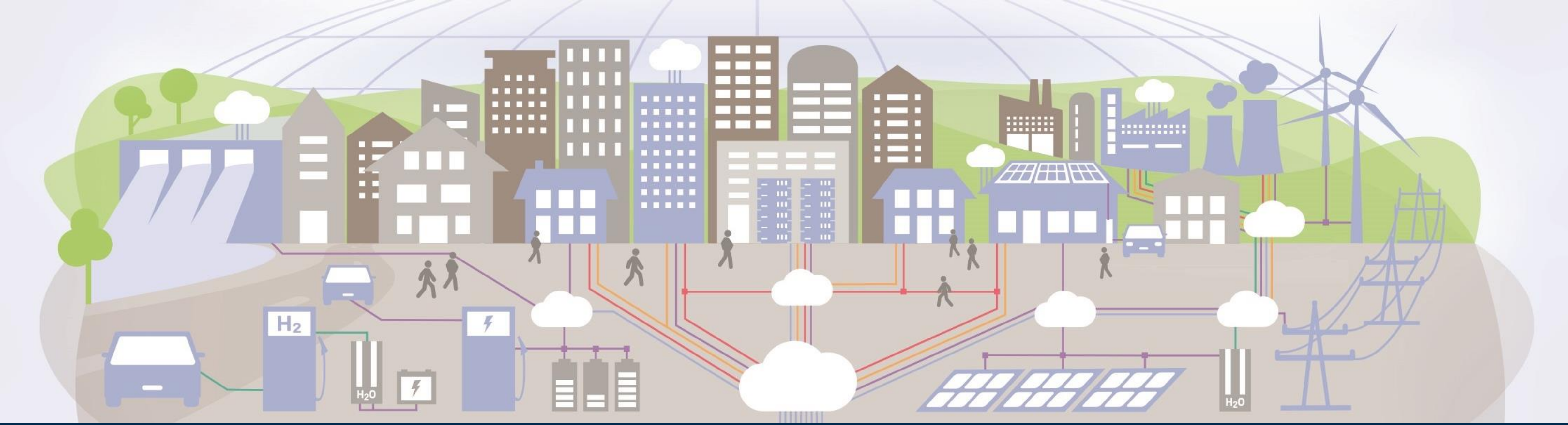


# QUANTUM ANNEALING BASED POWER GRID PARTITIONING FOR PARALLLEL SIMULATION

PROF. DR.-ING ANDREA BENIGNI



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# TRANSFORMATION OF THE ENERGY SYSTEM

## The Energy Transition Dilemma - The German Energiewende in a Changing World

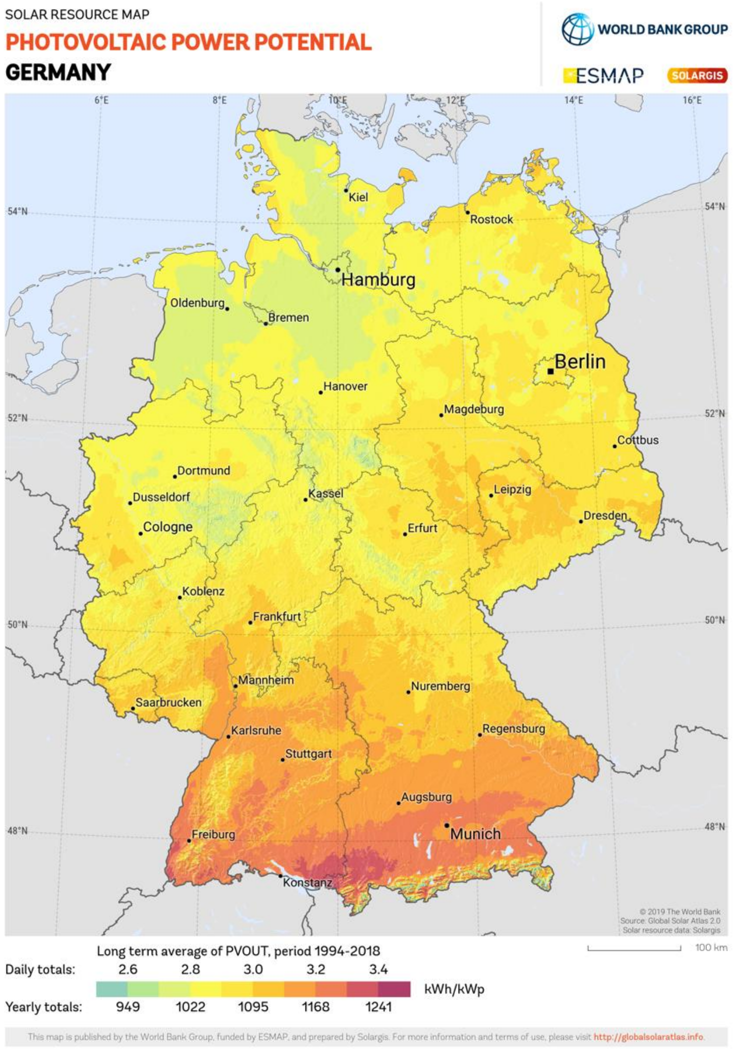

- Reduction of greenhouse gas emissions by 40% by 2020, 55% by 2030, and at least 80% by 2050 compared to 1990 levels?!
- Phase out of nuclear power by the end of 2022 (stretch operation until April 2023 in planning)?!
- Phase out of hard coal and lignite by the end of 2038?!
- Abandonment of gas from Russia as a bridging energy source!

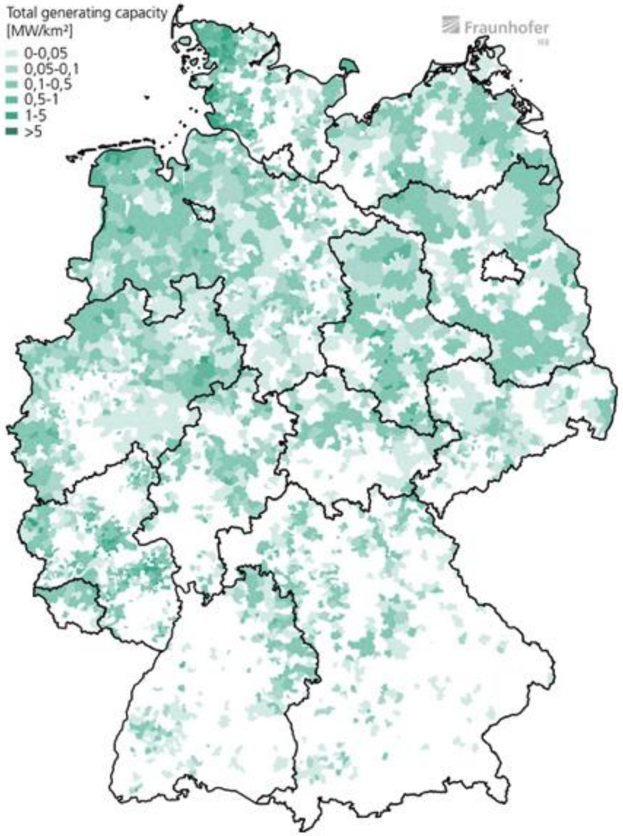
➢ How can we still ensure a reliable, affordable and sustainable energy supply?

➢ How can we handle the complexity of designing and operating resilient, more decentralized & sector-integrated energy systems?

