System stability in future power systems

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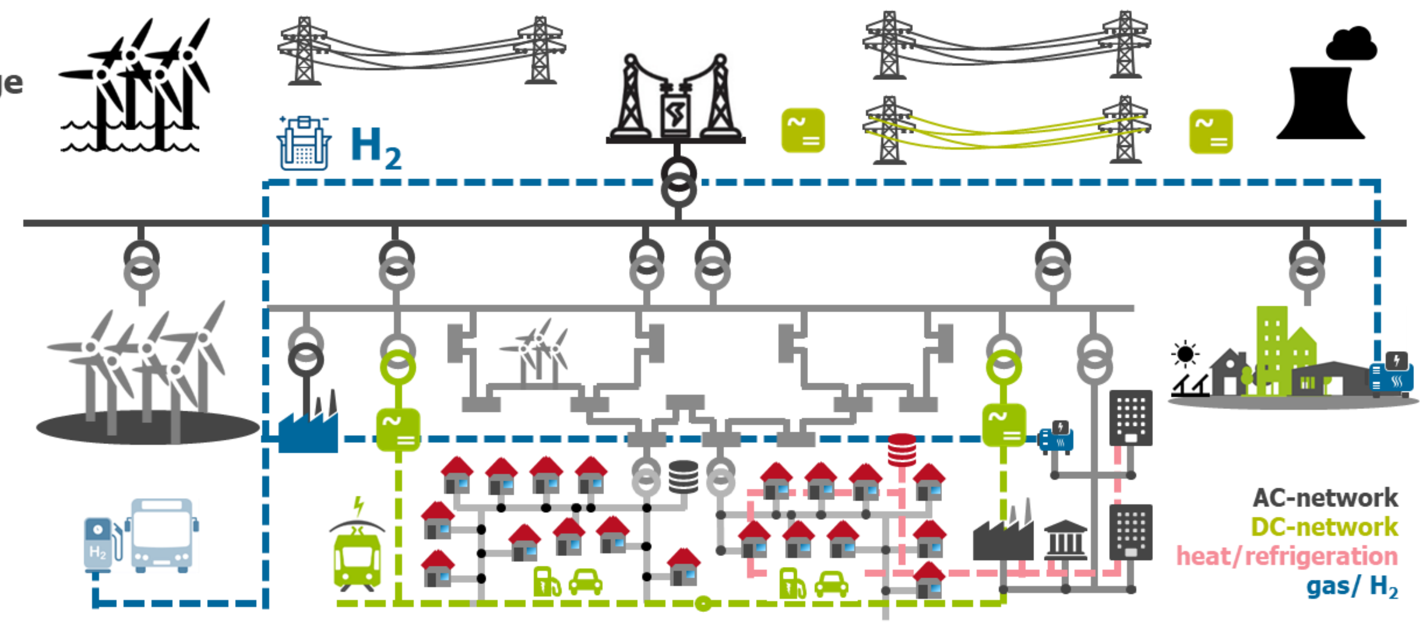
KAST, Leopoldina, Bilateral Symposium Energy Transition, Session IV Grid Management
January 15th 2025
Prof. Dr.-Ing. Jutta Hanson



Agenda

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Introduction to the German power system

System characteristics

Network and Converter control

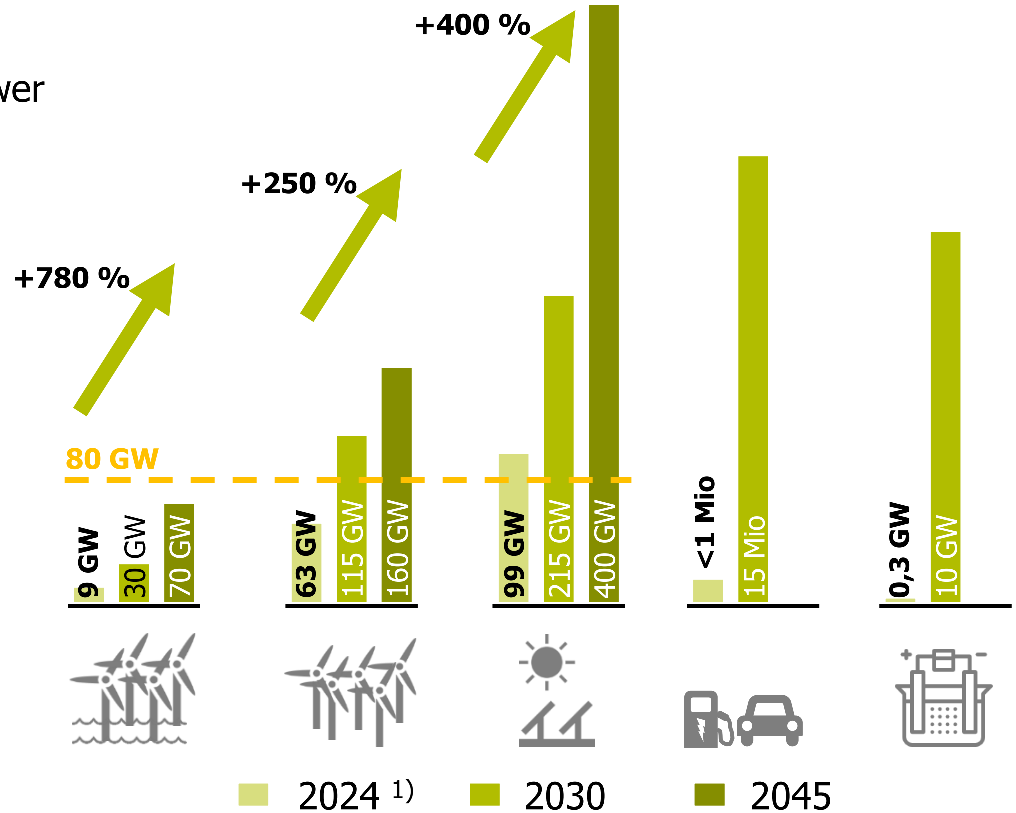
System stability

Outlook

Key facts of German "Energiewende"

Renewable Energies, Electrical vehicles, Hydrogen

- Greenhouse gas neutrality until 2045 [3)]
- Phase-out of coal-fired and nuclear power plants (in 2038, 2023)
- 80% of electrical energy consumption (750 TWh) in 2030 from renewable energies [3)]
- Power generation almost entirely from renewable energies by 2035 [3)]
- Making power supply reliable and consumption more flexible [2)]



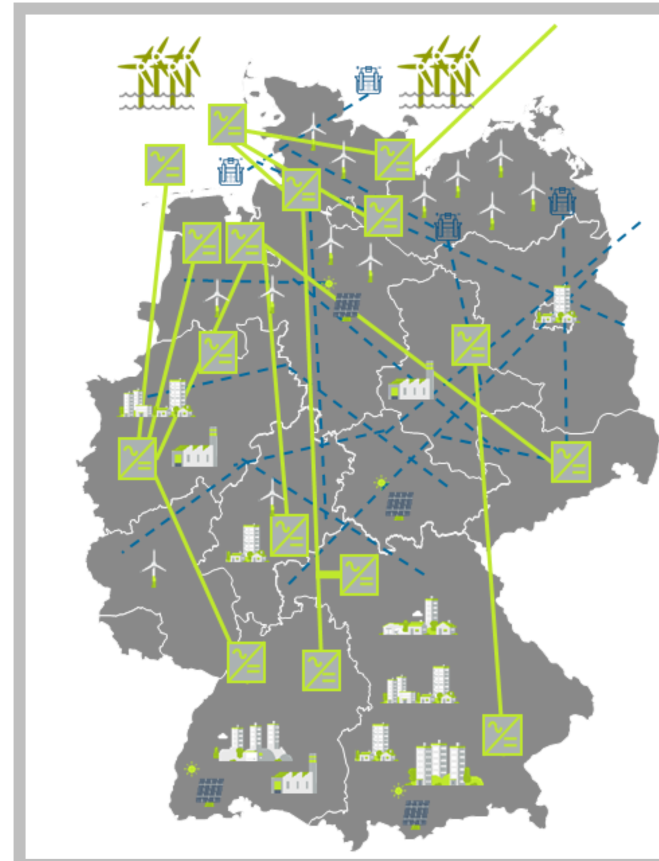
Sources:
1) https://www.umweltbundesamt.de/themen/erstes-halbjahr-2022-deutlich-mehr-strom-aus-wind
2) https://www.ewi.uni-koeln.de/de/aktuelles/ewi-analyse-das-bedeutet-der-koalitionsvertrag-fuer-den-stromsektor/
3) https://www.bmwk.de/Redaktion/DE/Downloads/Energie/0406_ueberblickspapier_osterpaket.pdf?__blob=publicationFile&v=14

The future transmission grid in Germany
Network development plan 2045

- Extension of **AC grid connections** and utilization of **embedded HVDC transmissions** for a hybrid AC/DC system
- **Onshore**
  - 20 point-to-point HVDC projects,
    → Expansion into a multi-terminal system in the future
  - 99 HVAC projects
- **Offshore**
  - 21 point-to-point HVDC projects

		Existing	In planning/construction	Future projects
Onshore	HVAC	38.000 km	8.222 km	4.600 km
	HVDC		5.212 km	2.800 km
Offshore	HVAC	2.158 km	479 km	300 km
	HVDC		3.357 km	8.155 km

Sources: www.netzentwicklungsplan.de, NEP 2037/2045, www.bmwk.de, "Stand des Übertragungsnetzes"



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Elektrische Energieversorgung unter Einsatz Erneuerbarer Energien

Agenda

System characteristics
Changes in system behavior

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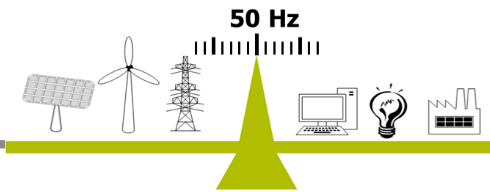
WHERE?

- **Distributed generation** in small units
- **Off-consumer generation** in large units
  - **Wind energy**, particularly offshore
  - **Hydro power** – Alps, Scandinavia



HOW?

- **Fluctuating** generation
- **Inaccuracy of generation due to weather forecast**
- **Generation units with power electronics**

1. Balancing fluctuations requires **flexibilities/storages**
2. An electrical network with this new energy mix tends to behave
   - **"weaker"** (less voltage stable)
   - **"faster"** (less frequency stable)

System characteristics

Challenges for system stability

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CHALLENGES

- Volatility
- Small time constants
- Off-consumer generation
- Weak grid / Islanded grid
- Control technology – no physical-based behavior

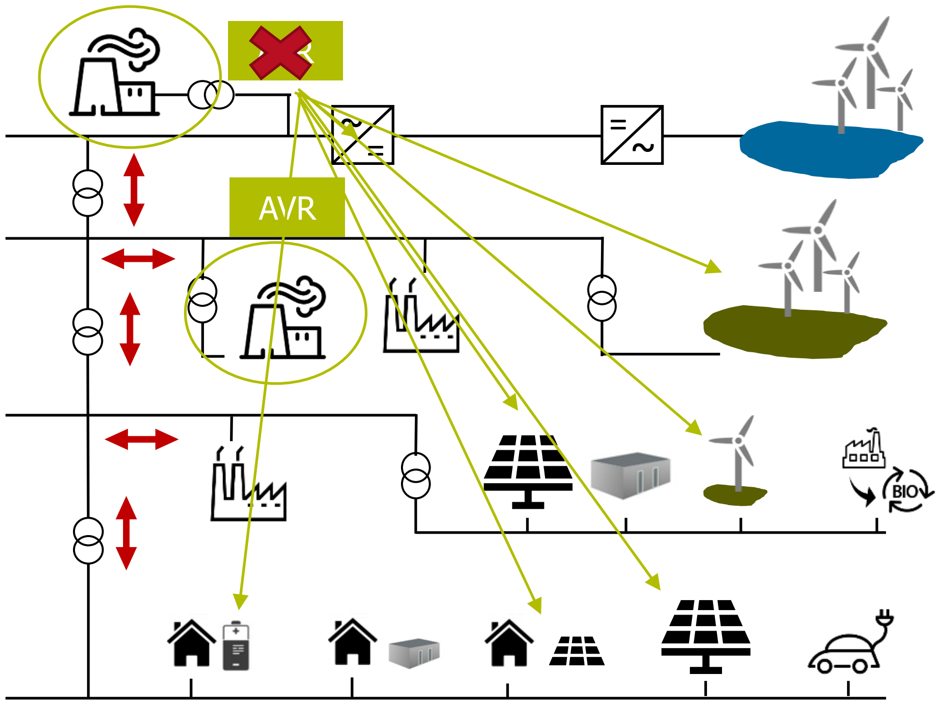
FOCUS STABILITY

- Modeling and simulation of the system
- Flexibility (Power-to-X, Storage)
- Higher utilization rate of equipment
- Complexity - Control of (many) power electronic devices

Agenda

- Introduction to the German power system
- System characteristics
- **Network and Converter control**
- System stability
- Outlook

Network Control
Change in generation structure



Increase in VSC-based generation in distribution grids

Conventional power plants in the transmission grid:
voltage-controlling with inertia

Usage of conventional power plants decreases with increasing infeed of renewables

Participation of VSC-based generation in network control

Influence on grid dynamics and system stability

Characteristics of Converter Control

Classification according to Cigré B4, TF77 (CSE 2019)

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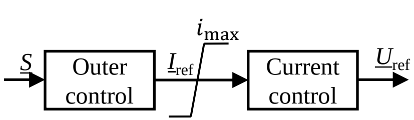
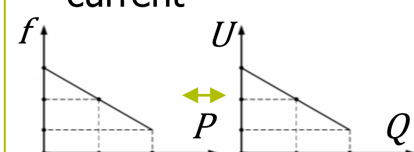
VSC-Control

Grid-following
- Grid-feeding with grid-support during faults
- Grid-parallel operation
- Short-circuit contribution rated current



Grid-forming
- Voltage and frequency control
- Stand-alone only (island operation)
- Short-circuit contribution rated current

Synchronous Grid-forming
- Voltage and frequency control
- Grid-parallel operation
- Short-circuit contribution rated current

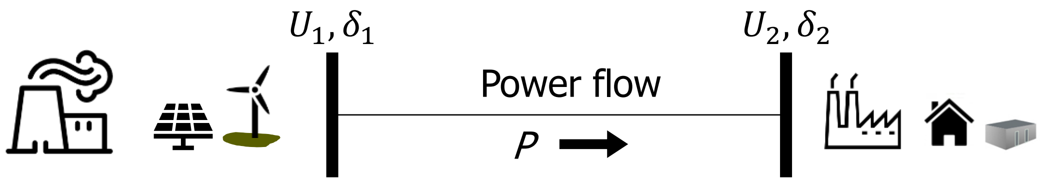


Virtual synchronous machine
- Voltage and frequency control
- Grid-parallel operation
- Higher short-circuit contribution
- Additional energy reserves

Network Control characteristics

Decoupled and coupled power-flow control

Power flow in the **transmission grid** (R/X ≈ 0)



$$P = \frac{U_1 U_2}{X} \sin \Delta\delta$$

$$Q = \frac{U_1^2 - U_1 U_2 \cos \Delta\delta}{X}$$

In inductive grids with a small transmission angle:
$P \sim \Delta\delta$, $Q \sim U_1 - U_2 = \Delta U$

VSC-based generation is mainly connected to the **distribution grid** (R/X ≠ 0)

- Coupling between Q and $\Delta\delta$
- Coupling between P and ΔU

Couplings must be taken into account in the control

Agenda

Introduction to the German power system

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Outlook

Research Project "Hybrid AC/DC Network"

System stability in a hybrid AC/DC Network

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Motivation

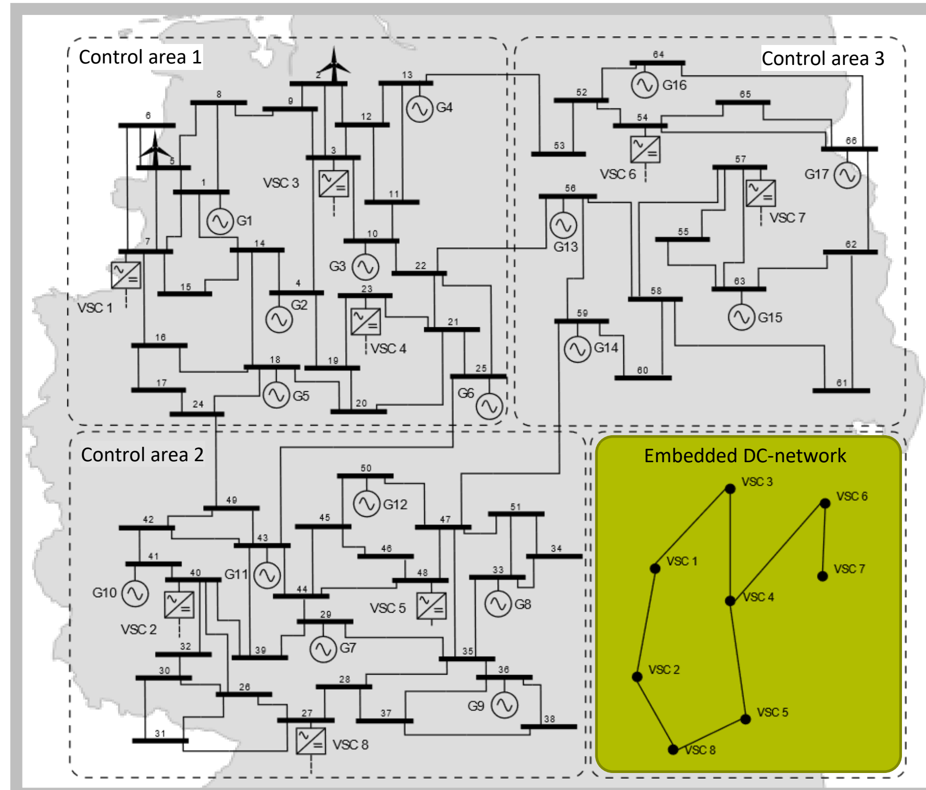
Using the degrees of freedom to improve steady-state and dynamic behavior in a hybrid AC/DC system

Investigate

- Stability support using HVDC systems
- Higher utilization of AC/DC equipment
- Tuning of converter control
- RMS/EMT modeling, Co-Simulation

Research topics

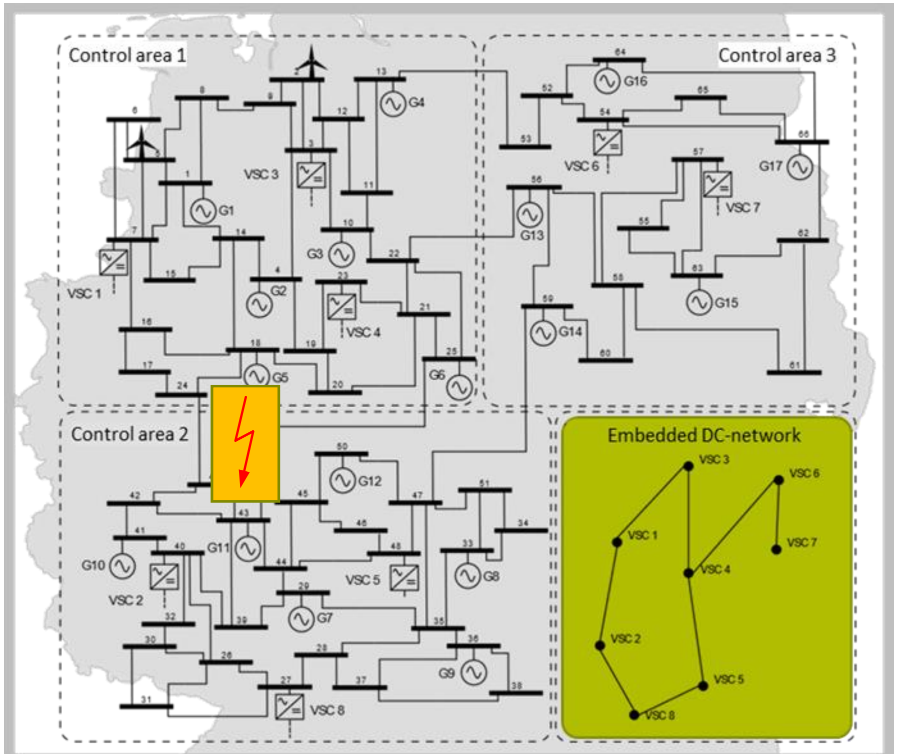
- Voltage/Rotor angle stability during steady-state operation and voltage stability during and after network faults
- Transient stability, frequency stability
- Power oscillation damping
- Resonance stability, converter-driven stability



