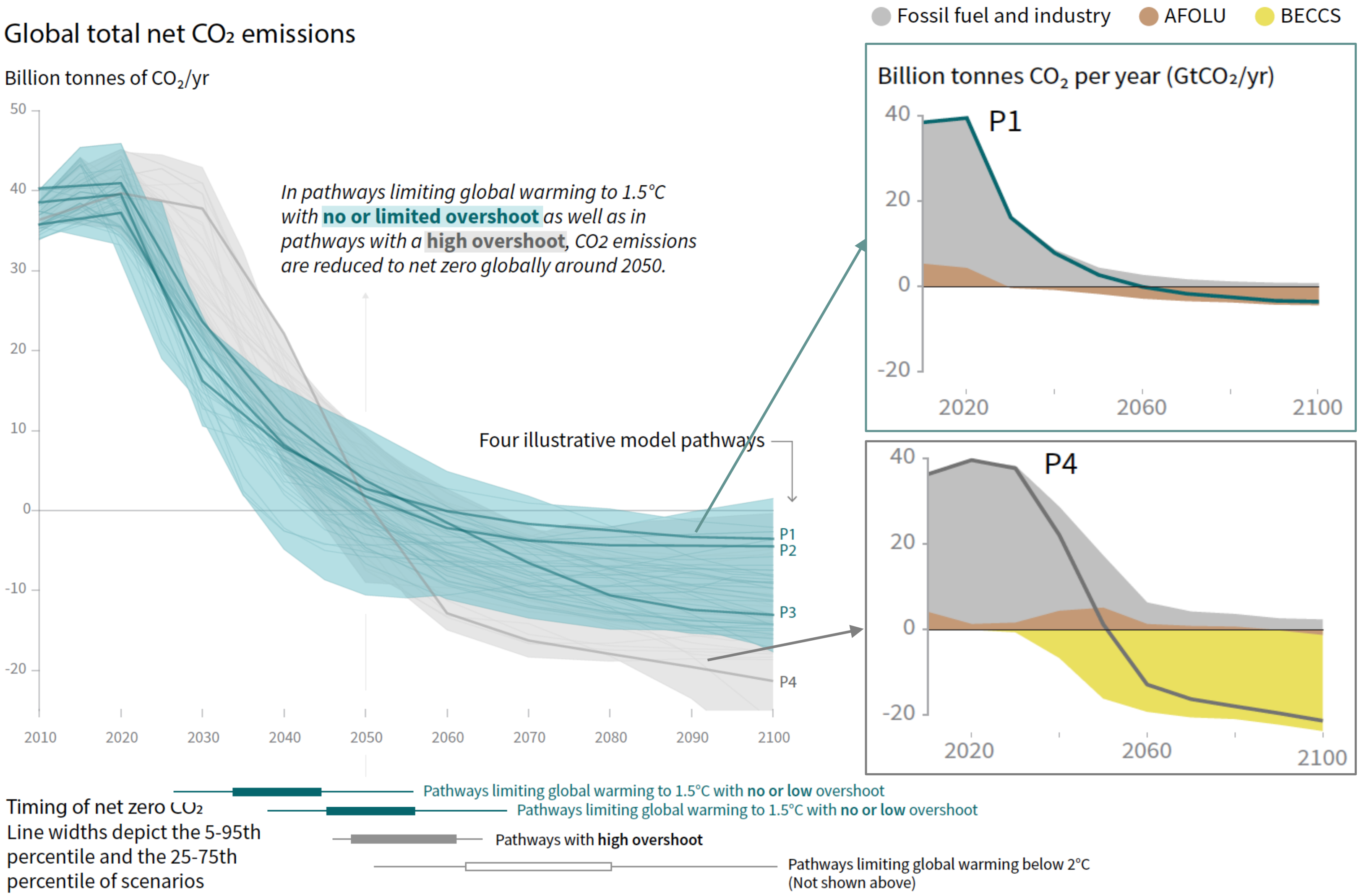
https://youtu.be/QeqDfDD4xbg

Climate change targets require transition to sustainable energy systems



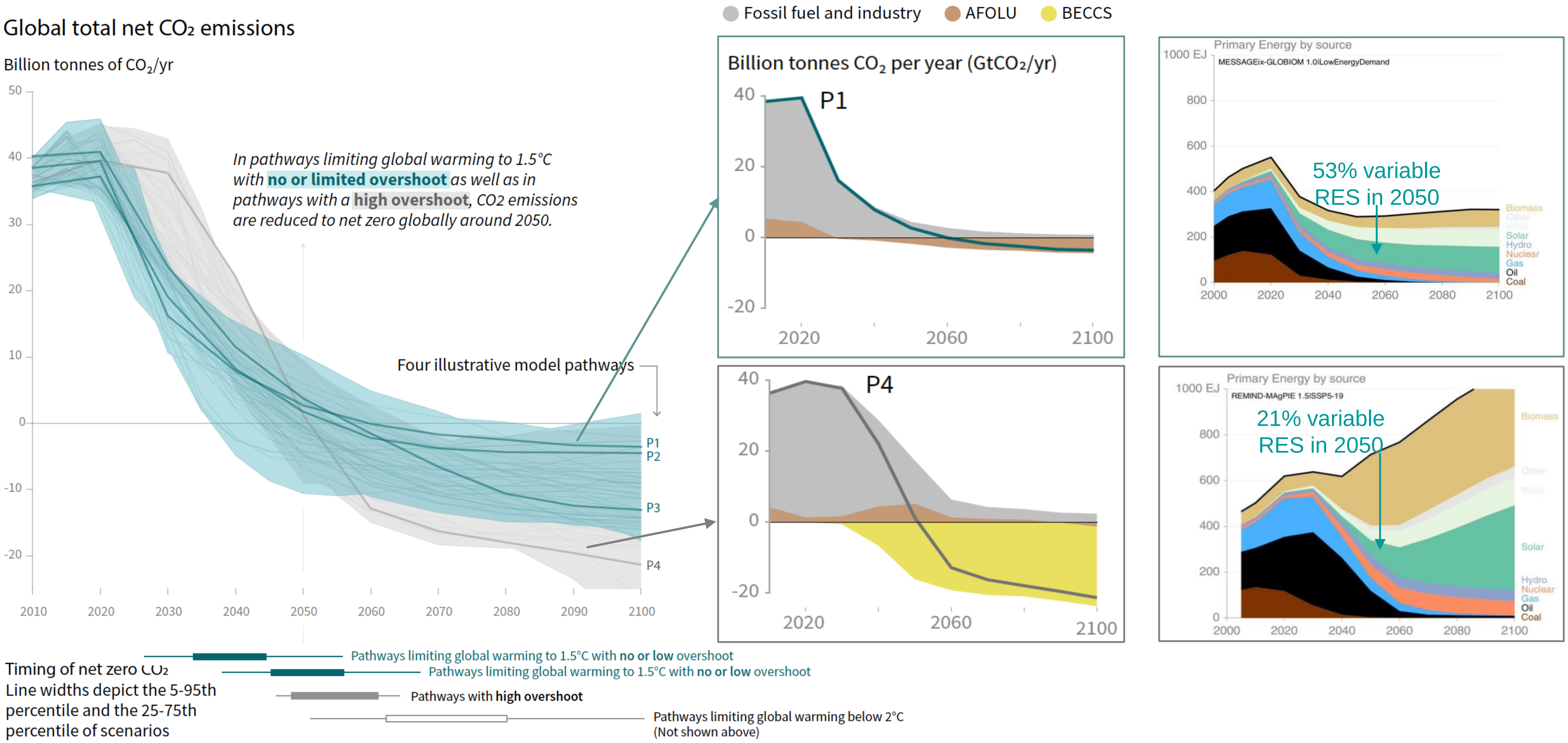
IPCC, *Global warming of 1.5°C*, **2018**

Climate change targets require transition to sustainable energy systems



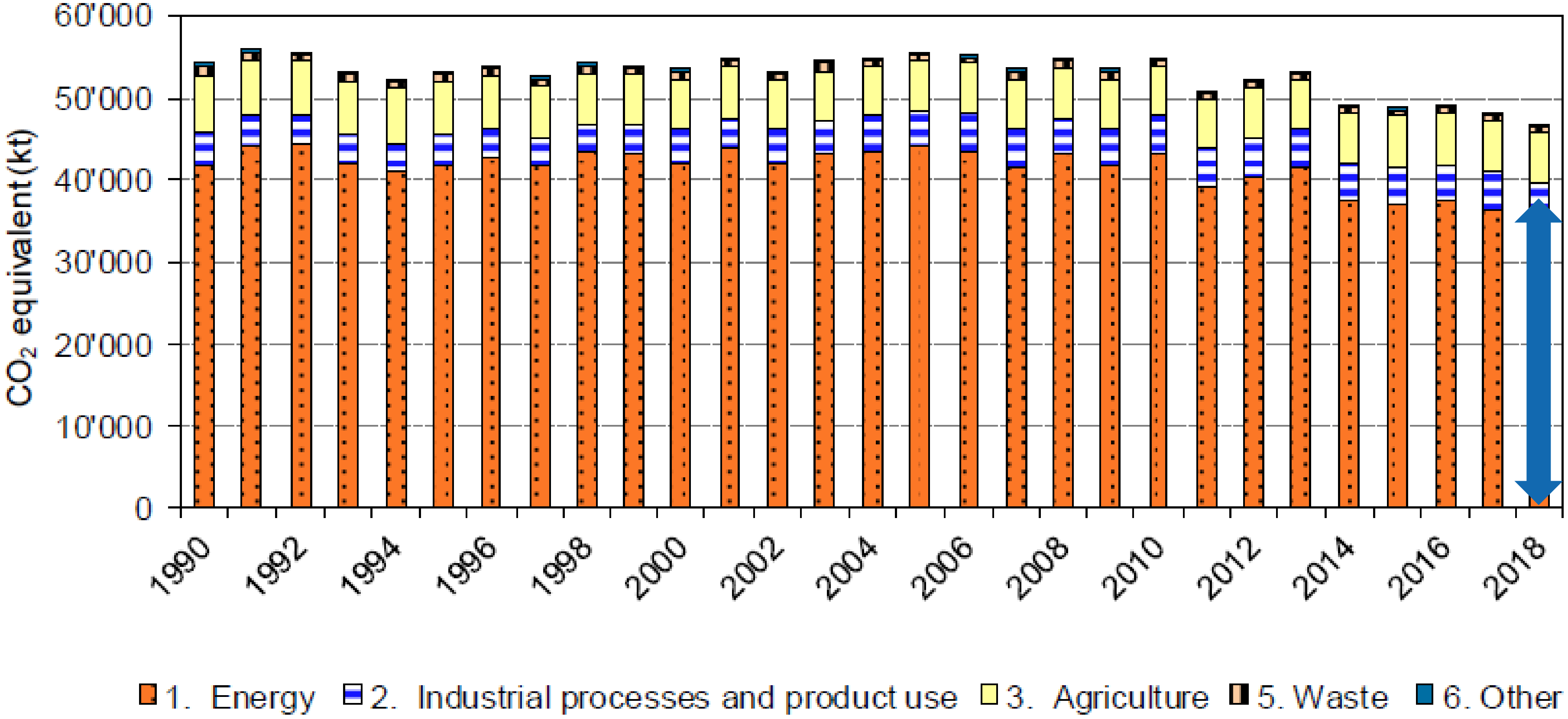
IPCC, *Global warming of 1.5°C*, **2018**

Climate change targets require transition to sustainable energy systems



IPCC, *Global warming of 1.5°C*, **2018**

Swiss greenhouse gas emissions (GHG) emissions: The role of energy



76%
of Swiss
GHG emissions

Figure 2-4 Greenhouse gas emissions in CO_2 equivalent (kt) by sectors (excluding LULUCF, excluding indirect CO_2).

Swiss plans for GHG emissions

- by 2030: -50% GHG emissions from 1990
- by 2050: no more net GHG emissions

achieve at least 30% in Switzerland and a maximum of 20% abroad

https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-76206.html

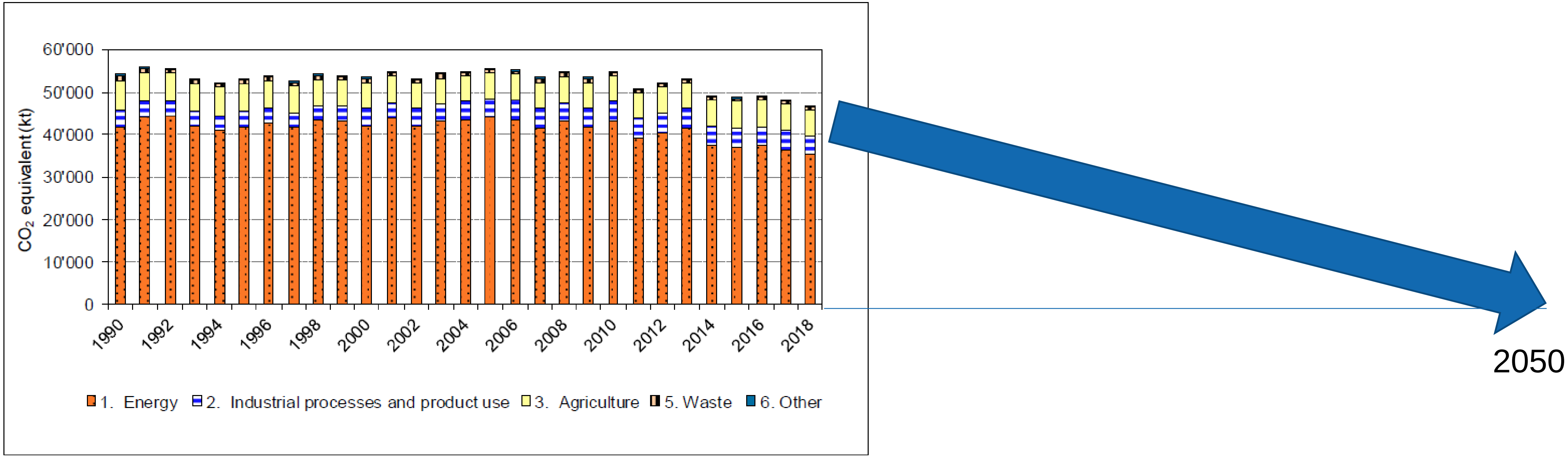


Figure 2-4 Greenhouse gas emissions in CO_2 equivalent (kt) by sectors (excluding LULUCF, excluding indirect CO_2).

ETH zürich

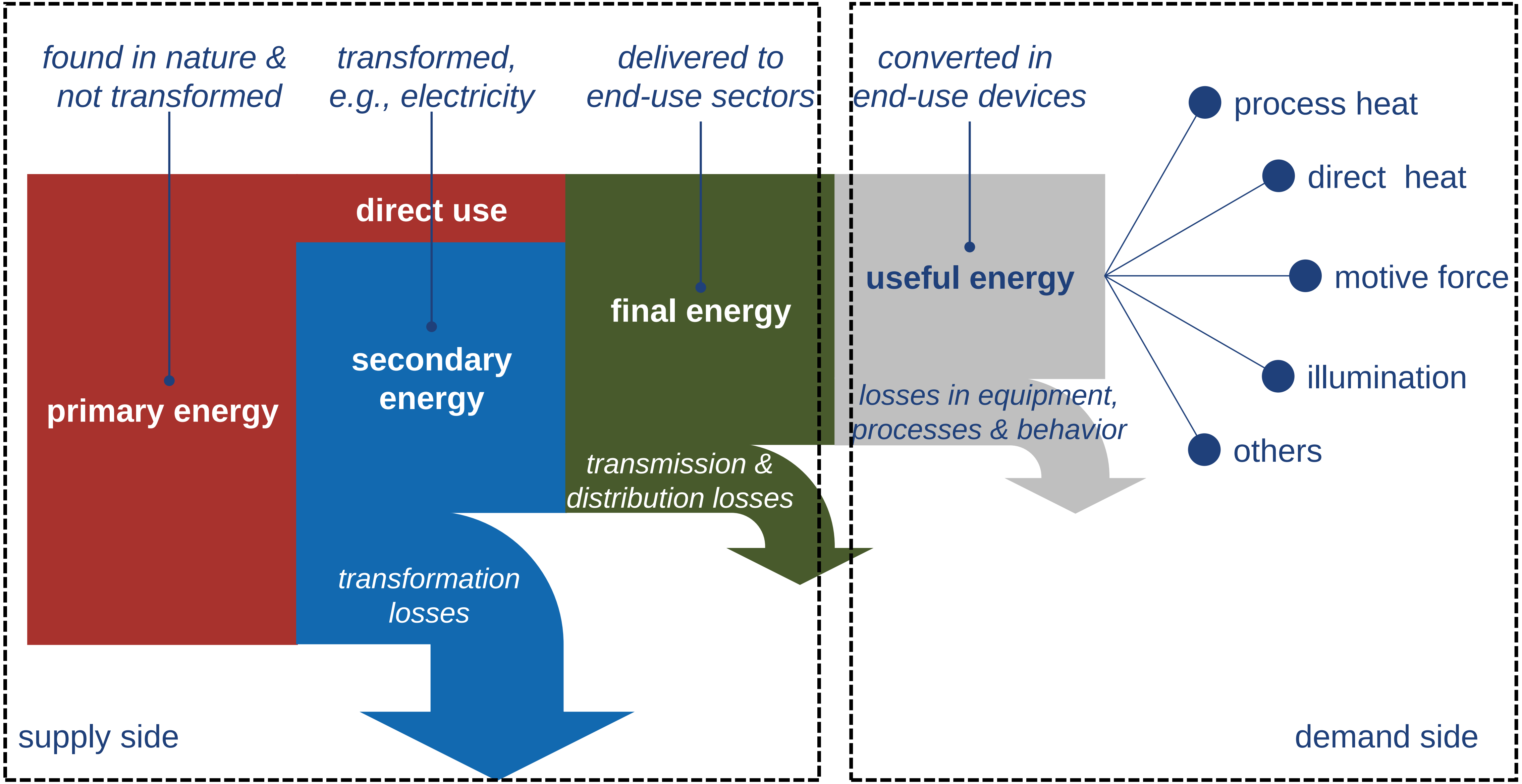
RRE Reliability and Risk Engineering | EPSE Energy & Process Systems Engineering

