Optimization in practice

From long to short, from planning to operation of (power) grids

Berlin, 27.09.2024

d-fine

analytical. quantitative. tech.

Short Profile

Dr Jennifer Uebbing
Senior Consultant

Experience

- Math. Optimization
  - Nonlinear and Mixed Integer Opt.
- Data integration
- Python/Ab Initio

Interests

- Ride motorcycle
- Running, hiking
- Drawing

Bachelor of Mathematics, Otto von Guericke University Magdeburg

Master of Mathematics, Otto von Guericke University Magdeburg

Research stay as PhD student, Carnegie Mellon University, Pittsburgh

Promotion Mathematics, Max-Planck Institute

Consultant @ d-fine

Founding member of team mathematical optimization

Senior Consultant @ d-fine

Short Profile

Merlin Viernickel

Senior Consultant

Specialization

- Mixed Integer Program Modelling
- Supply Chain Network Design

Interests

- Boardgames
- Sports & Hiking
- Game Development

Apr 2017

Working Student

Zuse Institute Berlin

Apr 2020

M.Sc.

Mathematics at Technische Universität Berlin

Dec 2020

d-fine

Starting job consultant @ d-fine

Jan 2022

d-fine

Started on project for energy grid investments

Jan 2023

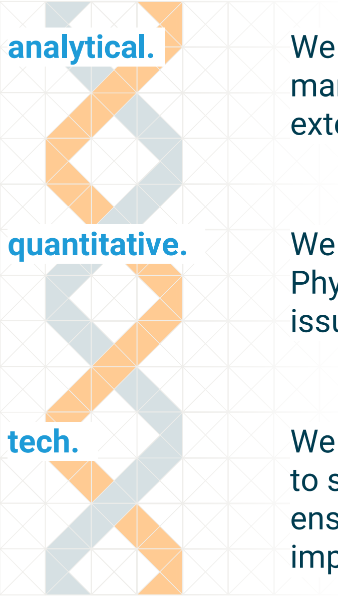
d-fine

Founding member of team mathematical optimization

Working at d-fine allows me to continue pursuing my academic passion of mathematical optimization and putting my expertise into practice by tackling real-world problems.

d-fine is a European consultancy focusing on analytical, quantitative and technological endeavours

Our DNA



analytical. We address your challenges in a structured manner and investigate key drivers using our extensive domain expertise.

quantitative. We leverage methods from Mathematics, Physics and Data Science to solve complex issues.

tech. We apply new and established technologies to support your business processes and ensure a dynamic and sustainable implementation into your IT ecosystem.

Our Team

■	50%	Physics
■	35%	Mathematics
□	15%	Other STEM subjects & Business
■	50%	PhD / doctorate

10+ Office locations

30+ Nationalities

100 % climate neutral

Our industry expertise

- Banking & Capital Markets
- Insurance & Asset Management
- Energy & Industrials
- Healthcare
- Consumer & Services
- Technology
- Public Sector

Together with our clients, we drive strategies, develop business designs and implement tailored IT solutions. A collaborative and trustworthy relationship is important to us.

Our industry experience and competences

Strategy & Governance | Methods & Simulation | Data & Analytics | Processes & Technologies

Banking & Capital Markets	Insurance & Asset Management	Energy & Industrials	Healthcare
Consumer & Services	Public Sector	Technology	Others

1000+
Successful Projects

200+
Satisfied Customers

1 - 70
Team size

We offer tailored solutions for established and new markets – from business strategy to technical implementation

d-fine project examples

OPTIMIZATION IN PRACTICE

01

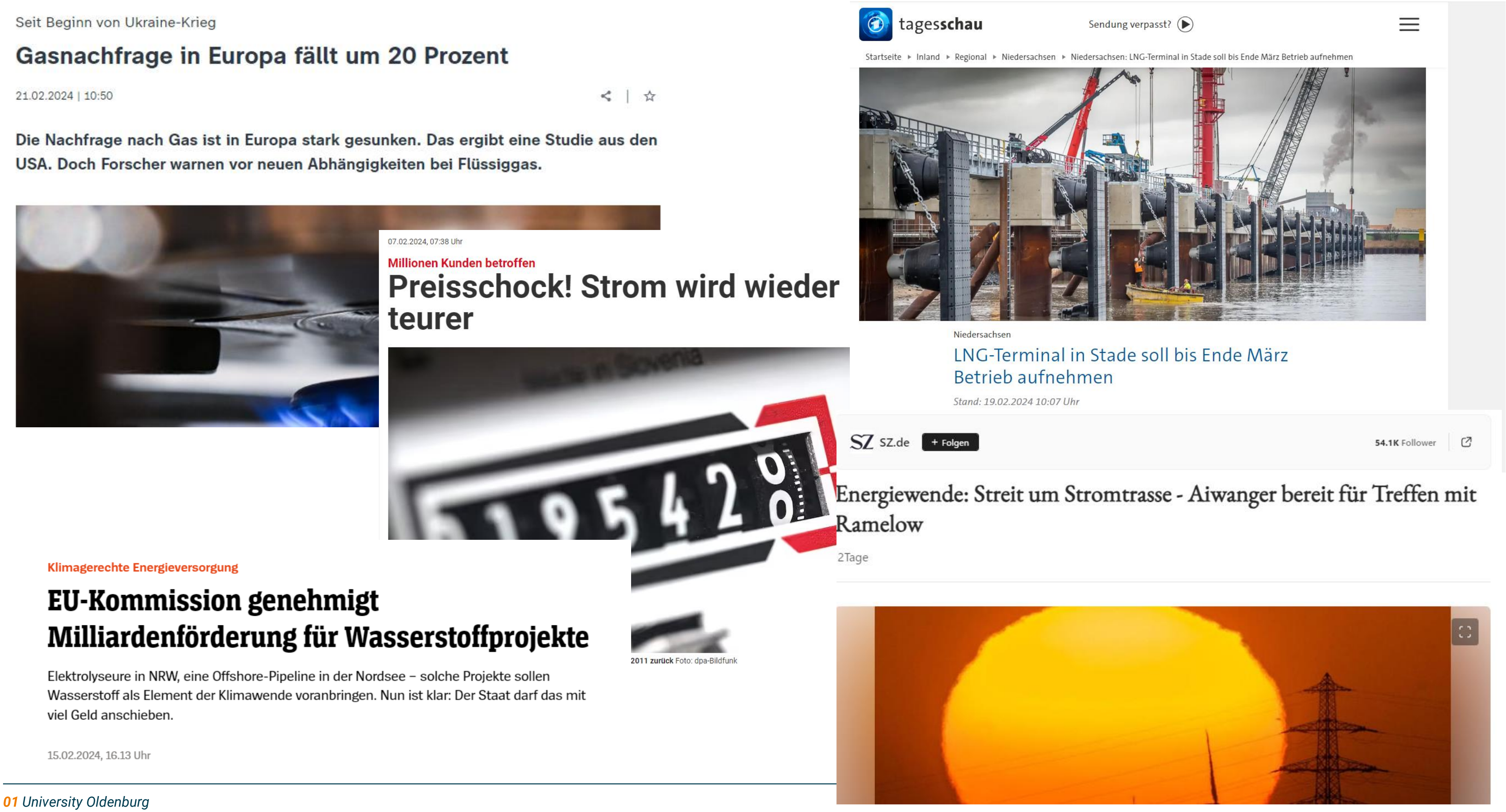
Project examples: Energy grid investments

PROJECT EXAMPLE: ENERGY GRID INVESTMENTS

01.01

Introduction

Energy transition – one of the greatest challenges of the 21st century[01]



Seit Beginn von Ukraine-Krieg

Gasnachfrage in Europa fällt um 20 Prozent

21.02.2024 | 10:50

Die Nachfrage nach Gas ist in Europa stark gesunken. Das ergibt eine Studie aus den USA. Doch Forscher warnen vor neuen Abhängigkeiten bei Flüssiggas.