# THE TRANSFORMATION OF THE ENERGY SYSTEM

## “Energiewende” started as a “Stromwende”




Exact postcode distribution of installed onshore wind capacity in Germany in 2018



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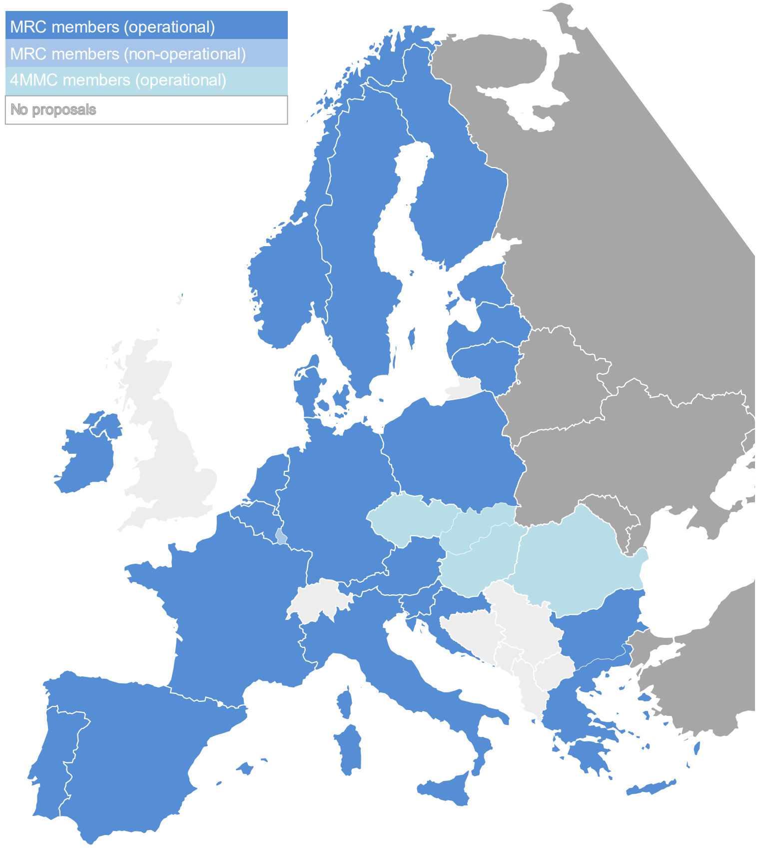
# COMPLEXITY OF LARGE-SCALE SYSTEMS

## The number of actors in the market is increasing strongly

- The European electricity market is a multiscale system that couples 28 countries representing 95% of the EU electricity demand
- The market coupling determines dispatch of generation, loads, prices and cross-border power flows
- Security of supply is secured by the n-1 criteria

➢ For the analysis of modern energy systems, both the continental and the local level must be considered in a multiscale fashion

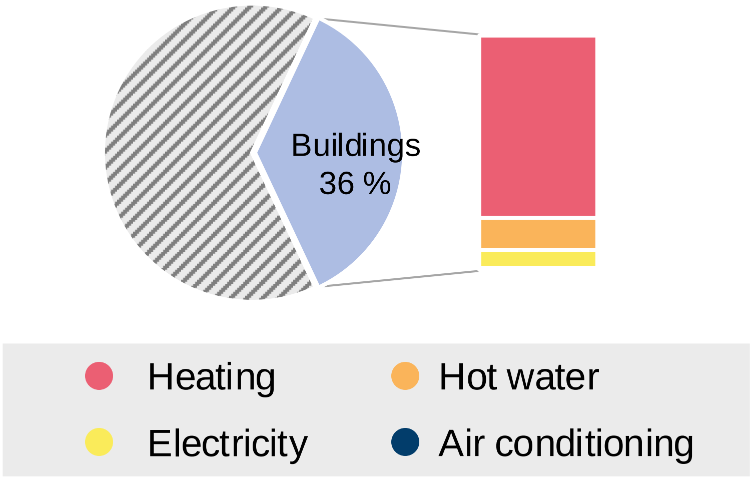


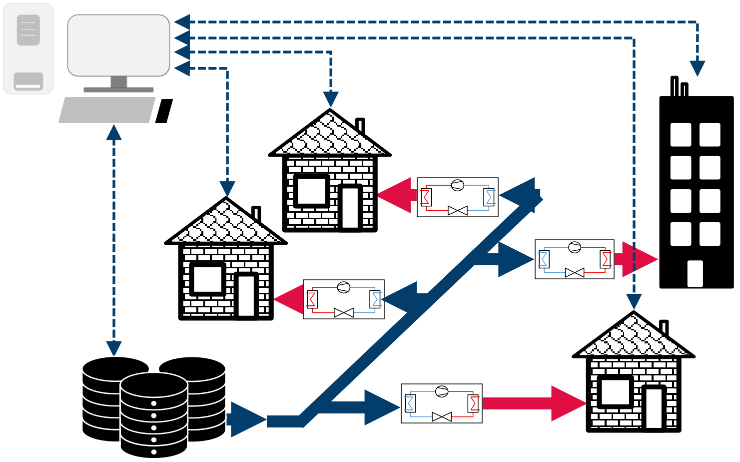

Source: https://www.entsoe.eu/network_codes/cacm/implementation/sdac/#sdac-geographical-scope-and-extensions

# THE TRANSFORMATION OF THE ENERGY SYSTEM

## “Energiewende“ and building sector

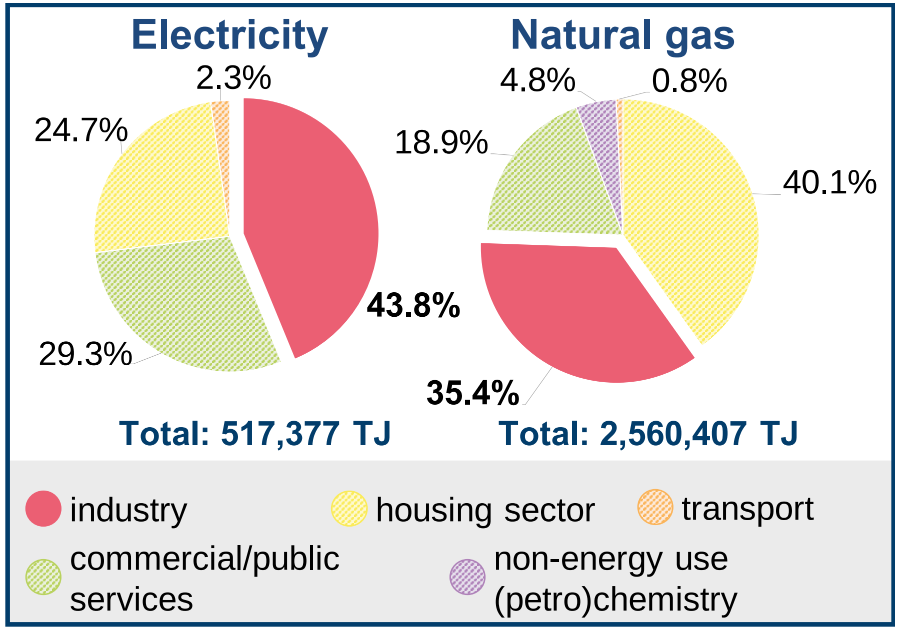
- Lowering energy demand and raised user awareness in buildings
  (while fulfilling higher comfort demand / cooling demand)
- Buildings can offer flexibility options to the electricity grid, e.g. by increased share of heat pumps in new buildings
- Modern district heating networks gain importance
  - Existing building stock aged (62 % built before 1979)
  - Gradual phase out of fossil plants
  - Integration of waste heat and renewables heat sources



# INDUSTRIAL SYSTEMS

## German Energy Demand* in 2016[1]




*relative to final energy demand

[1] International Energy Agency. *World Energy Statistics 2018*. Paris: IEA Publications, 2018.

Industry is responsible for a **large share of energy demand** (>30% of final energy for natural gas/electricity).

**Decarbonization**: Industry needs to satisfy its energy demand from **$CO_2$-neutral sources**.

To achieve cost competitiveness, **sector integration** and **demand side management** will be key.

# THE DECARBONISATION OF THE STEEL INDUSTRY

Handelsblatt

STAHLHERSTELLUNG

## CO2-freie Produktion bis 2050: Thyssen-Krupp will Hochöfen dichtmachen

von: Kevin Knitterscheidt
Datum: 21.01.2019 04:15 Uhr

Thyssen-Krupp will bis 2050 zehn Milliarden Euro in die CO2-freie Stahlerzeugung investieren. Für die Branche beginnt ein Rennen gegen die Zeit.