Introduction to Modeling and Optimization of **Sustainable Energy Systems**

Introduction

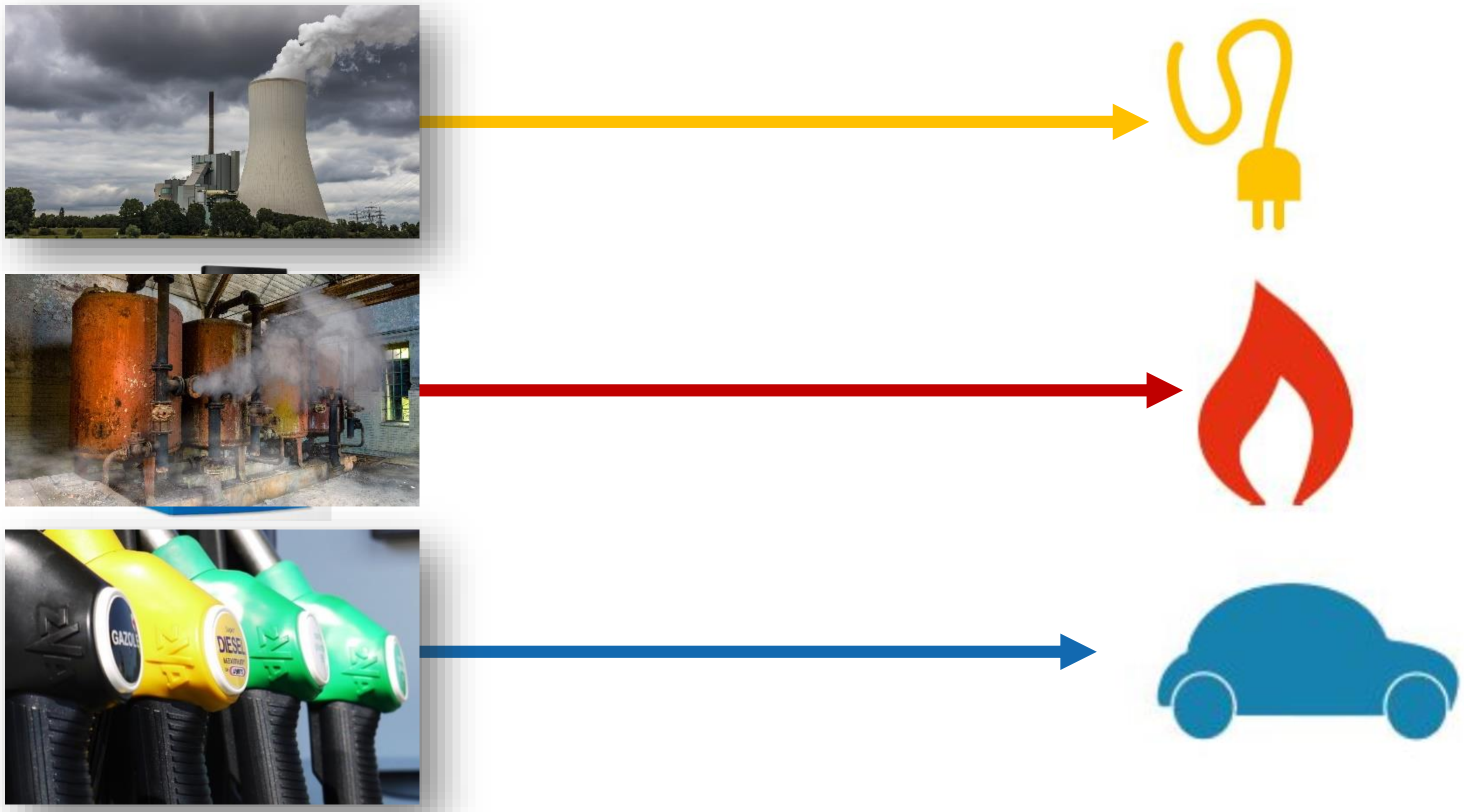
André Bardow & Giovanni Sansavini

Towards sustainable energy systems: The actors



Energy systems back in the day

Supply **Demand**



Energy systems today

supply

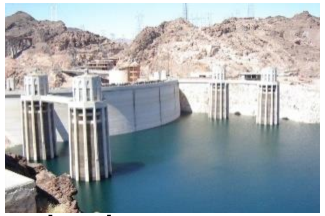

coal power


heating plant


wind


PV


concentrated solar

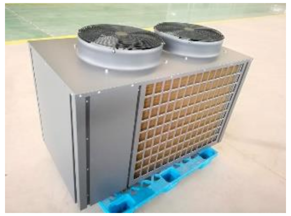

hydro power


fuel cell


biogas

coupling


CHP


heat pump


electric heating

©Siemens

electrolyser

storage


Li-ion battery


heat storage


(pumped) storage


gas storage

distribution


electric grid


gas grid

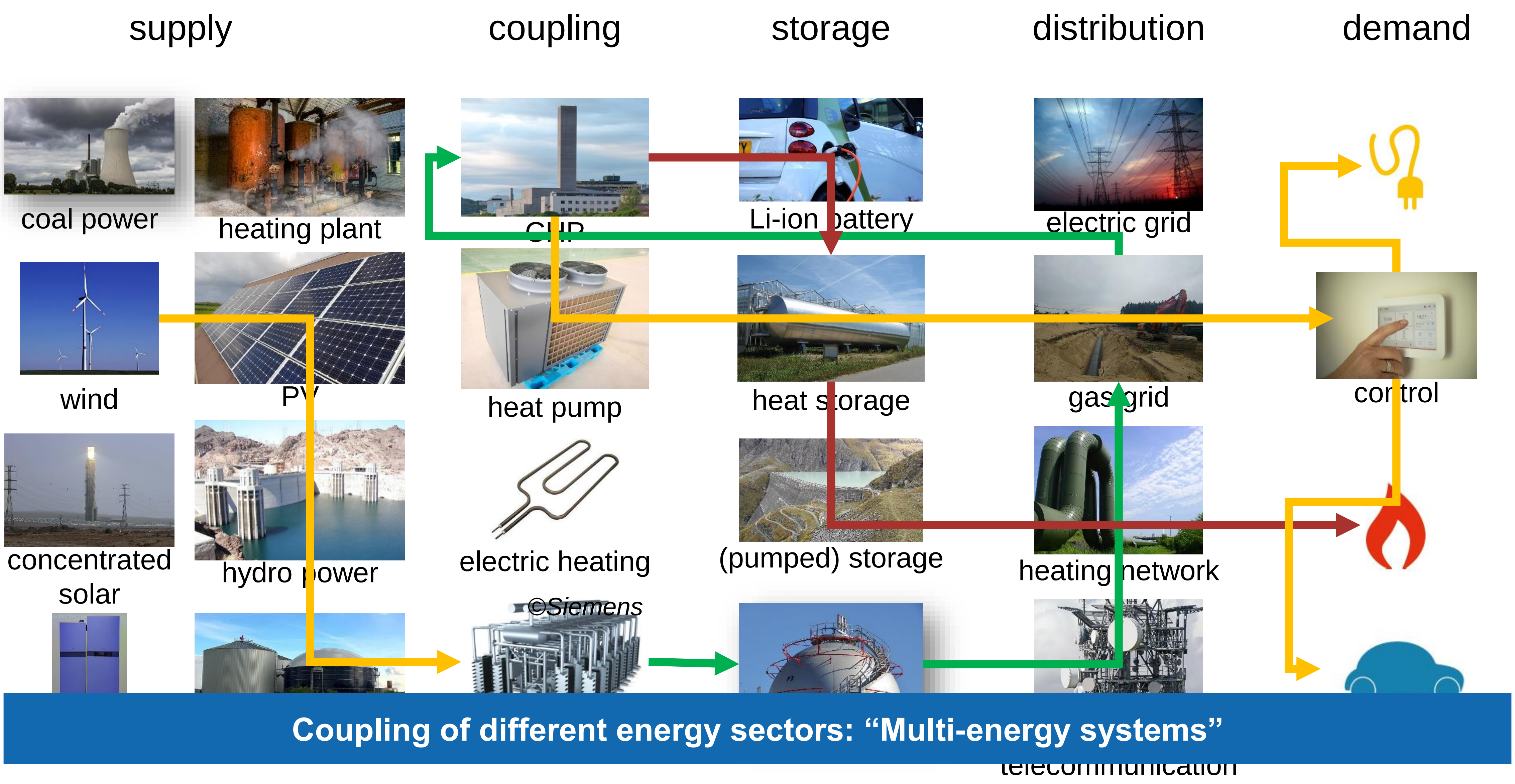

heating network


telecommunication

demand


control

Energy systems today: Multi-energy systems

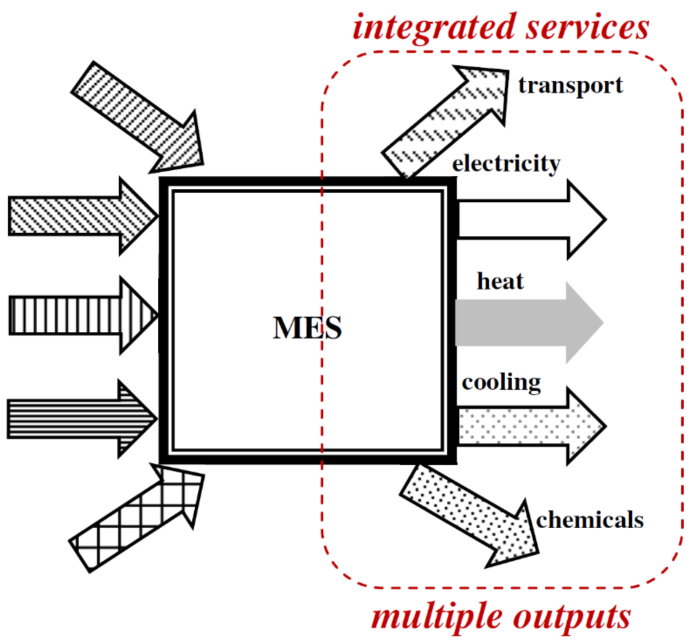


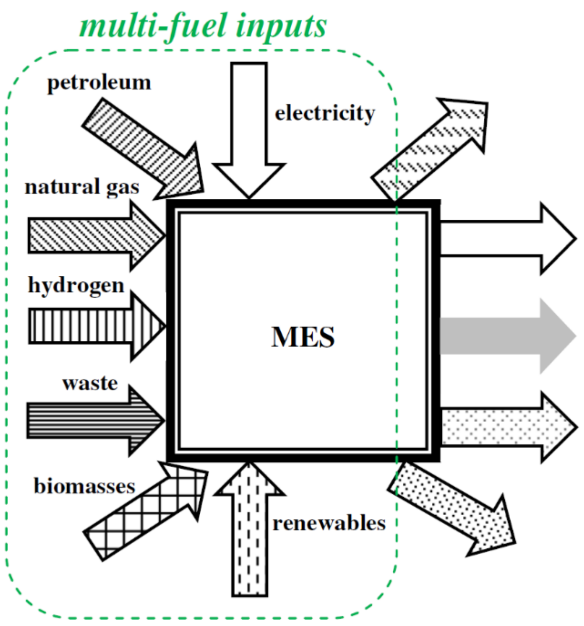
Coupling of different energy sectors: “Multi-energy systems”