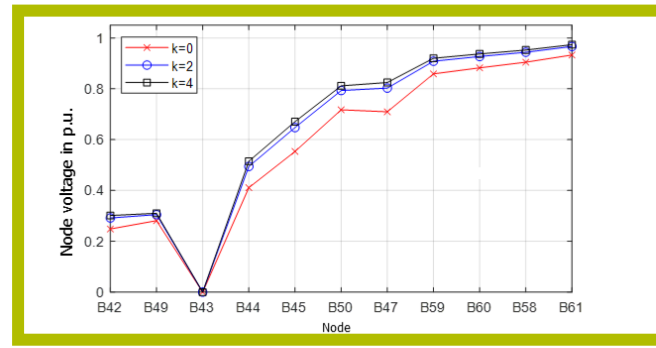
SOURCE: OVANET - OVERLAY NETWORKS FOR THE FUTURE funded by the German Ministry for Economic Affairs and Climate Action (BMWK)

Research Project "Hybrid AC/DC Network"

Voltage stability



Voltage gradients during short circuits

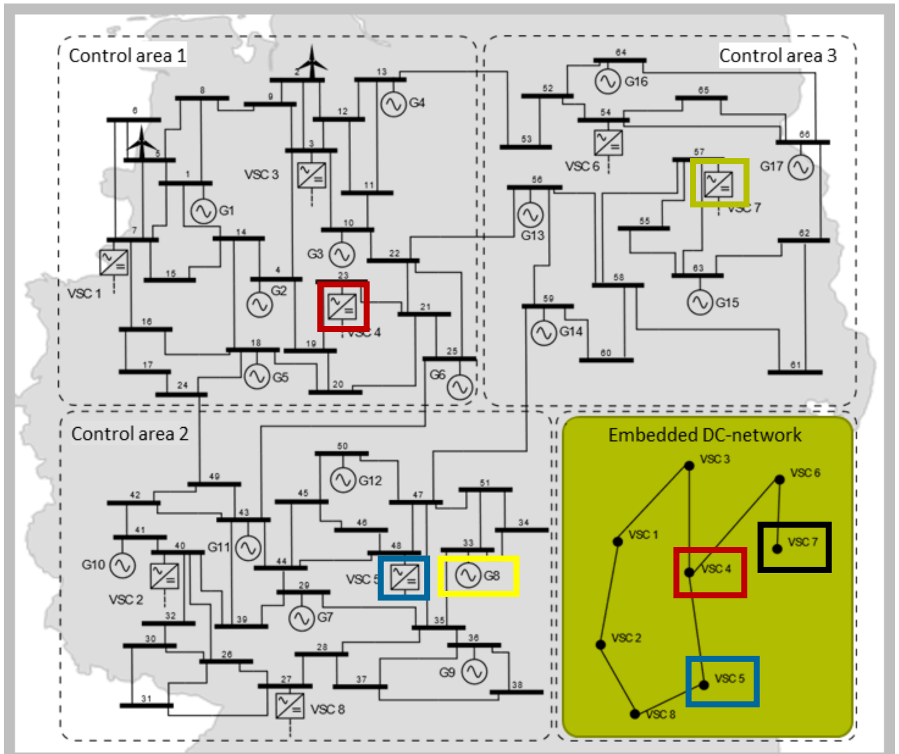


SOURCE: OVANET - OVERLAY NETWORKS FOR THE FUTURE funded by the German Ministry for Economic Affairs and Climate Action (BMWK)

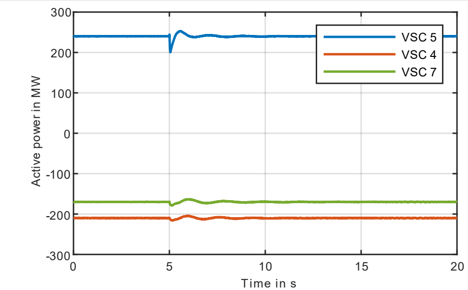
Source: X. Xiao, S. Choudhury, M. Coumont and J. Hanson. Impact of HVDC Fault Ride-Through and Continuous Reactive Current Support on Transient Stability in Meshed AC/DC Transmission Grids. 2022 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Novi Sad, Serbia, 2022, pp. 1-5

Research Project "Hybrid AC/DC Network"

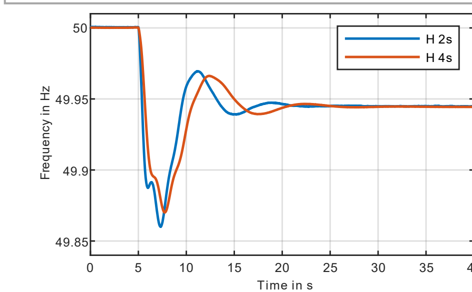
Frequency stability



Active power control during generator outage



Frequency during generator outage



SOURCE: OVANET - OVERLAY NETWORKS FOR THE FUTURE funded by the German Ministry for Economic Affairs and Climate Action (BMWK)

Research Topic "Hybrid AC/DC Network"

New Control algorithm for converter outages

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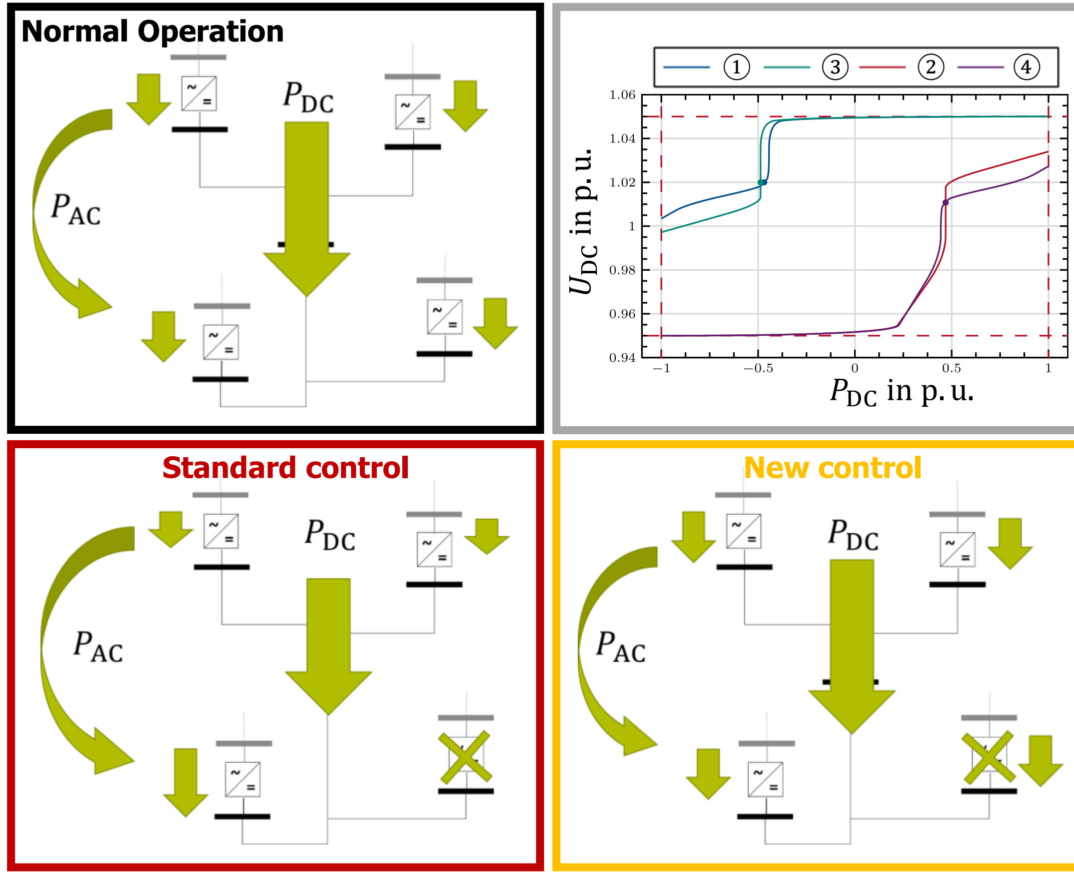
Approach

- One generalized control structure for all converters with flexible parameterization
- Multi-level concept depending on power flow direction
  (level: corresponds to height of power flow)
- Continuous operation without switching between different parameter sets
- Constant control dynamics

Results

- Influence on AC network is drastically reduced for the new control algorithm
  - Changes in power and voltage are locally limited
  - Reduced interaction with generator units



Source: Active Power Balancing, S. Weck, Phd-Thesis, TU Darmstadt, 2022

Agenda

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- Introduction to the German power system
- System characteristics
- Network and Converter control
- System stability
- **Outlook**

Outlook
System stability in future power systems

The future power system is undergoing a paradigm shift.

Operation
- without large onshore power plants,
- with central large offshore power plants and
- with converter-dominated distribution grids

has to be enabled.

High-voltage direct current transmission is a fundamental component for the success of the energy transition in Germany.

Degree of freedom of converter control is used to enable system stability and to increase utilization of equipment (preventive/curative measures).

Thank you for your attention.

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The role of digitalization in the energy transformation

Prof. A. Monti

Fraunhofer

ACS | Automation of Complex Power Systems

E.ON Energy Research Center

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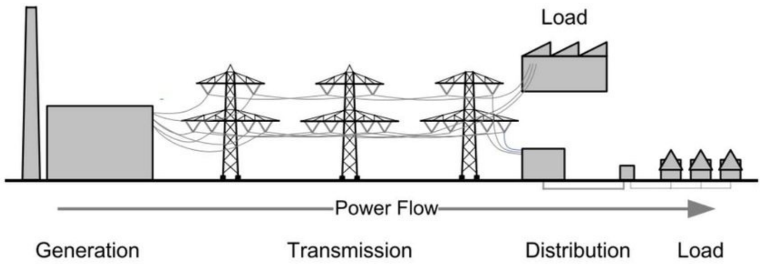
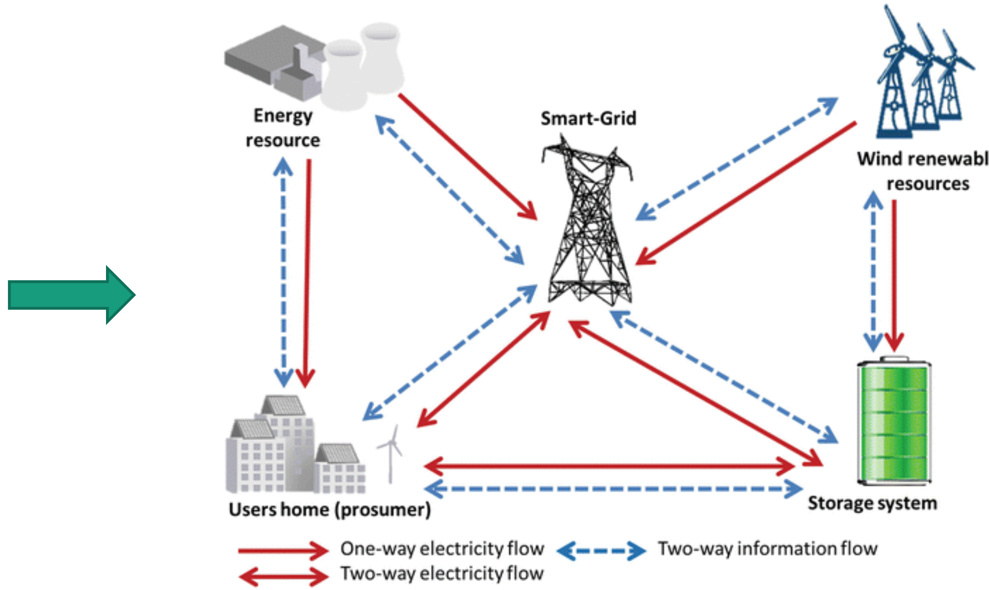
Motivation
Challenges of the Energy Transition

From unidirectional

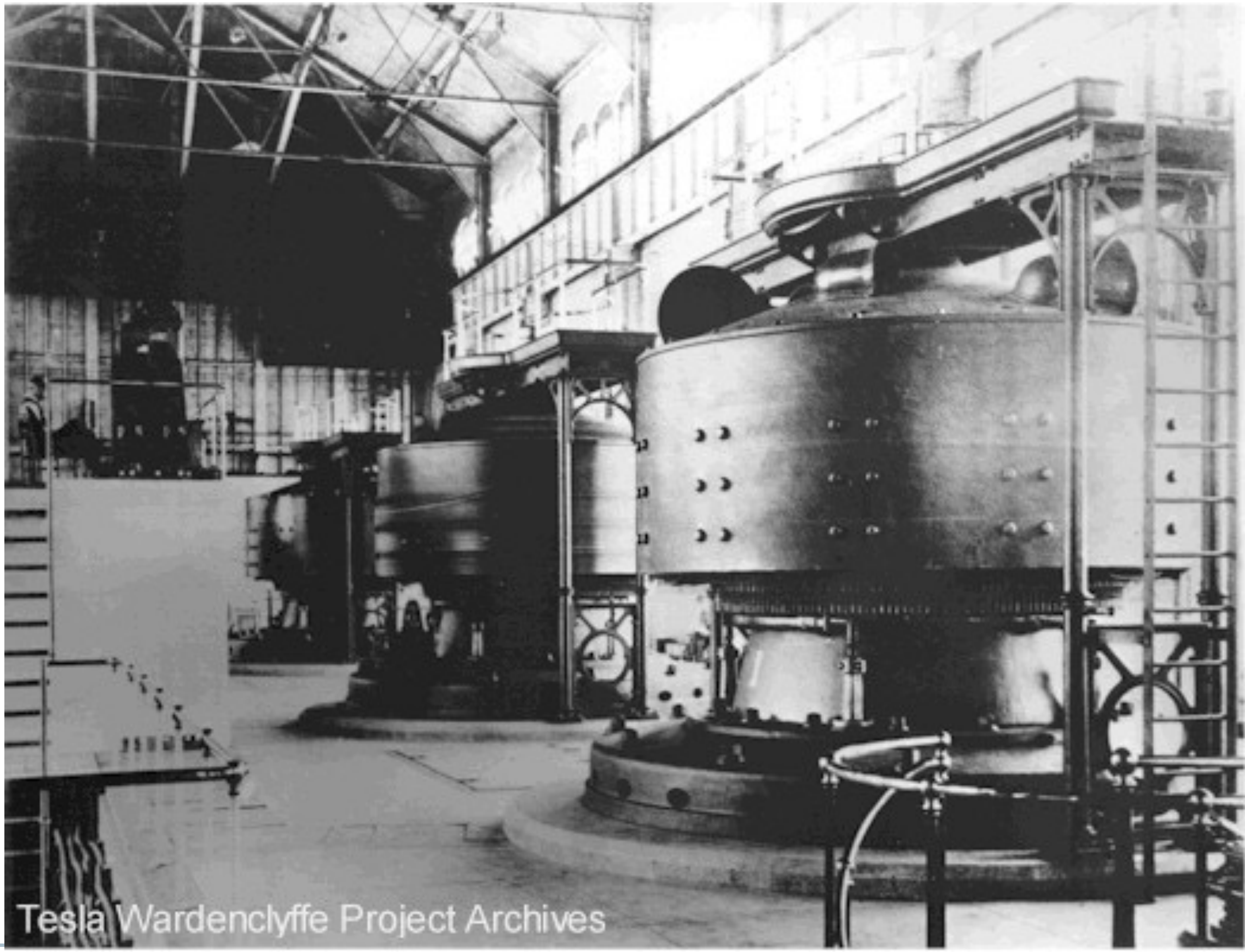


To multi-directional



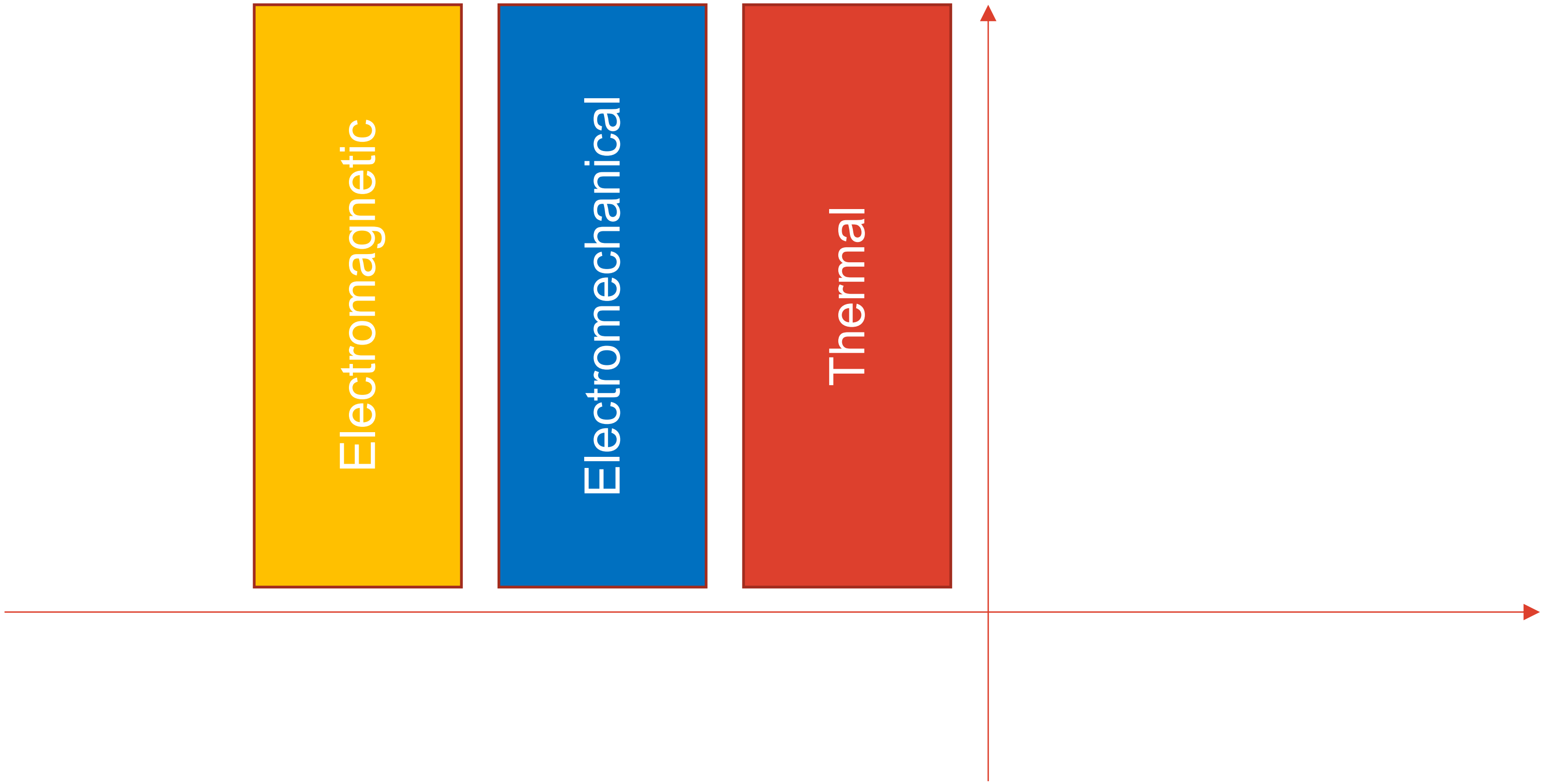
Source: https://www.agora-energiewende.de/

After more than 100 years .....