CO2-Verursacher

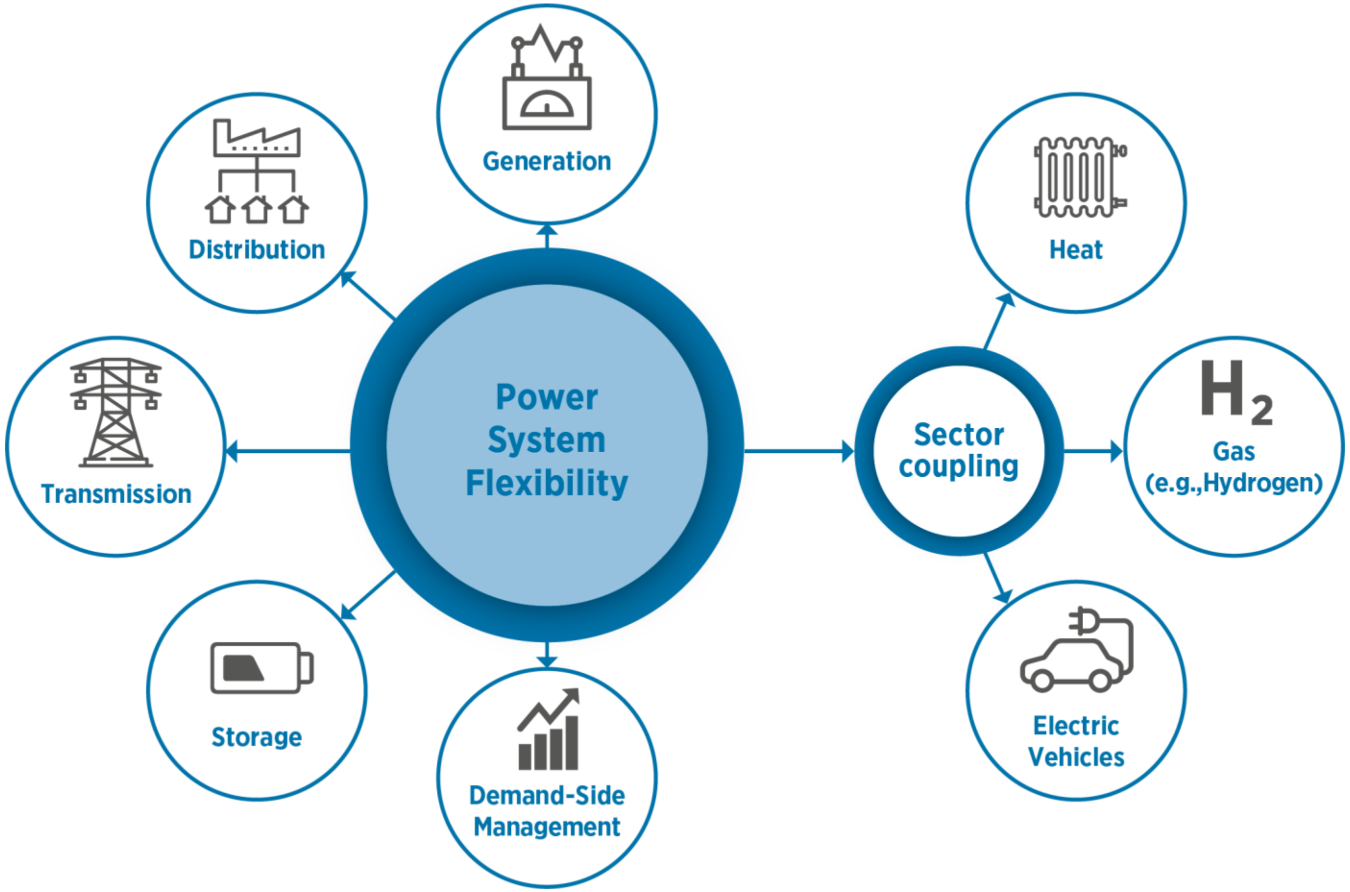
Die Stahlbranche denkt langsam um.

(Foto: dapd)

- It is the industry's task to make its contribution to climate protection, said Thyssen Krupp Steel Director Andreas Goss
- The company plans to invest a total of ten billion euros over the next 30 years in the modernization of its processes in order to replace coking coal.
- Over the next few decades, plants will be gradually modernized and rebuilt until the 2050 Duisburg blast furnaces are completely replaced by direct reduction systems and electric furnaces.

# FLEXIBILITY VS. SECTOR COUPLING

## Autonomous → sector coupling




**Flexibility** is the capability of power system to maintain its operation under uncertainties.

**Sector coupling** can offer flexibility to the power system with the focus is on the decarbonization of other sectors.

Source: https://www.irena.org/energytransition/Power-Sector-Transformation/Power-System-Flexibility.

# TRANSFORMATION OF THE ENERGY SYSTEM

| | |
|---|---|
| central | decentral |
| autonomous sectors | sector-coupling |
| demand-driven | production-driven |
| predictable | volatile |
| analog | digital |

Increased complexity, new and more players

Flexibility will become more valuable, e.g. storage, DSM

More information, more optimization potential

# COMPUTATIONAL CHALLENGES

- Need for longer simulation horizon while increasing temporal resolution (due to the reduced system inertia while introducing PtX technologies and seasonal storage)
- Need for spatial disaggregation (due to higher interconnections and distributed generation penetration)
- Need for higher number of contingencies and scenarios to considered (due to uncertainties and control dependencies)

Can quantum computing supports power system?
For which applications?

# QUANTUM-BASED ENERGY GRIDS

QuGrids

## Rethinking Planning and Operation of Energy Grids

### Planning and Design

Simulation and optimization are used to support topology and technology selection, components sizing, operating modes definition.

Existing approaches limited by computational complexity (Spatial and temporal span, Sector coupling)

### Quantum Computing for Energy Grids

Which computational challenge would benefit from QC?
How to combine quantum and traditional computing ?
Which impact would this have on systems metrics?

### Operation and Automation

Digital platform and ICT infrastructure used to monitor system operation, schedule assets (e.g. generators and storage), enable flexibility services

Existing approaches limited by the amount of involved players and generated data, latency and bandwicth, security and privacy concerns

### Quantum Communication for Energy Grids

How can QKD schemes be used in energy grid ?
Can we design a fully quantum-based automation architecture ?

# QUANTUM-BASED ENERGY GRIDS

## Rethinking Planning and Operation of Energy Grids

QuGrids

Develop first groundbreaking results so to highlight the value of quantum technologies, identify the shortcomings and define a research and development roadmap.