Multi-energy systems from different perspectives

multi-service perspective

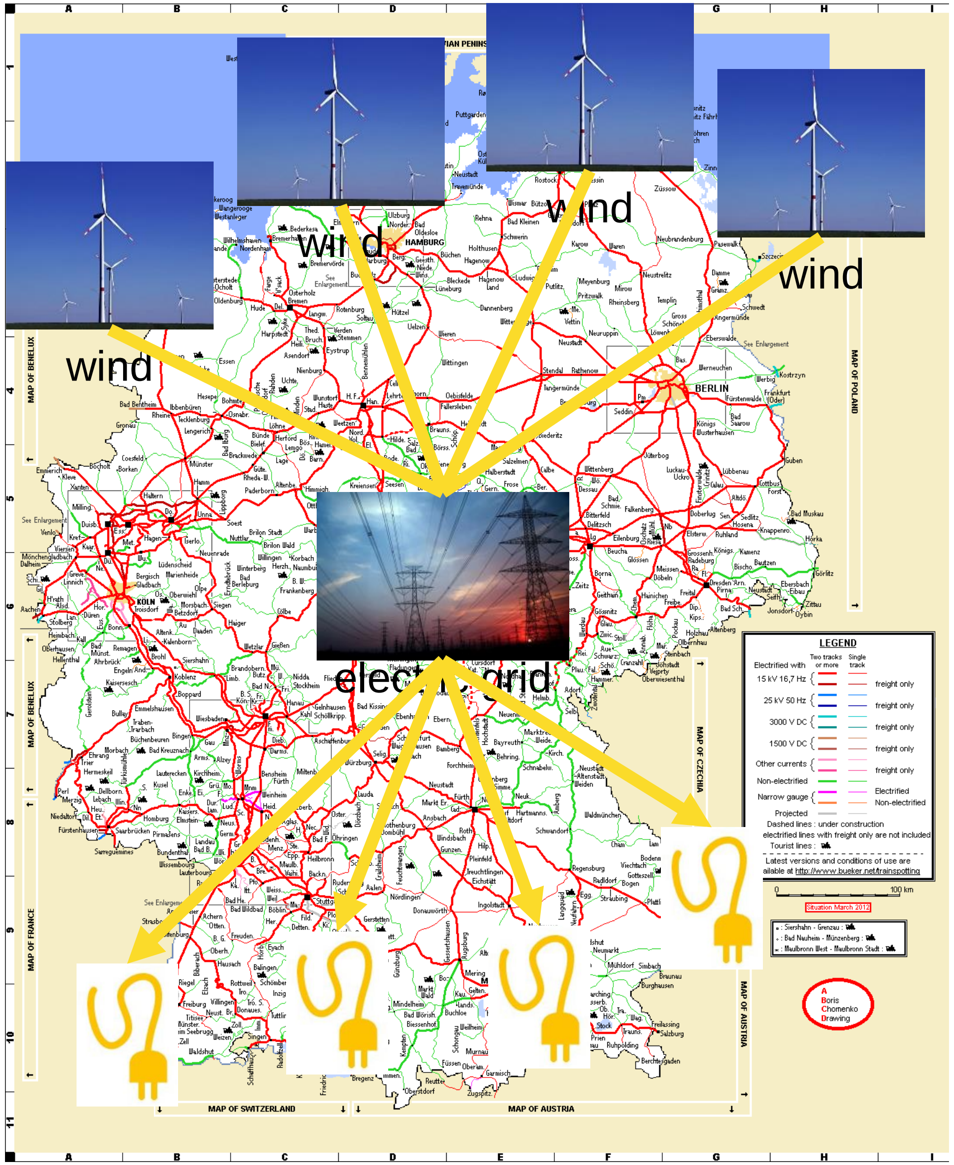
multi-fuel perspective

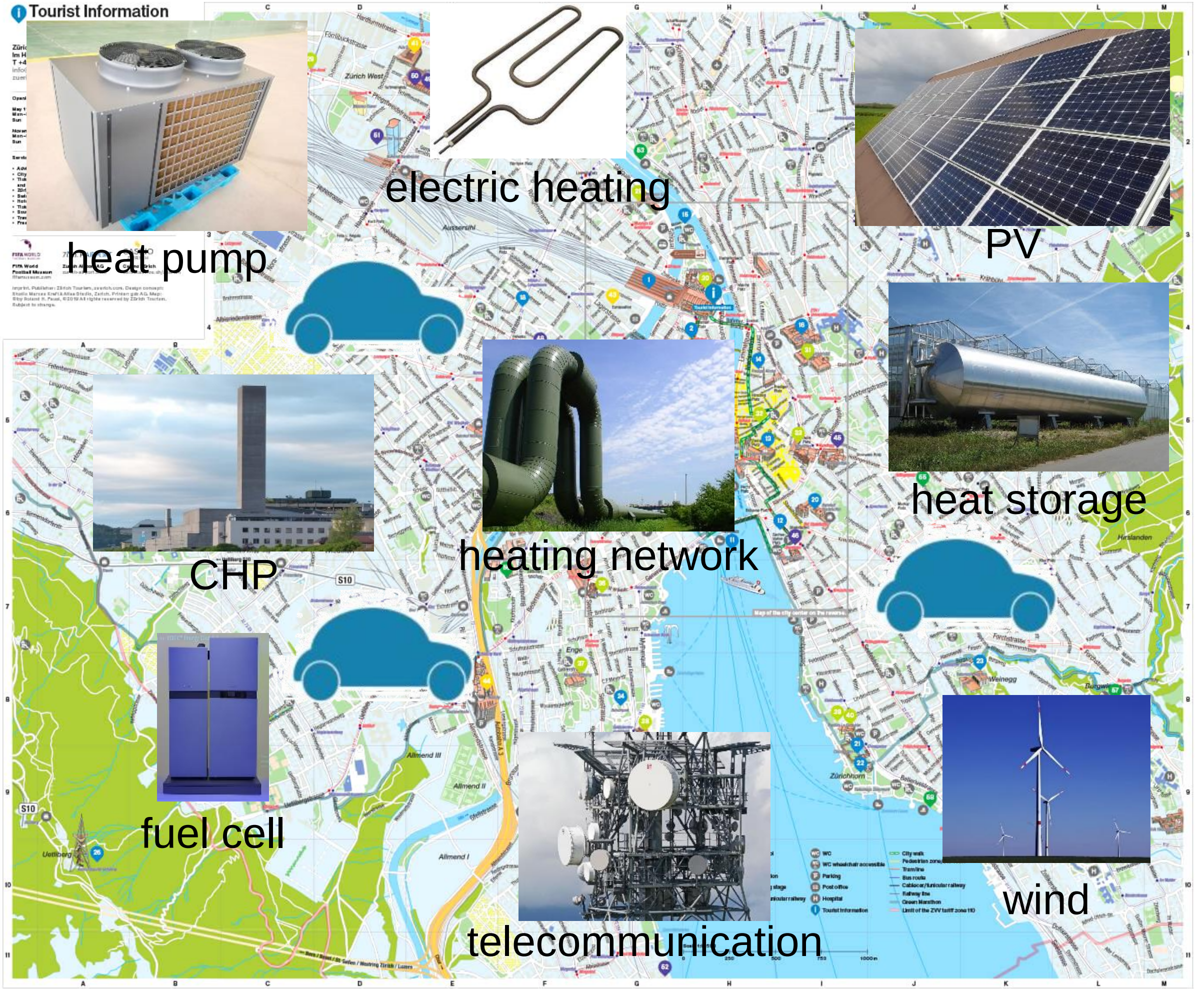




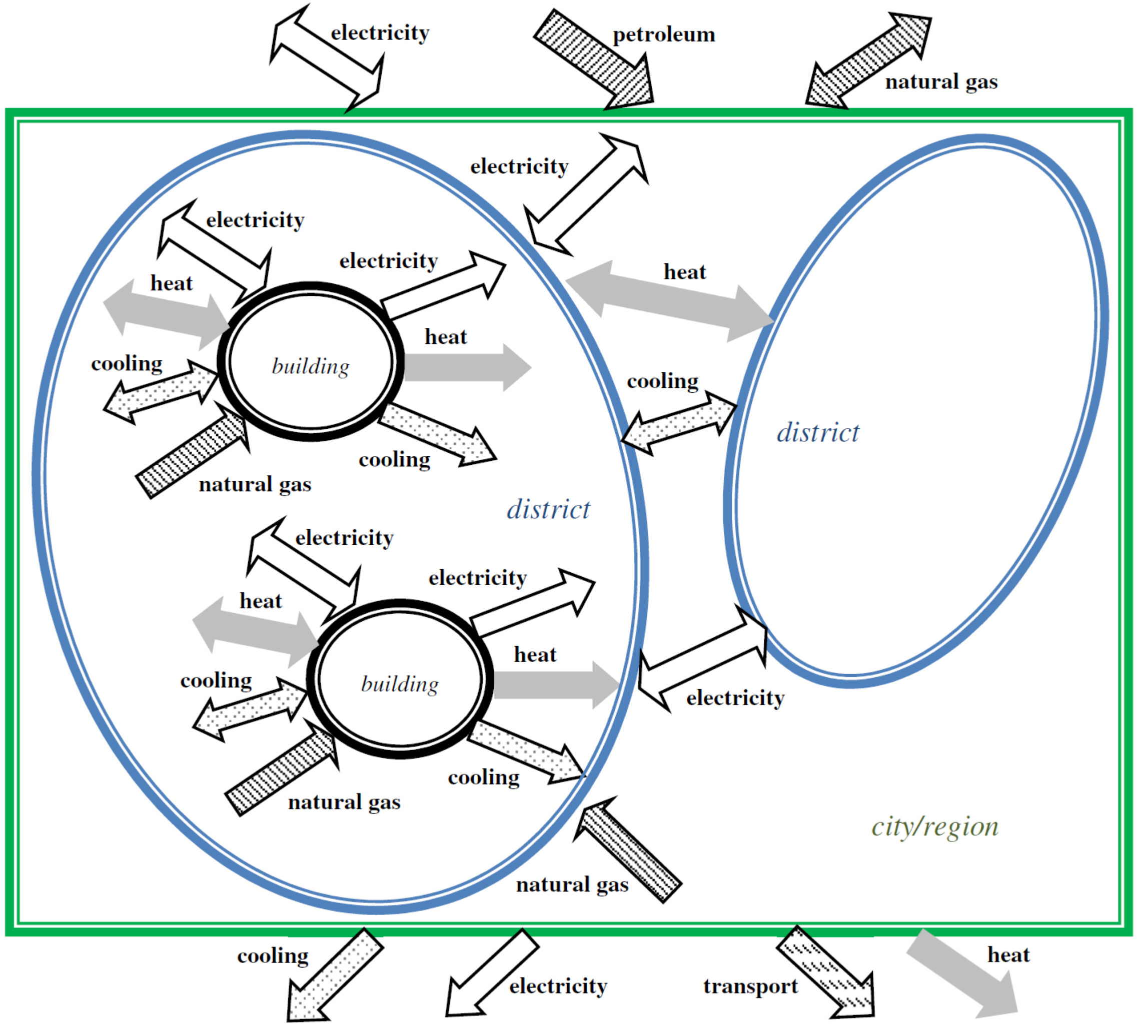
Mancarella P., 2014, MES (multi-energy systems): An overview of concepts and evaluation models P, Energy 65, 1-17.

Energy transmission and generation are spatially distributed



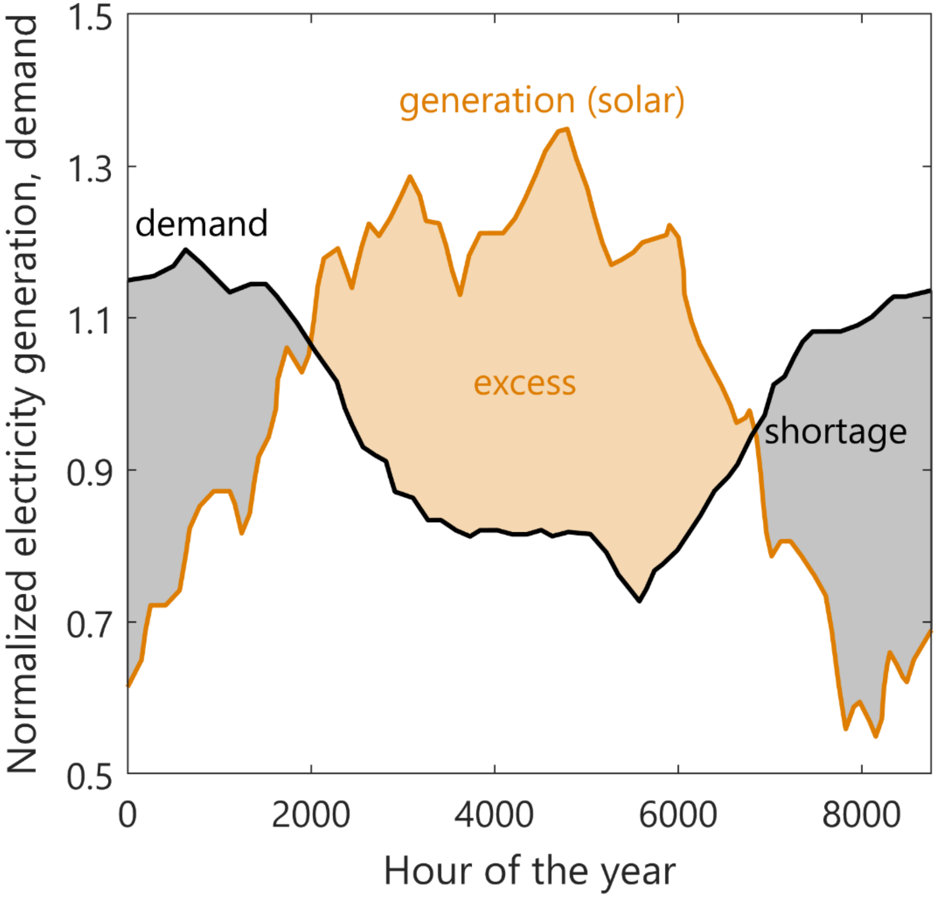


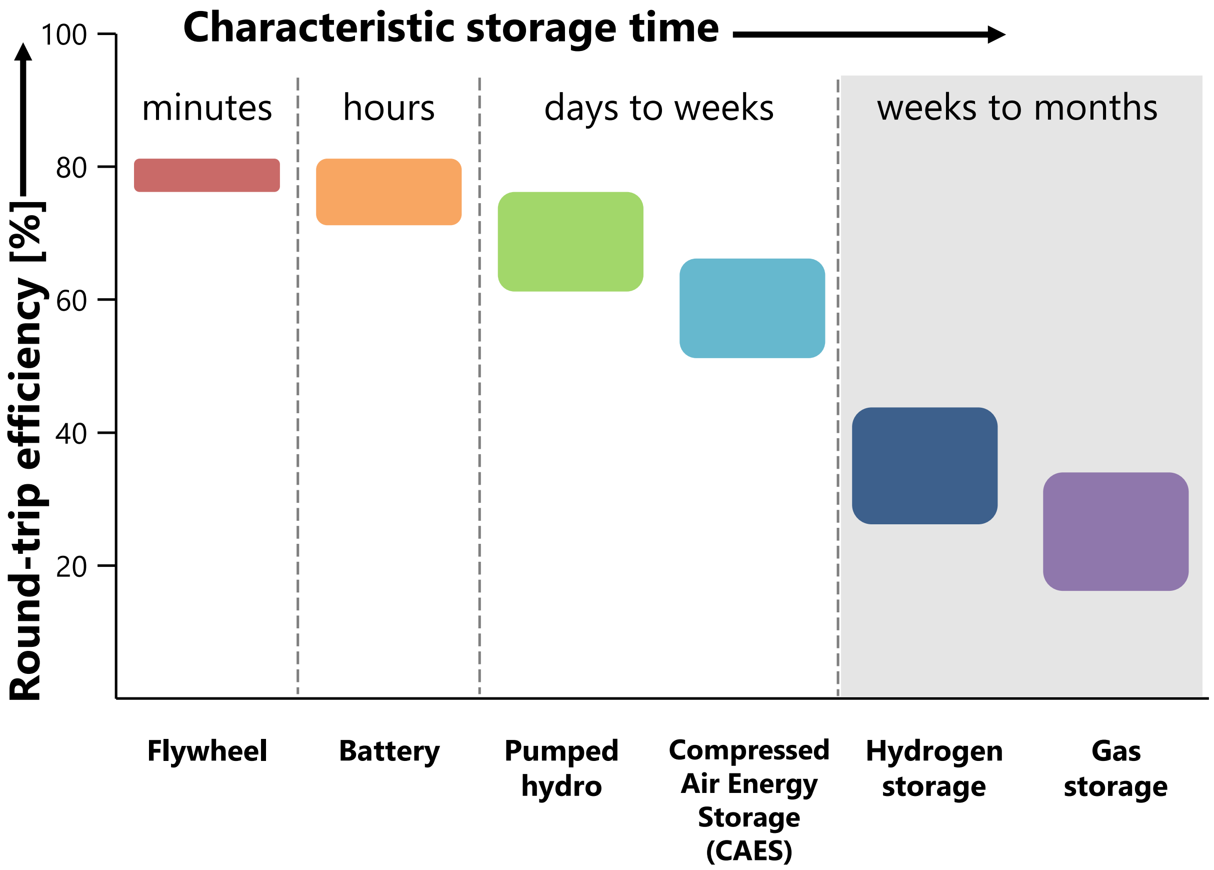
Multi-energy systems from different perspectives: spatial perspective



Mancarella P., 2014, MES (multi-energy systems): An overview of concepts and evaluation models P, Energy 65, 1-17.

Generation & consumption are temporally separated





adapted from: Ueckerdt et al., *Energy Econ*, **64**, 2017. Annual time series of weekly averages illustrating the time decoupling of electricity demand and solar generation for Europe (normalized over the corresponding average value).

Challenges in operation planning of multi-energy systems

1. many **energy services** need to be supplied
2. many **energy sources** to be employed
3. interdependence increases due to **sectors-coupling**
4. demand & supply are **spatially distributed**
5. demand & supply are **temporally separated**

need for (computer-aided) decision support and therefore **models**

After this lecture, you are able to…

- ✓ plan **your participation** in this course
- ✓ explain the **scope of this course**
- recognize tradeoffs in the **energy trilemma**
- classify **mathematical models**