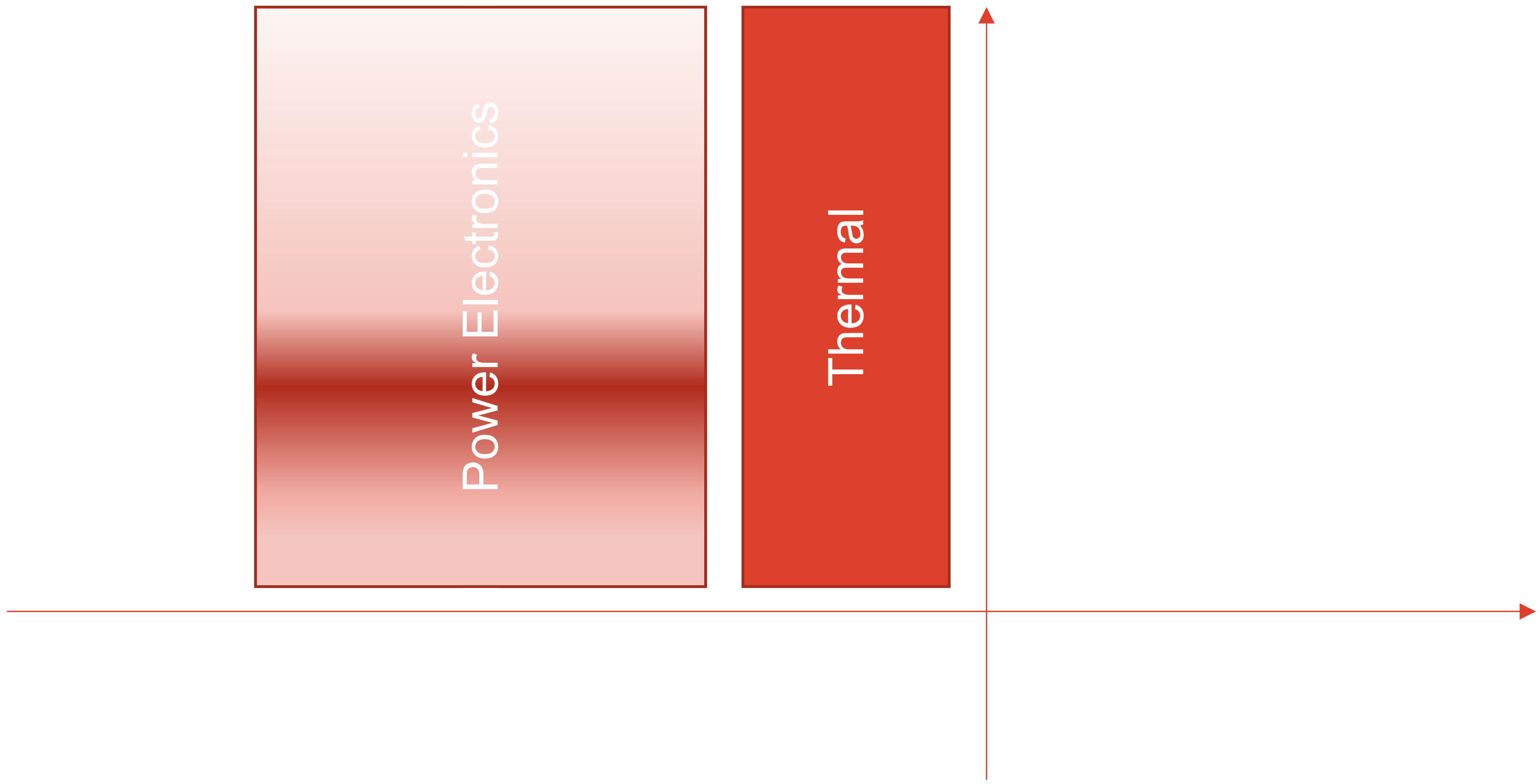
After more than 100 years .....

A question of eigenvalues



Classical Power System

A question of eigenvalues

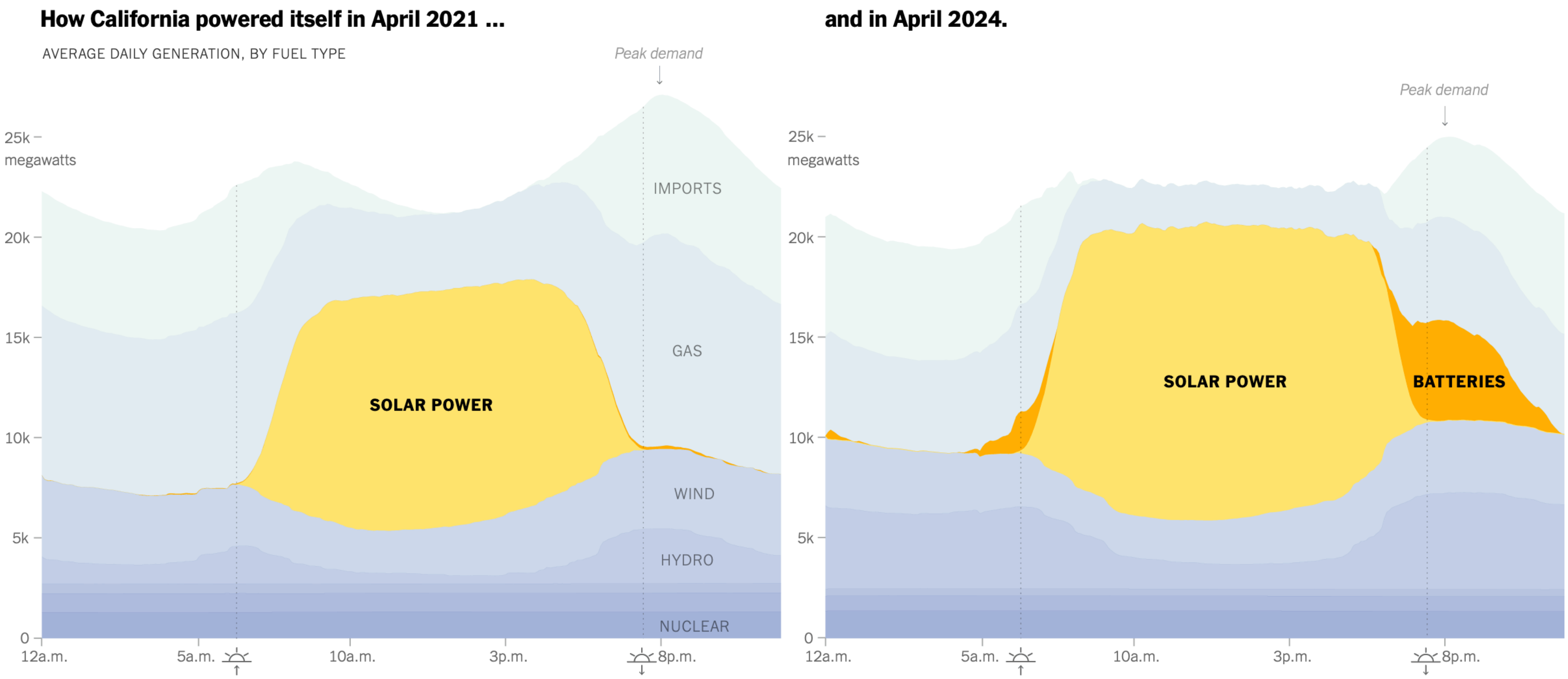


Classical Power System → Modern Power System

Consequences

- The physical characteristics of the systems are dramatically changing and this should be reflected in the control and automation
- The dynamics are different and dominated by completely different eigenvalues
- The role of the distribution grid is radically transformed
- The infrastructure is used in a way that is different from the original purpose
- The system is highly decentralized and not anymore suitable for a full top-down automation
- The electricity system is becoming a programmable system, many of the components are software defined.
- Modeling approaches are also becoming obsolete because based on old assumptions

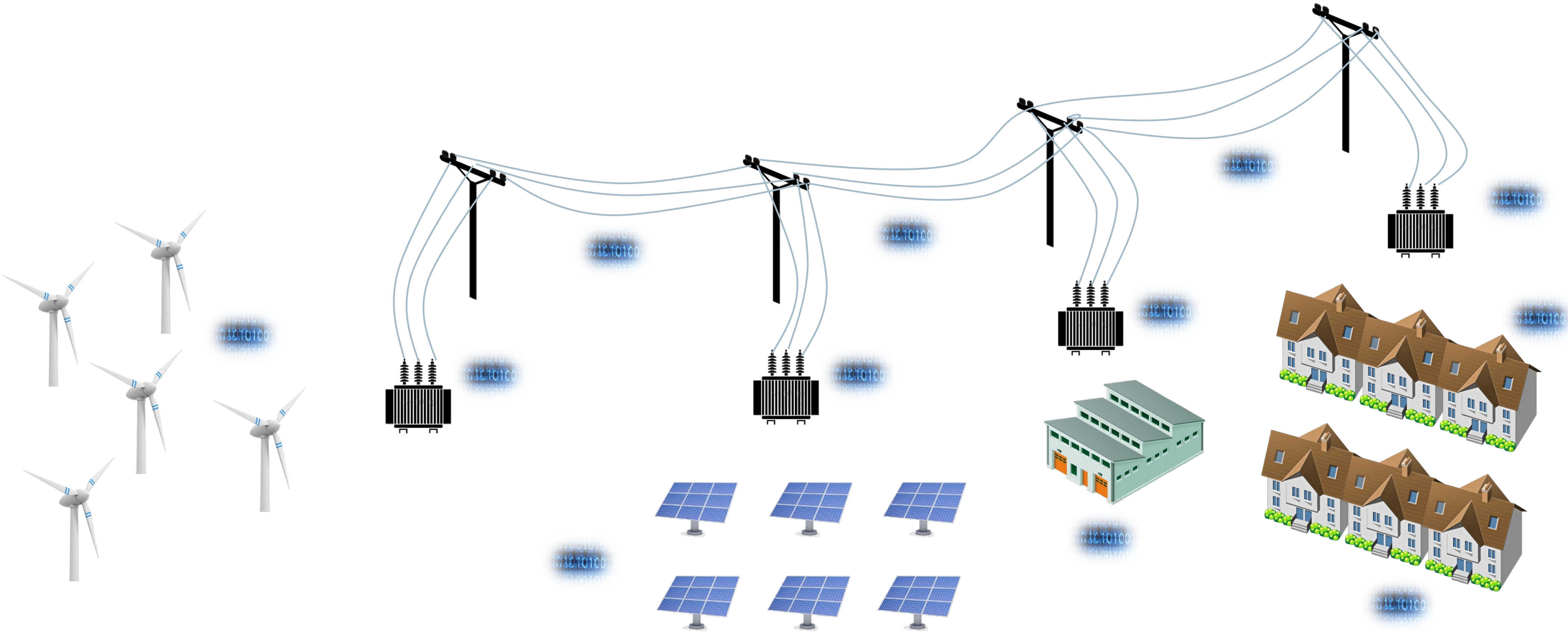
Is this really already happening?



Source: www.nytimes.com

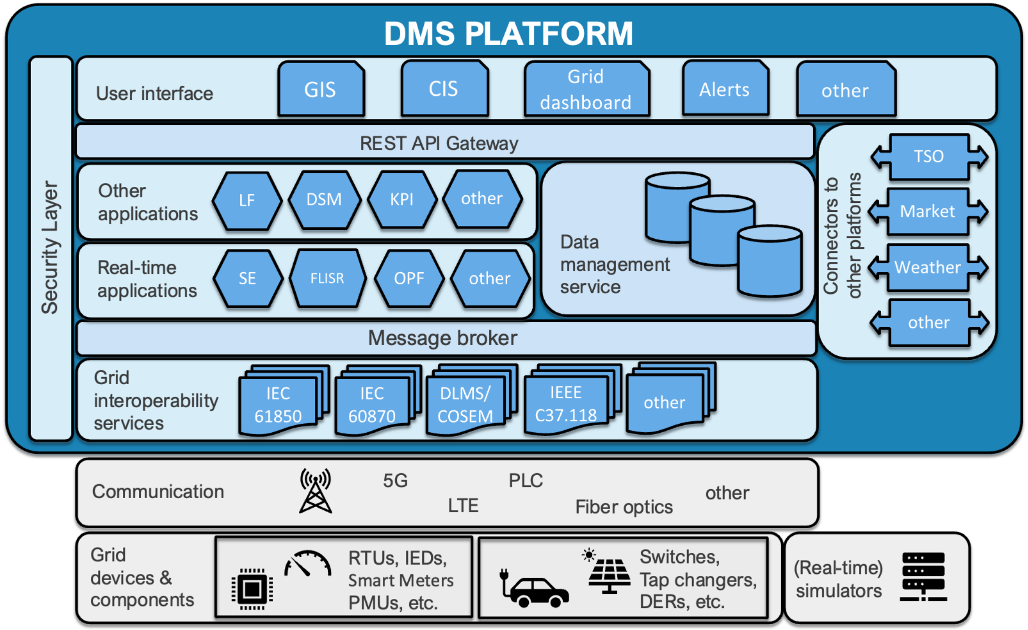
The new role of edge and distribution grids

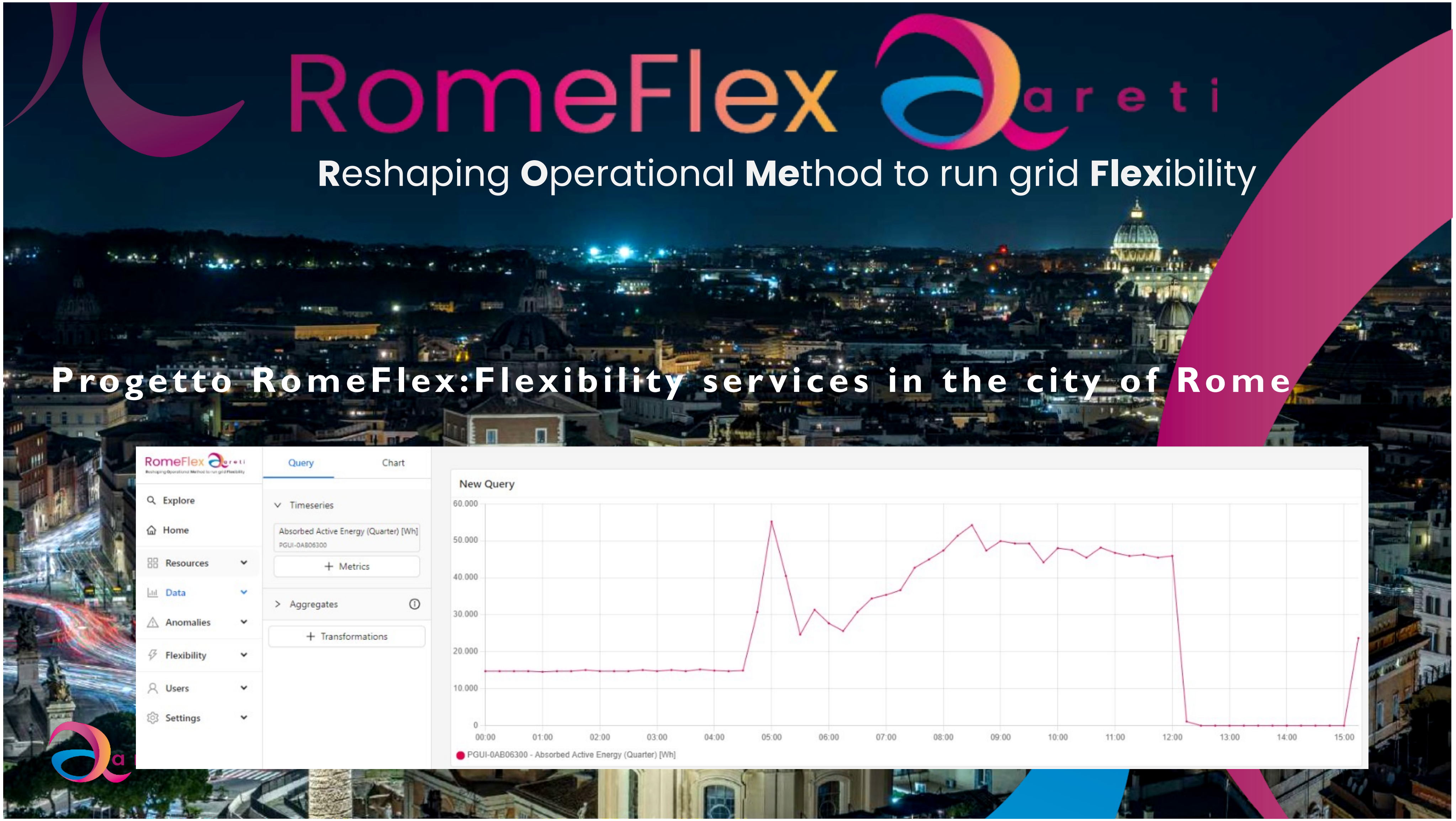
More data from more points



SOGNO platform and Linux Foundation Energy

- A microservices oriented power system automation platform
  - A control center software for distribution system operators
    - A power engineering task supported by cloud services
  - Started as EU project
  - Now part of the Linux Foundation Energy
- Awarded with "Innovationspreis NRW 2022"
- Selected for real implementation by a large grid operator




RomeFlex areti
Reshaping Operational Method to run grid Flexibility
Progetto RomeFlex:Flexibility services in the city of Rome
RomeFlex
Explore
Home
Resources
Data
Anomalies
Flexibility
Users
Settings
Query
Chart
Timeseries
Absorbed Active Energy (Quarter) [Wh]
PGUI-0AB06300
Metrics
Aggregates
Transformations
New Query
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PGUI-0AB06300 - Absorbed Active Energy (Quarter) [Wh]

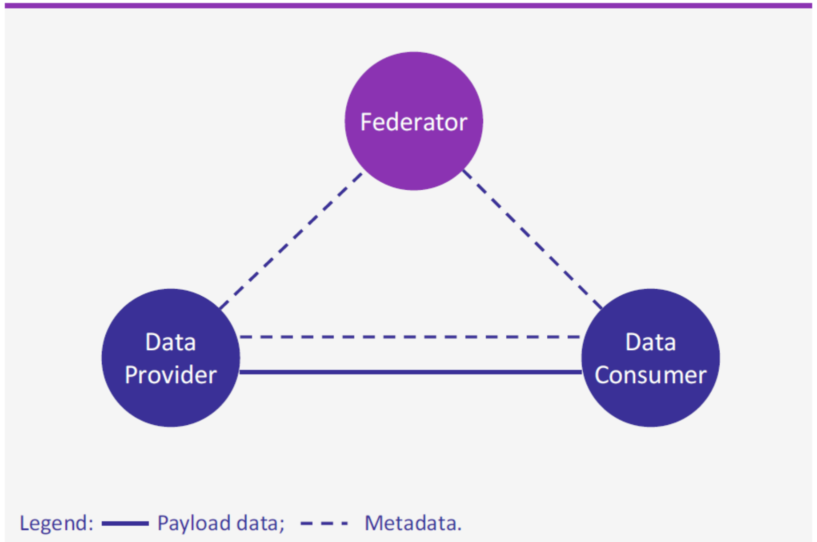
Data Space Roles and Interactions

Technological Perspective

- **Data Provider** and **Data Consumer**
  - Exchange of the data happens directly between the two
    - No central data store
  - No common database schema

    → Integration on semantic level (e.g. shared vocabularies)
  - Allow for data redundancies, "co-existence" of data
- **Federator**
  - Ensures security, trust, […] through intermediary services
  - e.g. cataloguing, brokering of data sources

Role Interactions



Source: Designing Data Spaces : The Ecosystem Approach to Competitive Advantage | SpringerLink