07.02.2024, 07:38 Uhr

Millionen Kunden betroffen

Preisschock! Strom wird wieder teurer

2011 zurück Foto: dpa-Bildfunk

Klimagerechte Energieversorgung

EU-Kommission genehmigt Milliardenförderung für Wasserstoffprojekte

Elektrolyseure in NRW, eine Offshore-Pipeline in der Nordsee – solche Projekte sollen Wasserstoff als Element der Klimawende voranbringen. Nun ist klar: Der Staat darf das mit viel Geld anschieben.

15.02.2024, 16.13 Uhr

Niedersachsen

LNG-Terminal in Stade soll bis Ende März Betrieb aufnehmen

Stand: 19.02.2024 10:07 Uhr

Energiewende: Streit um Stromtrasse - Aiwanger bereit für Treffen mit Ramelow

2Tage

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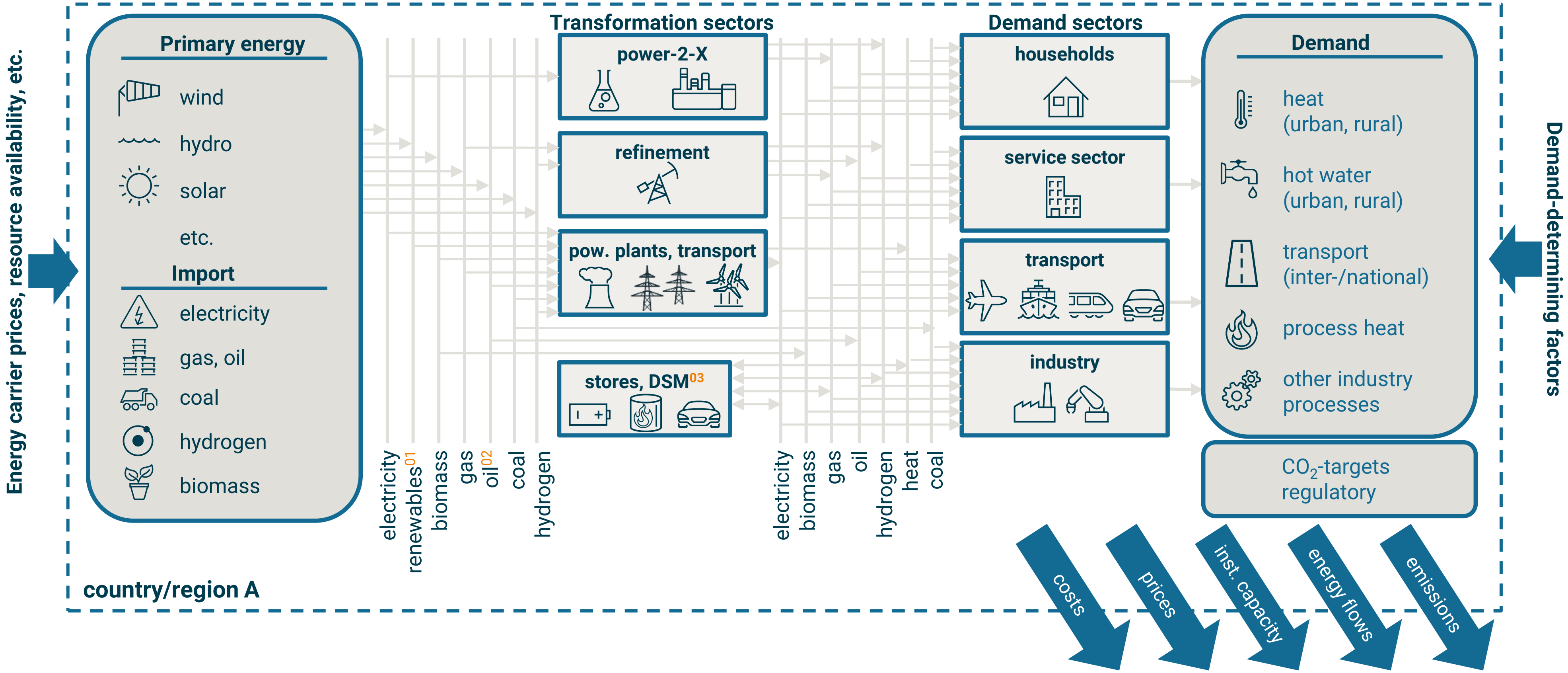
[01] University Oldenburg

Sector-linked view of the energy industry for optimal planning of future investments



Energy carrier prices, resource availability, etc.

Primary energy

- wind
- hydro
- solar
- etc.

Import

- electricity
- gas, oil
- coal
- hydrogen
- biomass

electricity, renewables[01], biomass, gas, oil[02], coal, hydrogen

Transformation sectors

- power-2-X
- refinement
- pow. plants, transport
- stores, DSM[03]

electricity, biomass, gas, oil, hydrogen, heat, coal

Demand sectors

- households
- service sector
- transport
- industry

Demand

- heat (urban, rural)
- hot water (urban, rural)
- transport (inter-/national)
- process heat
- other industry processes