ETH zürich

RRE Reliability and Risk Engineering

EPSE Energy & Process Systems Engineering

Introduction to Modeling **and Optimization of Sustainable Energy Systems**

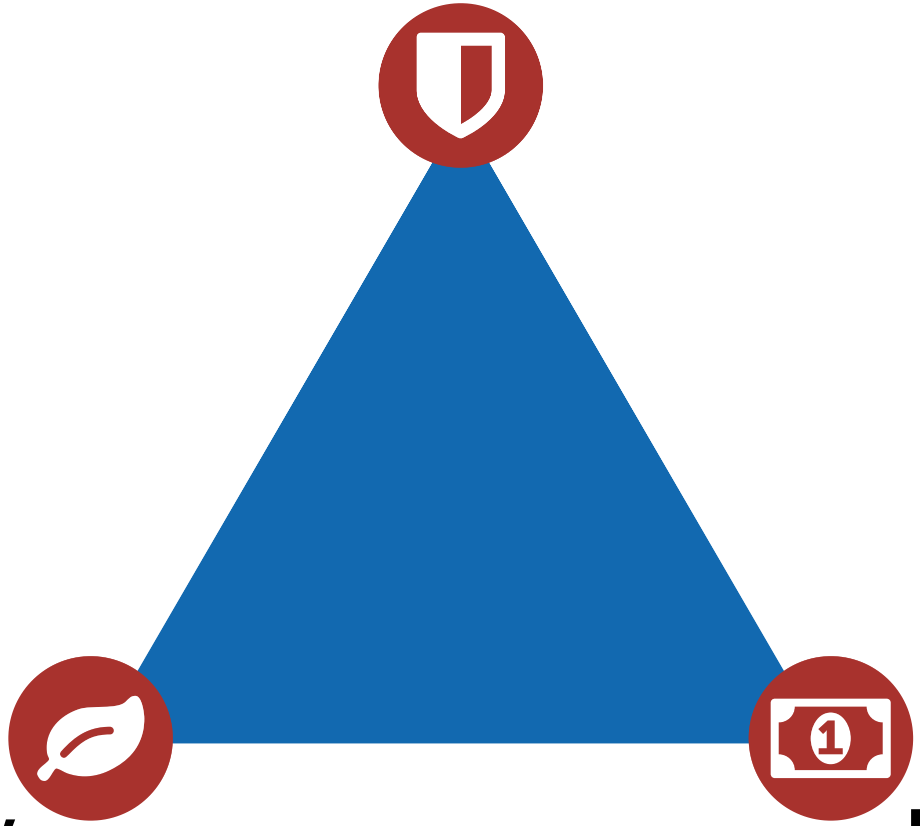
Introduction

André Bardow & Giovanni Sansavini

Energy trilemma – Objectives of the energy system

availability of sources
ensuring transport of energy

Security



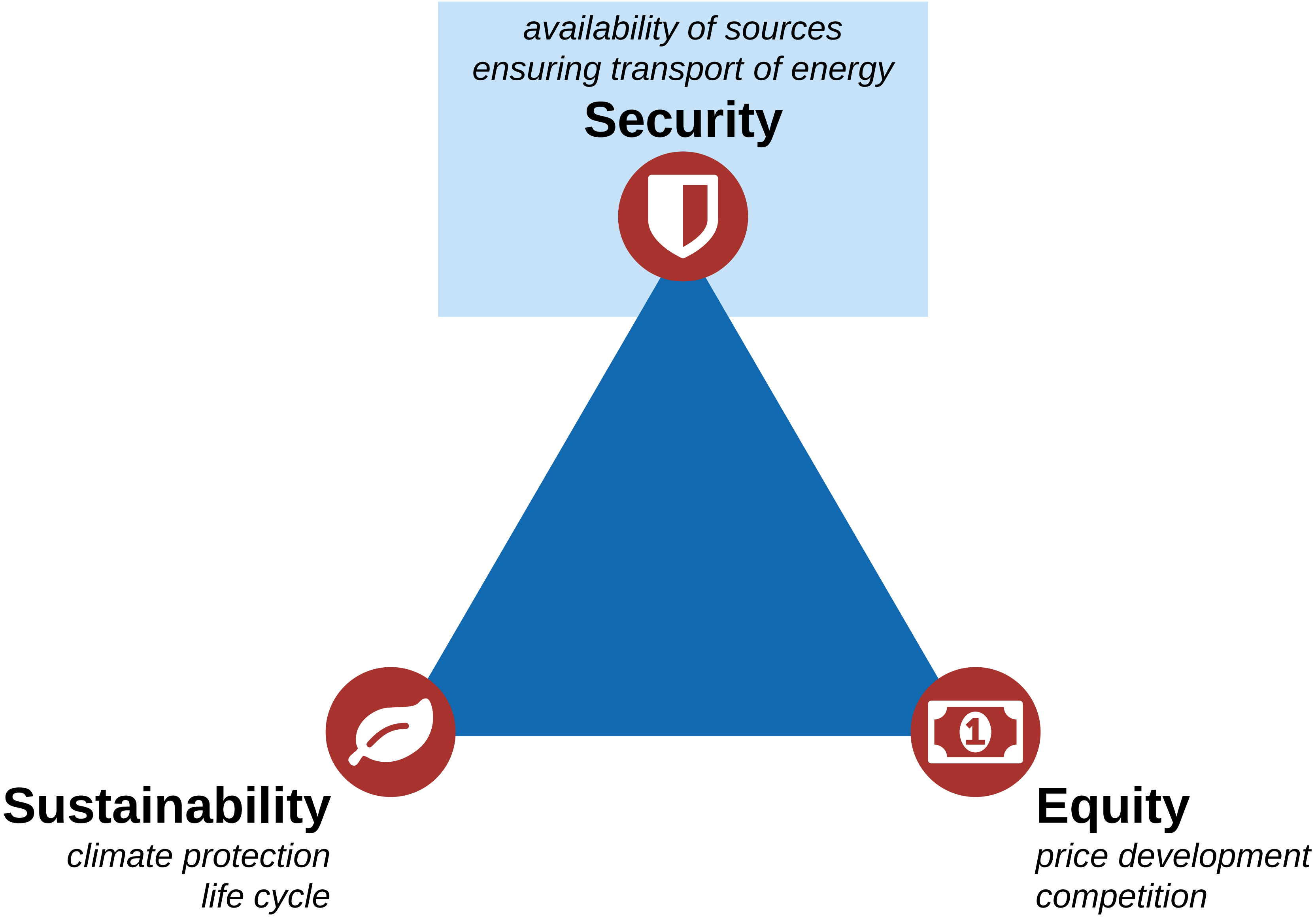
Sustainability

climate protection
life cycle

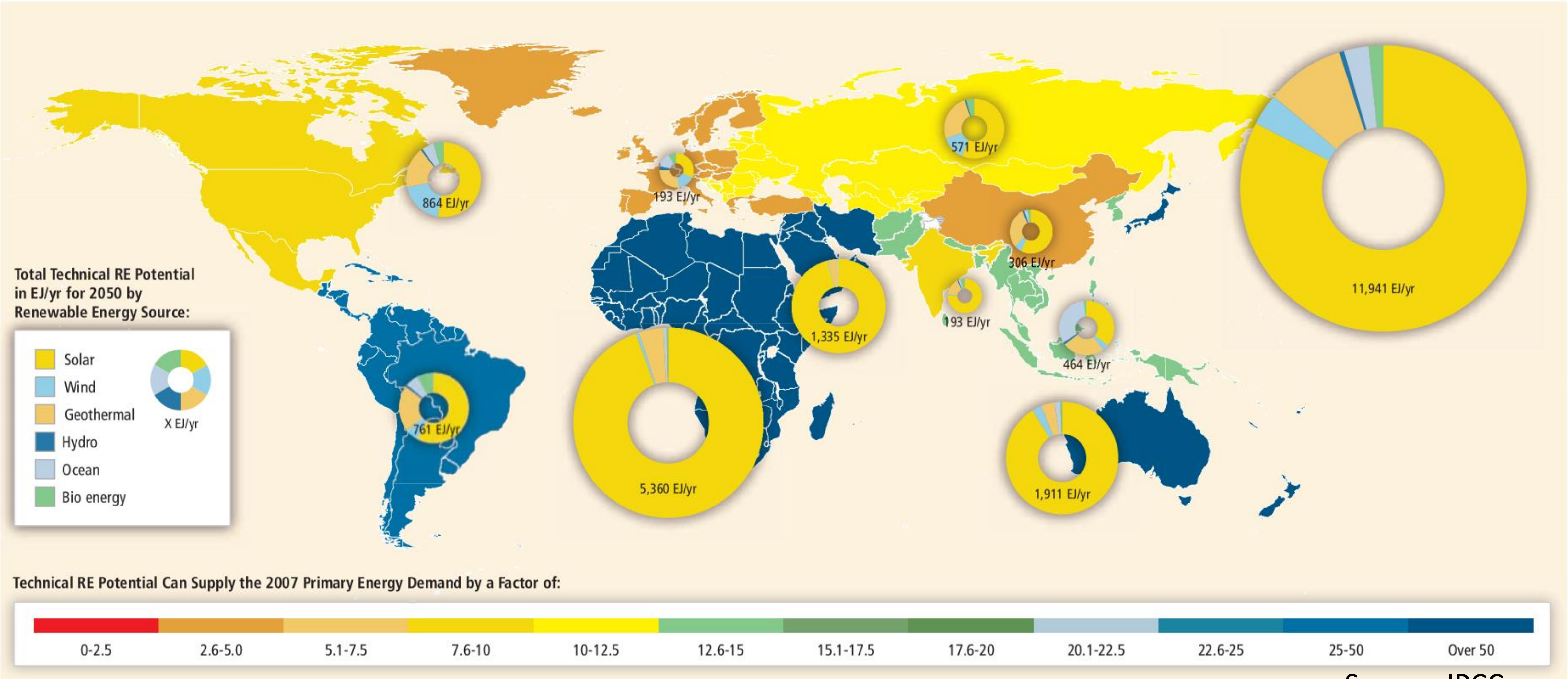
Equity

price development
competition

Energy trilemma – Objectives of the energy system

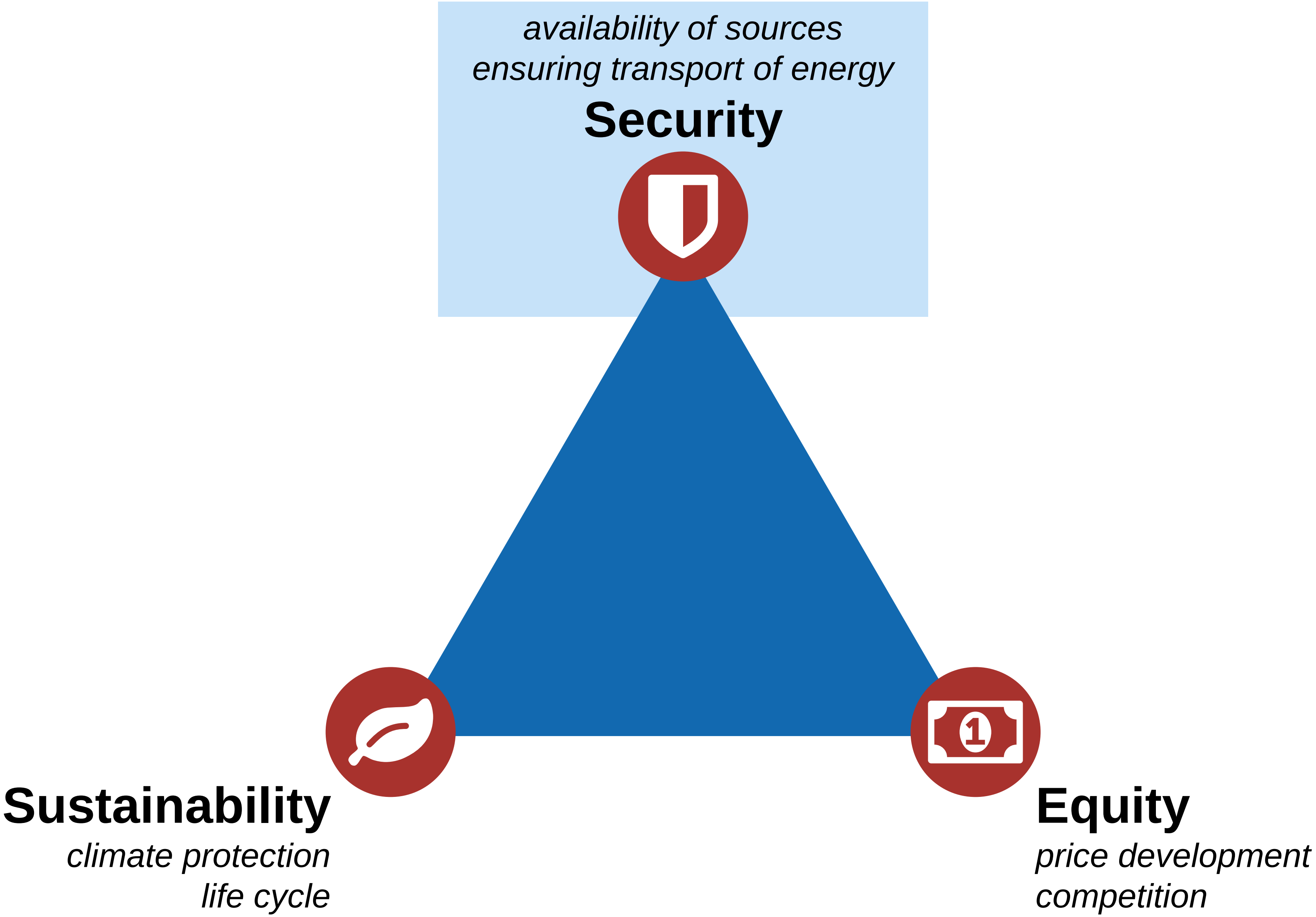


Global technical potential of renewable energies



Source: IPCC

Energy trilemma – Objectives of the energy system



Characteristics of renewables

energy source / technology		power / MW	characteristic time scales for power system operation	dispatchability	predictability
Bioenergy		0.1 – 100	seasons	+	+
Geothermal		2 – 100	years	+	+
sun	Photovoltaics	0.004 – 100	minutes	-	-
	concentrated solar power with thermal storage	50 – 250	hours	+/-	+
water	run of river	0.1 - 1.500	hours	+/-	+
	reservoir	1 - 20.000	days	+	+
	tides	0.1 – 300	hours	-	+
wind		5 - 300	minutes	-	-

Source: IPCC

Characteristics of renewables

energy source / technology		power / MW	characteristic time scales for power system operation	dispatchability	predictability
Bioenergy					+
Geothermal					+
sun	Photovo				-
	concent with the				+
water	run of river	0.1 - 1.500	hours	+/-	+
	reservoir	1 - 20.000	days	+	+
	tides	0.1 – 300	hours	-	+
wind		5 - 300	minutes	-	-

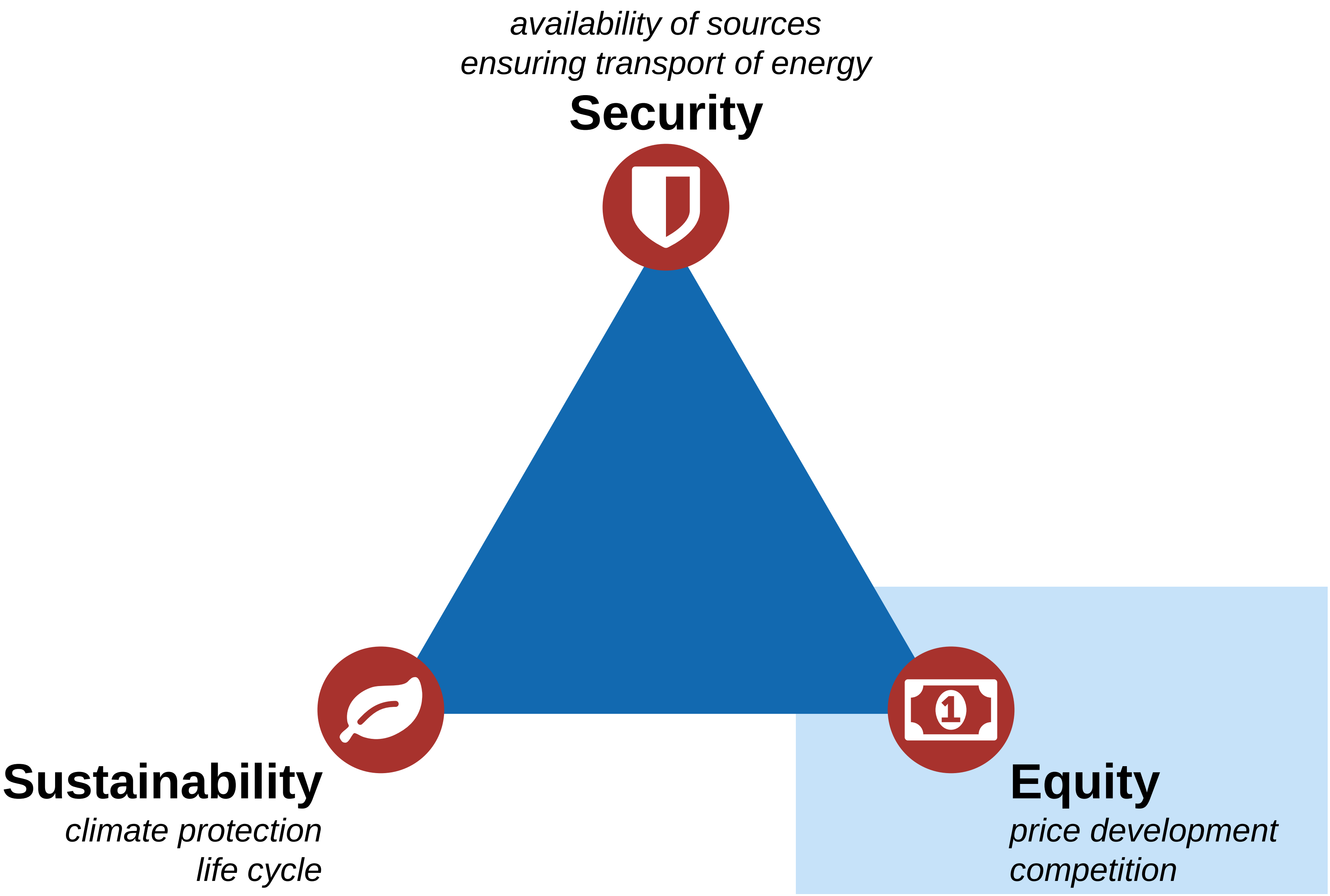
Why Wind Is Not Coal: On the Economics of Electricity Generation

Lion Hirth, Falko Ueckerdt,** and Ottmar Edenhofer****

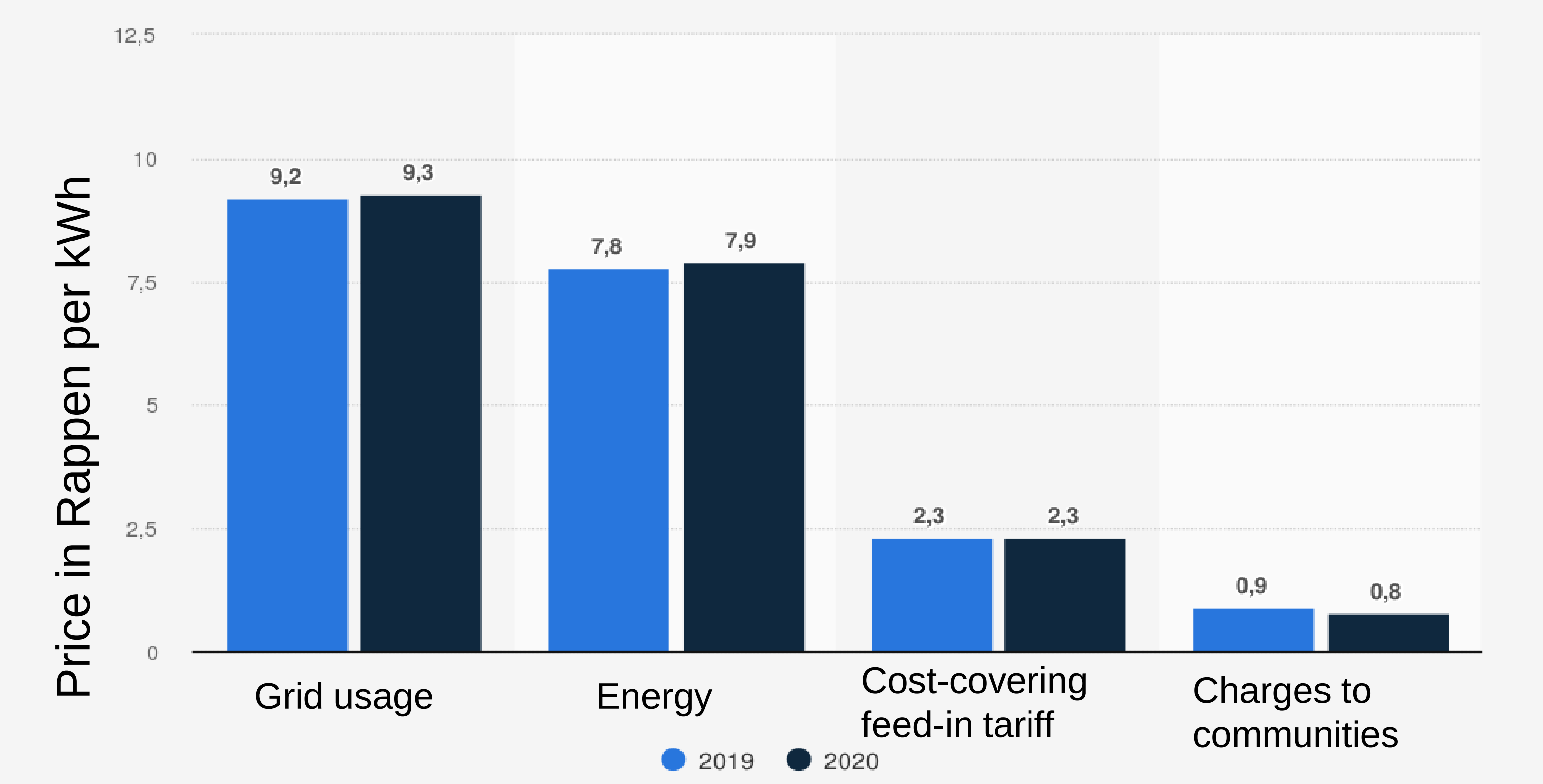
ABSTRACT

Source: IPCC

Energy trilemma - Requirements of energy systems



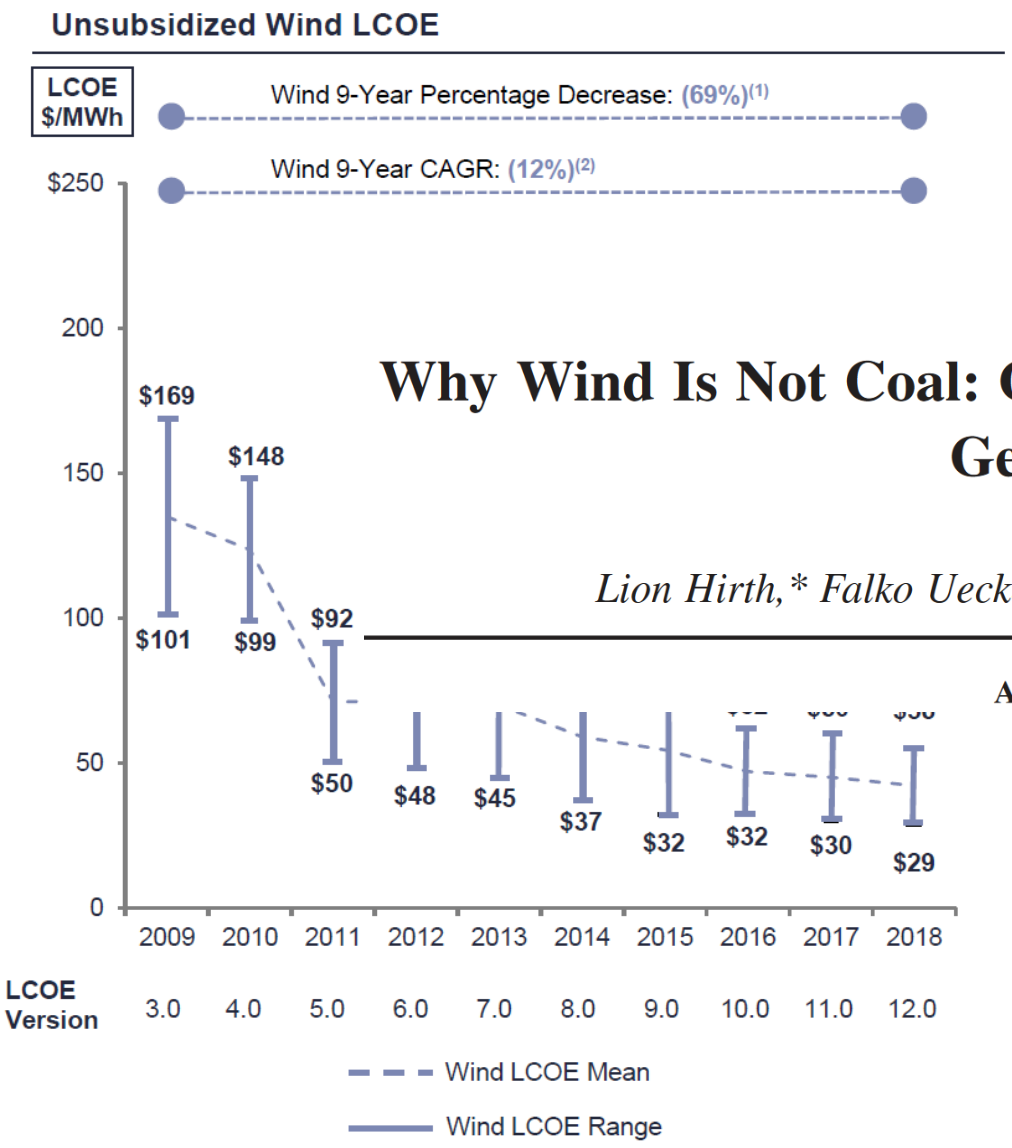
Electricity price for households in Switzerland