Develop the conditions for a long-term operation of the QuGrids consortium

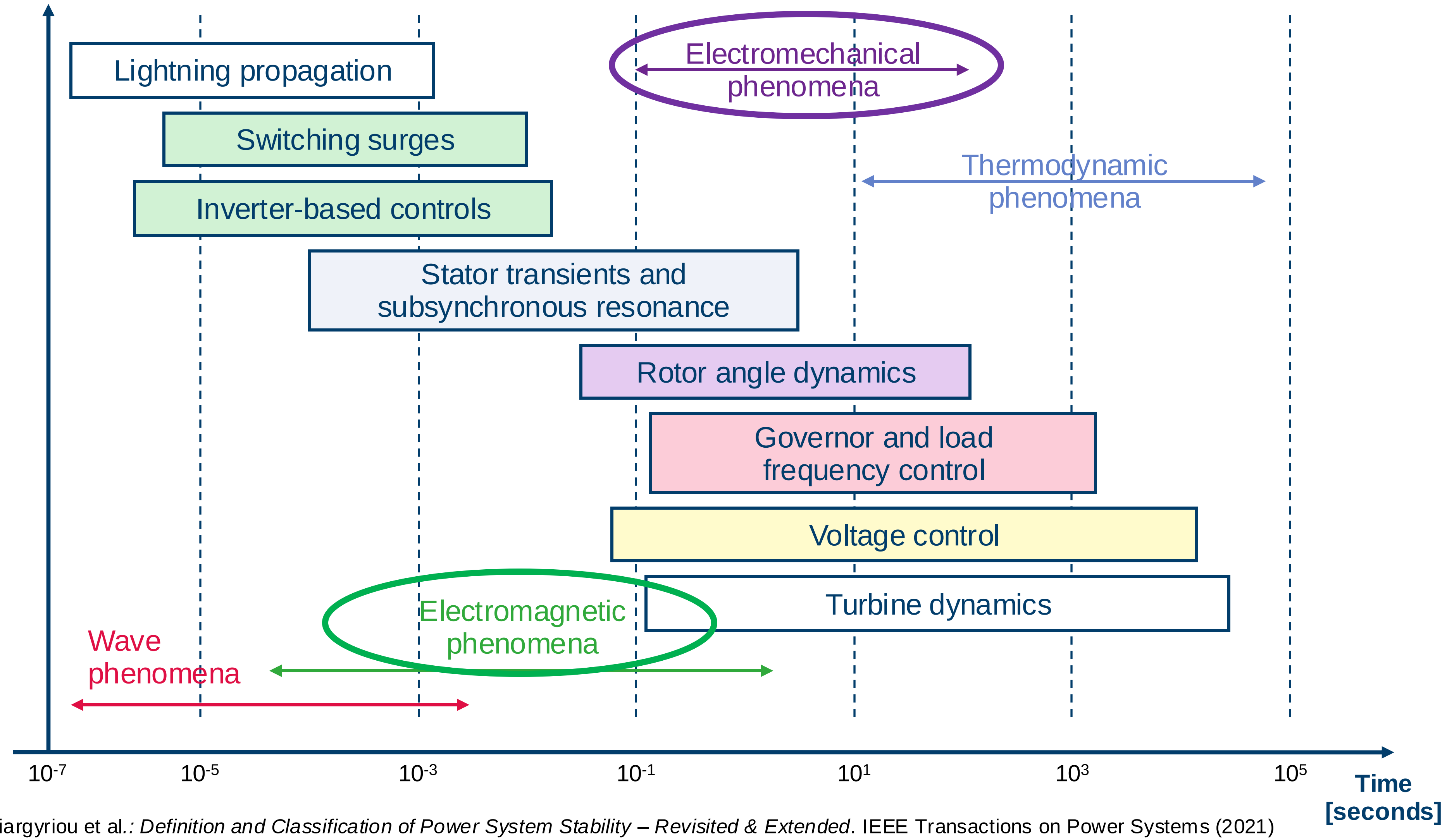
Create new teaching and training material for workforce development

# DEMO CASES FOR QUANTUM-BASED ENERGY GRIDS

**Objective:** Develop first groundbreaking results so to highlight the value of quantum technologies for energy grids and to identify the shortcomings of existing quantum technologies so to define a research and development roadmap.

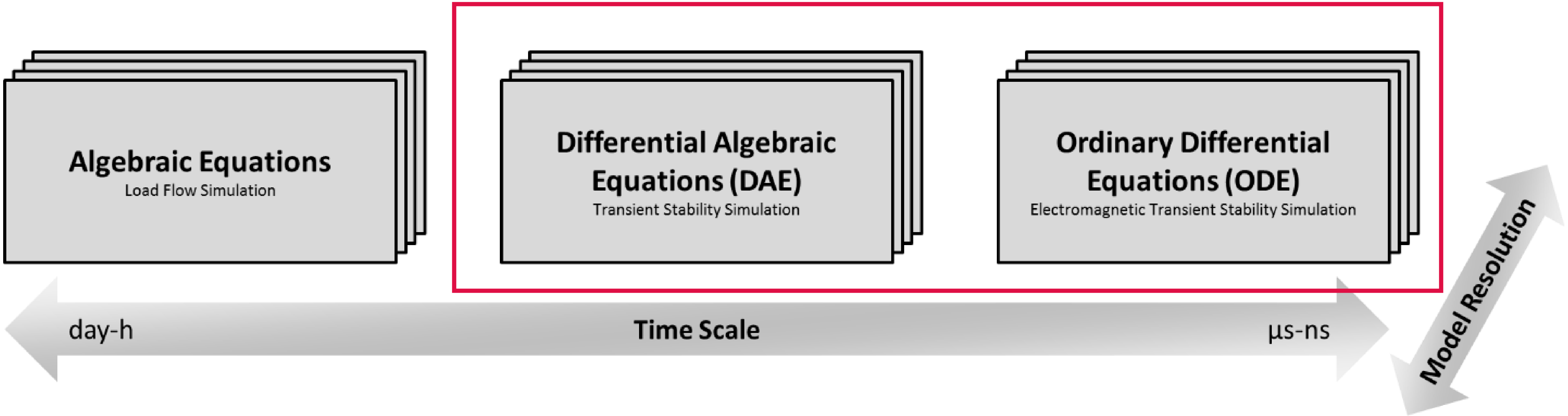
- WP1.1 Power System Monitoring
- WP1.2 Optimal Planning and Operation of Multi-Carrier Energy Networks
- WP1.3 Static and Dynamic Simulation Under Uncertainty
- WP1.4 Quantum based edge grids device
- WP1.5 Quantum communication in energy grids

# POWER SYSTEM TIME SCALES



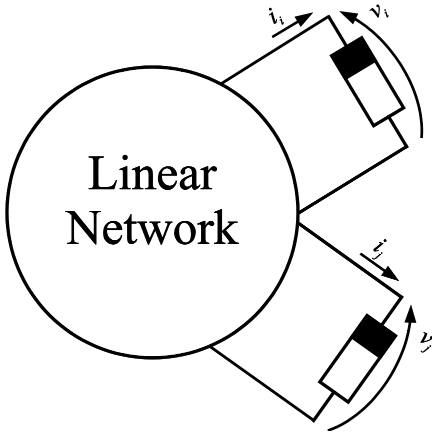

Hatziargyriou et al.: *Definition and Classification of Power System Stability – Revisited & Extended*. IEEE Transactions on Power Systems (2021)

# POWER SYSTEM SIMULATION



# POWER SYSTEM SIMULATION

## A parallel approach




$$\frac{di_i^n}{dt} = f(v, i, x_i^n, u_i^n, t) \qquad I_i^n(k+1) = f(v(k), i(k), x_i^n(k), u_i^n(k), k)$$

$$\frac{dv_j^n}{dt} = f(v, i, x_j^n, u_j^n, t) \qquad V_j^n(k+1) = f(v(k), i(k), x_j^n(k), u_j^n(k), k)$$