CO_2-targets regulatory

Demand-determining factors

country/region A

costs, prices, inst. capacity, energy flows, emissions

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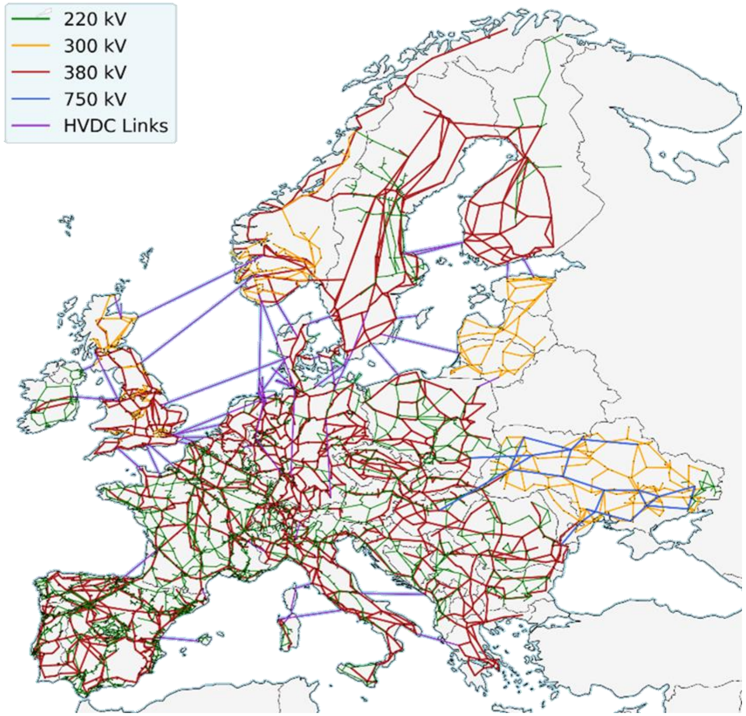
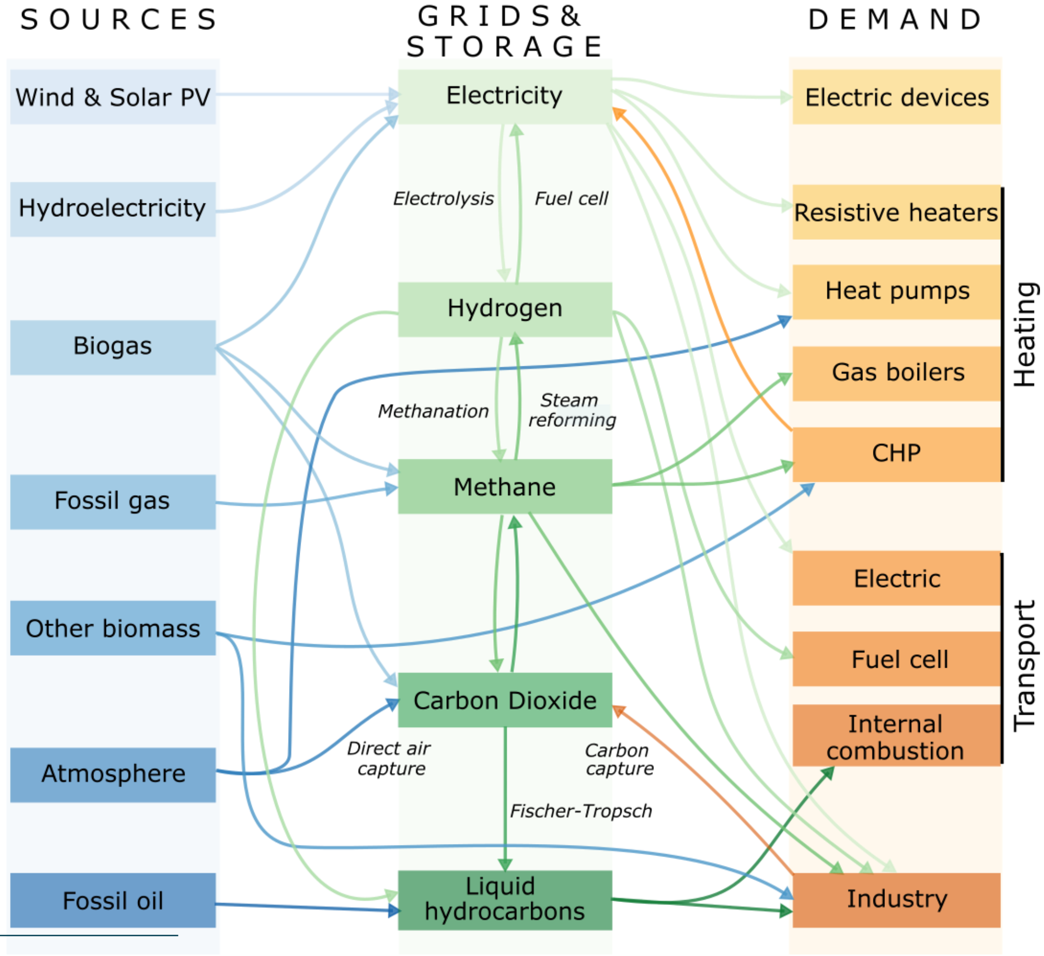
[01] Renewable energy (renewables) includes the energy sources wind, PV, etc.. [02] Oils includes crude oil as well as naphtha (chemical industry) and kerosene (aviation) from Fischer-Tropsch synthesis [03] Demand-side management (DSM) covers the household, industry & transport sectors as well as vehicle-2-grid (V2G).

PyPSA-Eur – An Open-Source Energy System Model

Knowledge about bottlenecks in the energy grid…



…is used for modelling all relevant energy sectors.[01]



SOURCES

Wind & Solar PV
Hydroelectricity
Biogas
Fossil gas
Other biomass
Atmosphere
Fossil oil

GRIDS & STORAGE

Electricity
Electrolysis
Fuel cell
Hydrogen
Methanation
Steam reforming
Methane
Carbon Dioxide
Direct air capture
Carbon capture
Fischer-Tropsch
Liquid hydrocarbons

DEMAND

Electric devices
Resistive heaters
Heat pumps
Gas boilers
CHP
Heating
Electric
Fuel cell
Internal combustion
Transport
Industry

- Fully equipped with data, solver, configuration, etc.
- Transparent development (GitHub)
- Over 47 users of the PyPSA framework in science and industry (e.g. Shell, TransnetBW, TUB, KIT, ...)

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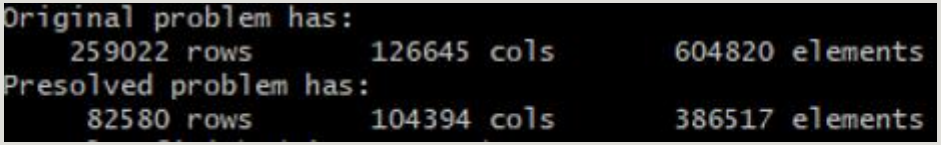
[01] *https://github.com/PyPSA/pypsa-eur*

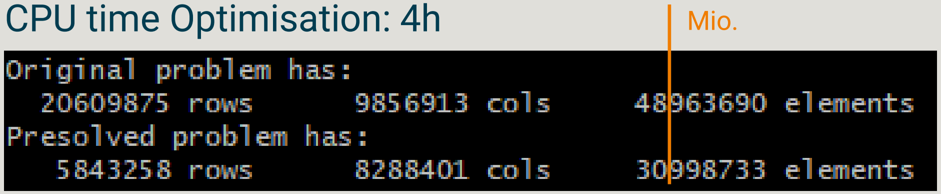
Why Linear Programming?

60 Nodes
10 Time steps, i.e. $\Delta t = 876h$
CPU time Optimisation: 5,6s



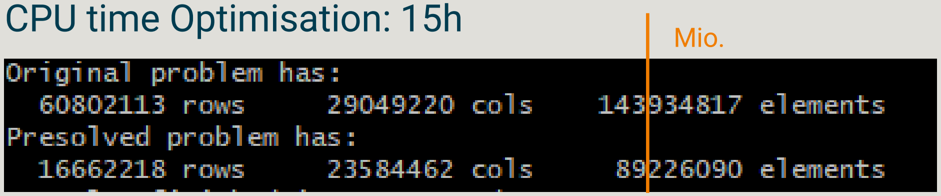
```
Original problem has:
    259022 rows        126645 cols        604820 elements
Presolved problem has:
     82580 rows        104394 cols        386517 elements
```

60 Nodes
730 Time steps, i.e. $\Delta t = 12h$
CPU time Optimisation: 4h



```
Original problem has:
  20609875 rows       9856913 cols       48963690 elements
Presolved problem has:
   5843258 rows       8288401 cols       30998733 elements
```

60 Nodes
2190 Time steps, i.e. $\Delta t = 4h$
CPU time Optimisation: 15h



```
Original problem has:
  60802113 rows      29049220 cols     143934817 elements
Presolved problem has:
  16662218 rows      23584462 cols      89226090 elements
```

Energy system models are “extreme-scale” and therefore modeling with non-linearities is only permissible for smaller sections (temporal or spatial).