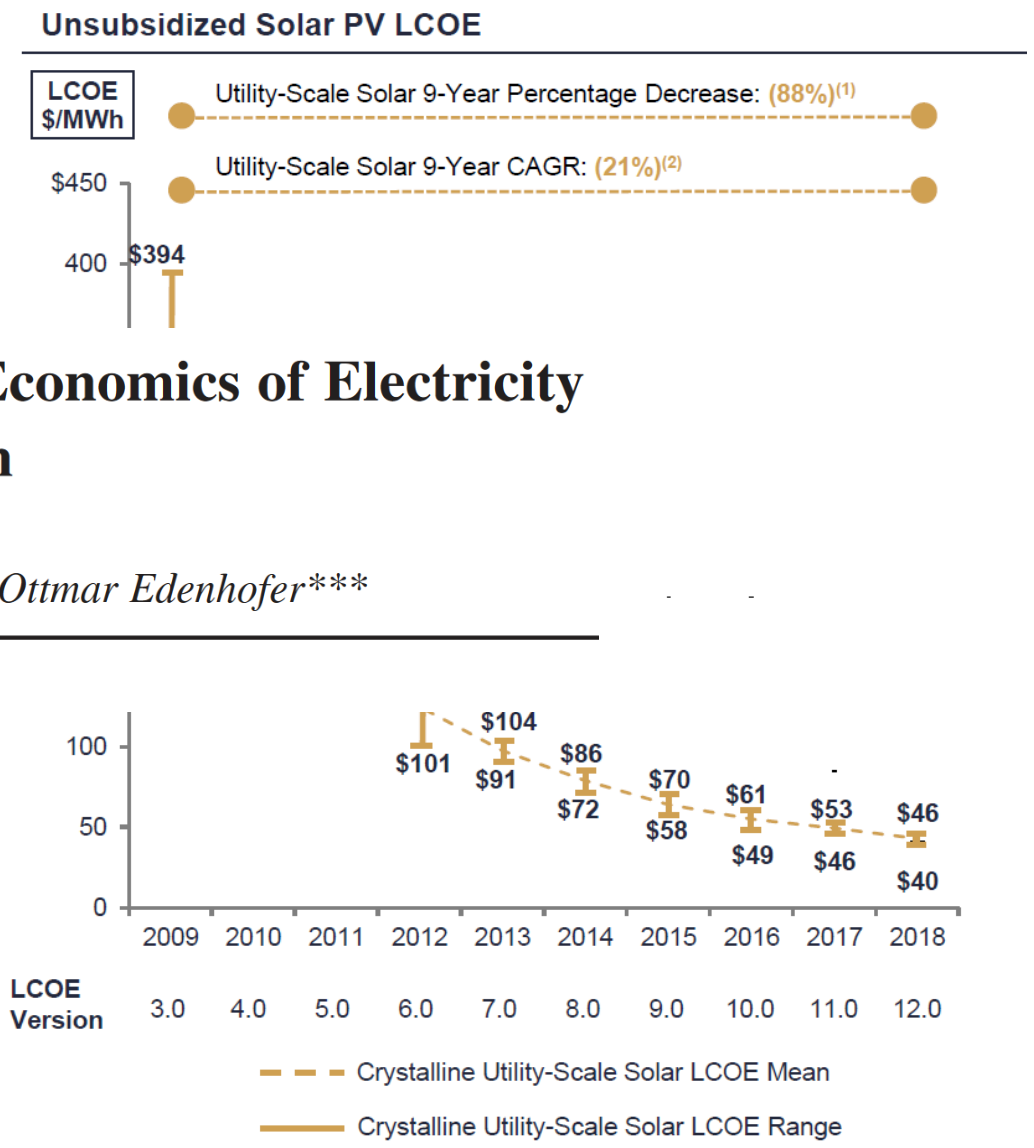


Source:
ElCom
Statista 2020

Levelized cost of renewable Energy

https://www.lazard.com/perspective/lcoe2019



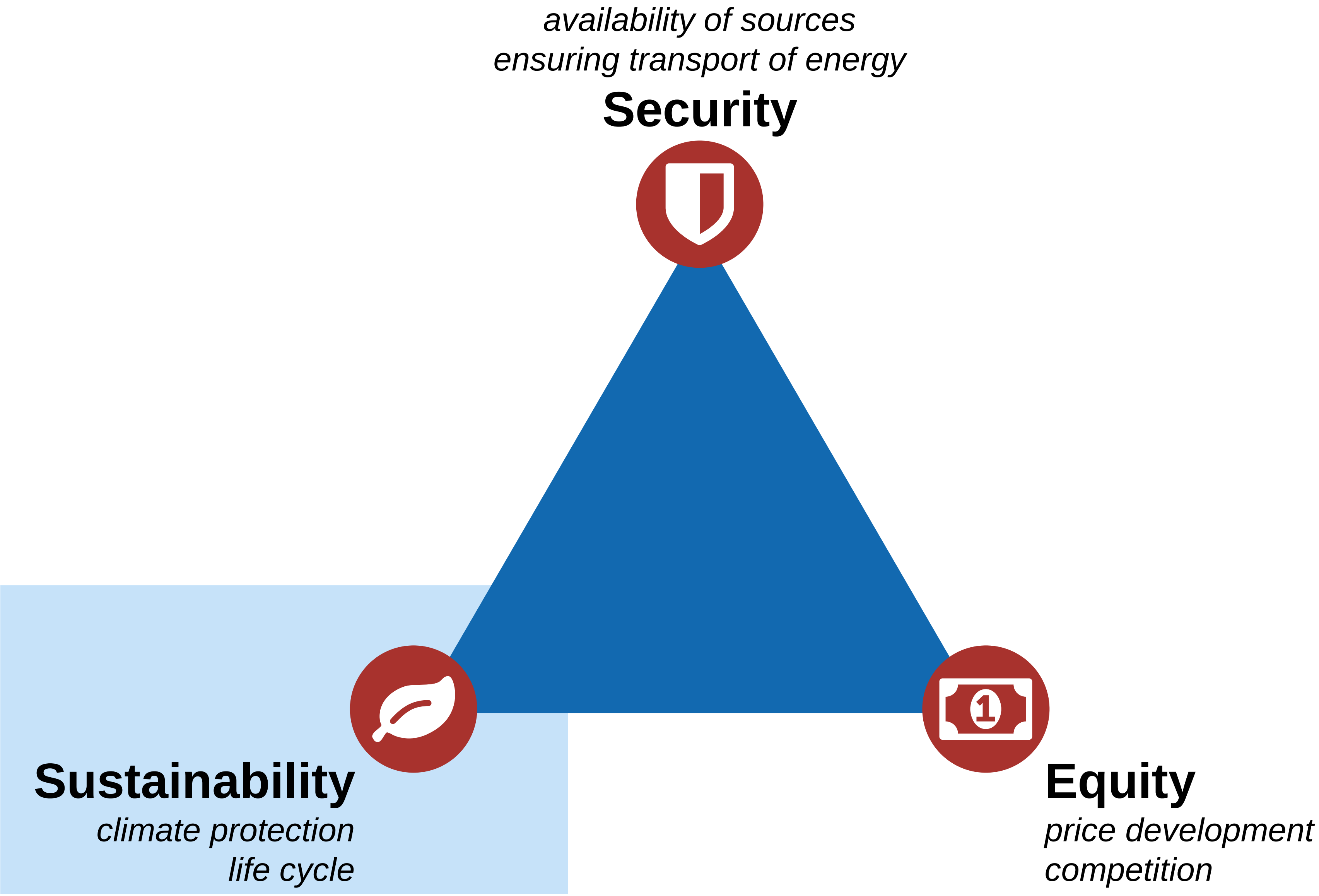


Why Wind Is Not Coal: On the Economics of Electricity Generation

Lion Hirth, Falko Ueckerdt,** and Ottmar Edenhofer****

ABSTRACT

Energy trilemma - Requirements of energy systems



Swiss plans for GHG emissions

- by 2030: reduce GHG emissions by 50% compared to 1990
- by 2050: no more net GHG emissions

achieve at least 30% in Switzerland and a maximum of 20% abroad

https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-76206.html

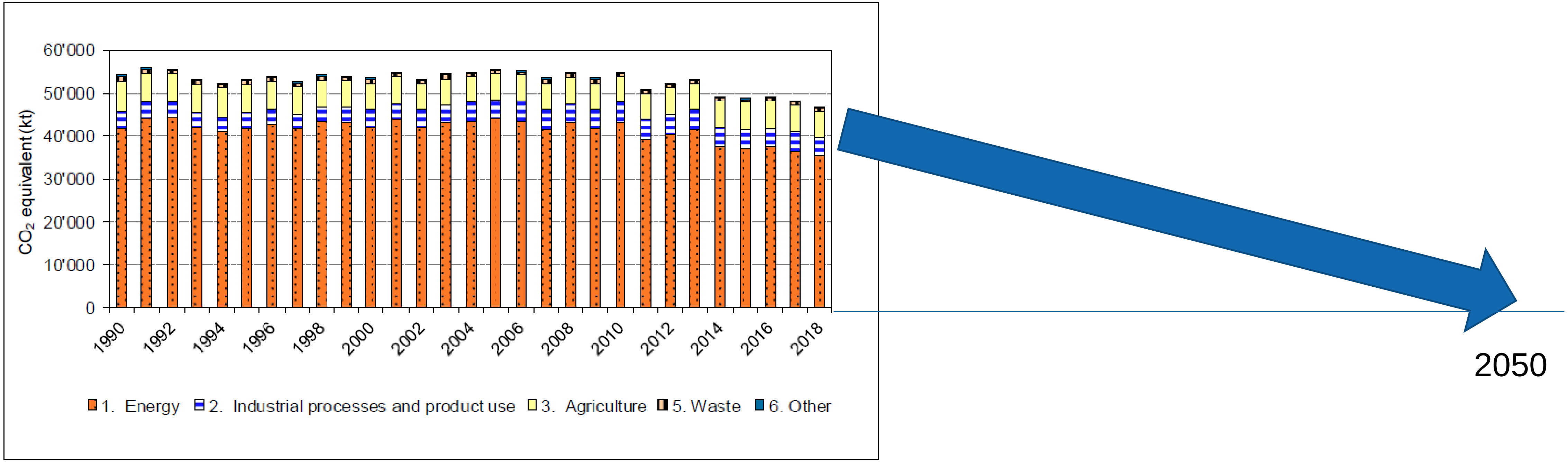
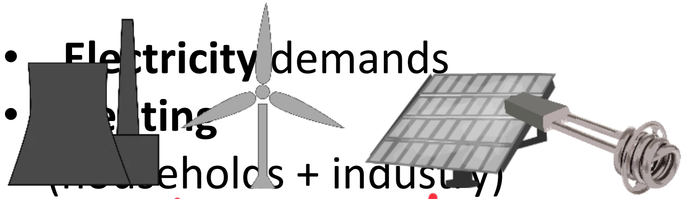


Figure 2-4 Greenhouse gas emissions in CO_2 equivalent (kt) by sectors (excluding LULUCF, excluding indirect CO_2).

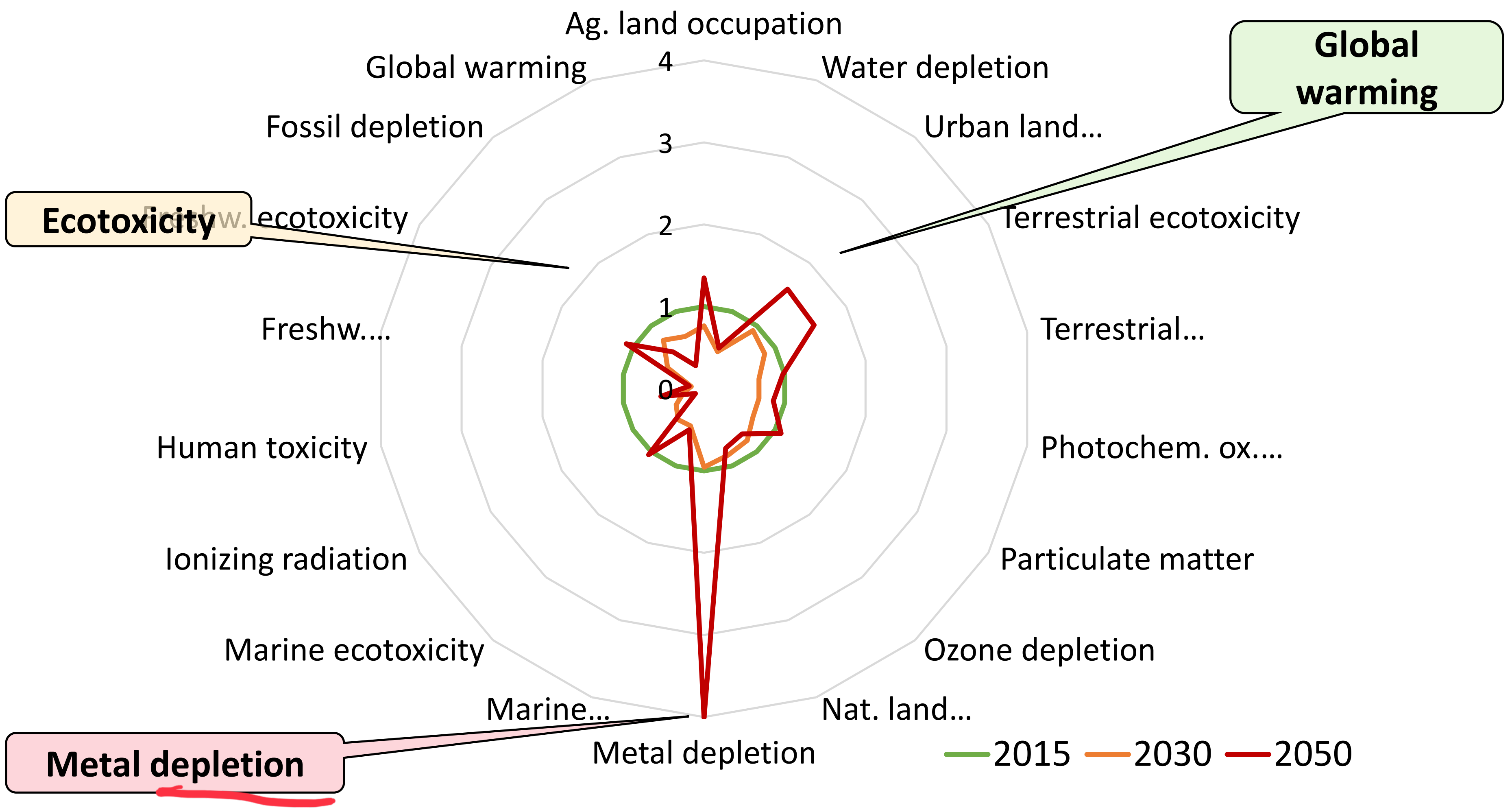
Example of a large-scale energy system model

- **28** countries (EU +)
- International grid 
- Fossil and renewable **plants**
- **Electricity** demands
- **Heating**
  (households + industry)
  (Households + industry)