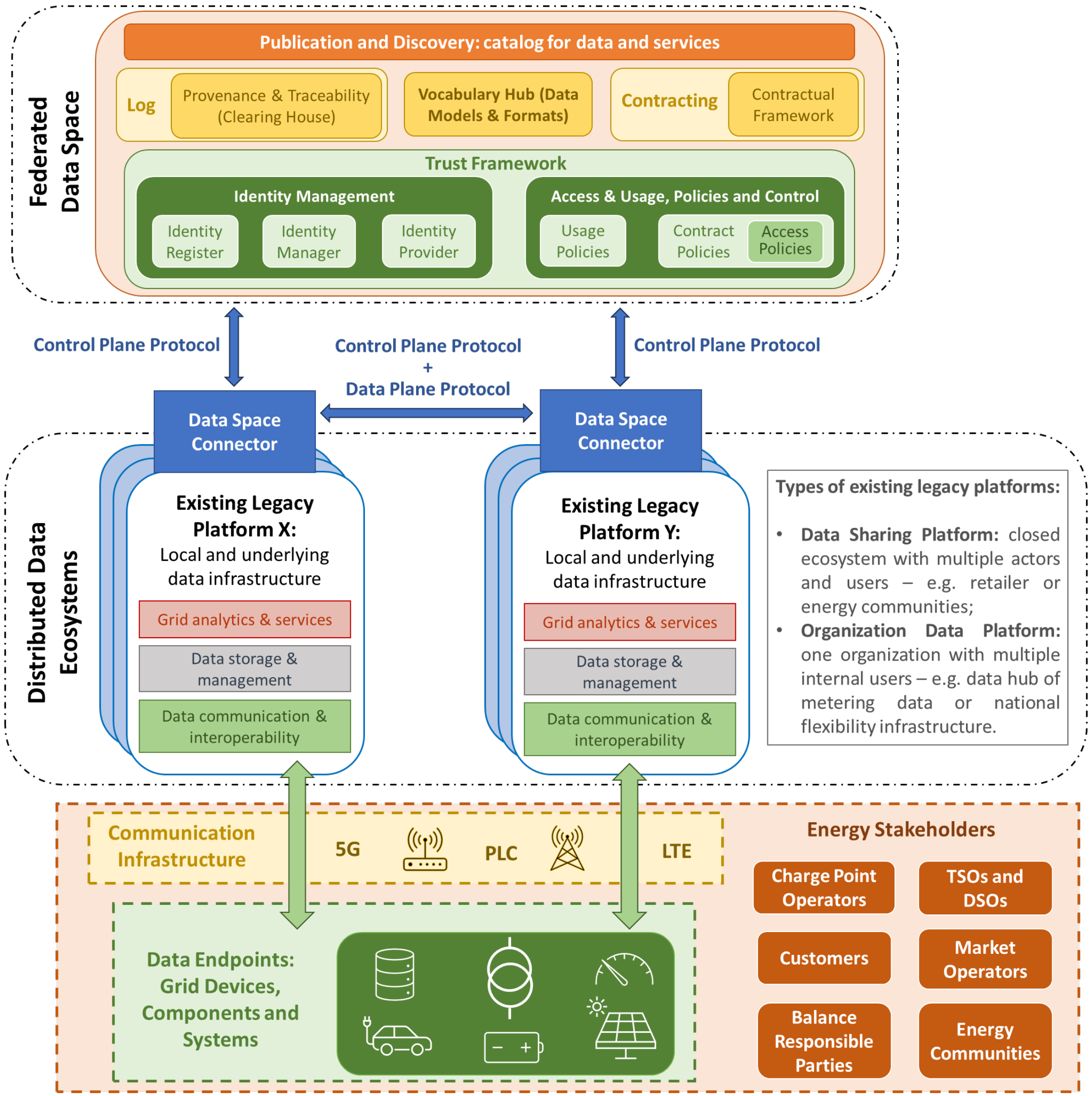
Energy data spaces
cluster

Blueprint of CEEDS

Goal: from Innovation Actions **to national initiatives and large-scale deployments** of data spaces

Content:

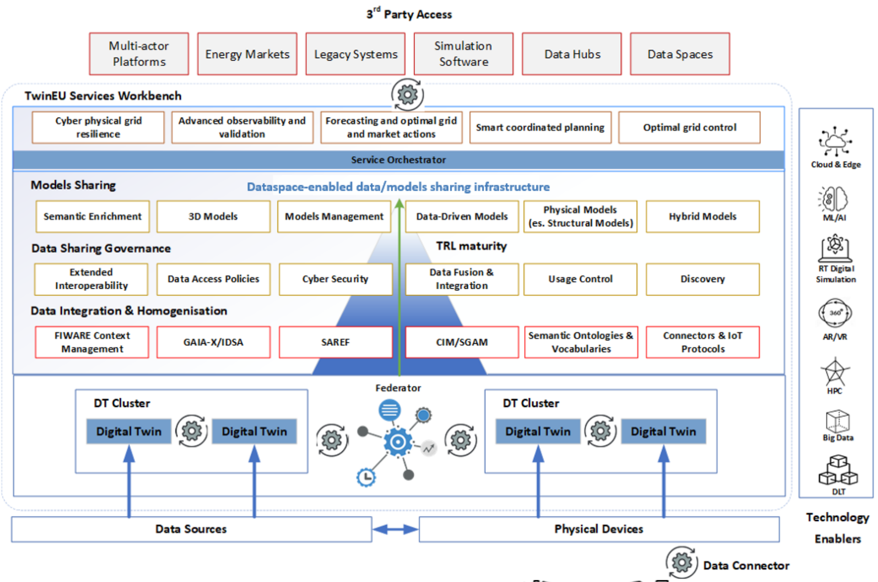
- **Business use-cases** of CEEDS:
  - Scenarios, Actors, Exchanged Data
- **Architecture**: **not MVP version, but with complete set of components**
- **Interoperability**:
  - Technical
  - Semantic
  - Governance

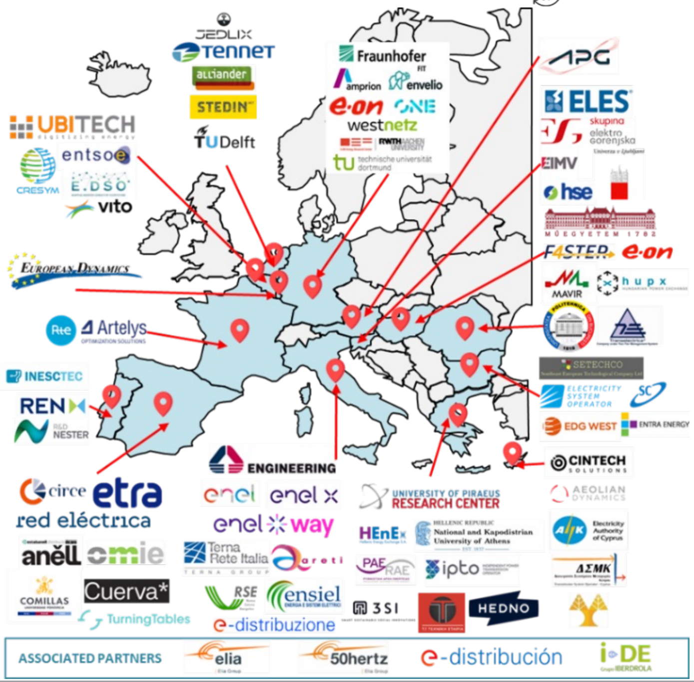


int:net

Building a European Digital Twin: TwinEU

- Large project with more than 70 partners.
- Large involvement of key european operators: 15 TSOs and 15 DSOs
- Main ambition to create a system of systems to interconnect digital twins developed at national level
- Strong link with the activity of Data Spaces and OneNet to facilitate data exchange among operators but also between operators and third parties
- Clear plan for long-term sustainability of the results thanks to the support of a research foundation: CRESYM





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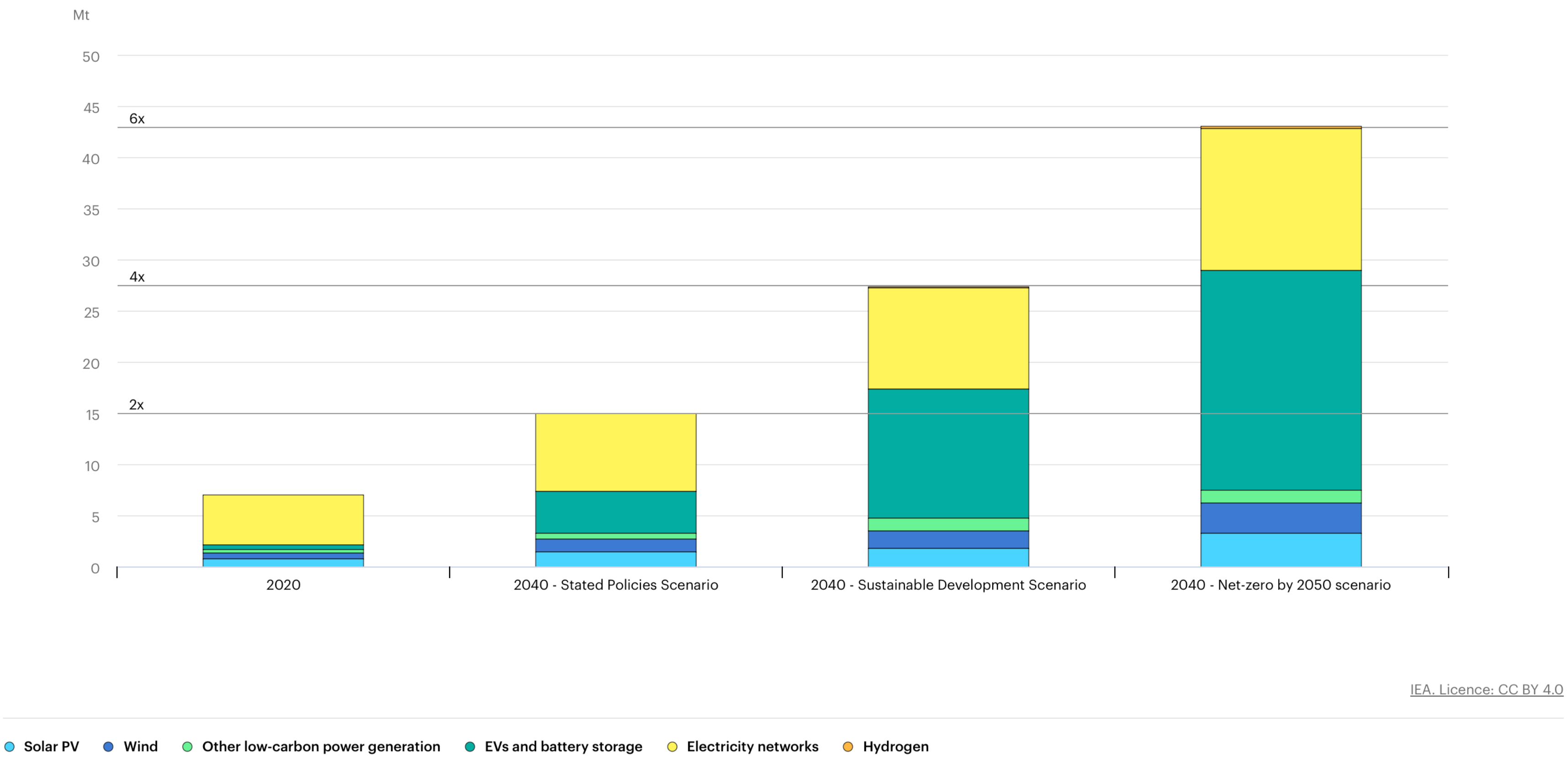
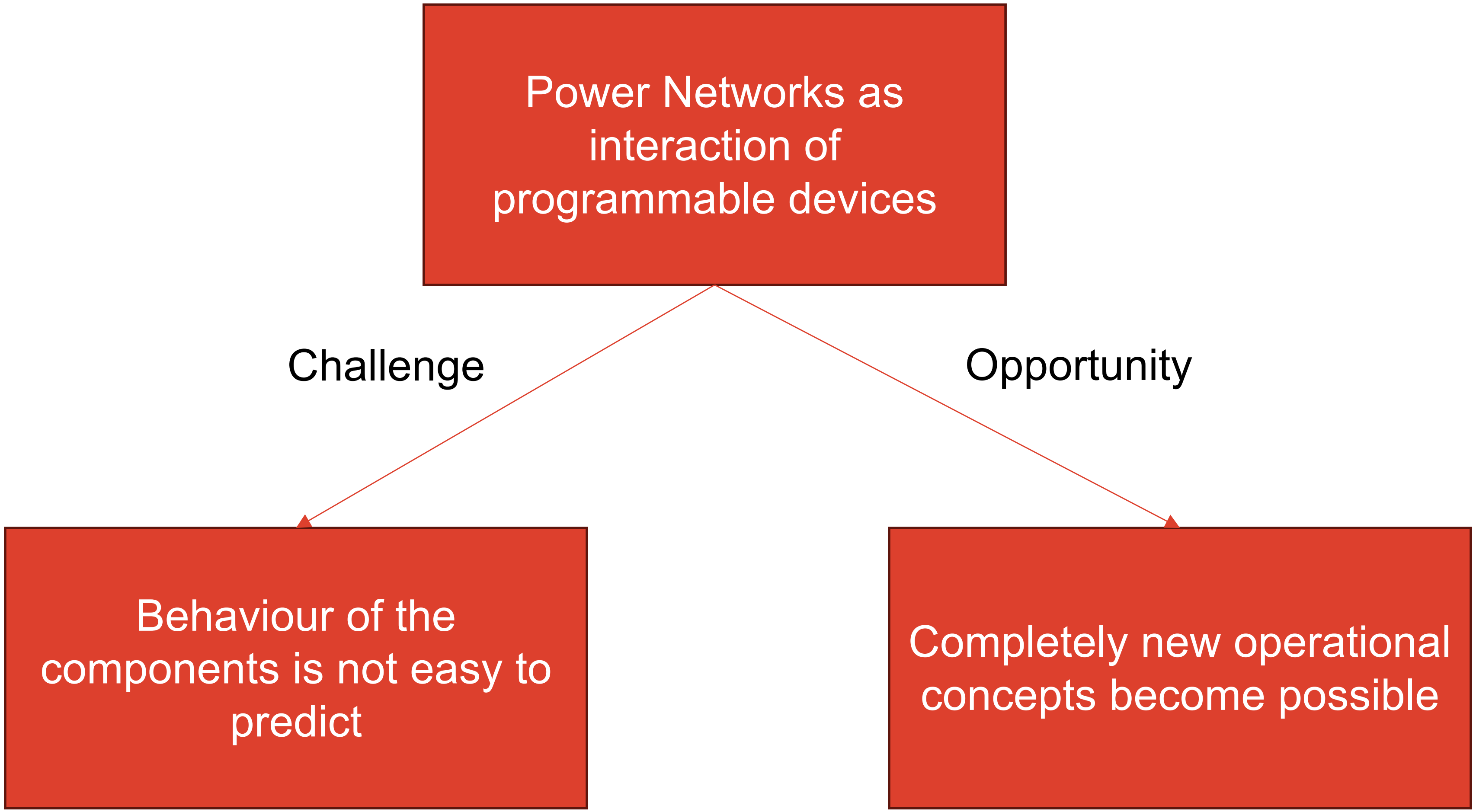
Do we have an alternative?

Digital solutions are critical to keep use of materials under control



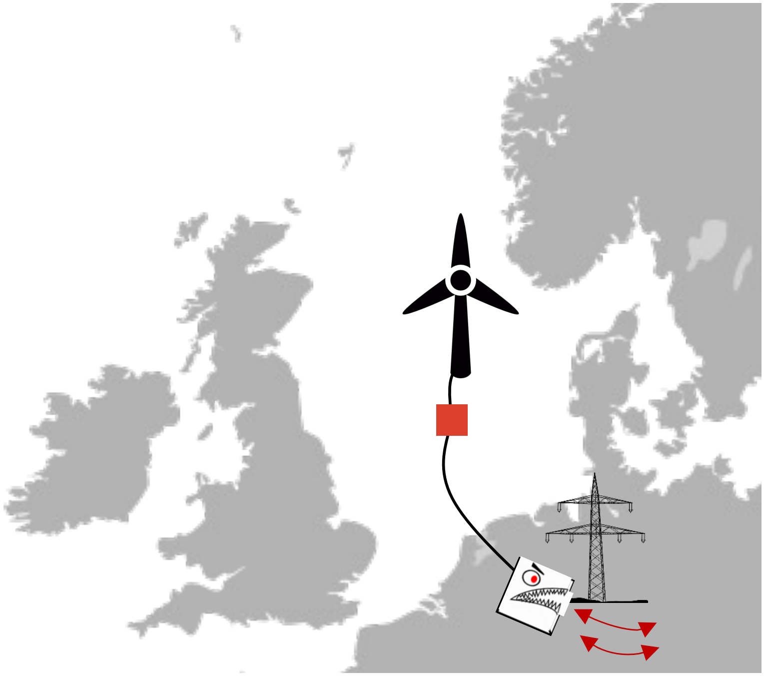
IEA (2021), Total mineral demand for clean energy technologies by scenario, 2020 compared to 2040, IEA, Paris https://www.iea.org/data-and-statistics/charts/total-mineral-demand-for-clean-energy-technologies-by-scenario-2020-compared-to-2040, Licence: CC BY 4.0

Software and programmability



Software and programmability

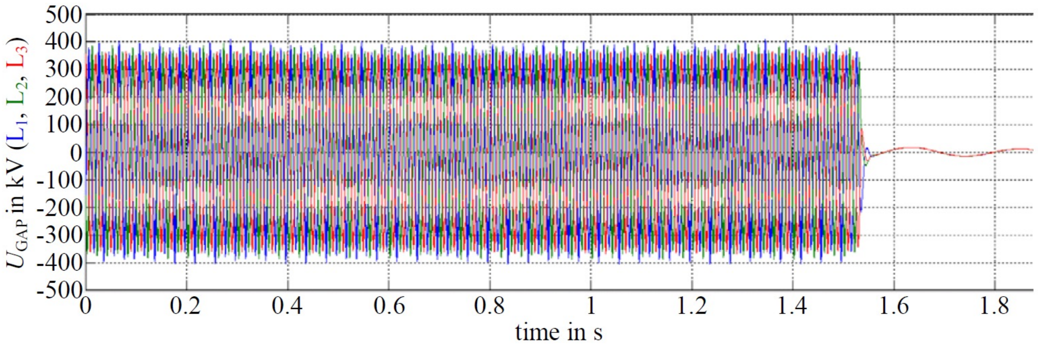
"Unwanted interaction"

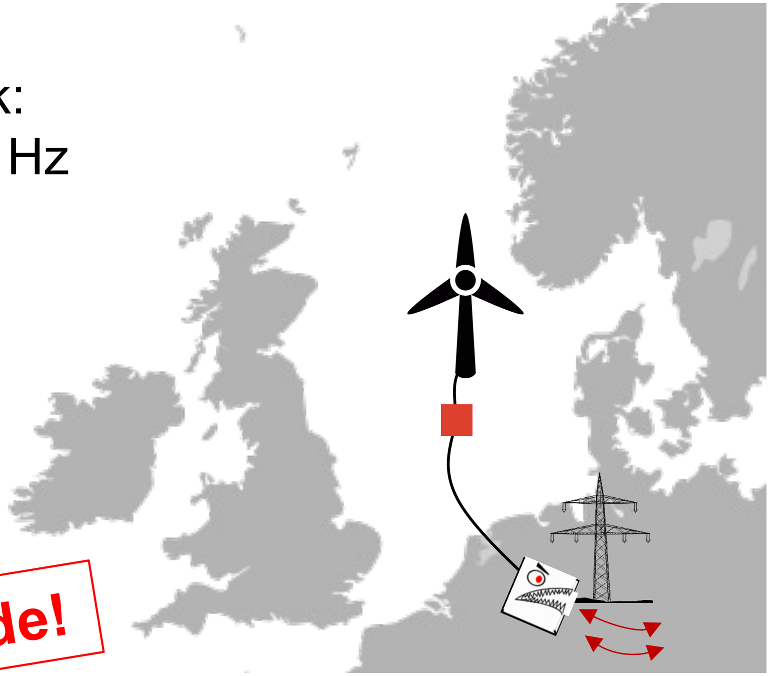


Source: Tacoma Narrows Bridge, Wikipedia

Challenges – Software-defined grid components

Real example from a German Offshore Link:
Continous harmonic current ca. 1500-1800 Hz



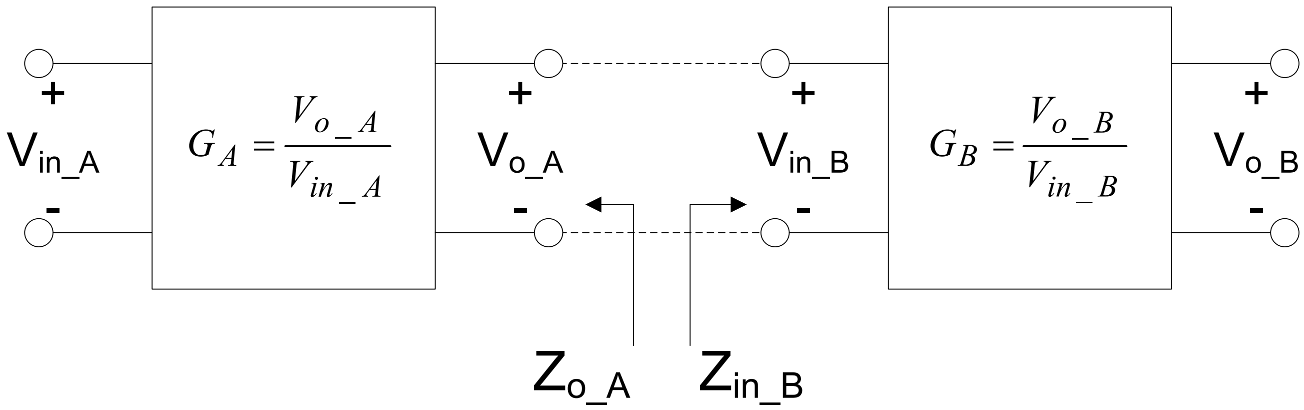


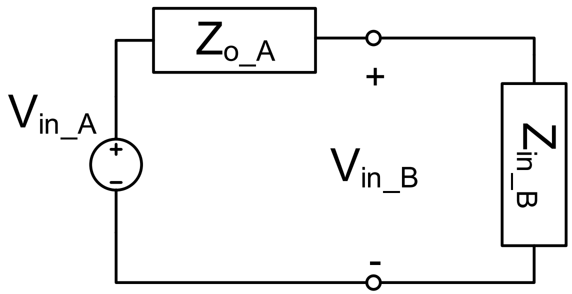
fixed with software upgrade!