$$I^n(k+1) = f(v(k), i(k), x(k), u(k), k)$$

$$V^n(k+1) = f(v(k), i(k), x(k), u(k), k)$$

$$YV(k+1) = b(v(k), i(k), I^n(k), V^n(k), k)$$

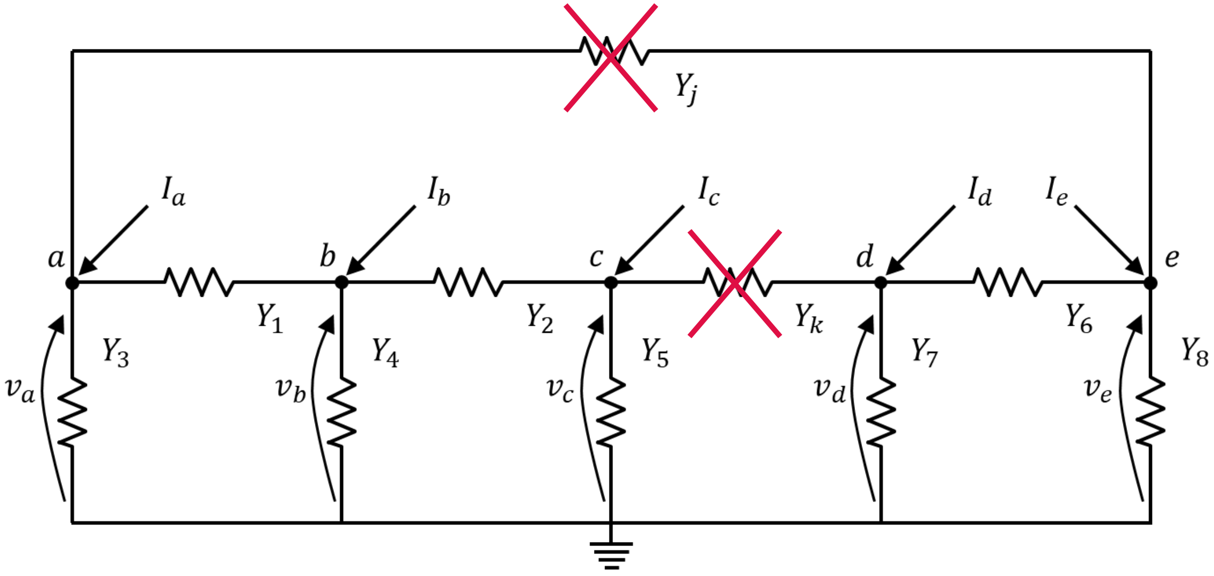
**Solved in parallel**

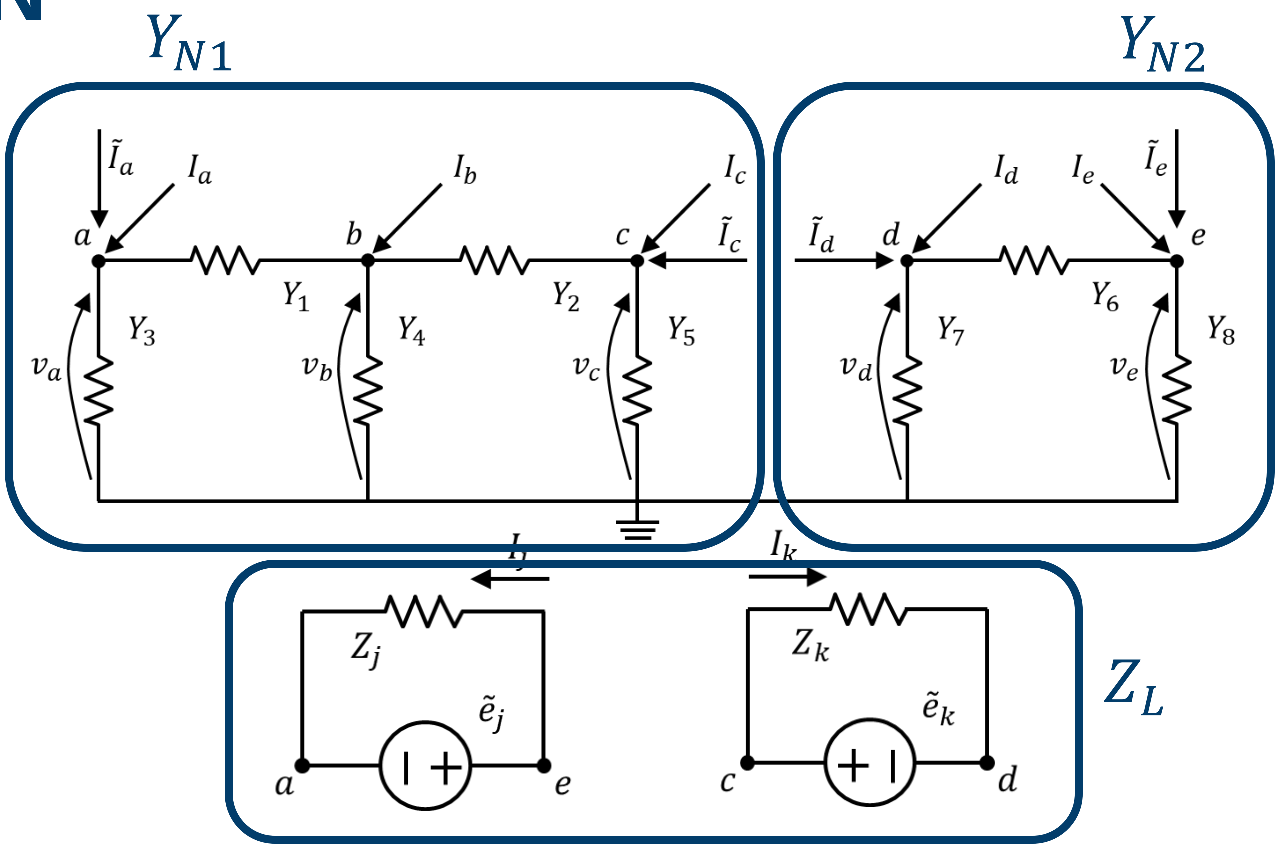
**Still quite large**

# POWER SYSTEM SIMULATION

## A parallel approach

$YV = b$




$$\begin{bmatrix} \begin{bmatrix} Y_{N1} & 0 \\ 0 & Y_{N2} \end{bmatrix} & C \\ C^T & -Z_L \end{bmatrix} \begin{bmatrix} v_{N1} \\ v_{N2} \\ i_L \end{bmatrix} = \begin{bmatrix} i_{N1} \\ i_{N2} \\ -V_L \end{bmatrix}$$

# POWER SYSTEM SIMULATION

## A parallel approach

Nodal admittance matrix for subsystem

Nodal voltages

Nodal current injections

$$\begin{bmatrix} \begin{bmatrix} Y_{N1} & 0 \\ 0 & Y_{N2} \end{bmatrix} & C \\ C^T & -Z_L \end{bmatrix} \begin{bmatrix} v_{N1} \\ v_{N2} \\ i_L \end{bmatrix} = \begin{bmatrix} i_{N1} \\ i_{N2} \\ -V_L \end{bmatrix}$$

Thévénin voltages on the branches

Cut to Subsystem current injection matrix

Thévénin impedance matrix for cut branches

branch currents on the cut

# POWER SYSTEM SIMULATION

## A parallel approach

$$\begin{bmatrix} 1 & 0 & Y_{N1}^{-1} C_{N1} \\ 0 & 1 & Y_{N2}^{-1} C_{N2} \\ 0 & 0 & C_{N1}^{\top} Y_{N1}^{-1} C_{N1} + C_{N2}^{\top} Y_{N2}^{-1} C_{N2} + Z_L \end{bmatrix} \begin{bmatrix} v_{N1} \\ v_{N2} \\ i_L \end{bmatrix} = \begin{bmatrix} Y_{N1}^{-1} h_{N1} \\ Y_{N2}^{-1} h_{N2} \\ C_{N1}^{\top} Y_{N1}^{-1} h_{N1} + C_{N2}^{\top} Y_{N2}^{-1} h_{N2} + V_L \end{bmatrix}$$

→ Subsystems are independent of each other except of the cut.

**Simulation steps in each time step**

1. Solve DAE for **components** to obtain injecitions (in parallel)
2. Solve **Network equations** over the cut
3. Solve **Network equations** of the subsystems (in parallel)

# POWER SYSTEM SIMULATION

## Optimize the partitioning

- Minimize cut overhead
- Balance the size of the subsystems
- Balance computational load of components between subsystems

Can we formulate the partitioning problem as a QUBO problem ?