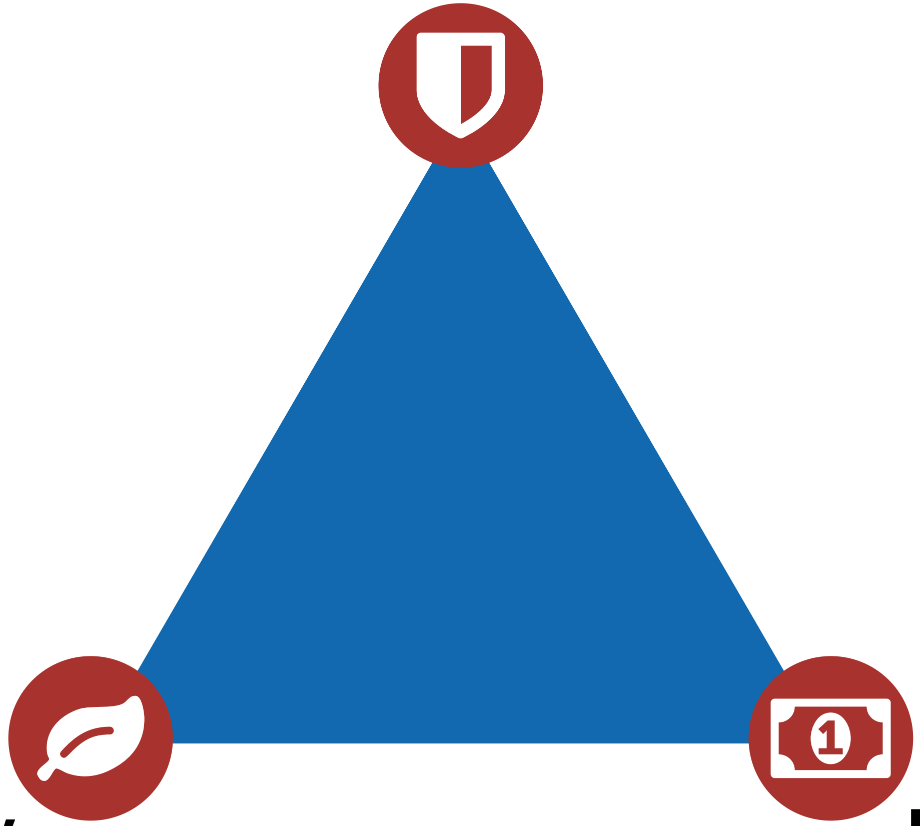


- **Transport (passenger cars)**
- Weather data 

Environmental impacts of the future energy system: Burden shifting



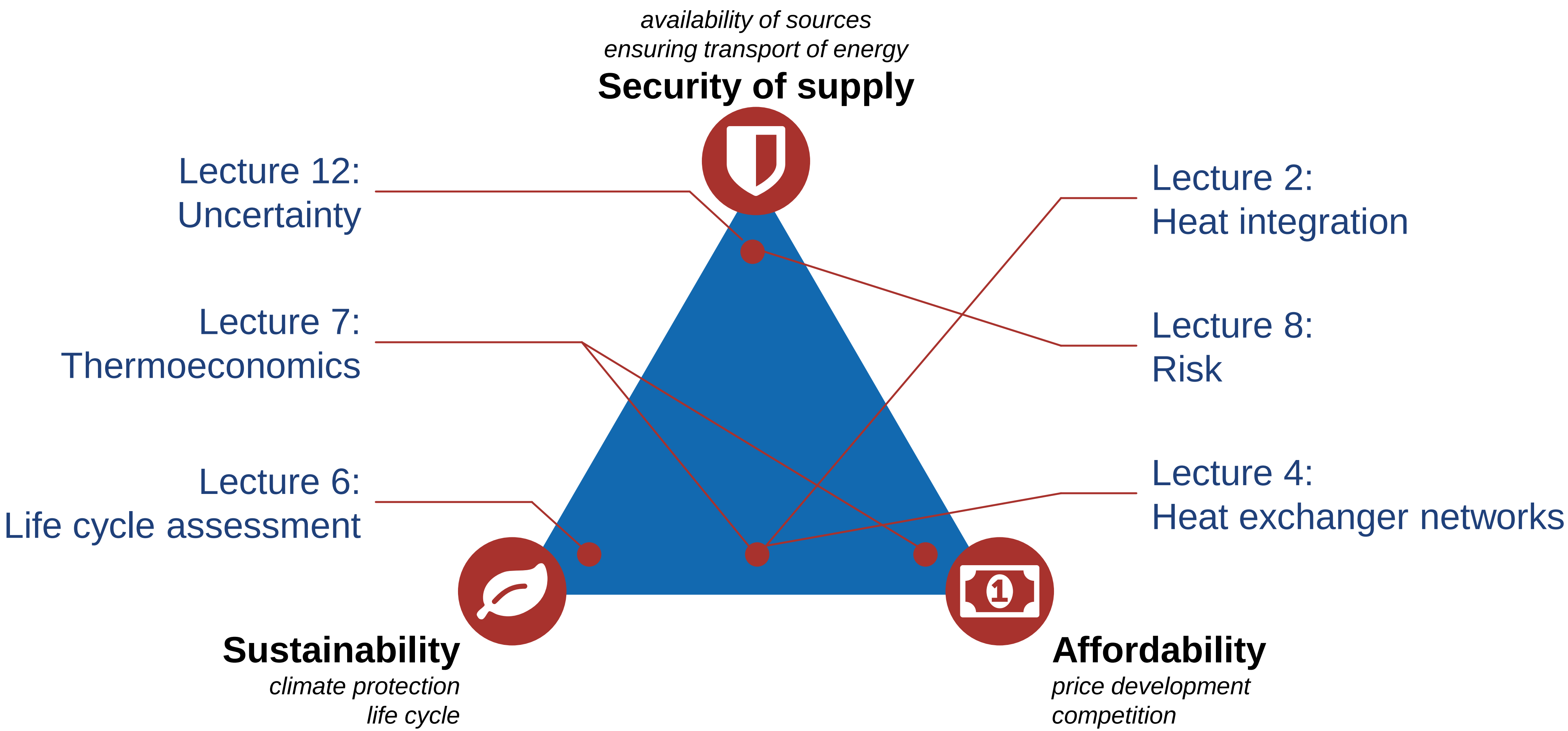
Energy trilemma – Objectives of the energy system



Lecture plan

No.	Date	Content	
1	29.09.	Introduction & Models	
2	06.10.	Heat integration	Applications
3	13.10.	Continuous Optimization	Methods
4	20.10.	Heat exchanger networks	Applications
5	27.10.	Discrete Optimization	Methods
6	03.11.	Life Cycle Assessment (LCA)	Applications
7	10.11.	Thermoeconomics	Metrics
8	17.11.	Risk Key Performance Indicators for Security	Metrics
9	24.11.	Multi-energy dimension: introduction	Methods & Applications
10	01.12.	Design dimensions: technology modelling	
11	08.12.	Space dimensions: energy networks	
12	15.12.	Uncertainty in energy systems	
13	22.12.	Recap (online)	

Course content in the energy trilemma



Methods & Models:

Lecture 3 & 5:
Optimization

Lecture 9:
Conversion

Lecture 10:
Storage

Lecture 11:
Transport

After this lecture, you are able to…

- ✓ plan **your participation** in this course
- ✓ explain the **scope of this course**
  - ✓ name the difference between primary energy, final energy, and useful energy.
  - ✓ discuss the need for sustainable energy systems.
  - ✓ summarize sources of complexity in multi-energy systems.
- ✓ recognize tradeoffs in the **energy trilemma**
- classify **mathematical models**

ETH zürich

RRE Reliability and Risk Engineering

EPSE Energy & Process Systems Engineering

Introduction to Modeling and Optimization of Sustainable Energy Systems

Modeling

André Bardow & Giovanni Sansavini

Why Modeling?

- A model allows the performance of experiments / measurements that cannot be performed on the real system.

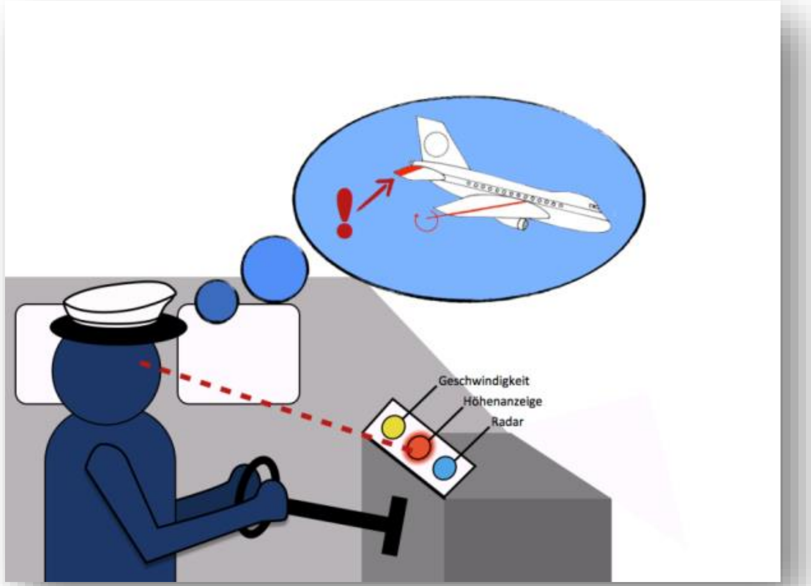
- A model is often cheaper than an experiment.

- No damage can be caused to the real system.

Model vs. reality

Types of models

- mental models



Types of models

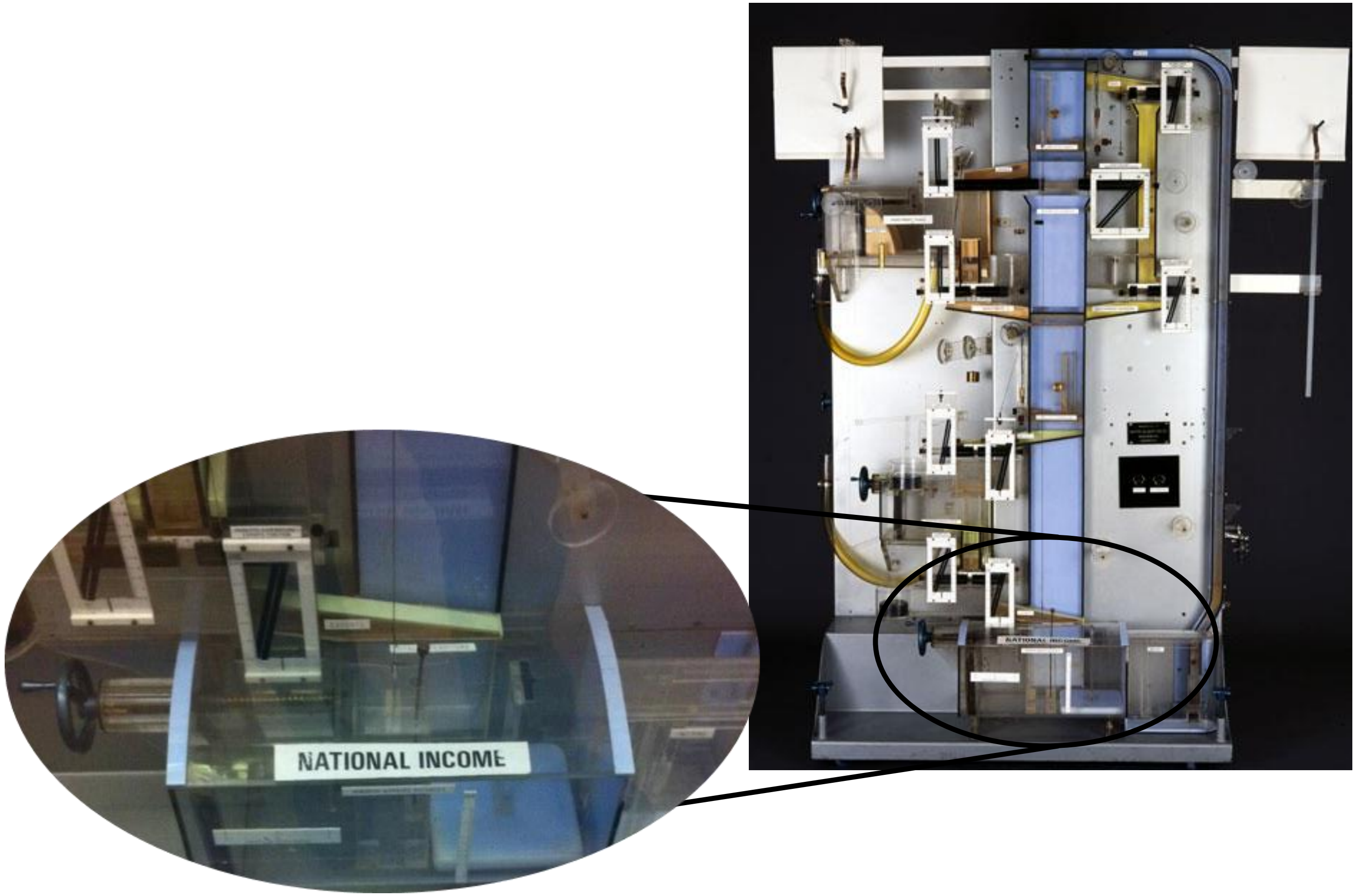
- mental models
- physical models

https://de.wikipedia.org/wiki/Datei:Europaviertel_modell.jpg

Types of models

- mental models
- physical models
- models from analogies

MONIAC: https://youtu.be/rAZavOcEnLg



collection.sciencemuseumgroup.org.uk/objects/co64127/phillips-economic-computer-analog-computer

Types of models

- mental models
- physical models
- models from analogies
- **Mathematical models**

$$C = \sum_{i=0}^{n} c_i(t)\ (m_\mathrm{B}\, H_\mathrm{U})_i$$

$$(m_\mathrm{B}\, H_\mathrm{U})_i = \int_{t=0}^{T} \eta_{\mathrm{th},i}(t)\, \dot{Q}_{\mathrm{H},i}(t)\, dt$$

$$\dot{Q}_\mathrm{H}(t) = \sum_{i=0}^{n} \dot{Q}_{\mathrm{H},i}(t)$$

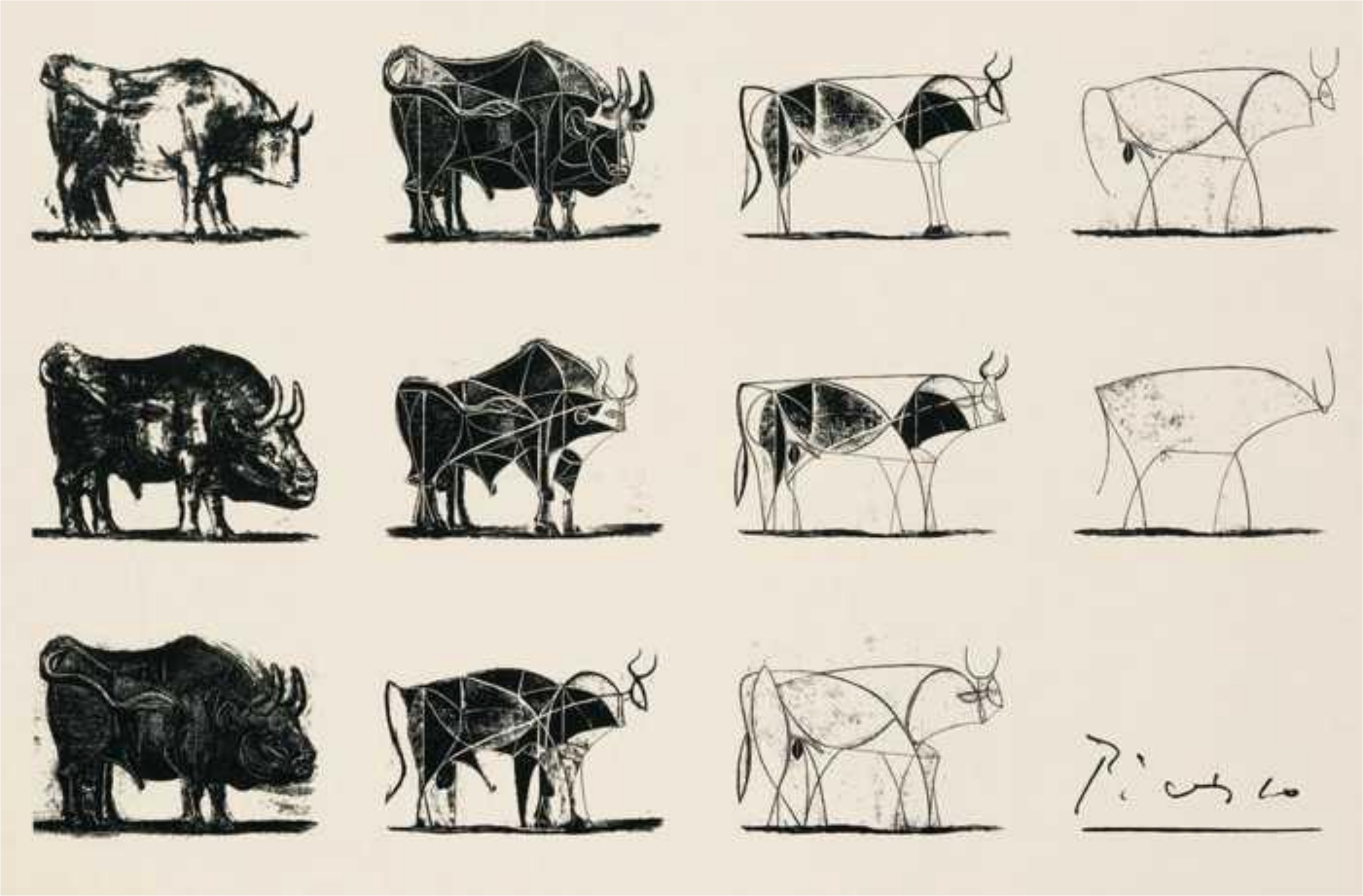
$$\dot{Q}_{\mathrm{H},i}(t) \leq u_i(t)\, \dot{Q}_{\mathrm{H},i}^{\mathrm{Nenn}} \qquad \forall i = 1..n$$

$$\dot{Q}_{\mathrm{H},i}(t) \geq u_i(t)\, x_\mathrm{min}\, \dot{Q}_{\mathrm{H},i}^{\mathrm{Nenn}} \qquad \forall i = 1..n$$

$$T_{\mathrm{min},i} \geq \int_{t=0}^{T} u_i(t)\, dt \qquad \forall i = 1..n$$

$$\eta_{\mathrm{th},i}(t) = f\left(\dot{Q}_{\mathrm{H},i}(t)\right) \qquad \forall i = 1..n$$

Which model is the right model?