Source: Koochack Zadeh et al., Operating experience of HVDC links, CIGRE 2017 Colloquium, Winnipeg, Canada

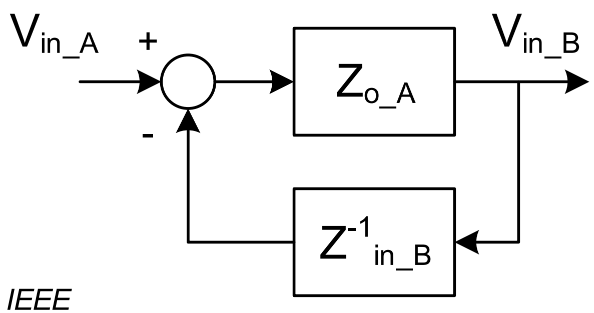
Wide-band impedance analysis

- On one hand with power electronics voltage stability becomes a problem over a wide range of frequencies and not a 50Hz question
- On the other hand with power electronics is possible to create virtual impedances able to shape the frequency domain response





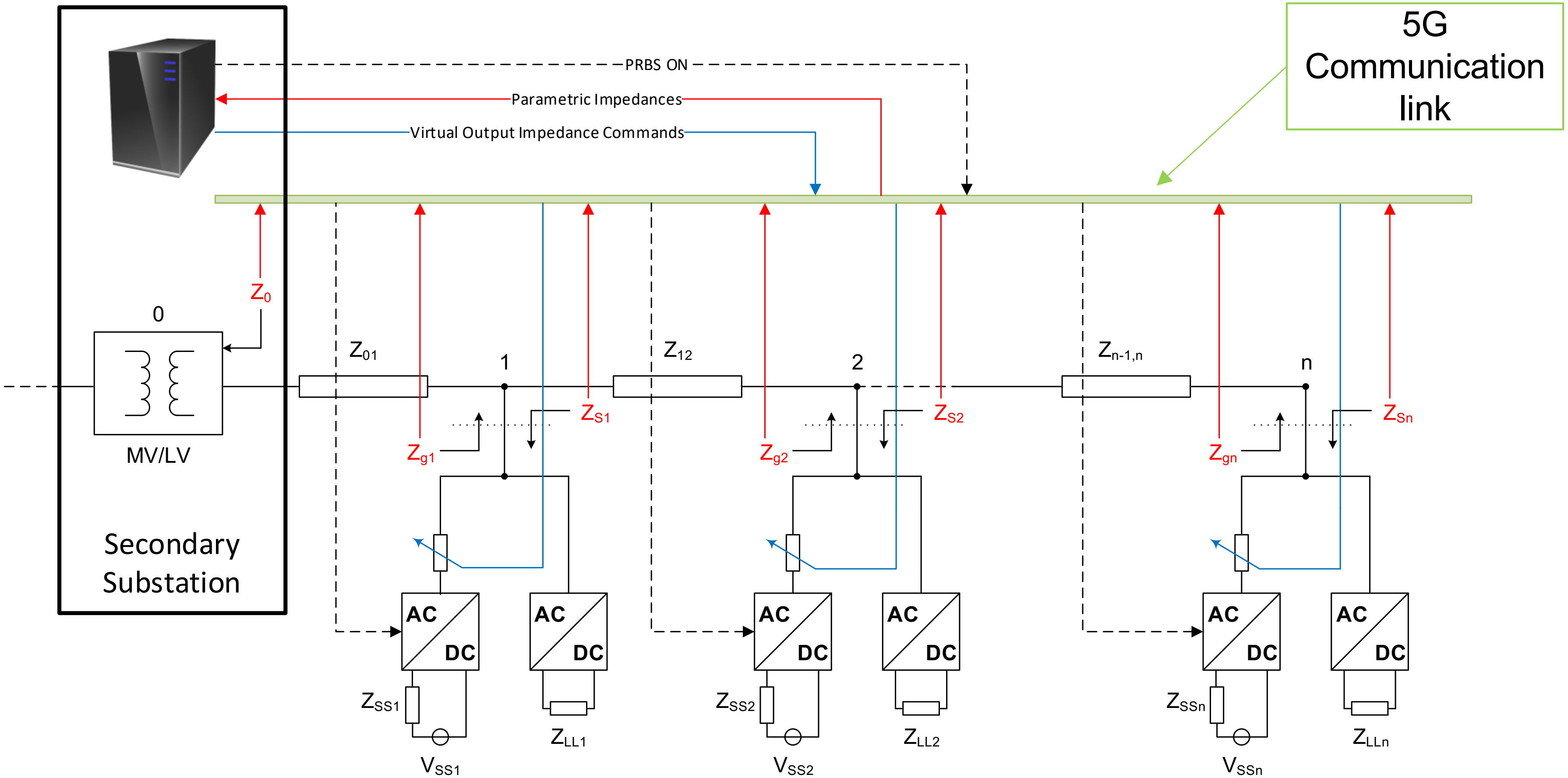
$$G_{AB} = G_A G_B \cdot \frac{Z_{in\_B}}{Z_{in\_B} + Z_{o\_A}} = \frac{G_A G_B}{1 + T_{MLG}} \quad \text{where} \quad T_{MLG} = \frac{Z_{o\_A}}{Z_{in\_B}}$$



A. Riccobono and E. Santi, "Comprehensive Review of Stability Criteria for DC Power Distribution Systems," in *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3525-3535, Sept.-Oct. 2014

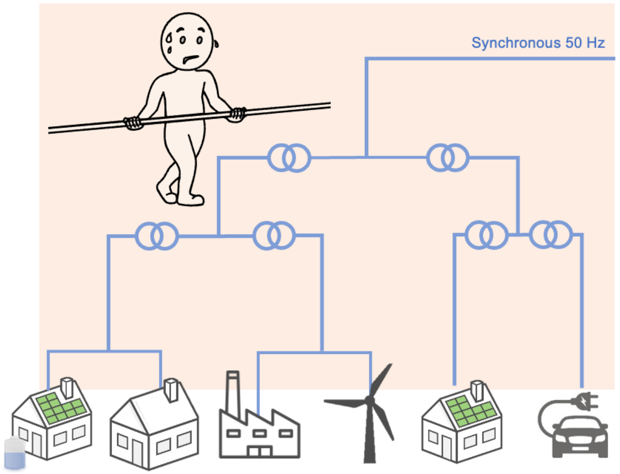
Consequences

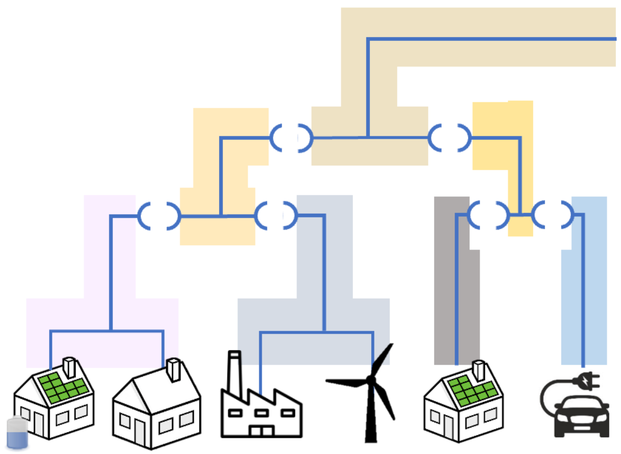
- Review impedance concept to span over a large frequency region
- Control shapes the impedances and not only passive components
- On-line estimation of the frequency response as a key tool to ensure stability of operation



Synchronous
Global Balancing of Power

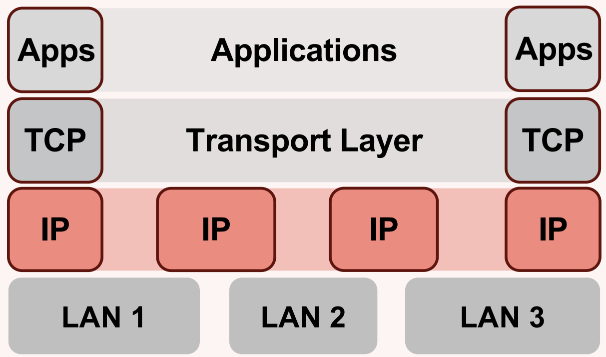
Asynchronous
Local Balancing of Energy





aGrids (asynchronous subgrids):

- Isolated and locally stable
- Protected from remaining grid
- Balance & exchange energy



Internet Architecture
(scalable, flexible and robust)

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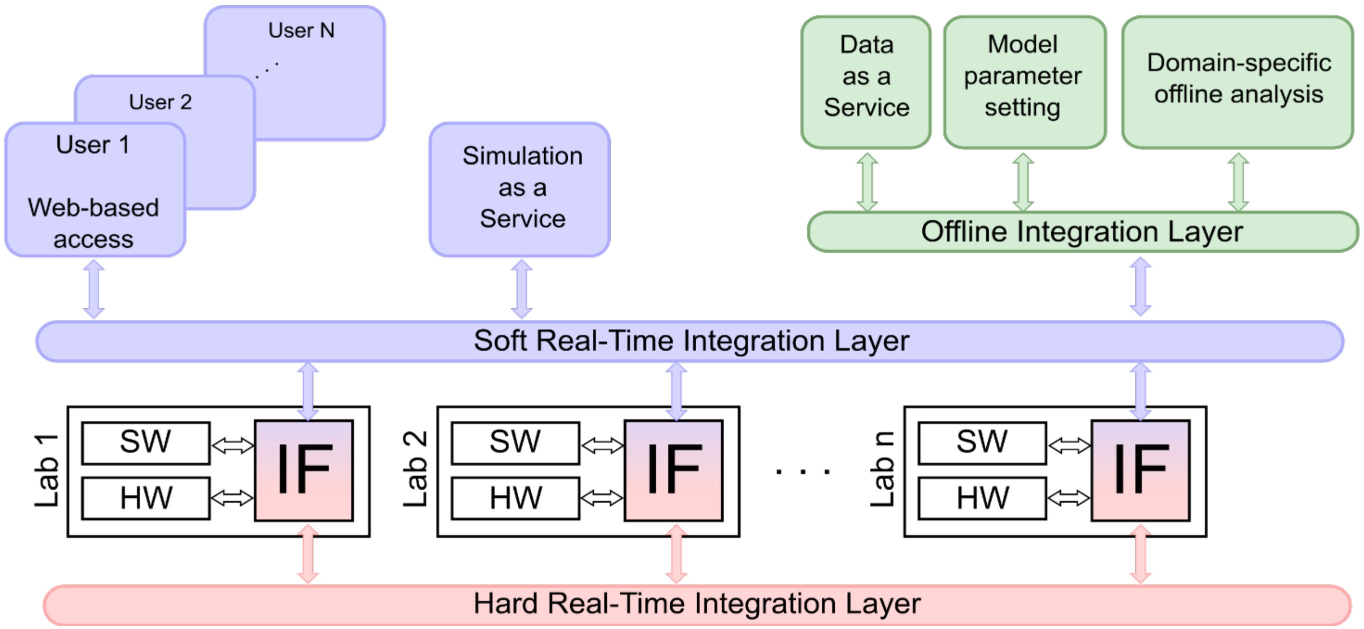
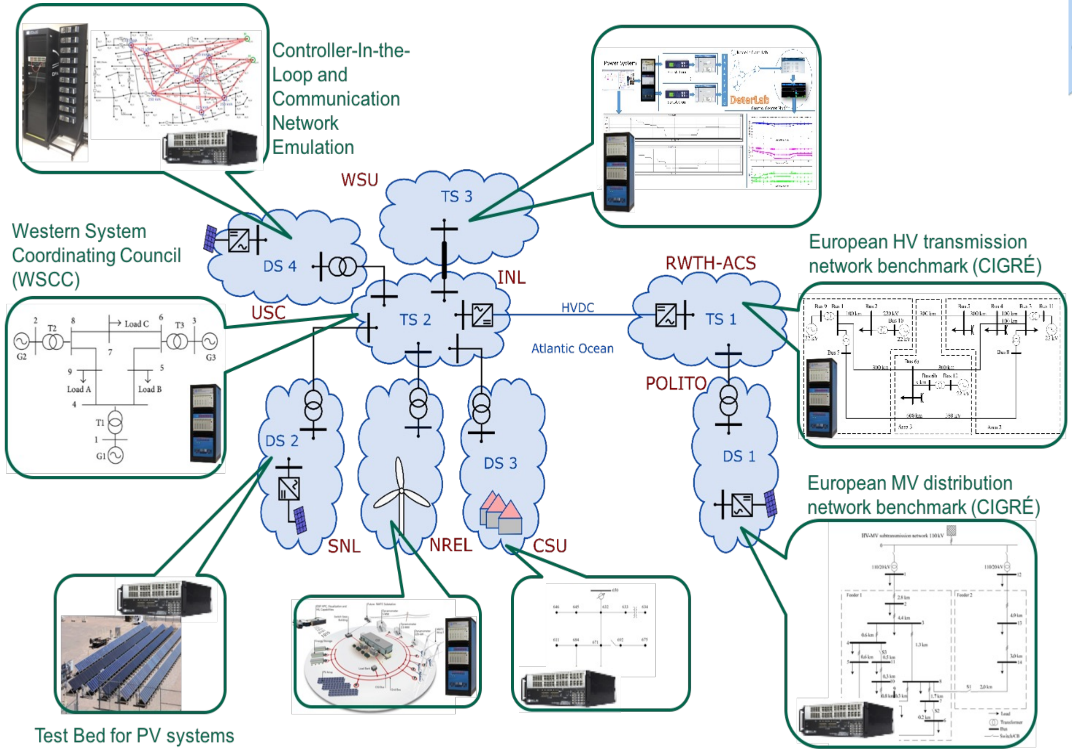
VILLAS Framework

- VILLAS stays for Virtually Integrated Laboratory for Large System Simulation
- VILLAS offers a set of tools to integrate real-time simulation across the network
- VILLAS enables creation of very large simulation scenario integrating the resources available in different laboratories



Examples



The SuperLab in cooperation with the US

Digital Twin of Germany in ENSURE Project

Conclusions

- Electrical grids are becoming fully programmable: which is a challenge and opportunity
- Role of data is growing requiring new approaches to data management
- Cooperation is key to reach solutions in time

int:net

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Kontakt

E.ON Energy Research Center
Mathieustraße 10
52074 Aachen
Germany

Providing Flexibility with Distributed Energy Resources in DSO Circumstances

15 Jan. 2025

Dr. Dongjun Won, Inha University

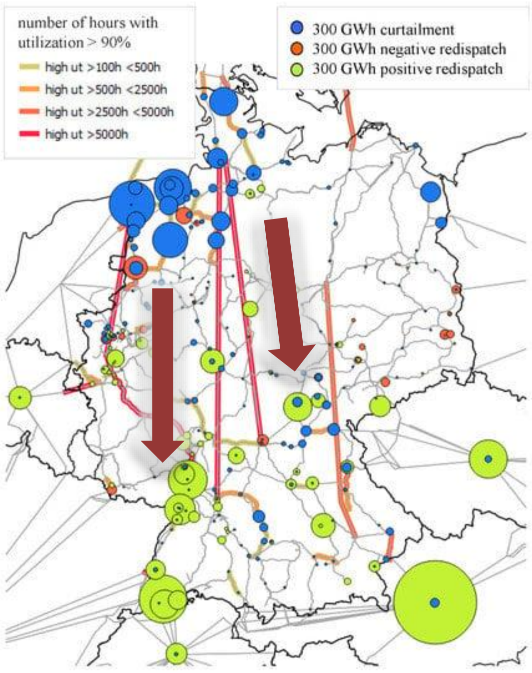
Inha Univ. Power System Lab

Outlines

- **Transition to Distributed Energy System**
- **Development of new DER based System in Korea**
  - New Market
  - Distribution System Planning
  - Non-Wires Alternatives(NWAs)
  - Distribution System Operator(DSO)
  - TSO/DSO/VPP Coordination
- **Local Flexibility Market**
  - Design of LFM
  - Platform for LFM
  - Korea's Action plan

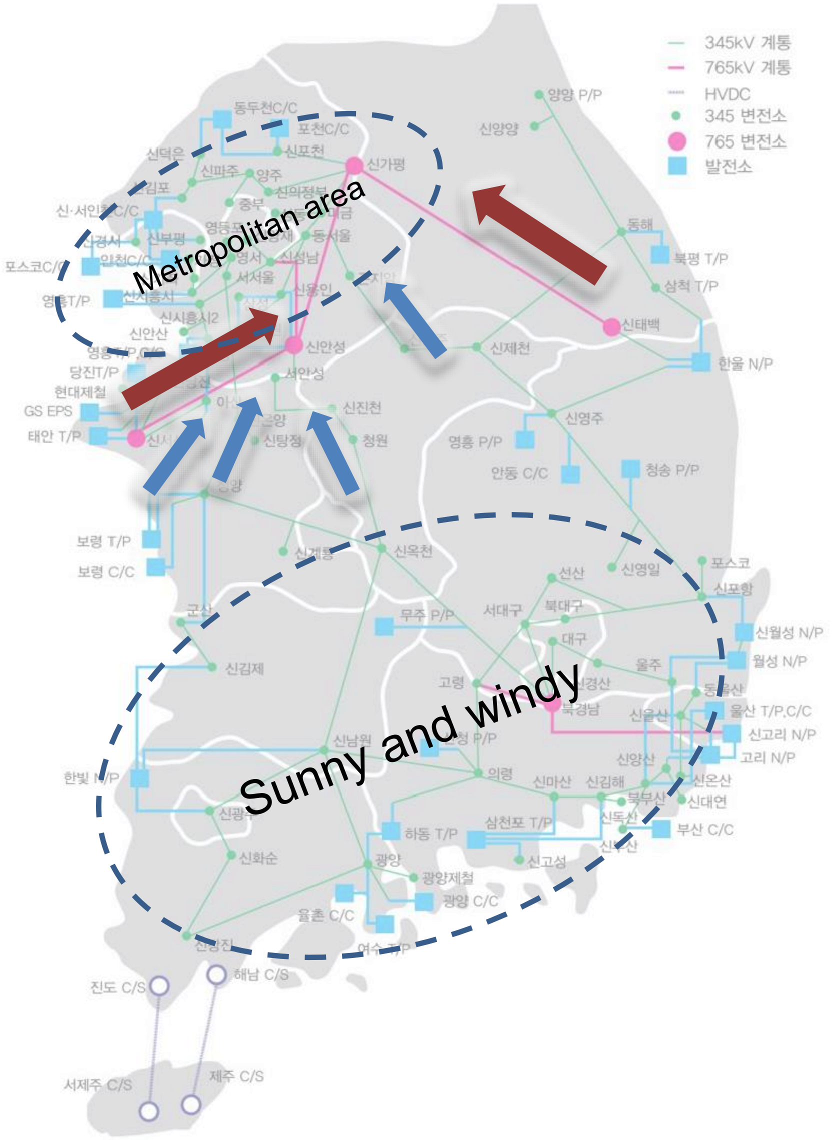
Difficulties in power system operation with renewables

1. **Increase of uncertainty and variability**
2. **Low base generation, reserve and inertia**
3. **Congestion of network**
4. **Inconsistency in renewable energy and consumption location → Need for distributed energy system**



Korea →

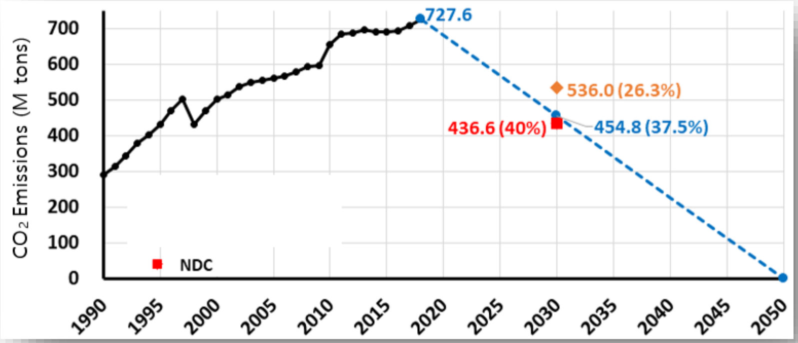
← Germany



Transition to Distributed Energy Resource(DER) System

- **Aggressive NDC Target for Carbon Neutrality**
  - Renewable energy, electrification with EV etc.
  - Need to solve power grid problems (Renewable curtailment, network congestion, instability in frequency and voltage etc.)