PROJECT EXAMPLE: ENERGY GRID INVESTMENTS

01.02

PyPSA: Power System Analysis

Example Network Optimization: Minimum-cost flow problem

Given a network consisting of a directed Graph $G = (V, E)$ with node supply/demand b_i for each node $i \in V$, costs $c_{i,j} \in \mathbb{R}$ and capacities $u_{i,j} \in \mathbb{R}$ for each edge $(i,j) \epsilon E$. Find the cheapest possible way to meet the demand in the network.[01]

Assumption: The demand equals the given supply

$$\sum_{i \in V} \boldsymbol{b_i} = \boldsymbol{0}$$

Objective function

$$\min \sum_{(i,j) \in E} \boldsymbol{c_{i,j} x_{i,j}}$$

Flow balancing constraints

$$\sum_{j:(i,j) \in V} \boldsymbol{x_{i,j}} - \sum_{j:(j,i) \in V} \boldsymbol{x_{j,i}} = \boldsymbol{b_i} \textbf{ for every } \boldsymbol{i} \in \boldsymbol{V}$$

Capacity constraints

$$\boldsymbol{0} \leq \boldsymbol{x_{i,j}} \leq \boldsymbol{u_{i,j}} \textbf{ for all } (\boldsymbol{i}, \boldsymbol{j}) \in \boldsymbol{E}$$

Real-world application of network optimization:

- communication systems
- manufacturing systems
- transportation systems
- water systems
- energy systems

Remarks

$$\boldsymbol{b_j} \begin{cases} \leq 0, \text{demand at node } j \in V \\ > 0, \text{supply at node } j \in V \end{cases}$$

$\boldsymbol{c_{i,j}}$ costs for edge $(i,j) \in E$

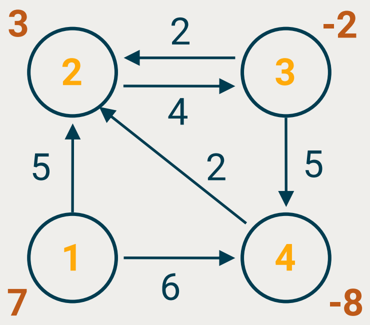
$\boldsymbol{x_{i,j}}$ flow over edge $(i,j) \in E$

$\boldsymbol{u_{i,j}}$ capacity of edge $(i,j) \in E$

Note:

$$x_{i,j} = -x_{j,i} \; \forall \; (i,j) \in E$$

Example:



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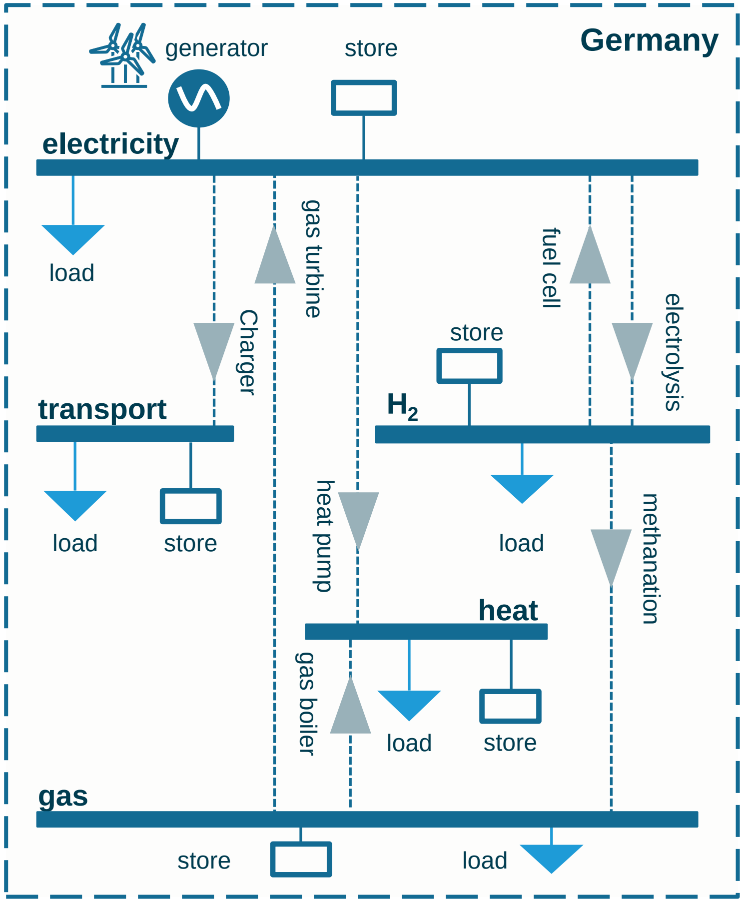
[01] https://ocw.mit.edu/courses/sloan-school-of-management/15-082j-network-optimization-fall-2010/lecture-notes/MIT15_082JF10_lec01.pdf

Lets take a look at energy system modelling with PyPSA …

- **PyPSA minimizes** the **total system costs** and can be used to simultaneously **optimize dispatch** and **capacity** of conversion technologies, stores and grid infrastructure**.**
- The package has **predefined components**, for example
  - Generators
  - Stores
  - Links
  - Loads
- Moreover, every component has predefined properties, for example all components that convert, transfer or store energy have **fixed** and **variable costs**.
- The **loads** are **inelastic** and have to be met for every time step.
- The dispatch and capacity **variables** are **continuous**. Therefore, the resulting **optimization problem** is **linear**, if unit commitment for generators is not included.
- It's possible to model technologies, which can **transfer energy in both directions** (bidirectional edge).



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01 Figure based on: T. Brown et al, Synergies of sector coupling and transmission extension in a cost-optimised, highly renewable European energy system, Energy, Vol. 160, Pages 720-739, 2018.

Energy system modelling – Objective function

In PyPSA[01] the objective function minimizes the sum of all capital and operational costs (variable part) for all components for the given time horizon.

$$\textbf{minimize} \sum_{n,s} c_{n,s}\bar{g}_{n,s} + \sum_{n,s} c_{n,s}\bar{h}_{n,s} + \sum_{l} c_l F_l + \sum_{t} w_t \left[\sum_{n,s} o_{n,s,t} g_{n,s,t} + \sum_{n,s} o_{n,s,t} h_{n,s,t} + \sum_{l,} o_{l,t} f_{l,t} \right]$$

Variables/Parameters

$n \in N$	set of nodes/buses	$h_{n,s,t}$	energy from store s at bus n at time step t
$t \in T$	time step, which is called snapshot	$\bar{h}_{n,s}$	nominal energy of store s at bus n
$l \in L$	label of a branch	$f_{l,t}$	flow over branch l at time step t
$s \in S$	label for different technology types at each bus	F_l	capacity for branch l
$\bar{g}_{n,s}$	nominal power of technology s at bus n	$c_{n,s}$	costs for extending the nominal power of technology s at bus n by one MW
$g_{n,s,t}$	dispatch from technology s at bus n at time step t	$o_{n,s}$	variable costs for technology s at bus n for each MWh of dispatch
w_t	weighting of time step t		

---

[01] *https://pypsa.readthedocs.io/en/latest/optimal_power_flow.html#objective-function*

Energy system modelling – Other constraints

Most use-cases require **additional constraints** in order to represent **political goals** or **technology restrictions**. One example is the **reduction of CO_2-emissions**.[01] Keep in mind this actual constraint depends highly on the specific model and how CO_2 emissions are included.