Classes of mathematical models
Example energy system

Classes of mathematical models
Example energy system: Boiling water on a camping stove

Idea: use a model to make predictions about boiling water.

Mathematical modeling: Steam production

How much steam do we produce when boiling?

understand the problem

Which properties are relevant?

- temperature of water T_{water}
- gas flow of stove $\dot{m}_{gas}$
- geometry of pot r, h
- heating supply $\dot{Q}_{stove}$
- …

identify relationships

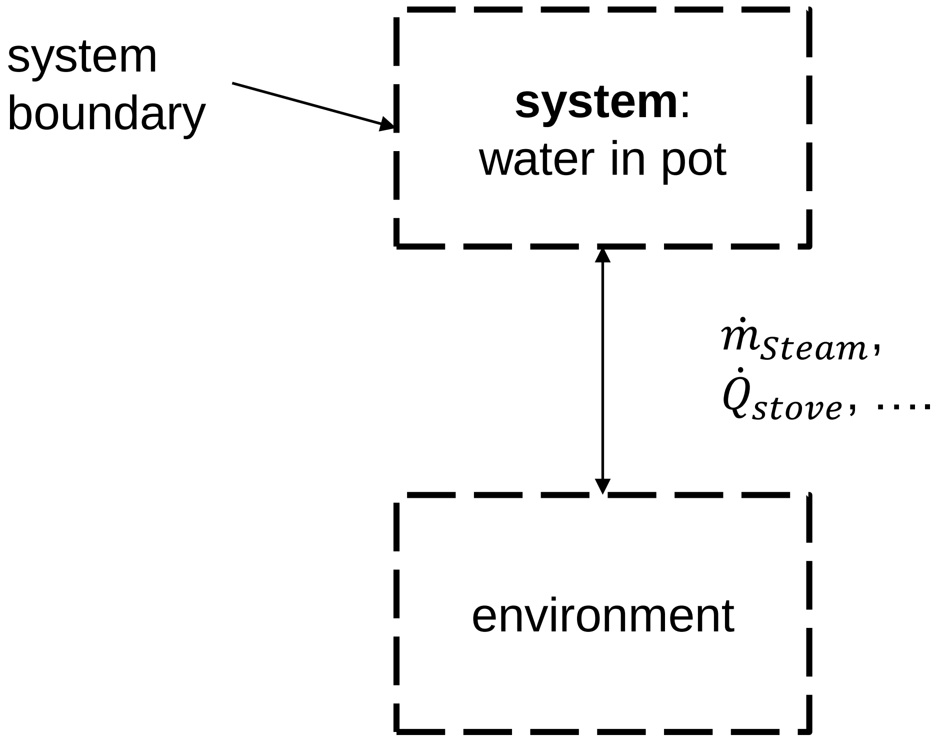
heating supply ↔ gas flow of stove

…

Mathematical modeling: Balances

How much steam do we produce when boiling?

real system



abstract physical system

Mathematical modeling: Steam production

How much steam do we produce when boiling?

system:
water in pot

$\dot{m}_{Steam}$,
$\dot{Q}_{stove}$, ….

environment

abstract physical system

assumptions

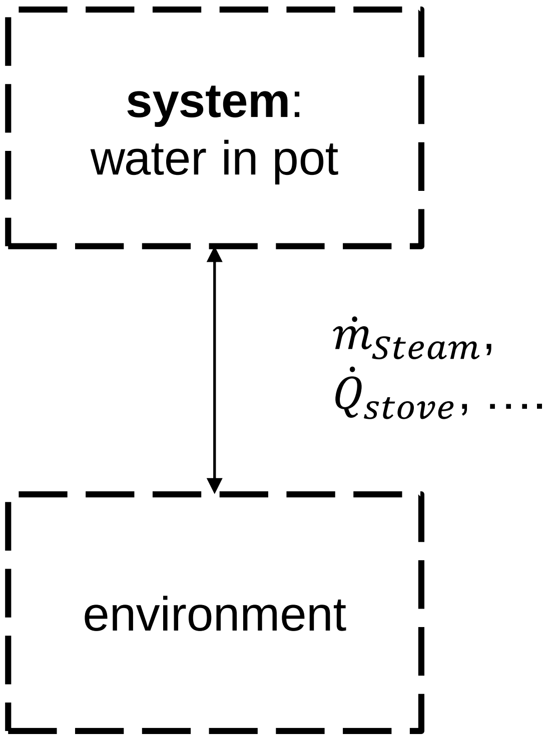
• ideally mixed water	dimension	0D
• steady state	time	static
• no uncertain events	predictability	deterministic

Mathematical modeling: Steam production

How much steam do we produce when boiling?

unknown = **variables**

known = **parameters**



Balance equations:

$$0 = \dot{Q}_{stove} - \dot{m}_{steam} \cdot \boxed{h''(100\,°C, 1\,bar)} - \dot{Q}_{loss}$$

Literature

#variables > #equations
⇒**Underdetermined system**

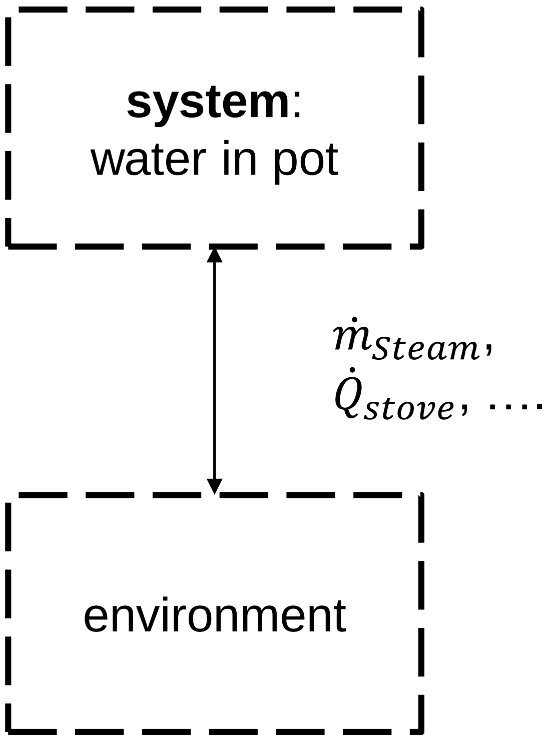
Do we know more equations?

abstract physical system

dimension	0D
time	static
predictability	deterministic

Mathematical modeling: Steam production

How much steam do we produce when boiling?



abstract physical system

unknown = **variables**

known = **parameters**

Balance equations:

$$0 = \dot{Q}_{stove} - \dot{m}_{Steam} \cdot \boxed{h''(100\,°C, 1\,bar)} - \dot{Q}_{loss}$$

$$\dot{Q}_{Stove} = \boxed{\dot{m}_{gas}} \cdot \boxed{\Delta h_{gas}}$$ Literature

Manual of stove

Literature

Thermometer

$$\dot{Q}_{loss} = \boxed{A_w} \cdot \boxed{\alpha} \cdot (\boxed{T_{water}} - \boxed{T_{envir}})$$

Geometry

100°C

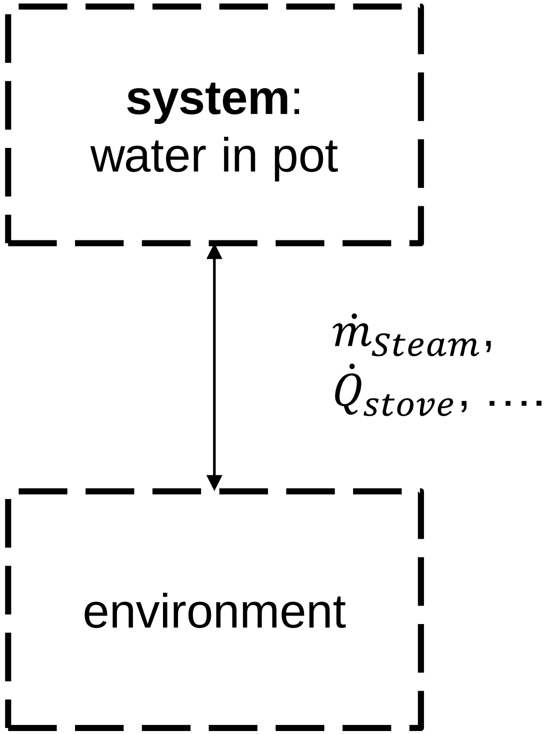
#variables = #independent equations

→**solvable**

dimension	0D
time	static
predictability	deterministic

Mathematical modeling: Steam production

How much steam do we produce when boiling?



abstract physical system

unknown = **variables**	
known = **parameters**	

Balance equations:

$$0 = \dot{Q}_{stove} - \dot{m}_{Steam} \cdot h''(100\,°C, 1\,bar) - \dot{Q}_{loss}$$

$$\dot{Q}_{Stove} = \dot{m}_{gas} \cdot \Delta h_{gas}$$

$$\dot{Q}_{loss} = A_{\mathrm{w}} \cdot \alpha \cdot (T_{water} - \mathrm{T}_{envir})$$

Variables are only multiplied with parameters. All equations are linear!

All variables are continuous

equations	linear
variables	continuous
dimension	0D
time	static
predictability	deterministic

Mathematical modeling: Steam production

How much steam do we produce when boiling?

real system

increasing complexity →

dimension	0D	?
time	static	?
variables	continuous	?
equations	linear	?
predictability	deterministic	?

Mathematical modeling: Steam production

How long does it take until the water boils?

Balance equations:

$$0 = \dot{Q}_{stove} - \underbrace{\cancel{\dot{m}_{steam}}}_{=0} \cdot h''(100\,°C, 1\,bar) - \dot{Q}_{loss}$$

$$\dot{Q}_{stove} = \dot{m}_{gas} \cdot \Delta h_{gas}$$

$$\dot{Q}_{loss} = A_{\mathrm{w}} \cdot \alpha \cdot (T_{water} - \mathrm{T}_{envir})$$

increasing complexity →

dimension	0D	
time	static	
variables	continuous	
equations	linear	
predictability	deterministic	

Mathematical modeling: Steam production

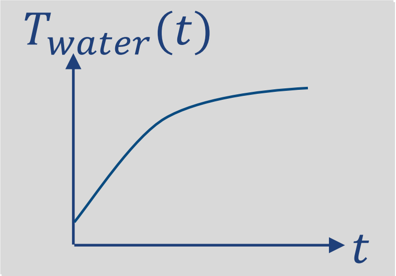
How long does it take until the water boils?

Balance equations:

$$m \cdot c_p \cdot dT_{water}(t)/dt = \dot{Q}_{stove} - \dot{Q}_{loss}$$

$$\dot{Q}_{stove} = \dot{m}_{gas} \cdot \Delta h_{gas}$$

$$\dot{Q}_{loss} = A_{\mathrm{w}} \cdot \alpha \cdot (T_{water}(t) - \mathrm{T}_{envir})$$



increasing complexity →

dimension	0D	
time	static	dynamic
variables	continuous	
equations	linear	
predictability	deterministic	

Mathematical modeling: Steam production

How long does it take until the water boils?

?

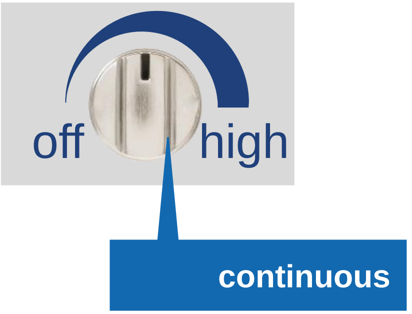
Balance equations:

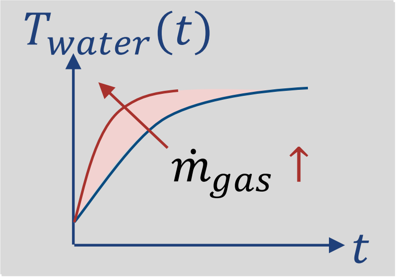
$$m \cdot c_p \cdot dT_{water}(t)/dt = \dot{Q}_{stove} - \dot{Q}_{loss}$$

$$\dot{Q}_{stove} = \boxed{\dot{m}_{gas}} \cdot \Delta h_{gas}$$

$$\dot{Q}_{loss} = A_{\mathrm{w}} \cdot \alpha \cdot (T_{water}(t) - \mathrm{T}_{envir})$$

controllable





increasing complexity →

dimension	0D	
time	static	dynamic
variables	continuous	
equations	linear	
predictability	deterministic	

Mathematical modeling: Steam production

How long does it take until the water boils?

?

Balance equations:

$$m \cdot c_p \cdot dT_{water}(t)/dt = \dot{Q}_{stove} - \dot{Q}_{loss}$$

$$\dot{Q}_{stove} = \boxed{\dot{m}_{gas}} \cdot \Delta h_{gas}$$

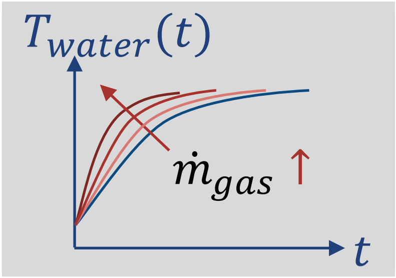
$$\dot{Q}_{loss} = A_\mathrm{w} \cdot \alpha \cdot (T_{water}(t) - \mathrm{T}_{envir})$$

controllable

on high

off low

discrete:
yes/no, on/off,
discrete options…



increasing complexity

dimension	0D	
time	static	dynamic
variables	continuous	
equations	linear	
predictability	deterministic	

Mathematical modeling: Steam production

$$\alpha = \frac{k}{L}\left(0.825 + \frac{0.387\mathrm{Ra}_L^{1/6}}{\left(1+(0.492/\mathrm{Pr})^{9/16}\right)^{8/27}}\right)^2 \qquad \mathrm{Ra}_L < 10^{12}$$

k is the thermal conductivity of the fluid,

L is the characteristic length with respect to the direction of gravity

… until the water boils?

$$\mathrm{Ra}_x = \frac{g\beta}{\nu\alpha}(T_s - T_\infty)x^3 = \mathrm{Gr}_x \mathrm{Pr}$$

where:

x is the characteristic length

Ra_x is the Rayleigh number for characteristic length x

g is …

β is … ature).

ν is …

α is …

T_s is the surface temperature

T_∞ is the quiescent temperature (fluid temperature far from the surface of the object)

Gr_x is the Grashof number for characteristic length x

Pr is the Prandtl number

Nonlinear!

Balance equations:

$$m \cdot c_p \cdot dT_{water}(t)/dt = \dot{Q}_{stove} - \dot{Q}_{loss}$$

$$\dot{Q}_{Stove} = \dot{m}_{gas} \cdot \Delta h_{gas}$$

$$\dot{Q}_{loss} = A_w \cdot \alpha(T_{water}(t)) \cdot (T_{water}(t) - T_{Envir.})$$

**Thermo II:
Heat transfer coefficient
is not constant**

of

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} = \frac{\mu/\rho}{k/(c_p\rho)} = \frac{c_p\mu}{k}$$

where:

- ν : momentum diffusivity (kinematic viscosity), $\nu = \mu/\rho$, (SI units: m^2/s)
- α : thermal diffusivity, $\alpha = k/(\rho c_p)$, (SI units: m^2/s)
- μ : dynamic viscosity, (SI units: Pa s = N s/m^2)
- k : thermal conductivity, (SI units: W/m·K)
- c_p : specific heat, (SI units: J/kg·K)
- ρ : density, (SI units: kg/m^3).

increasing complexity →

dimension	0D	
time	static	dynamic
variables	continuous	discrete
equations	linear	
predictability	deterministic	

Mathematical modeling: Steam production

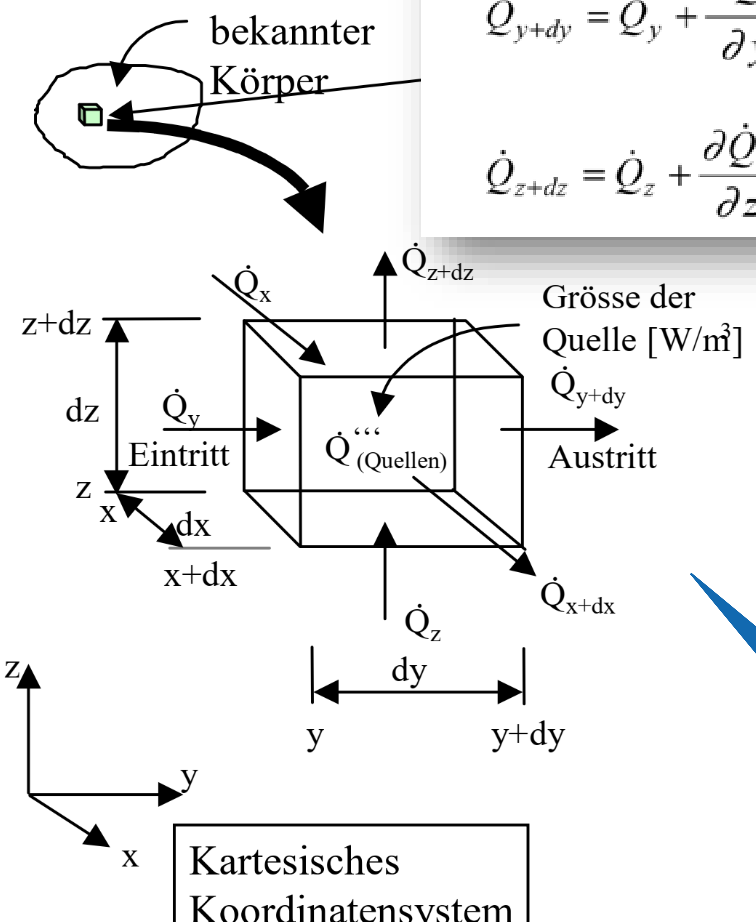
How long does it take until the water boils?