"It's GRID, stupid!"



- **In June 2023, DER Promotion Act in Korea is announced**
  - Paradigm shift to distributed energy system
  - Deploy Distributed Energy Resources (Renewables, EV, ESS, MG, SMR etc.)
  - Increase the hosting capacity of existing power system
  - Localize energy generation and consumption
  - Deploy non-wires alternatives(NWAs) solutions
  - Create new markets for DER

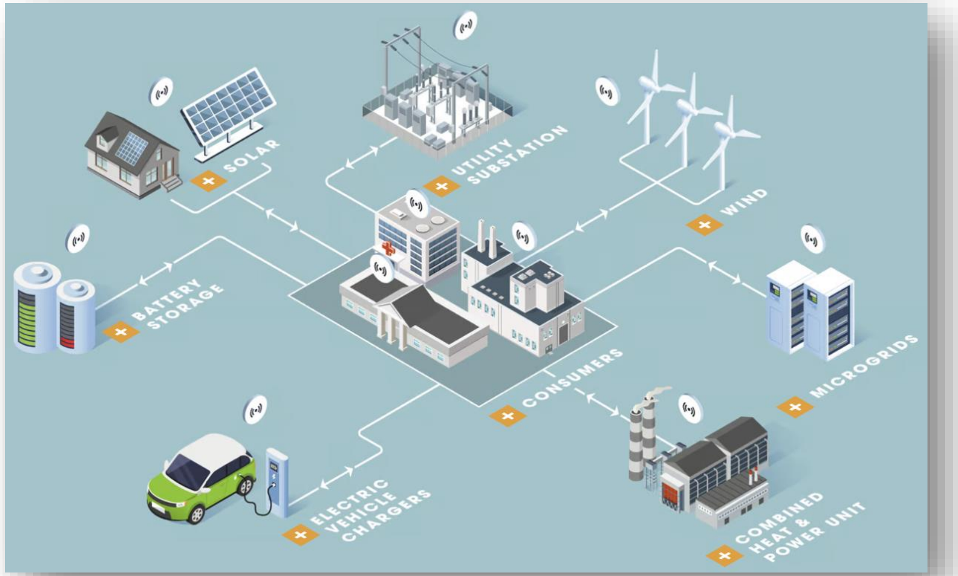
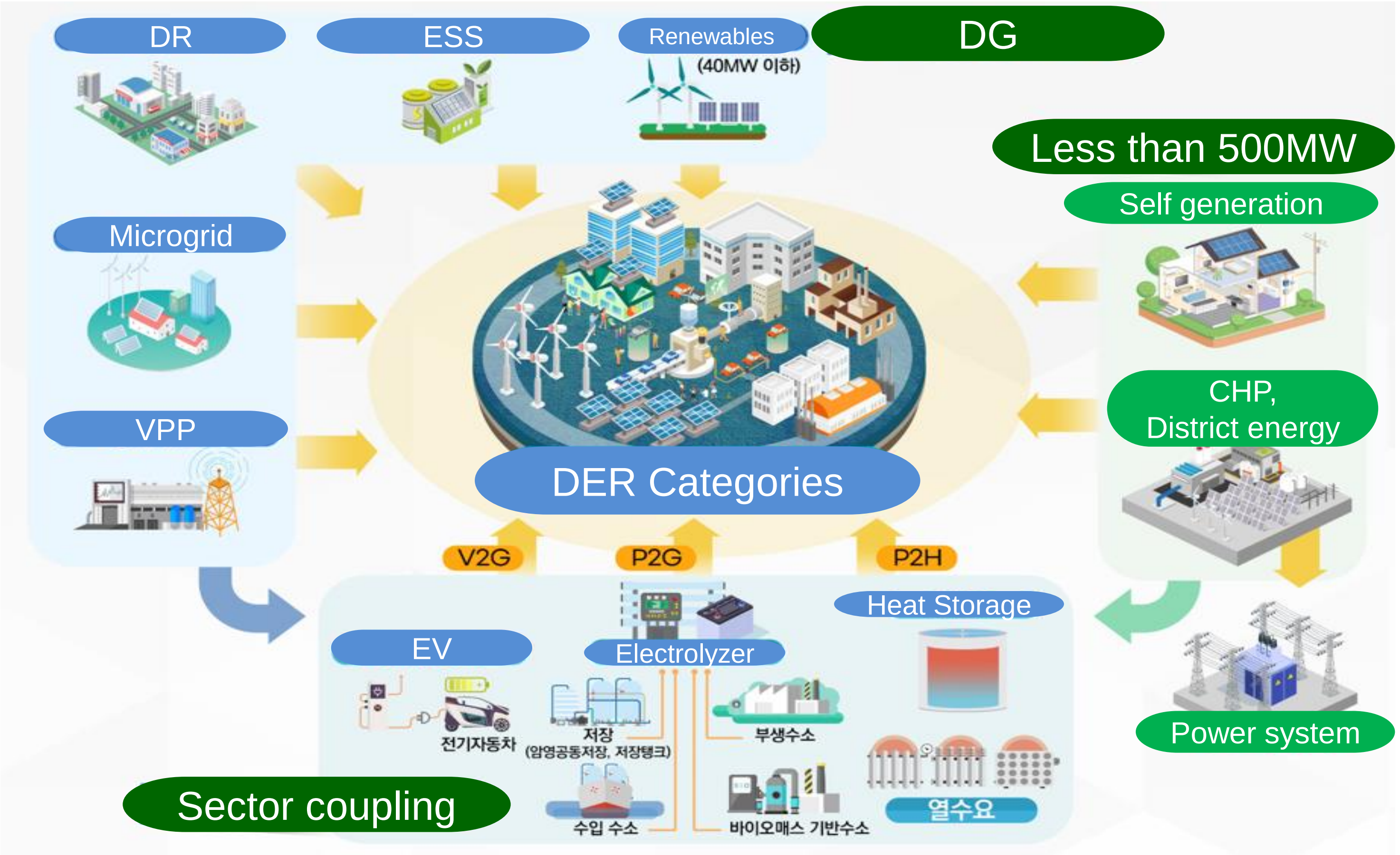


Figure source : https://www.stantec.com/en/markets/energy/grid-modernization/distributed-energy-resources

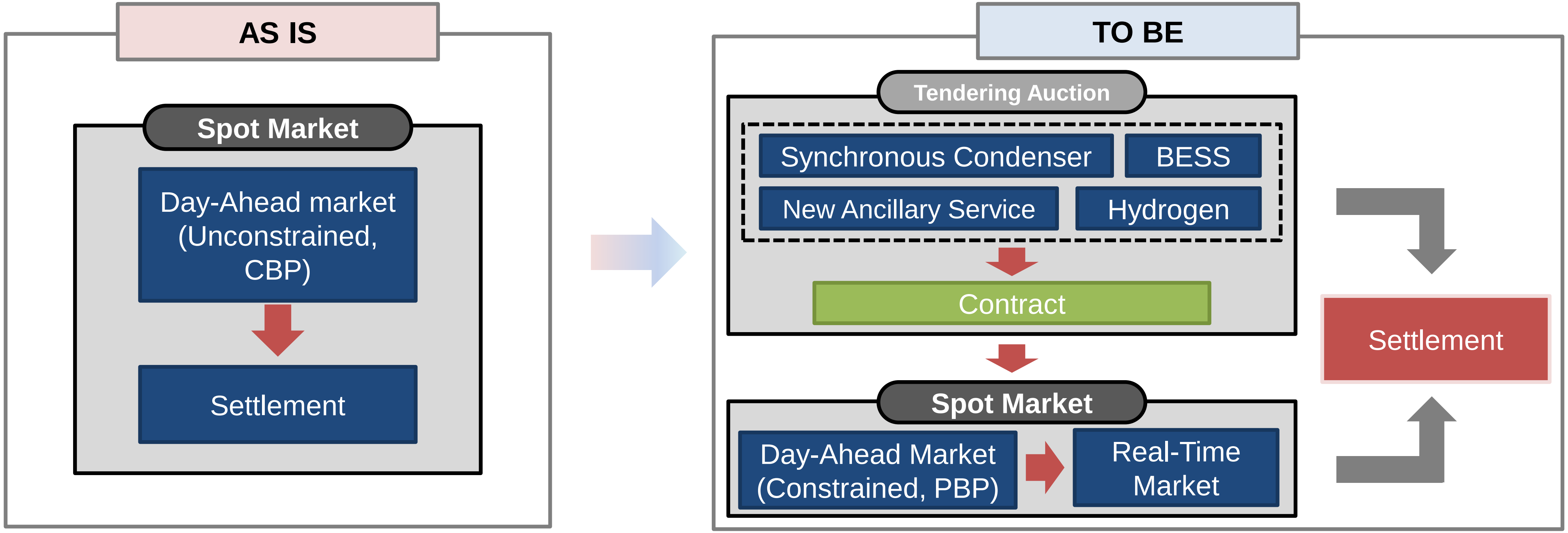
DER Promotion Act (June 2023)

- **Key action plans**
  - Basic National DER promotion plan every 5 years
  - Mandatory DER installation in large customers
  - Mandatory system impact study for large new loads
  - Sandbox area for DER promotion
  - VPP market
  - Locational Marginal Pricing (LMP)
  - Distribution System Operator (DSO)



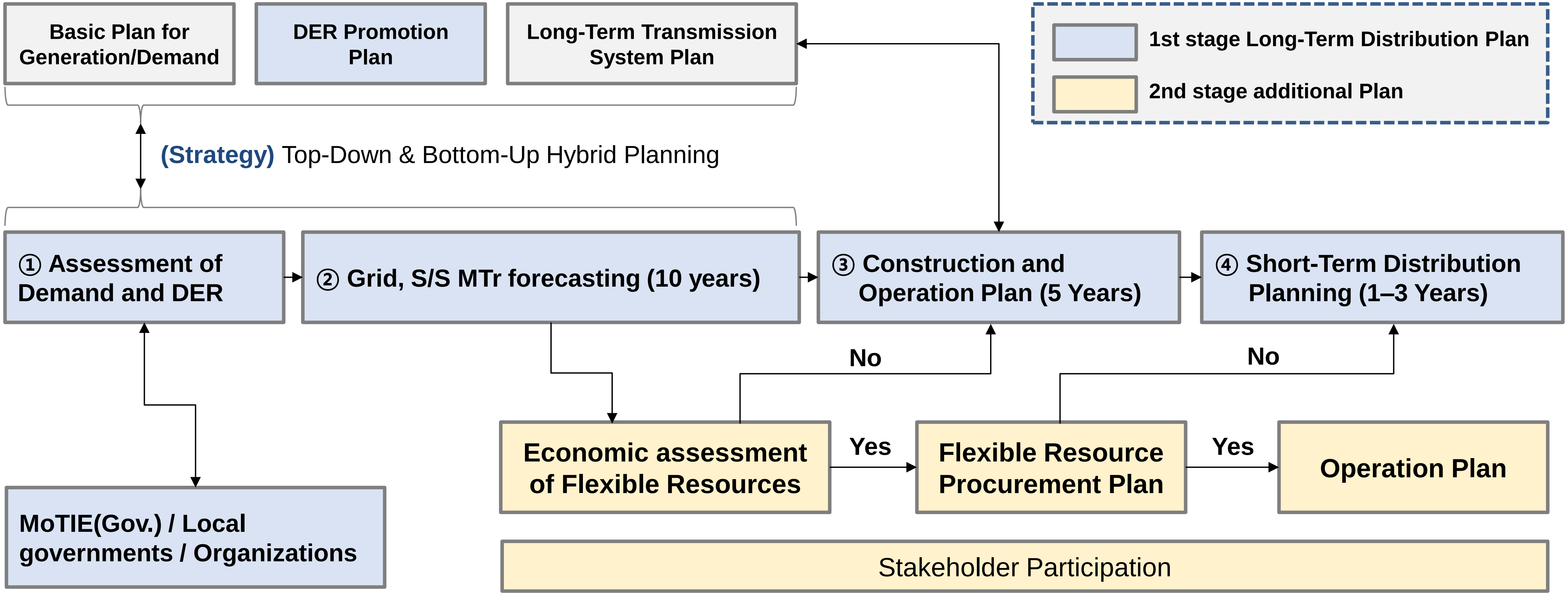
Development of New Market in Korea (2024)

- **Spot Market (Day-Ahead) → Tendering Auction (Centralized) + Spot Market (Real-Time)**
  - Promote DER (DR, ESS, H_2 etc.) to handle the variability of renewable energy
  - DER has more chances to get benefit from the market by providing flexibility



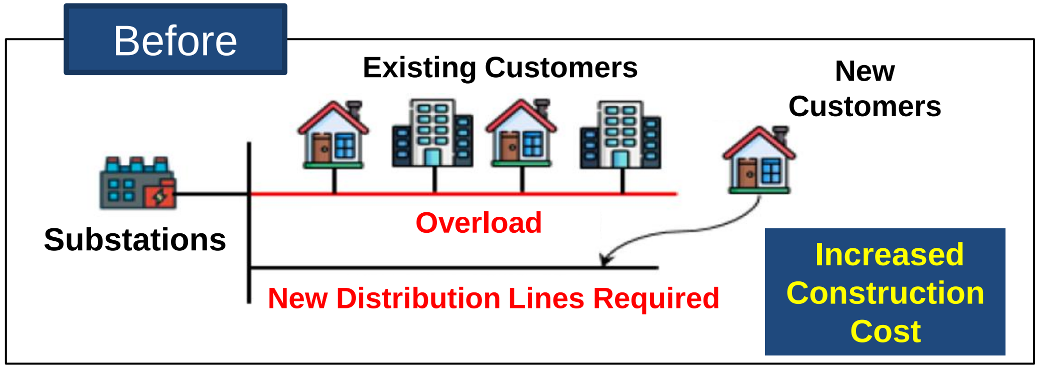
Distribution System Plan in Korea (2024)

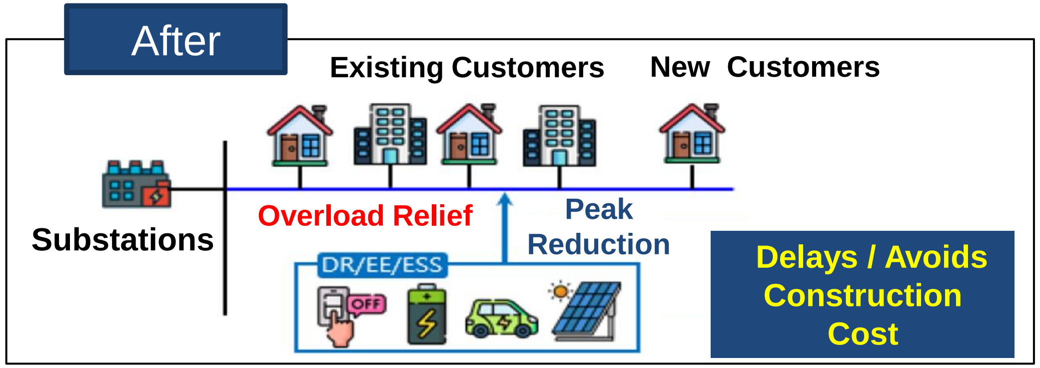
- Distribution system plan become a part of national plan



Non-Wires Alternatives(NWAs) in Jeju island

- **Definition : Alternatives to delay the grid investment with application of DER**





- **Utilization of Flexible DERs (ESS, EV, etc.) to expand distribution benefits and provide flexibility**

<< Jeju ESS Project >>

- Operator: LG Energy Solution
- Installation Area: Seogwipo City
- Capacity: 2.5 MVA (PCS) / 6.267 MWh (Battery)
- Connection Line: Pyosun S/S 1D (Exceeding 10 MW)
- Project Cost: 3 billion KRW (100% private investment)
- Purpose: **participation in wholesale market as VPP** and **avoidance of over-generation penalty + NWA**

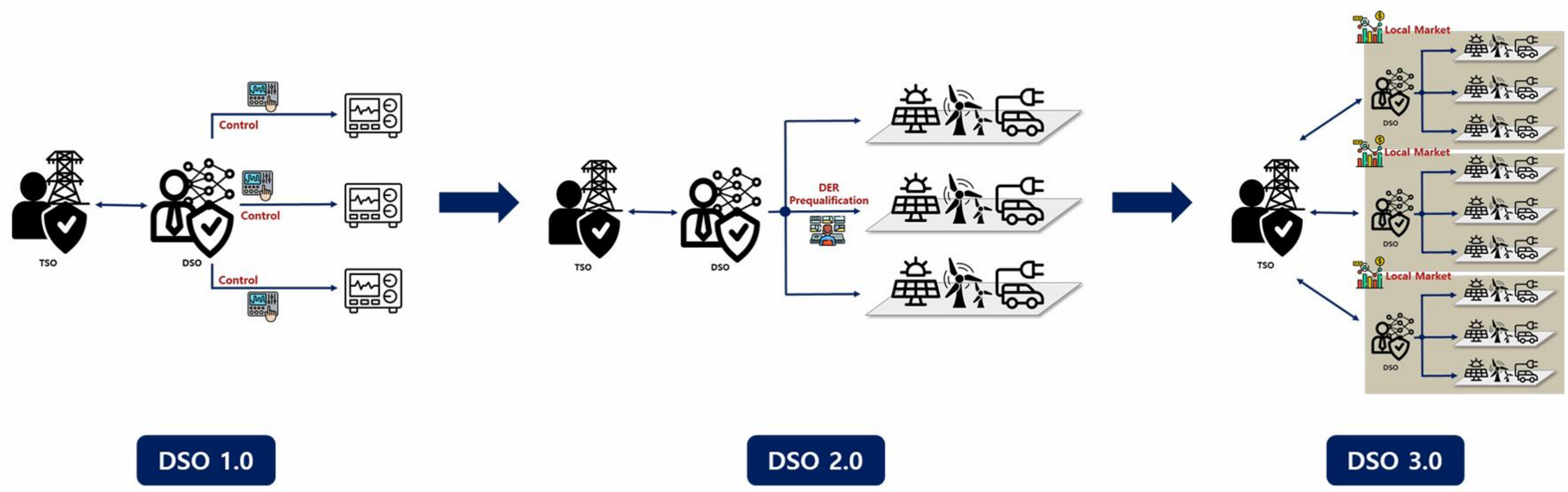
<< Jeju V2G Integration Project >>

- Operator: Hyundai Motor Group
- Installation Area: Jeju Island
- Capacity: 11 kW chargers 130 unit
- Purpose: **Participation in wholesale markets and demand response program + NWA (Sandbox project)**

DSO (Distribution System Operator) by KEPCO (2024)

- **Definition of DSO**
  - A ‘**neutral**’ operator responsible for the active control, dispatch, and market operation of DER and distribution system