# GRID PARTITIONING FOR PARALLEL SIMULATION

## How to solve QUBOs using Quantum Annealing

Problem Hamiltonian

**Q**uadratic **U**nconstrained **B**inary **O**ptimization:

$$\min_{\{x_n \in [0,1]\}} Q$$

$$Q = \sum_{n,m} x_n Q_{n,m} x_m$$

⟷

$$s_n = 2x_n - 1$$

Find ground state of **Ising Hamiltonian**

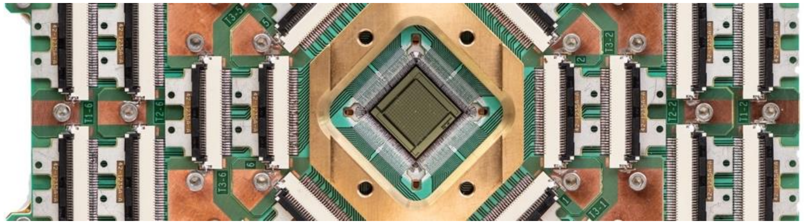
# GRID PARTITIONING FOR PARALLEL SIMULATION

## How to solve QUBOs using Quantum Annealing

### D-Wave Quantum Annealing

- Implementation of „AQC“ to solve optimization problems
- Initial / Driver Hamiltonian $H_D$ is fixed
- Problem Hamiltonian $H_P$ is programmable Ising Hamiltonian
- QPU: currently 5000+ flux qubits and 40000+ couplers aranged in Pegasus topology

→ Not AQC (not universal) since a open system and limited choice for $H_P, H_D$

D-Wave Advantage™ System JUPSI (JSC)

# GRID PARTITIONING FOR PARALLEL SIMULATION

## QUBO for Optimal Graph Partitioning for Parallel Simulation of Power Grids

### Parallel Simulation of Partitioned Grid

- Simulation steps in each time step:
1. Solve DAE for **components**
2. Solve **Network eq.** over the **cut**
3. Solve **Network eq.** of the **subsystems**

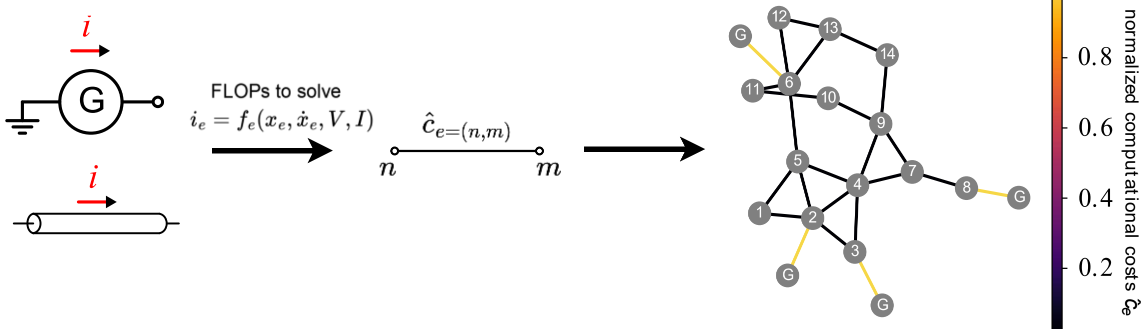
- Objectives for partitioning:
1. Reduce Idle time components in Subs.
2. Minimize overhead cut
3. Reduce Idle time subnetworks

### QUBO formulation for optimal partitioning

- Create Graph where every **component** is an **edge** and computational cost as edge weight
- **Binary Encoding** of Partitioning

$$x_n = \begin{cases} 1 & \text{node } n \in \text{Part } 1, \\ 0 & \text{node } n \in \text{Part } 2. \end{cases}$$

IEEE test case with 14 buses



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# GRID PARTITIONING FOR PARALLEL SIMULATION

## QUBO for Optimal Graph Partitioning for Parallel Simulation of Power Grids

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→

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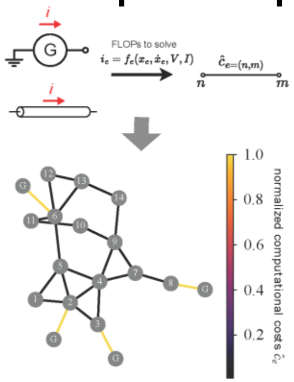
### QUBO formulation for optimal partitioning

Graph Representation:




$$x_n = \begin{cases} 1 & n \in \text{Part } 1, \\ 0 & n \in \text{Part } 2. \end{cases}$$

Formulate QUBO objective functions that **estimate** the overhead:

# GRID PARTITIONING FOR PARALLEL SIMULATION

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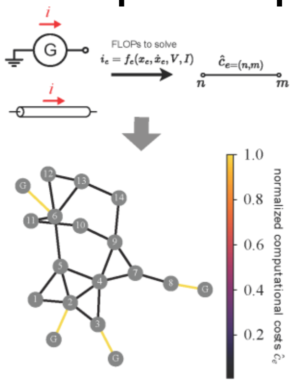


$$x_n = \begin{cases} 1 & n \in \text{Part } 1, \\ 0 & n \in \text{Part } 2. \end{cases}$$

Formulate QUBO objective functions that **estimate** the overhead:

1. Balance components:

$$Q_{comp} = \left( \sum_{e:\text{Part } 1} c_e - \sum_{e:\text{Part } 2} c_e \right)^2 = \left( 2 \sum_{n \in V_{bus}} \alpha(n) x_n - \sum_{n \in V_{bus}} \alpha(n) \right)^2$$

$$\alpha(n) := \frac{1}{2} \sum_{m \in V_{bus}} c_{(n,m)} + \sum_{m \in V_{gen}} c_{(n,m)}$$

# GRID PARTITIONING FOR PARALLEL SIMULATION

## QUBO for Optimal Graph Partitioning for Parallel Simulation of Power Grids

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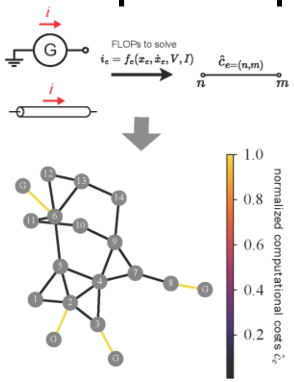


$$x_n = \begin{cases} 1 & n \in \text{Part } 1, \\ 0 & n \in \text{Part } 2. \end{cases}$$

Formulate QUBO objective functions that **estimate** the overhead:

2. Minimize overhead due to cut:

$$Q_{cut} \approx \sum_{e:\text{Cut}} c_e + 4(N-1)M_{cut} = \frac{1}{2}\sum_{n,m \in V_{bus}} A_{n,m}\left(c_{(n,m)} + 4(N-1)\right)\left(-2x_n x_m + x_n + x_m\right)$$

component cost

Forward-Backward substitution for LU decomposition + updating injections

# GRID PARTITIONING FOR PARALLEL SIMULATION

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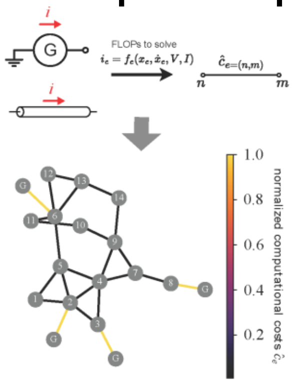


$$x_n = \begin{cases} 1 & n \in \text{Part } 1, \\ 0 & n \in \text{Part } 2. \end{cases}$$

Formulate QUBO objective functions that **estimate** the overhead:

3. Balance Subnetwork size:

$$Q_{network} = (2N-1)^2 \left( 2 \sum_n x_n - N \right)^2$$

Difference for Forward-Backward substitution based on LU decomposition

# GRID PARTITIONING FOR PARALLEL SIMULATION

## QUBO for Optimal Graph Partitioning for Parallel Simulation of Power Grids

### Parallel Simulation of Partitioned Grid

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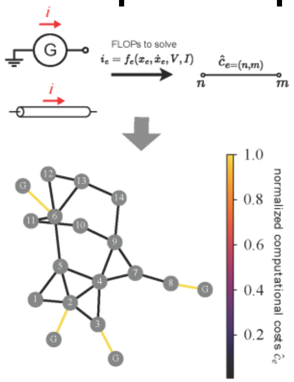



$$x_n = \begin{cases} 1 & n \in \text{Part } 1, \\ 0 & n \in \text{Part } 2. \end{cases}$$