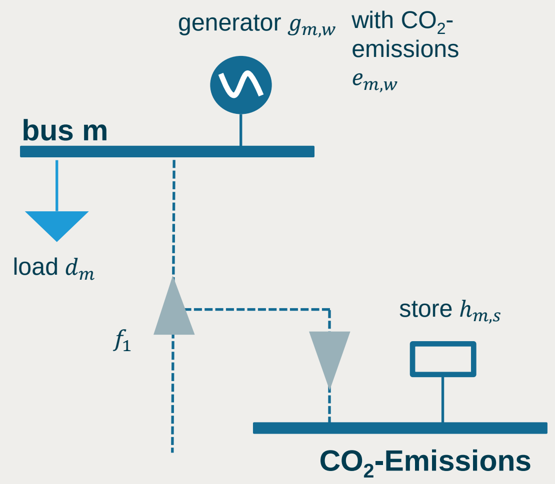
$$\sum_{n,s,t} \frac{1}{\eta_{n,s}} w_t * g_{n,s,t} * e_{n,s} + \sum_{n,s} \left(e_{n,s,t=-1} - e_{n,s,t=|T|-1}\right) * e_{n,s} \leq \mathrm{CAP}_{CO2}$$

Variables/Parameters

$\eta_{n,s}$	efficiency generator s at bus n
w_t	weighting of time step t
$g_{n,s,t}$	dispatch from technology s at bus n at time step t
$e_{n,s}$	CO_2-equivalent-tonne-per-MWh of the energy carrier of generator/store s at bus n
$e_{n,s,t}$	energy in store s at bus n at time step t
CAP_{CO2}	upper limit on CO_2-equivalent emissions in t/MWh

Note: The shadow price of this equation is the system wide CO_2 price.

Example[02] – PyPSA-Eur-Sec



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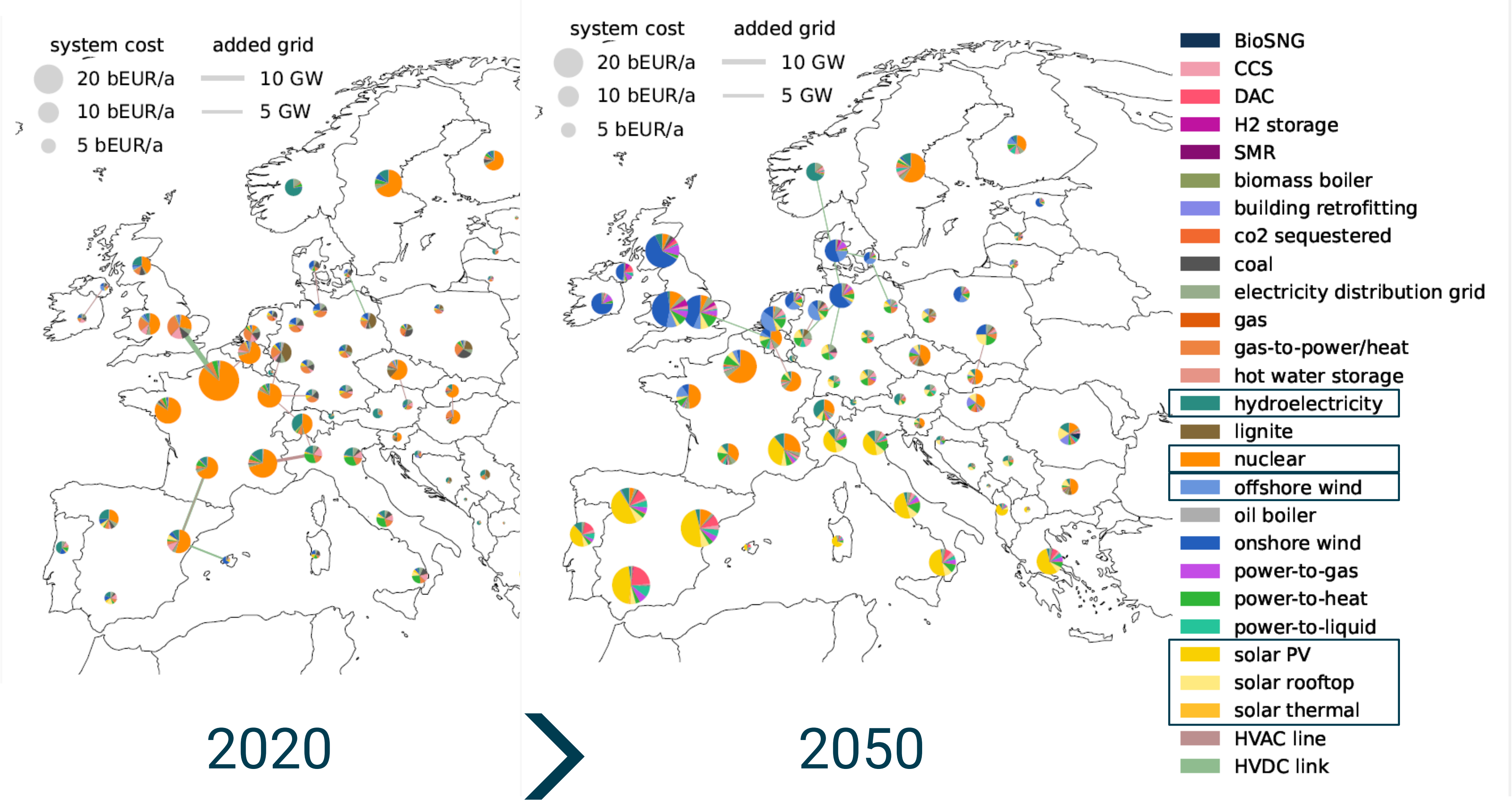
[01] https://pypsa.readthedocs.io/en/latest/optimal_power_flow.html#global-constraints [02] https://github.com/PyPSA/pypsa-eur-sec

PROJECT EXAMPLE: ENERGY GRID INVESTMENTS

01.03

Outlook

Renewable energies are gaining ground and energy costs are rising



2020

2050

The grids are a connecting element and enable the energy transition

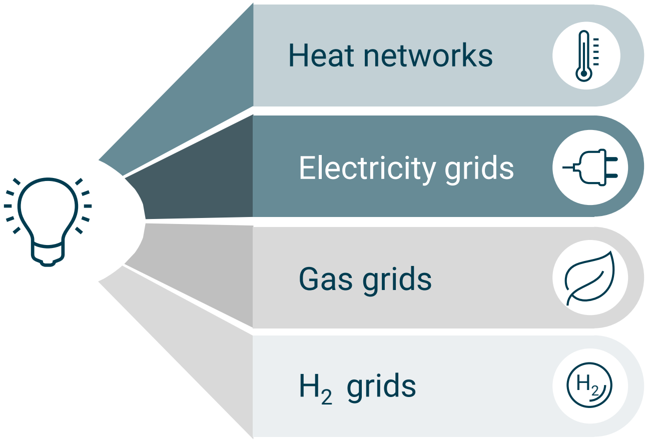
ENERGY GRIDS AS FACILITATORS OF THE ENERGY TRANSITION

The transportation and distribution of individual energy sources will change significantly as a result of sectoral integration:

Few, centralized producers → many, decentralized consumers → prosumers

Gas imports → Biogas & syngas

CH4 → H2 admixture, hydrogen network



Heat networks

Electricity grids

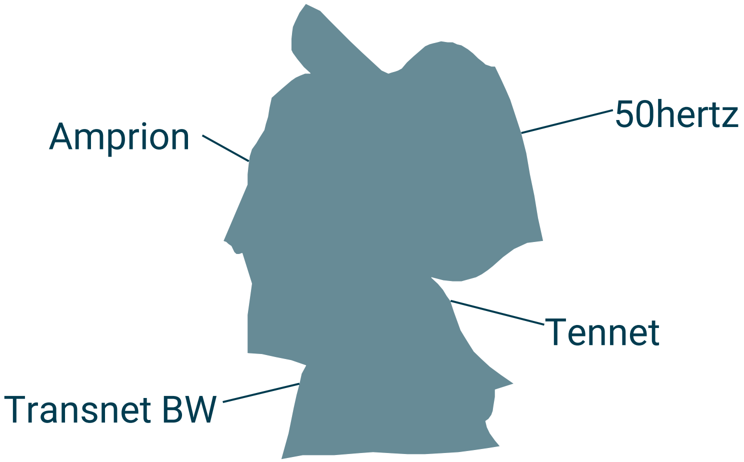
Gas grids

H_2 grids

THE POSSIBLE ADDITIONAL ROLE OF NETWORK OPERATORS

The new challenges are turning grid operators into service providers and points of contact for customer-specific questions:

- Should I produce my own hydrogen or obtain it from the grid?
- How can I operate my vehicle fleet in a grid-friendly way?
- Are there potential customers for my waste heat?
- How can I make optimum use of the energy generated on site?



OPTIMIZATION IN PRACTICE

02

Project example: Optimization of Remedial Actions

PROJECT EXAMPLE: OPTIMIZATION OF REMEDIAL ACTIONS

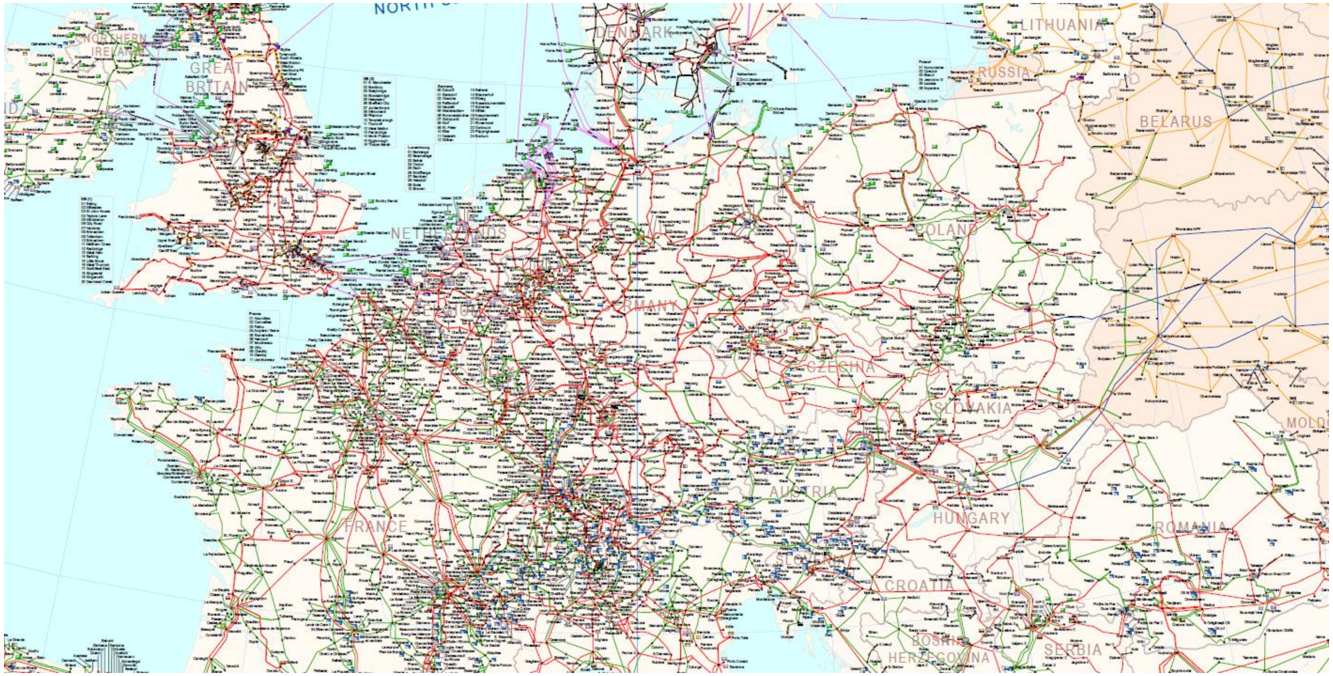
02.01

Project Background

Motivation and background

The European energy grid is subject to fluctuations and uncertainties

- The share of renewable energies in the grid is steadily increasing
- Renewable energies are subject to strong fluctuations and uncertainties
- The energy grid must be increasingly protected against unexpected fluctuations



01 https://www.entsoe.eu/data/map/

Energy production and consumption must be balanced

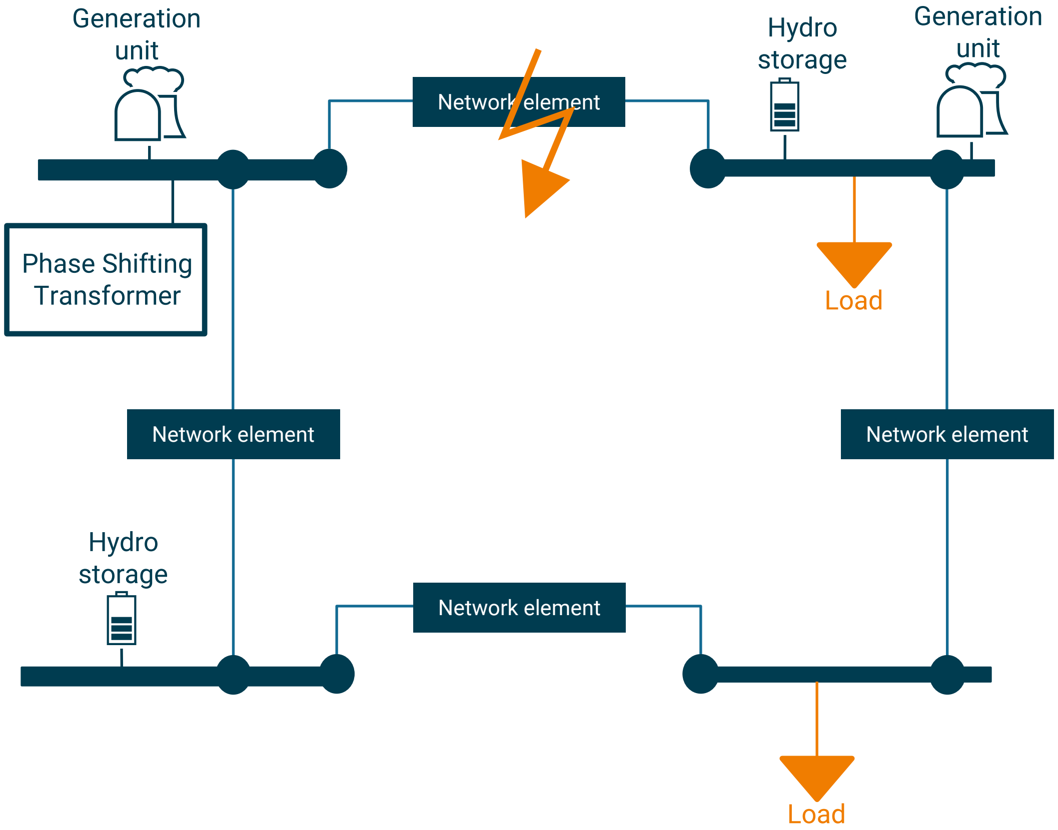
The grid must be able to transport energy from the producer to the consumer

The grid must remain stable even in the event of outages

Grid stability must remain guaranteed even with increasing uncertainties.