ETH Thermodynamik II

$$\dot{Q}_{x+dx} = \dot{Q}_x + \frac{\partial \dot{Q}_x}{\partial x} dx + \underbrace{\left(\frac{1}{2!} \cdot \frac{\partial^2 Q}{\partial x^2} \cdot dx^2 + \ldots\ldots\right)}_{\text{Glieder höherer Ordnung}}$$

$$\dot{Q}_{y+dy} = \dot{Q}_y + \frac{\partial \dot{Q}_y}{\partial y} dy + (\text{G.h.O.})$$

$$\dot{Q}_{z+dz} = \dot{Q}_z + \frac{\partial \dot{Q}_z}{\partial z} dz + (\text{G.h.O.})$$



s:

$\ldots t)/dt = \dot{Q}_{stove} - \dot{Q}_{loss}$

Δh_{gas}

$\ldots_{water}(t)) \cdot (T_{water}(t) - T_{Envir.})$

location dependent

Thermo II: Heat transfer in multiple dimensions →temperature gradient in pot

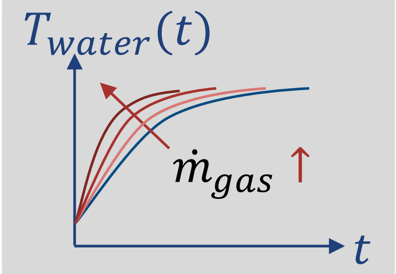
increasing complexity →

dimension	0D	
time	static	dynamic
variables	continuous	discrete
equations	linear	nonlinear
predictability	deterministic	

Mathematical modeling: Steam production

How long does it take until the water boils?

discrete:
yes/no, on/off,
discrete options…



location dependent

Balance equations:

$$m \cdot c_p \cdot d\boxed{T_{water}}(t)/dt = \dot{Q}_{stove} - \dot{Q}_{loss}$$

$$\dot{Q}_{Stove} = \boxed{\dot{m}_{gas}} \cdot \Delta h_{gas}$$

$$\dot{Q}_{loss} = A_{\mathrm{w}} \cdot \boxed{\alpha(T_{water}(t))} \cdot \boxed{(T_{water}(t)} - \boxed{\mathrm{T}_{Envir.}})$$

Stochastic changes

increasing complexity →

	0D	3D
time	static	dynamic
variables	continuous	discrete
equations	linear	nonlinear
predictability	deterministic	

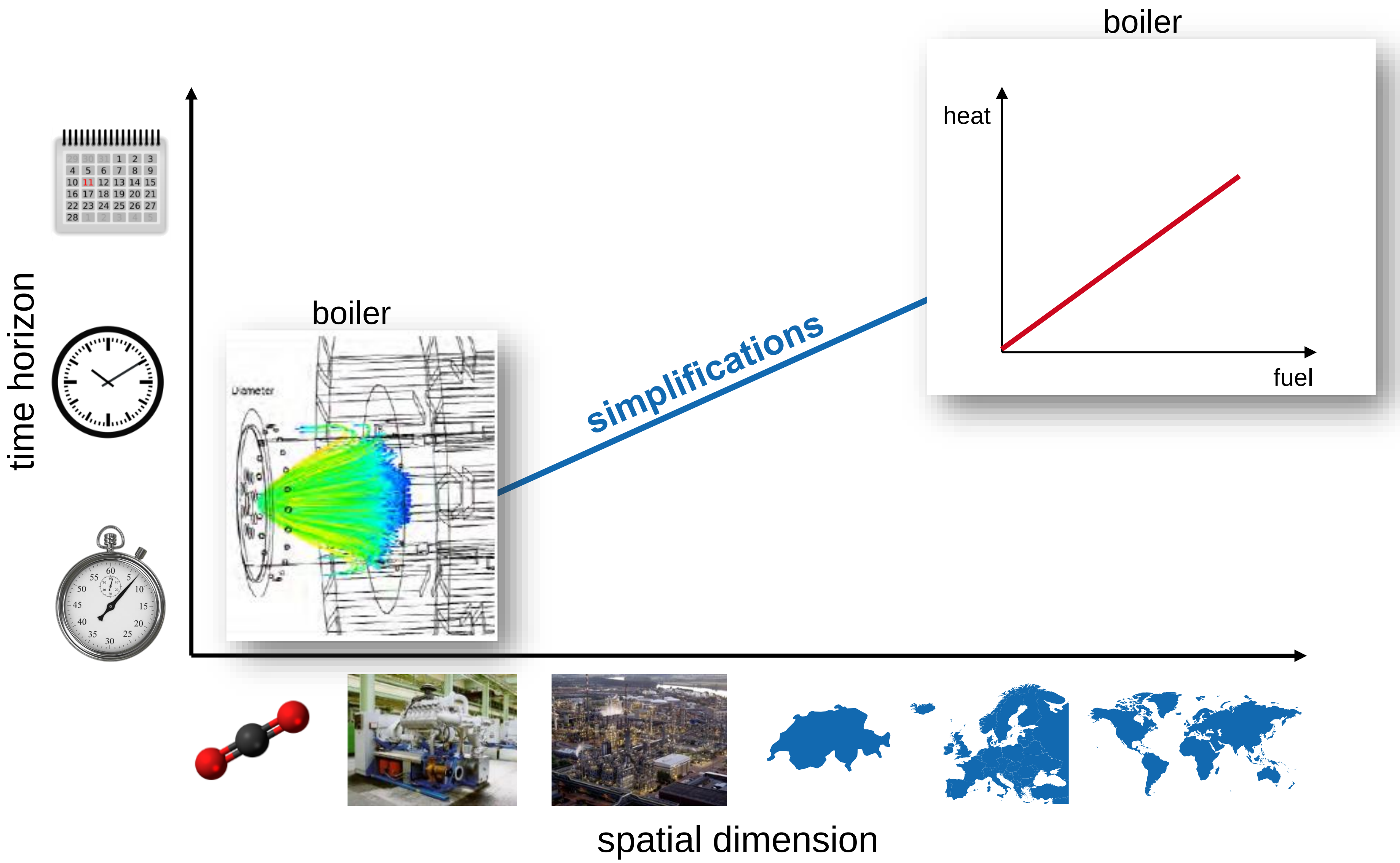
Mathematical model types
Summary

increasing complexity

dimension	0D	1D, 2D, 3D
time	static	dynamic
variables	continuous	discrete
equations	linear	nonlinear
predictability	deterministic	stochastic

There is no single "right" model! The choice of model type depends on the problem at hand!

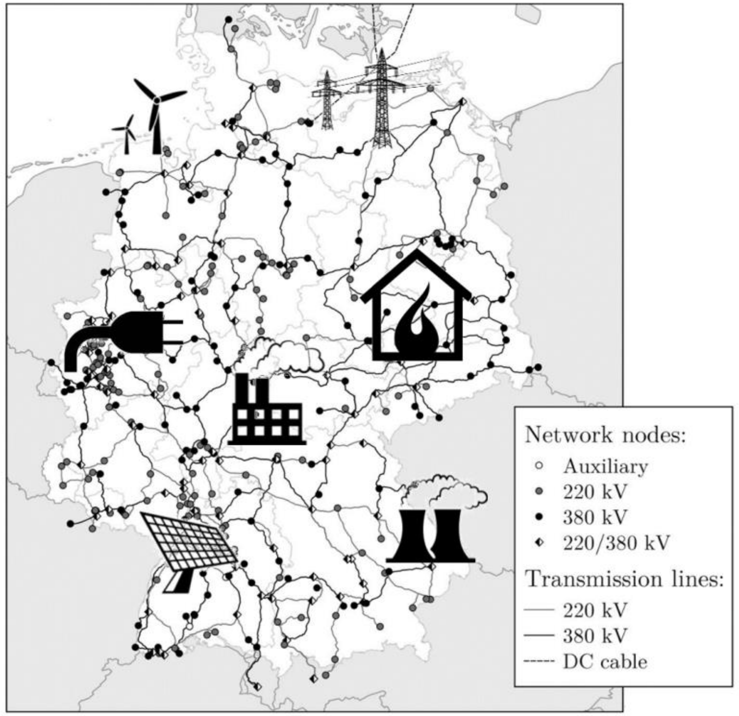
Modeling scales



BHKW, *MAN Dezentrale Energiesysteme;* Chemical part, BASF, Standort Ludwigshafen, basf.com

National energy system models

How to steer the energy transition?



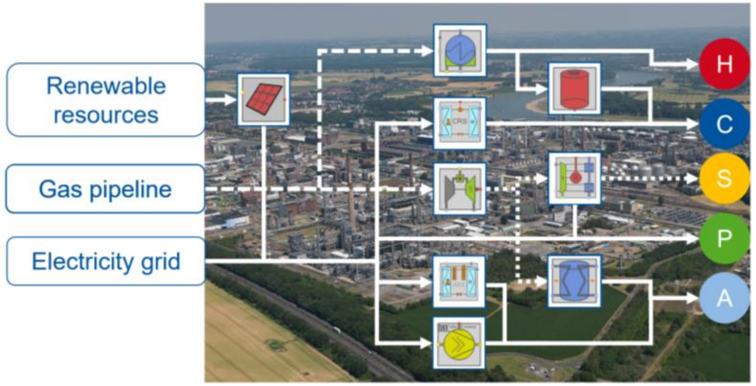
increasing complexity

dimension	0D	1D, 2D, 3D
time	static	dynamic
variables	continuous	discrete
equations	linear	nonlinear
predictability	deterministic	stochastic

Figure: Egerer,2016, Open Source Electricity Model for Germany (ELMOD-DE)

Industrial energy system design

How to invest into new equipment?

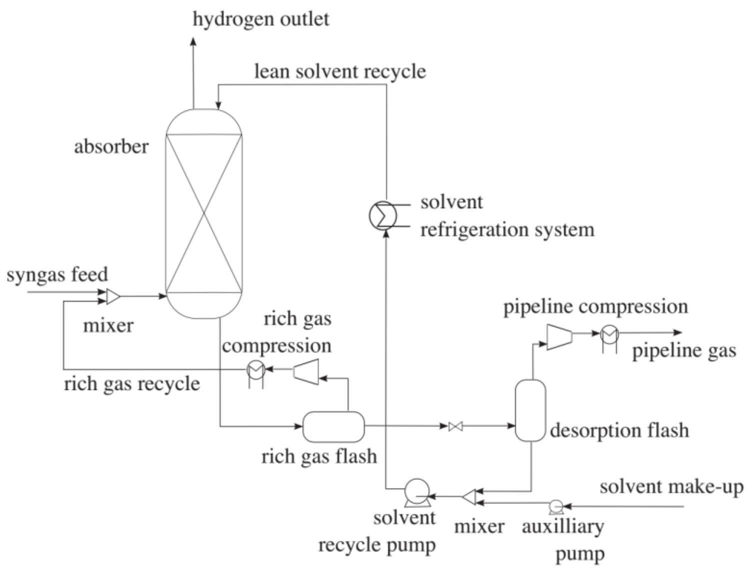


increasing complexity →

dimension	0D	1D, 2D, 3D
time	static	dynamic
variables	continuous	discrete
equations	linear	nonlinear
predictability	deterministic	stochastic

Working fluid selection

Which working fluid to use to capture CO_2 ?



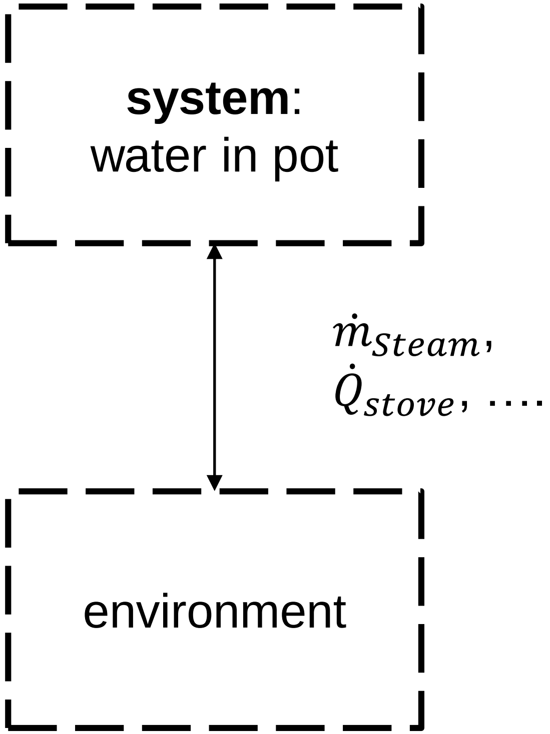
increasing complexity →

dimension	0D	1D, 2D, 3D
time	static	dynamic
variables	continuous	discrete
equations	linear	nonlinear
predictability	deterministic	stochastic

Lampe, Matthias, et al. *Computer-aided molecular design in the continuous-molecular targeting framework using group-contribution PC-SAFT*. *Computers & Chemical Engineering* 81 (2015).

From mathematical modeling to optimization

Before: How much steam do we produce when boiling?



abstract physical system

unknown = **variables**

known = **parameters**

Balance equations:

$$0 = \dot{Q}_{stove} - \dot{m}_{Steam} \cdot h''(100\,°C, 1\,bar) - \dot{Q}_{loss}$$

$$\dot{Q}_{Stove} = \dot{m}_{gas} \cdot \Delta h_{gas}$$ Literature

$$\dot{Q}_{loss} = A_{\mathrm{w}} \cdot \alpha \cdot (T_{water} - \mathrm{T}_{envir})$$

#variables = #independent equations
→**solvable**

dimension	0D
time	static
predictability	deterministic

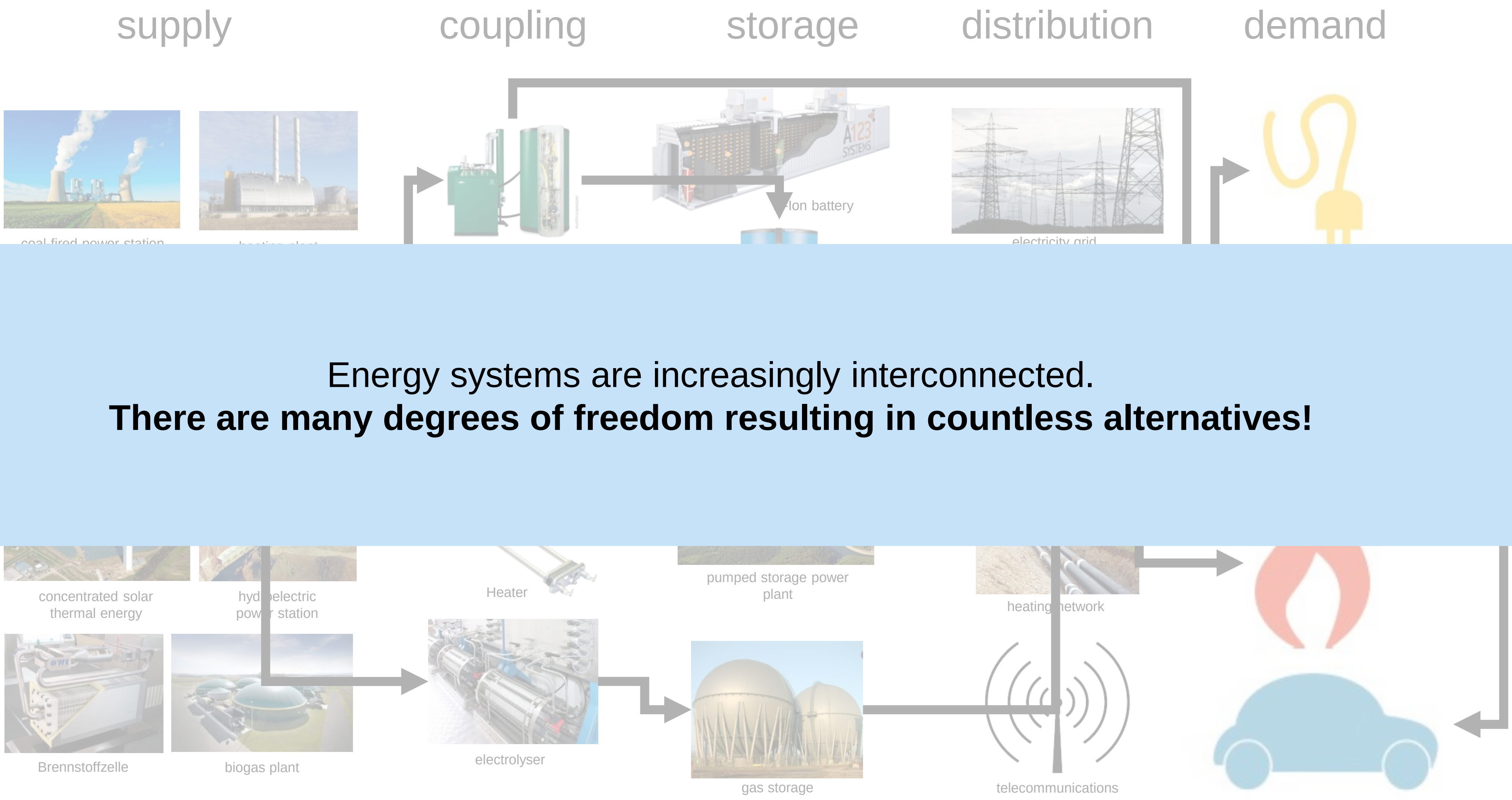
Degree of freedom analysis

Degree of freedom d of a model
is the difference of number of variables n_x
and number of independent equations n_e.

$$d = n_x - n_e$$

$d > 0$:
There is no unique solution!
Which one of many solutions is the best?

Energy systems today: Which one of many solutions is the best?



Energy systems are increasingly interconnected.
There are many degrees of freedom resulting in countless alternatives!

After this lecture, you are able to…

- ✓ explain the **scope of this course**
- ✓ explain **your participation** in this course
- ✓ recognize tradeoffs in the **energy trilemma**
- ✓ classify **mathematical models**