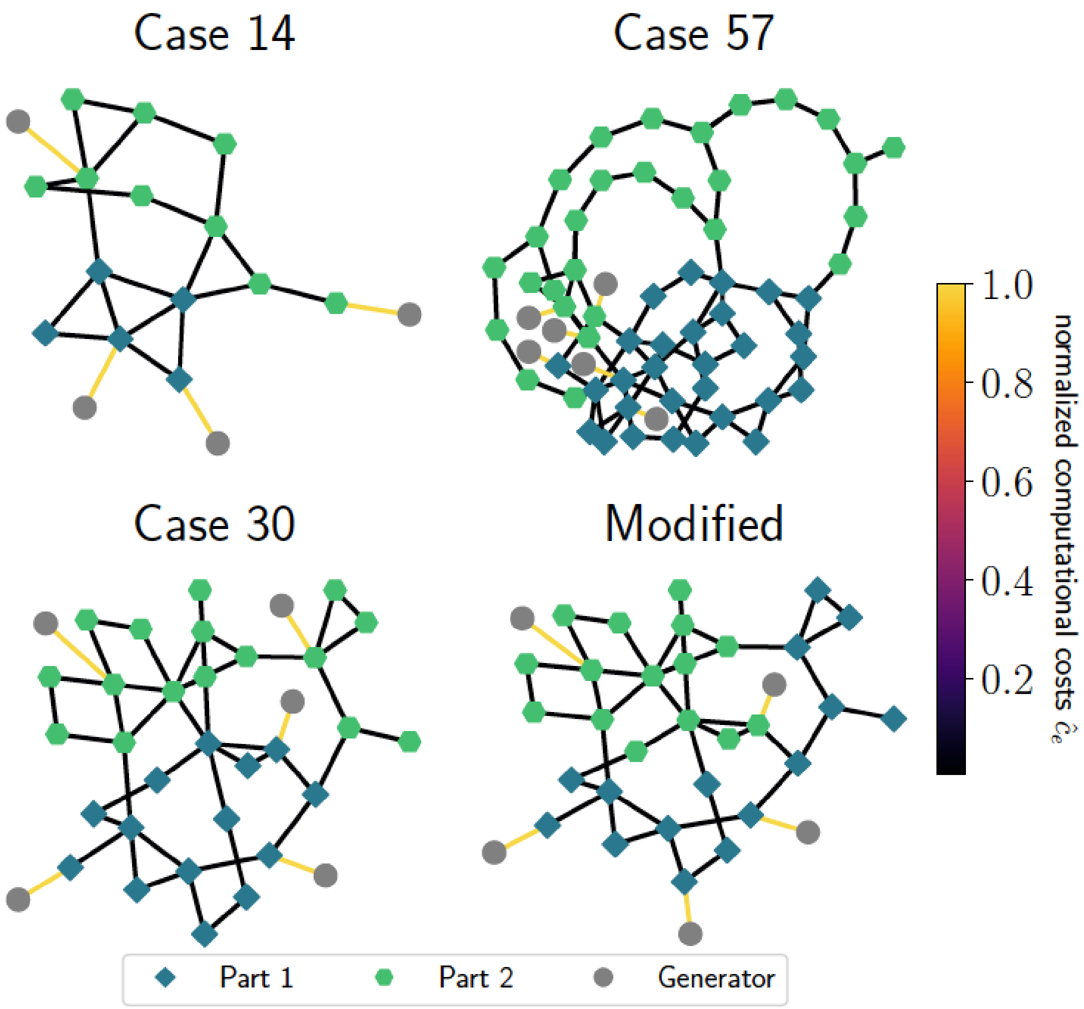
Full QUBO:

$$Q = Q_{comp} + Q_{cut} + Q_{net}$$

Estimates the complete overhead of a partitioning.

# GRID PARTITIONING FOR PARALLEL SIMULATION

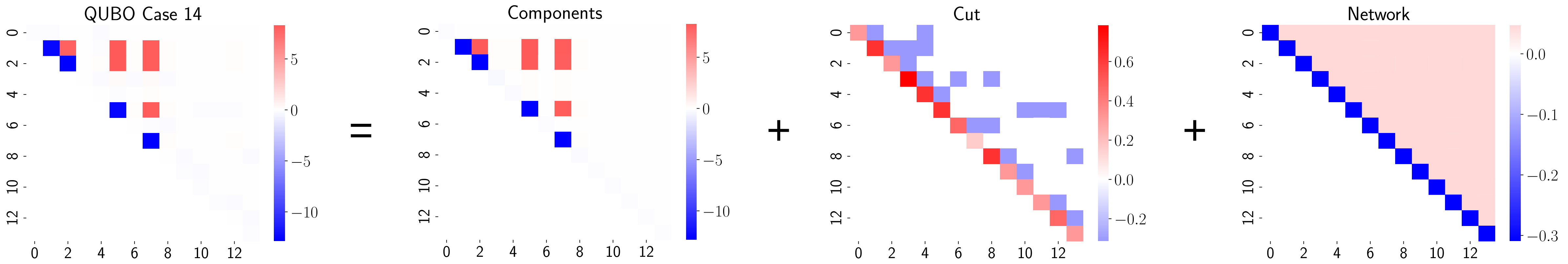
## QUBO for Optimal Graph Partitioning for Parallel Simulation of Power Grids – Gurobi solution



# GRID PARTITIONING FOR PARALLEL SIMULATION

## Solving on D-Wave annealer

The Need For Embedding

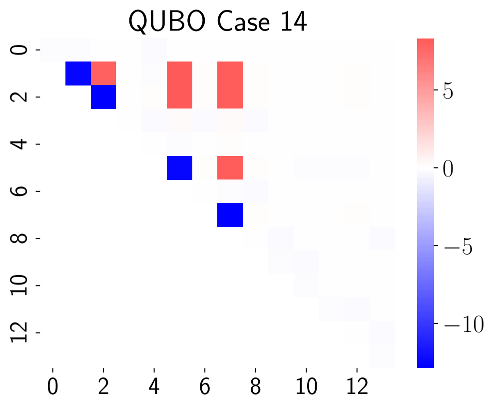



- Some QUBO terms are fully connected

# GRID PARTITIONING FOR PARALLEL SIMULATION

## Solving on D-Wave annealer

### The Need For Embedding




- Some QUBO terms are fully connected
- QPU has limited qubit connectivity

➡ Need (minor) Embedding: **chain** of physical qubit represent one logical qubit