What are remedial actions?

Remedial actions (RAs) are used to maintain **grid stability**. Various remedial actions are available to eliminate congestion on grid elements. Some are triggered automatically, others can be controlled by the operator.



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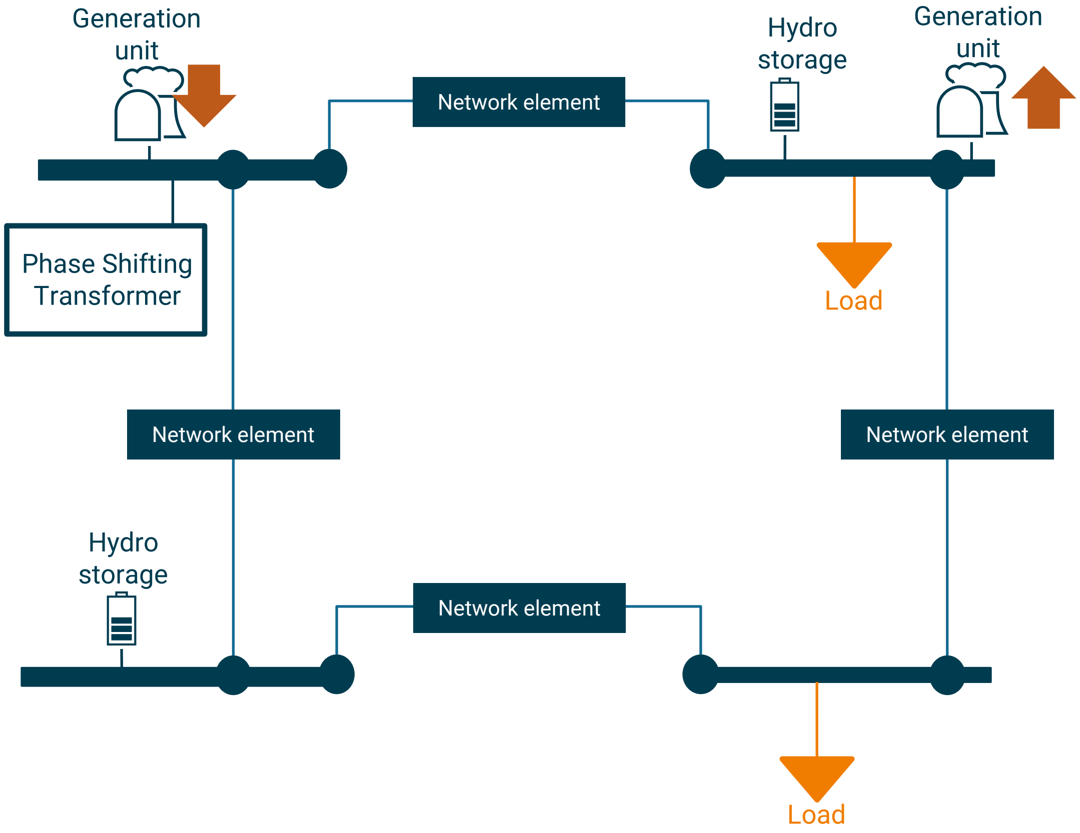

Redispatch

The **amount of electricity** supplied (dispatched) by the power plants or water reservoirs in different parts of the grid is changed. This is a **costly RA** with long activation times.

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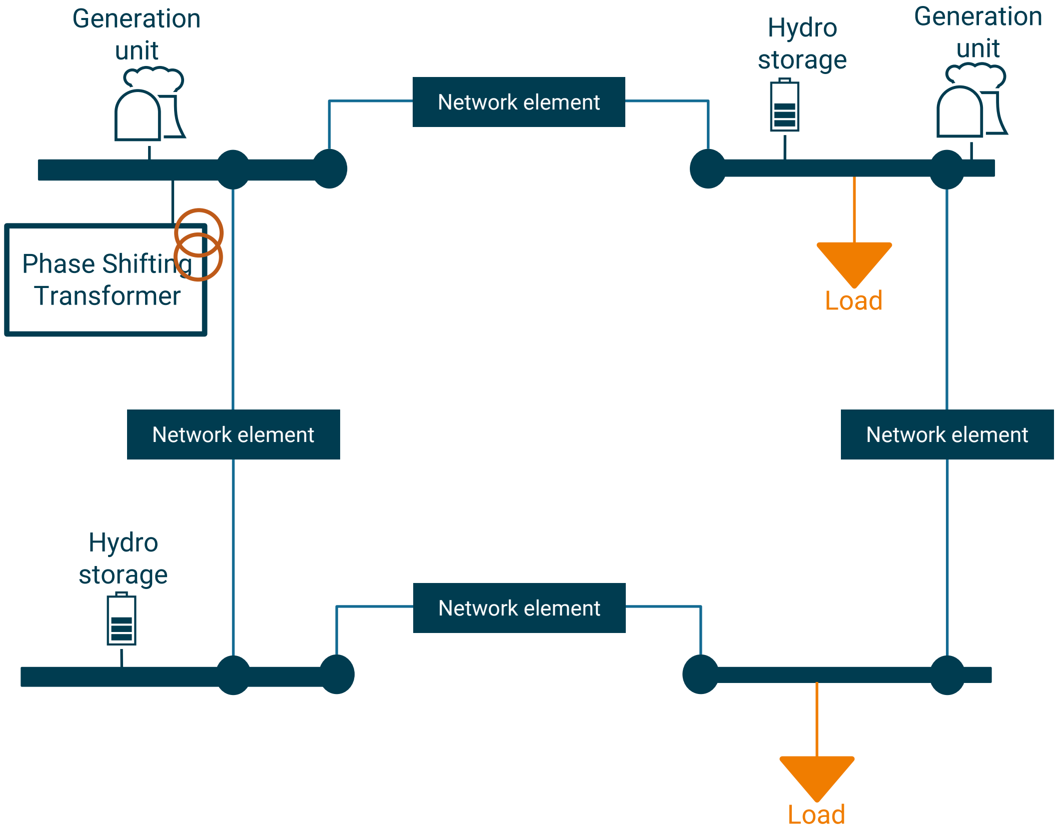

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Phase Shifting Transformer

A phase-shifting transformer is used to **manipulate the active power flow** in a line. It is a **non-costly RA** with **discrete tap positions** that can unbalance the grid if not compensated for.