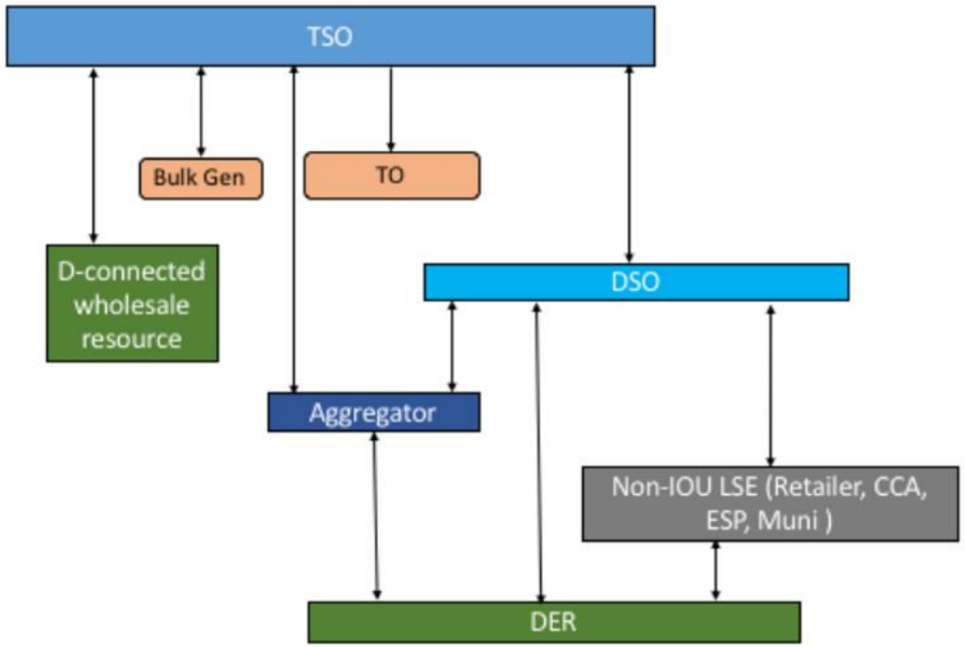
DSO 1.0	DSO 2.0	DSO 3.0
• Utilization of controllable resources • Providing limited local flexibility	• Integrated management of DERs • Providing **global system flexibility**	• Decentralized management of variability and uncertainty of RES **through market**



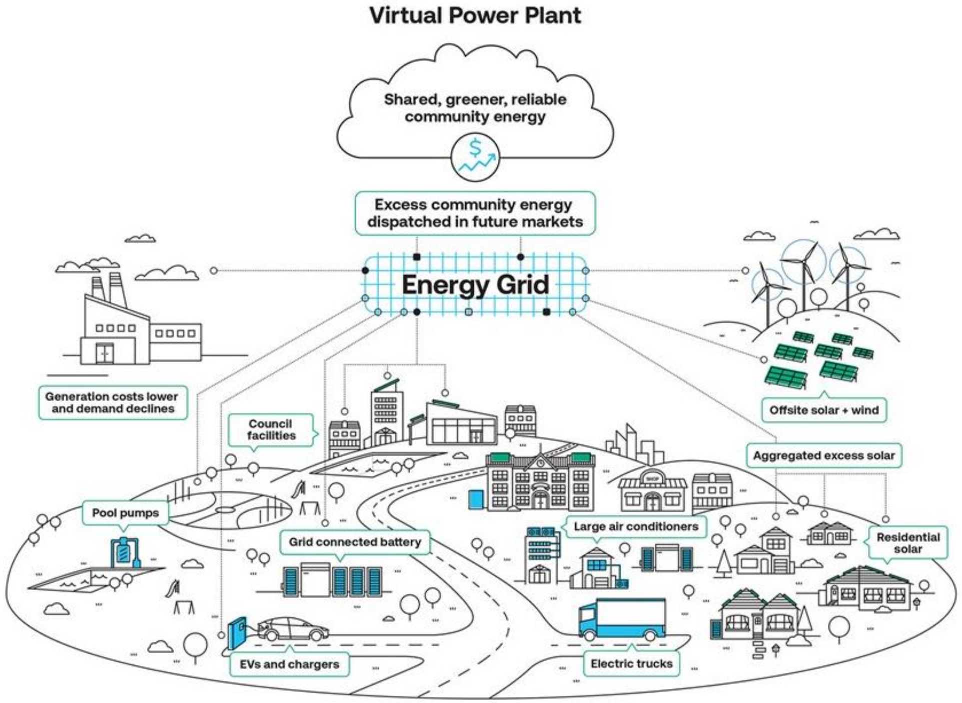
TSO/DSO/VPP Coordination and Governance

- VPP participate in wholesale market but DERs are located in distribution system
- Need coordinated control between TSO-DSO-VPP

TSO-DSO Coordination in NY

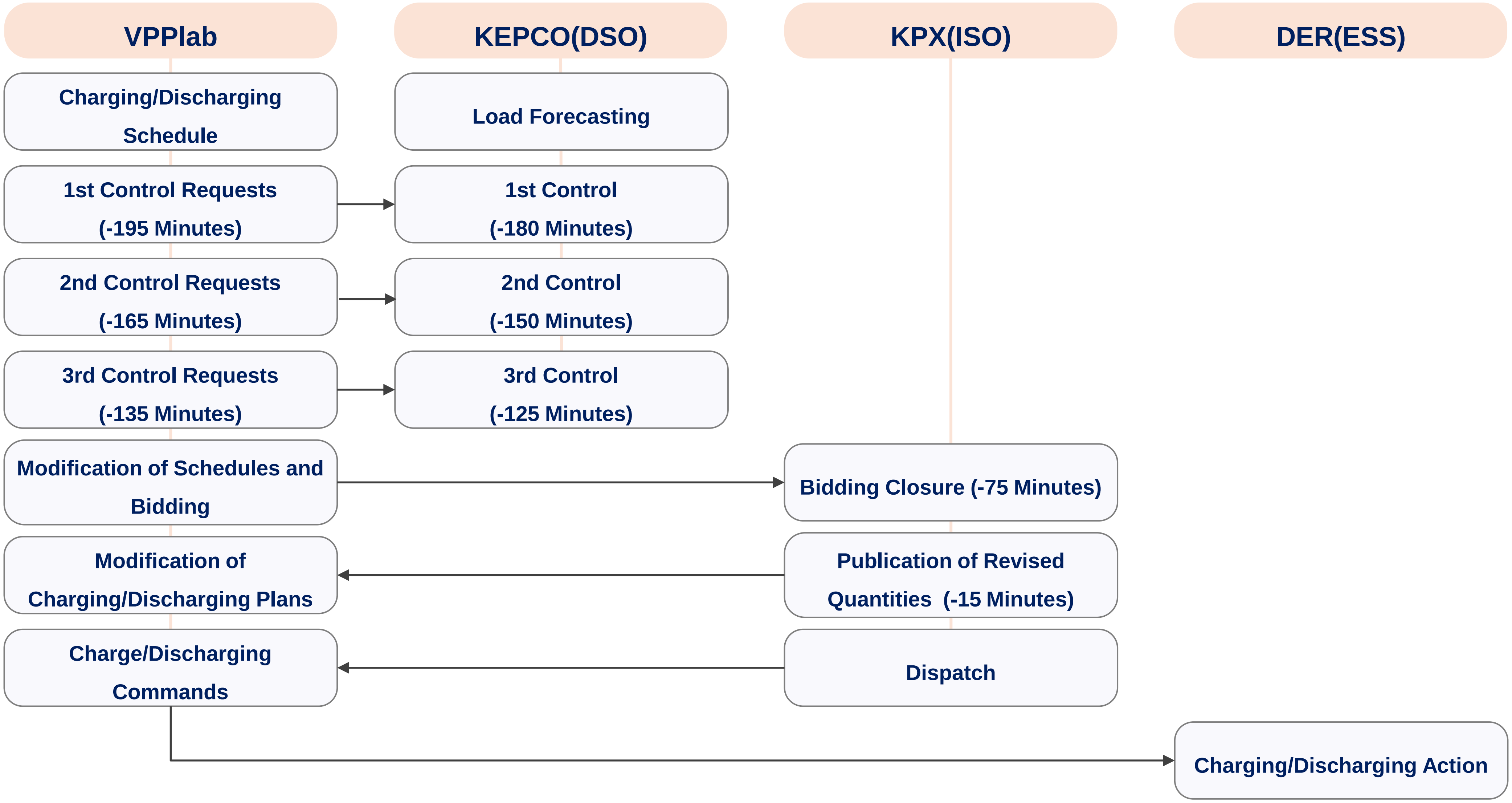


Virtual Power Plant and grid operation



TSO: Transmission System Operator, DSO: Distribution System Operator, VPP: Virtual Power Plant

Example of TSO/DSO/VPP Coordination in Jeju island



3 Types of Flexibility and 4 economic models (France)

Inha Univ. Power System Lab

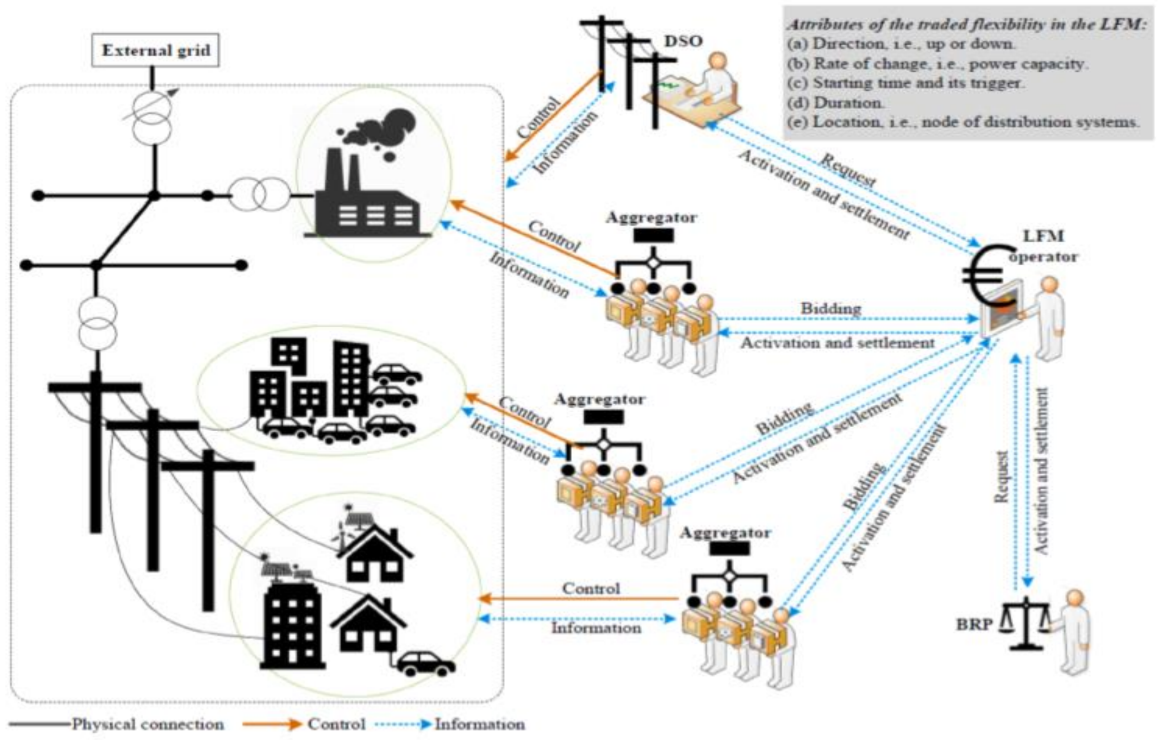
	Structural flexibility	Operational flexibility	Safeguard flexibility
Tariff-based	**Off-peak time in winter at night** (hot water boilers and recharging electric vehicles) **"Solar" off-peak time in summer**	**Dynamic time ToU**	X
Rules-based	**Definition of limitation quotas in contracts** allowing works (eg. S3RENR).	**Optimization of the unavailability of assets and the use of quotas.** Use of capacity short term reservation contracts (a few months or weeks). Examples: • Avoidance of power cuts during works • To get through cold peaks	**Emergency disconnection** **Rotating outages** Example: "temporary power limitation" tested with positive feedback during winter 2023-2024 on 100 000 Linky customers.
Flexible connection agreements	**Permanent smart connections, i.e., more customers can be connected to the same structure.**	**Activating forward capacity allocation (FCA).**	X
Market-based	**Flexibility contracts with capacity reservation** to postpone the reinforcement date.	**Flexibility with or without capacity.**	X

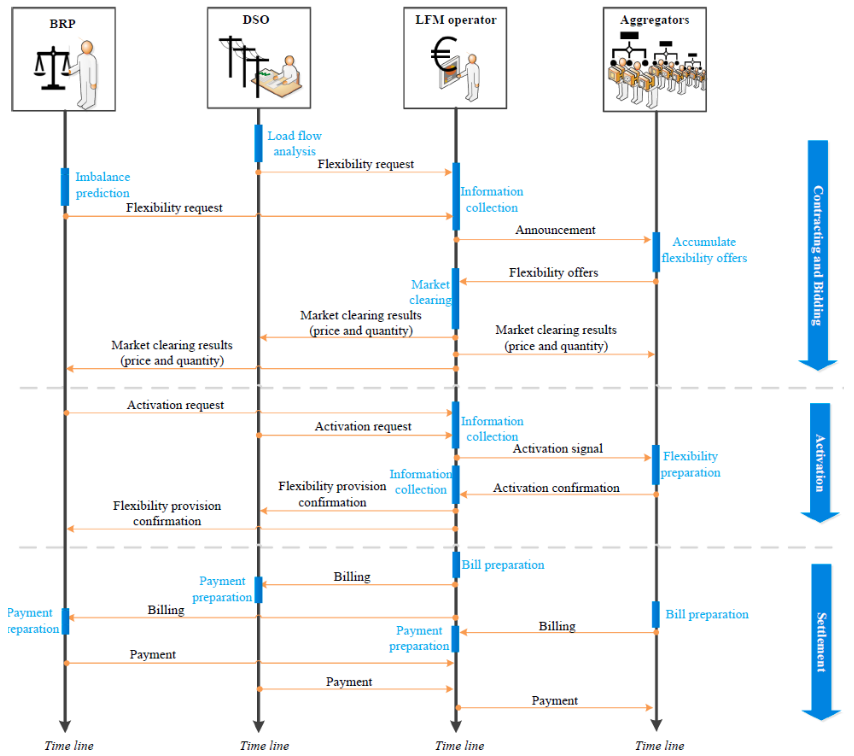
Source : CIRED Webinar, How are DSOs using flexibility to deliver the low carbon energy transition now and in the future?, Dec. 2024

Local Flexibility Market

- Introduce local flexibility market to respond to the uncertainty and variability of local DERs
- Market operation and bidding strategies for DER and aggregators
- Local solutions for reactive power/voltage control

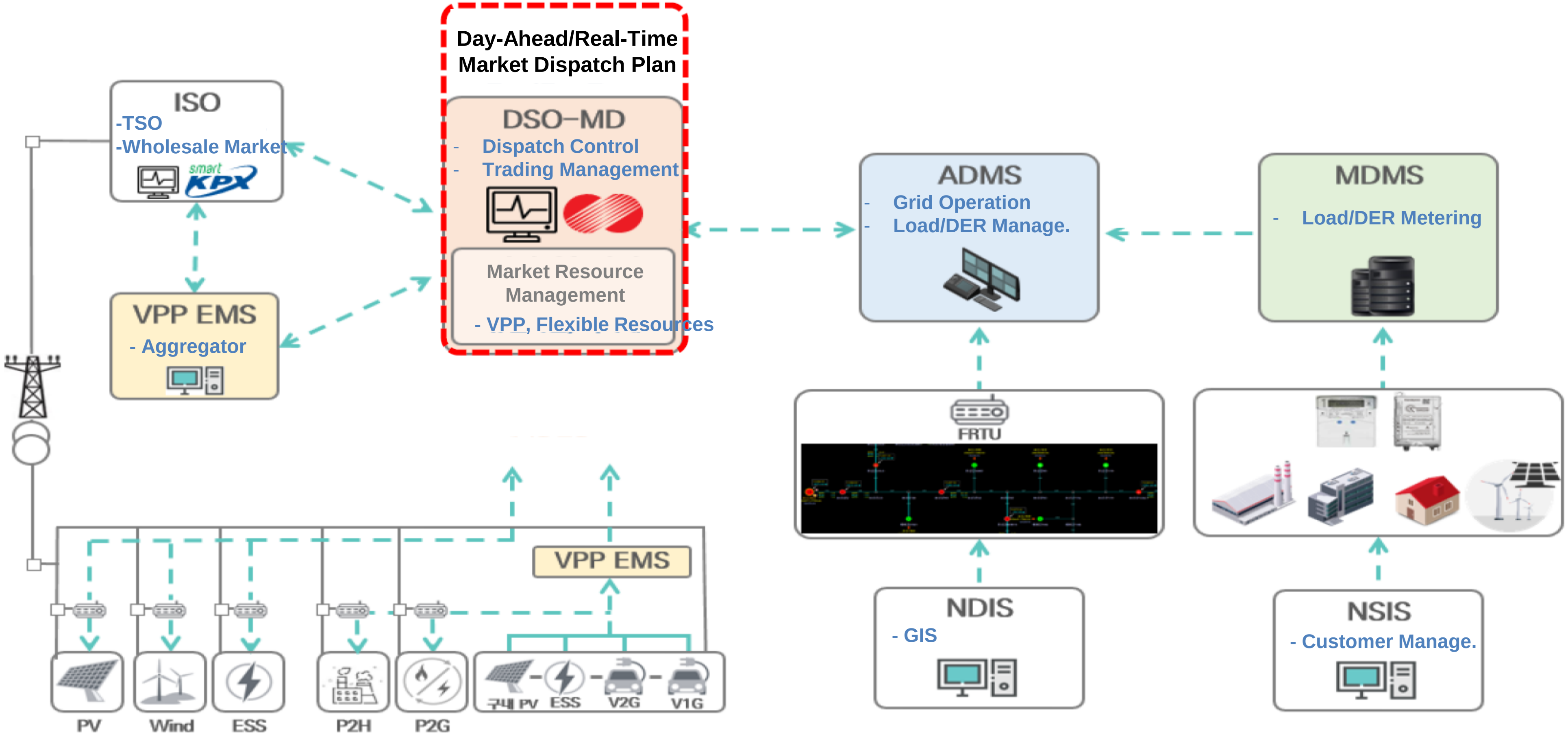
Local Energy Market Structure and Operation





Platform for VPP Bidding & Flexibility Market in Korea

- Establish a system (**DSO-MD**) for VPP market bidding and **grid congestion management**
- Prepare for the future DSO and LFM in Korea



Korea's Action Plan for DSO and LFM

Inha Univ. Power System Lab

Design Local Flexibility Market

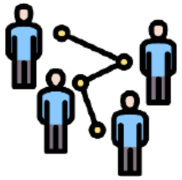
◆ **Design Market Structure**: To enhance the value of local flexibility

➢ **DERs → Value Stacking / DSO → Cost reduction and neutral operation**

Collaboration Framework with Wholesale Market

◆ **Collaboration framework** with wholesale market and operations

➢ MO – Stabilize price fluctuation / Retailer – Minimize energy cost / DSO – Optimize distribution system operation