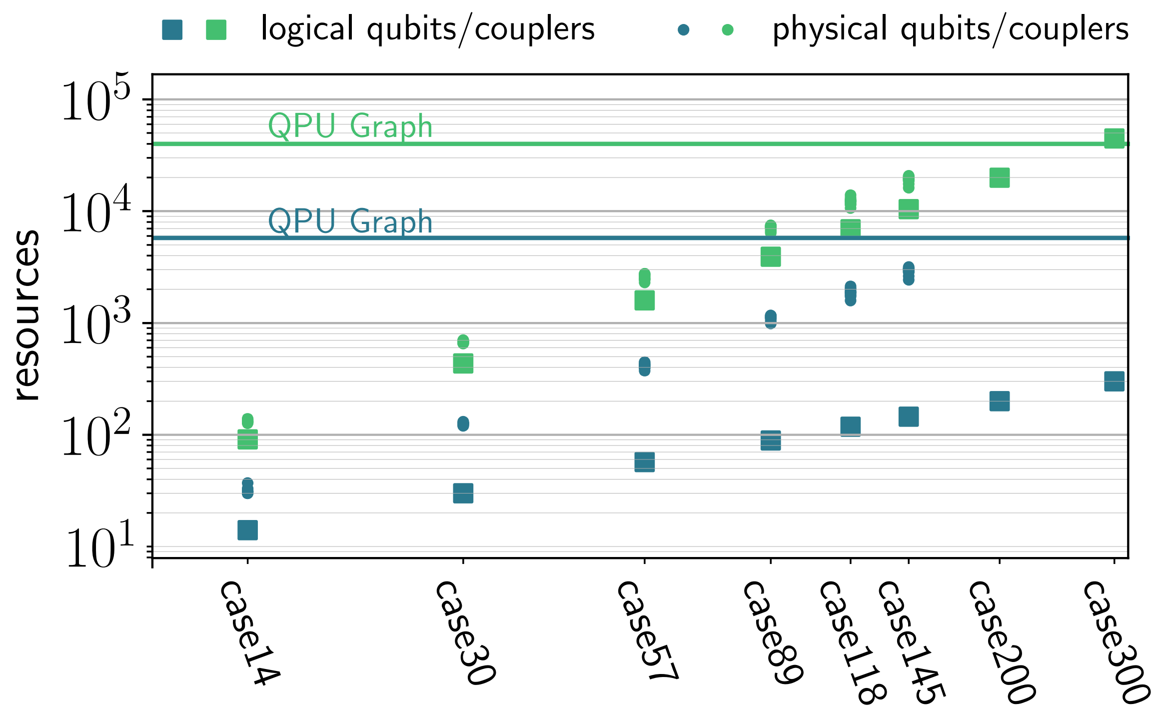
# GRID PARTITIONING FOR PARALLEL SIMULATION

## Solving on D-Wave annealer

### The Need For Embedding

Limited connectivity on QPU ➡ Dense QUBOs must be embedded

### Consequences of Embedding



# GRID PARTITIONING FOR PARALLEL SIMULATION

## Solving on D-Wave annealer

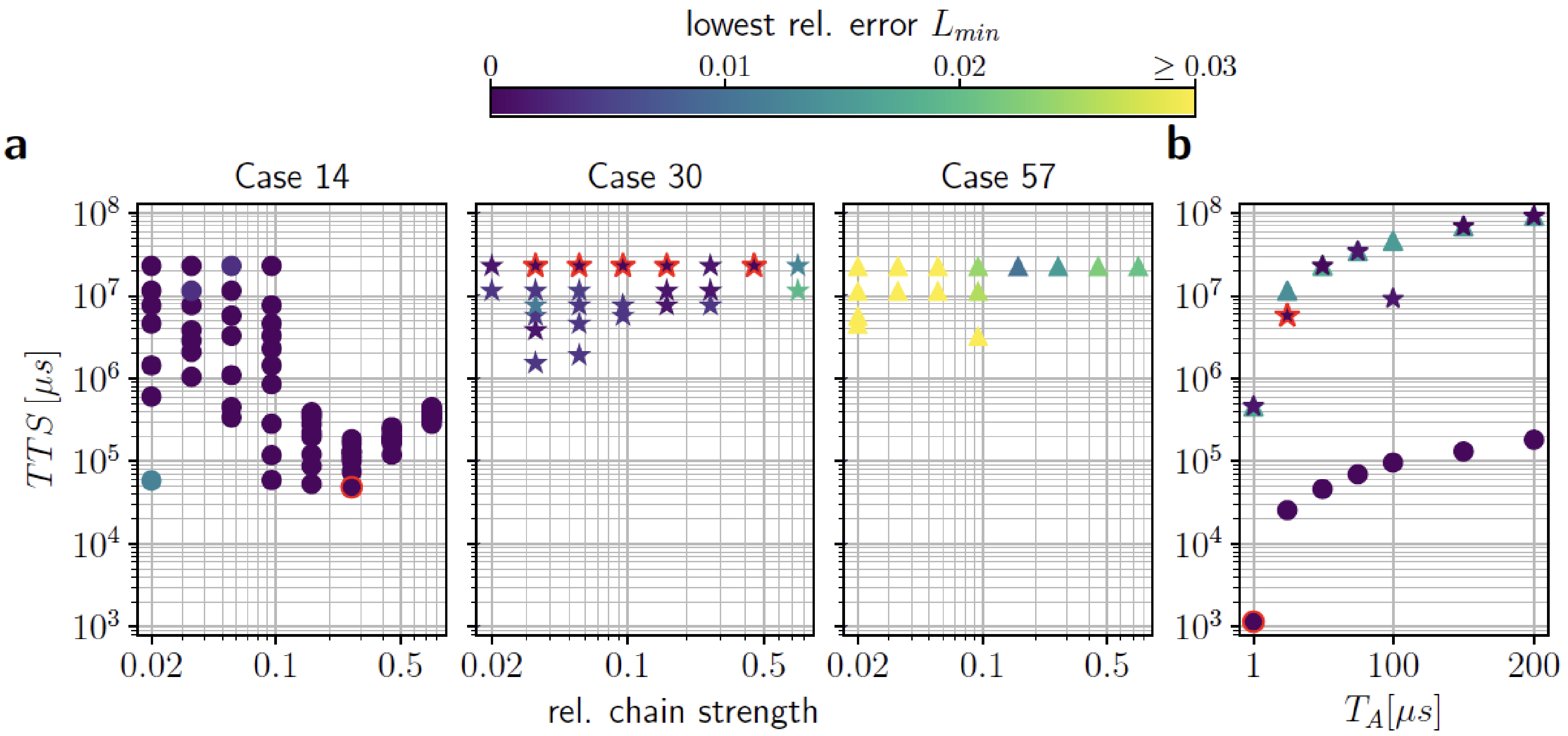
**Relative Error**

$$L = \frac{|E_{min,\,global} - E_{sampled}|}{|E_{min,\,global}|}$$

$$L_{min} := \min_{E_{sampled}} L\,.$$

**Time to Solution**

$$TTS(p_S, T_A) := \frac{\log(1-p_S)}{\log(1-\frac{N_{opt}}{N_s})} T_A,$$



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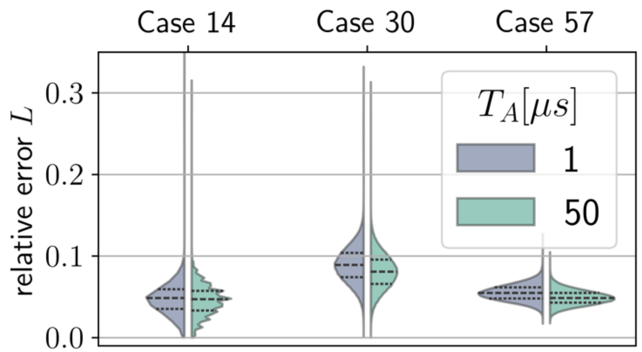
# GRID PARTITIONING FOR PARALLEL SIMULATION

## Outlook: What could be next for partitioning?

1. Embeddings are the major bottelneck for scaleability:
   - Prune the QUBO, so it becomes more sparse
   - Test other reduction methods (Ohzeki. et al: „Breaking limitation of quantum annealer in solving optimization problems under constraints")
2. Near-optimal solutions can be sampled fast:
   - Evalauate near optimal solutions in the simulation loop
   - What is the optimal number of samples to achieve fast simulation with high probability.
3. The QUBO does not enforce that the subsystems are connected:
   - Try to formulate additional constraints that are efficient.



Distribution of relative error in the Sampleset

# CONCLUSION

- A preprint of the paper used for this lecture can be found at: https://arxiv.org/pdf/2408.04097

- Quantum computing can support power system simulation and optimization but:
  - What is the gain ?
  - Which problem ?

- If you are interested in working on the topic contact me!

  https://www.fz-juelich.de/en/ice/ice-1

  Andrea Benigni a.benigni@fz-juelich.de