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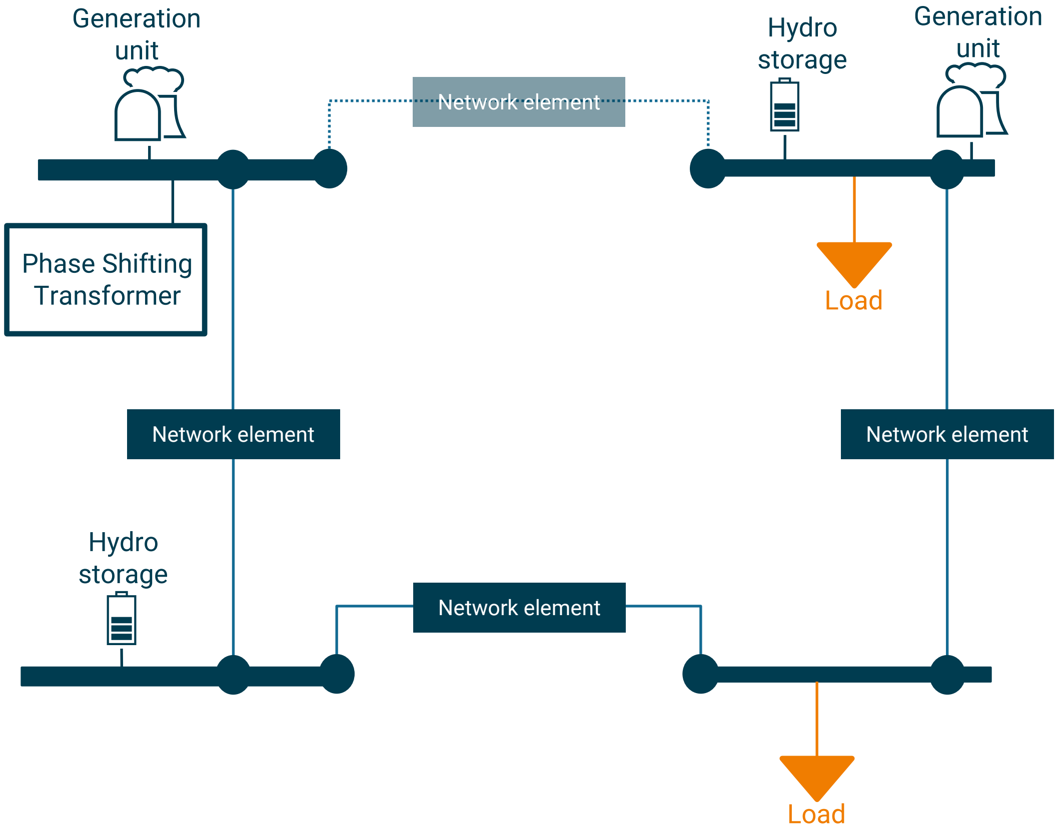

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Topology changes

To avoid grid overloads, a line can be **disconnected**. This can **significantly change other load flows** and the model becomes more complex.

PROJECT EXAMPLE: OPTIMIZATION OF REMEDIAL ACTIONS

02.02

Optimization Problem Formulation

Optimization problem for the application of remedial actions

The aim is to **reduce the cost** of using RAs. In addition, we can reduce the volume and number of RAs. In order to ensure grid stability, the **load flow limits** on the transmission lines must be adhered to.

$$\min_{RA} \sum c_{RA}\, B_{RA,ON} + c_{\Delta,RA} \sum \Delta P_{RA} + w_{n,RA} \sum |B_{RA}|$$

Variables / Parameters

$\boldsymbol{B_{RA,ON}}$	Indicator for start/shutdown of RA
$\boldsymbol{c_{RA}}$	Costs for start/shutdown of RA
$\boldsymbol{\Delta P_{RA}}$	Volume of redispatch of RA
$\boldsymbol{c_{\Delta,RA}}$	Costs per volume of redispatch of RA
$\boldsymbol{B_{RA}}$	Indicator for use of RA
$\boldsymbol{w_{n,RA}}$	Penalty for use of RA
$\boldsymbol{t \in 0, \dots, T}$	Time step
$\boldsymbol{P^t}$	Initial load flow at time t
$\boldsymbol{P_{temp,max}}$	Temporary load flow limit
$\boldsymbol{P_{perm,max}}$	Permanent load flow limit

Load flows must remain **below the limit** of the network elements.

- **A temporary limit** must never be exceeded in order to prevent network element failures.

$$P^t + \Delta P_{RA}{}^t \leq P_{temp,max}$$

- **A permanent limit** allows small overloads for a short time.

$$P^t > P_{perm,max} \Rightarrow P^{t+k} + \Delta P_{RA}{}^{t+k} \leq P_{perm,max}$$

Grid balance

After the application of RA, the grid must be balanced, i.e. the sum of all power flow changes must be zero.

$$\sum \Delta P_{RA,up} + \sum \Delta P_{RA,down} = 0$$

Alternating current (AC) power-flow model

To ensure the security of the grid a **high accuracy** of the model is needed. We use an AC load flow model instead of an DC approximation. The AC power flow is a **non-linear** system of equations.

Active and reactive power balance

$$0 = -P_i + \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik})$$

$$0 = -Q_i + \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik})$$

Variables / Parameters

$\boldsymbol{P_i}$	Active power at bus i
$\boldsymbol{Q_i}$	Reactive power at bus i
$\boldsymbol{V_i}$	Voltage magnitude at bus i
$\boldsymbol{\theta_{ik}}$	Voltage angle between bus i and bus k
$\boldsymbol{G_{ik}}$	real part of the bus admittance matrix of bus i and bus k
$\boldsymbol{B_{ik}}$	reactive part of the bus admittance matrix of bus i and bus k

Newton-Raphson solution method

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = -J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

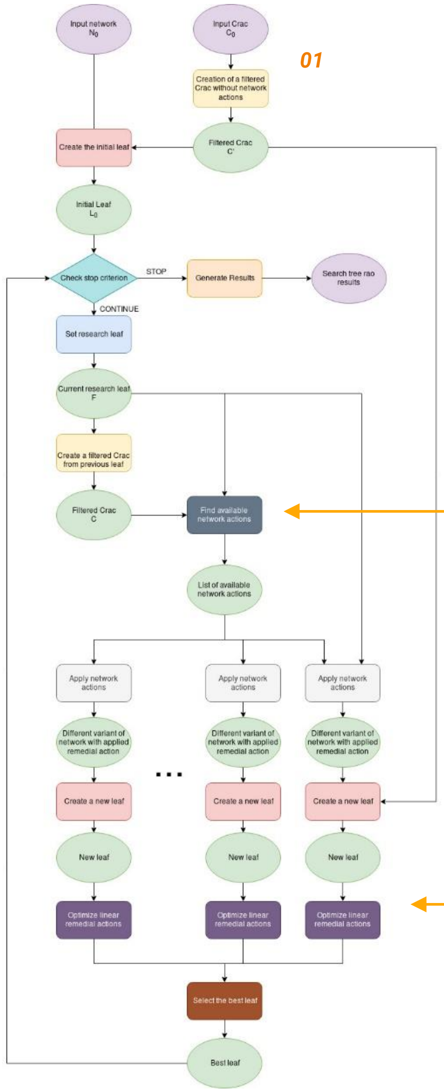
with

$$\Delta P_i = -P_i + \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik})$$

$$\Delta Q_i = -Q_i + \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik})$$

$$J = \begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} \\ \frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|} \end{bmatrix}$$

Open source remedial action optimization and capacity calculation



01

Find topological actions

Optimization of linear RAs

Open-source

- Open source toolboxes for remedial actions optimization
- Support remedial action optimization or capacity calculation
- Several models are publicly available on GitHub (e.g. CASTOR[01], farao[02])

Heuristic approach

- A heuristic search over separate steps of AC load flow calculation, topological actions and linearized remedial action optimization is used to find a solution

Technical Implement. of CASTOR

GitHub

Java

LF ENERGY POWSYBL

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[01] https://powsybl.readthedocs.io/projects/openrao/en/latest/castor.html [02] https://farao-community.github.io/

Reach out to us with your questions!

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