Develop human resources and knowledge

◆ Develop **human resources and knowledge** for DSO and LFM

➢ Local flexibility market and DSO → National energy paradigm innovation

How AI can Enhance Grid Operational Flexibility: Challenges and Opportunities

Prof. Hongseok Kim

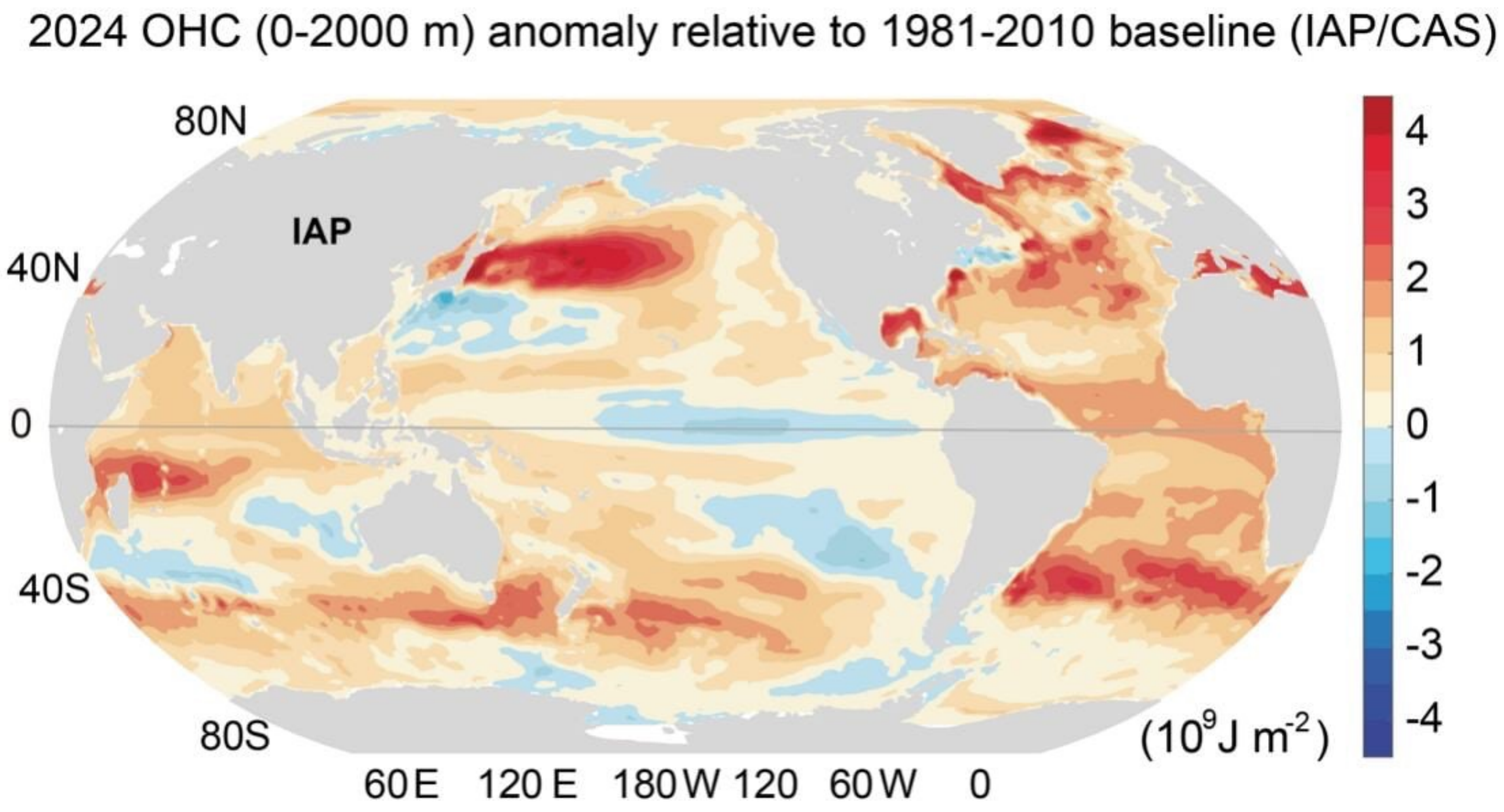
Sogang University

2025.01.15

http://nice.sogang.ac.kr

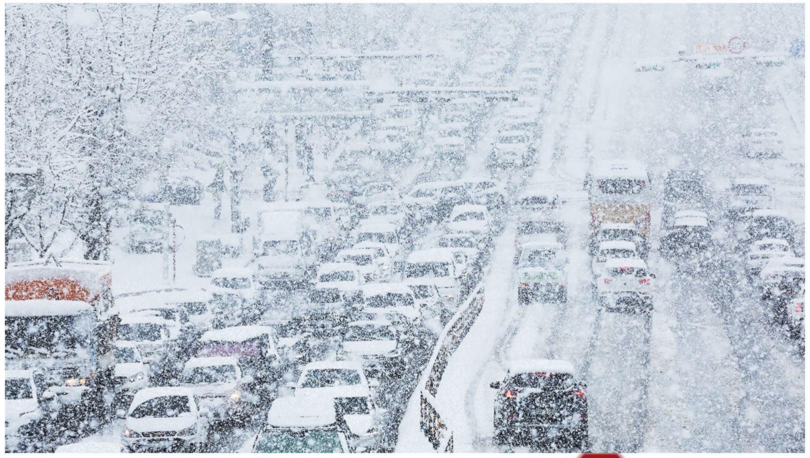
Global Climate Crisis: Abnormal is now Normal?

The ocean temperature of 2024 was all-time high.



Wildfire of LA, California (US)

Heavy snow (2024.11 Seoul)



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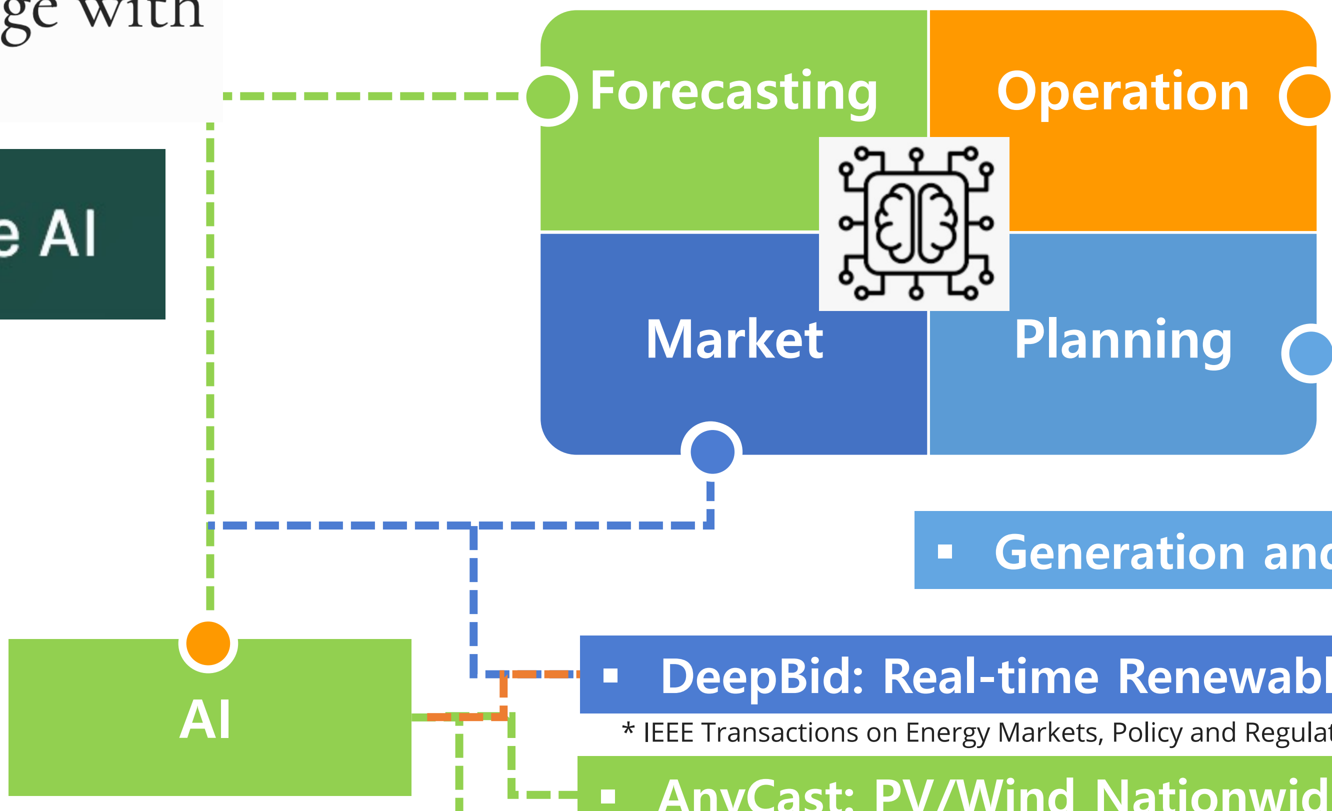
NeurIPS 2024 Workshop on Tackling Climate Change with Machine Learning

Climate Change AI

AI in Power Systems



- Generation and Grid Expansion
- DeepBid: Real-time Renewable Market, UC

  * IEEE Transactions on Energy Markets, Policy and Regulation, 2023
- AnyCast: PV/Wind Nationwide Forecasting

  * IEEE Transactions on Sustainable Energy, 2024
- **DeepLDE**: AI ACOPF using Implicit Layer, UC

  * IEEE Transactions on Power Systems, 2025
- ProADD: ESS and V2G

  * Applied Energy, 2024

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Forecasting and Bidding Competition

IEEEDataPort™ DATASETS | SUBMIT A DATASET | COMPETITIONS | IEEE

Competition

Archived Competition

HYBRID ENERGY FORECASTING AND TRADING COMPETITION

Submission Dates: 02/19/2024 to 05/18/2024

Citation Author(s):
Jethro Browell (University of Glasgow)
Sebastian Haglund (rebase.energy)
Henrik Kälvegren (rebase.energy)
Edoardo Simioni (Ørsted)
Ricardo Bessa (INESC TEC)
Yi Wang (University of Hong Kong)
Dennis van der Meer (Ørsted)

Submitted by: Jethro Browell

Last updated: Wed, 06/26/2024 - 06:49

DOI: 10.21227/5hn0-8091

Links:
Ørsted
rebase.energy
rebase Slack - Ask questions here
Getting Started Example (GitHub)
API Online Documentation

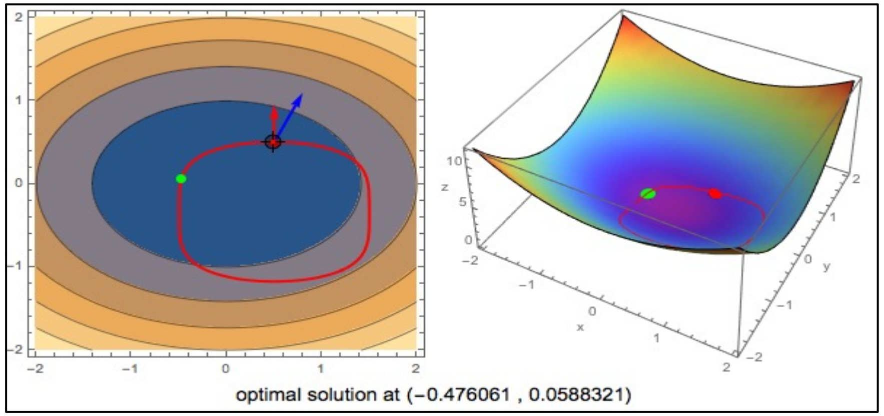
Categories: Machine Learning, Power and Energy, Weather, Financial

Keywords: Energy Forecasting, energy trading

AI-Aided Optimization

☐ Solve constrained optimization problems using NNs

+

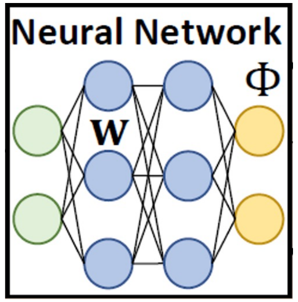


$$\min_{\mathbf{y}\in\mathbb{R}^n} f_{\mathbf{d}}(\mathbf{y}),$$

$$\text{s.t.} \quad g_{\mathbf{d}}(\mathbf{y}) \leq 0, \quad h_{\mathbf{d}}(\mathbf{y}) = 0,$$

AI Inference

Training Data



Solution y

Mathematical Solver

Single Input d

Solution y

AC Optimal Power Flow

☐ Nonconvex Optimization

$$\min_{P_i, Q_i, V_i, \forall i \in \mathcal{G}} \quad \sum_{i \in \mathcal{G}} C_i(P_i)$$

$$\text{subject to} \quad \underline{P}_i \leq P_i \leq \overline{P}_i, \forall i \in \mathcal{G},$$

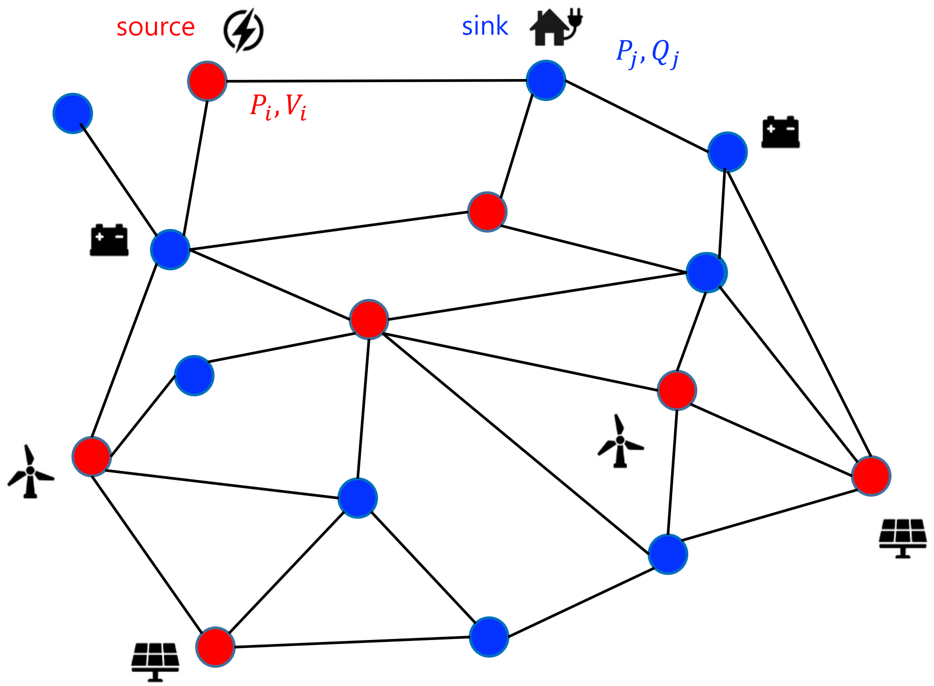
$$\underline{Q}_i \leq Q_i \leq \overline{Q}_i,$$

$$|\underline{V}_i| \leq |V_i| \leq |\overline{V}_i|,$$

$$|V_i(V_i^* - V_j^*)Y_{ij}^*| \leq \overline{S}_{ij}, \forall (i,j) \in \mathcal{E},$$

$$P_i = \sum_{(i,j) \in \mathcal{E}} \text{Re}(V_i(V_i^* - V_j^*)Y_{ij}^*),$$

$$Q_i = \sum_{(i,j) \in \mathcal{E}} \text{Im}(V_i(V_i^* - V_j^*)Y_{ij}^*),$$



arpa·e

GRID OPTIMIZATION (GO) COMPETITION

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$3 million in prizes awarded in Challenge 3

Challenge 3

Event 4 results are now available. Sandbox submissions for the Grid Optimization Competition Challenge 3 are open.

arpa·e Advanced Research Projects Agency • ENERGY | AIMMS | AMPL | GAMS

GUROBI OPTIMIZATION | IBM | mosek | anua Technologies | SIEMENS Ingenuity for life

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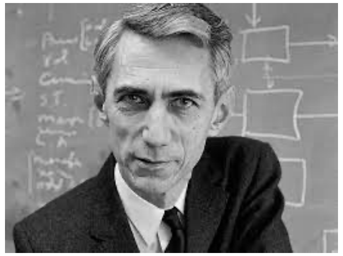
Holy Grail of Power Systems



OPF is something like
Shannon Capacity (1948)

- ☐ **Optimal Power Flow since *1962***
  - **Nonconvex Optimization**
  - **Deep Learning based OPF was introduced in *2019***

1962 *2012* *2016* *2019* *2020* *2021* *2022* *2023* *2024*

DeepOPF
(IEEE SmartGridComm 2019)

DC-OPF Supervised

Xiang Pan, Minghua Chen,
City University of Hong Kong

OPF-DNN (AAAI 2020)

Lagrange Dual (LDF)

Ferdinando Fioretto, Syracuse University
Pascal Van Hentenryck, Gatech

DC3 (ICLR 2021)

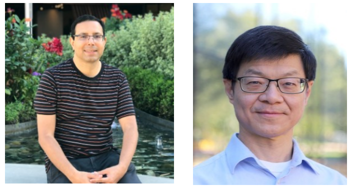
OptNet & Implicit Layer (DC3)

Priya L. Donti, MIT
Zico Kolter, CMU

DeepOPF+ (ICLR 2023)

Tianyu Zhao, Chinese Univ. of Hong Kong
Steven Low, Caltech

Zero duality gap in optimal power flow problem
(IEEE Transactions on Power Systems)



Javad Lavaei, UC Berkely
Steven Low, Caltech

PA-DNN
(IEEE SmartGridComm 2022)

Minsoo Kim, Hongseok Kim
Sogang University

DeepLDE (TPWRS 2024) **K-LDE, ExpressOPF**

Keunju Song, Hien Thanh Doan,
Hongseok Kim, Sogang University

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Challenges and Opportunities of AI AC-OPF

Feasibility (Implicit Layer)

Ensure solutions comply with physical and operational constraints

Speed

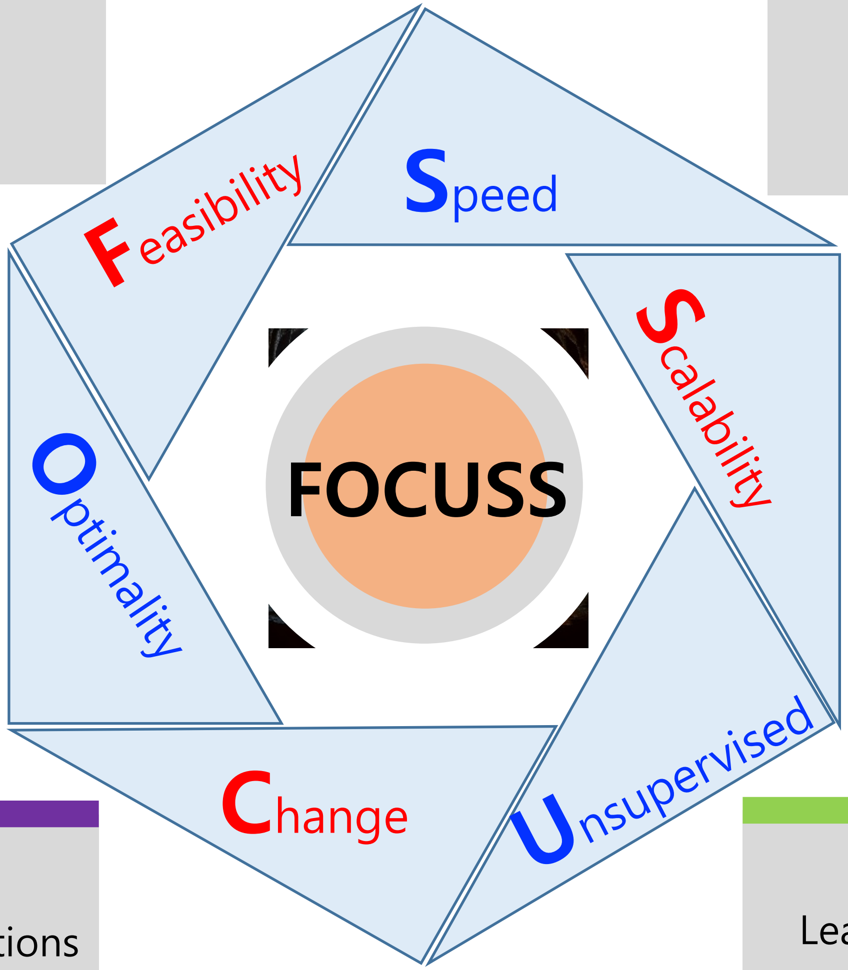
Much faster than conventional solvers (Gurobi, CPLEX, IPOPT, MIPS, etc.)

Optimality

Find an optimal (or near optimal) solution satisfying constraints

Scalability

The ability to effectively learn OPF in large-scale, complex power systems



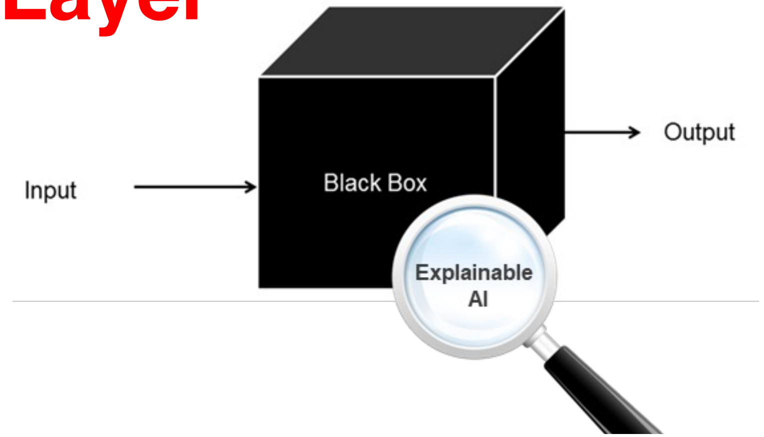
Flexible to Changes

The ability to learn and adjust OPF solutions in response to topology changes

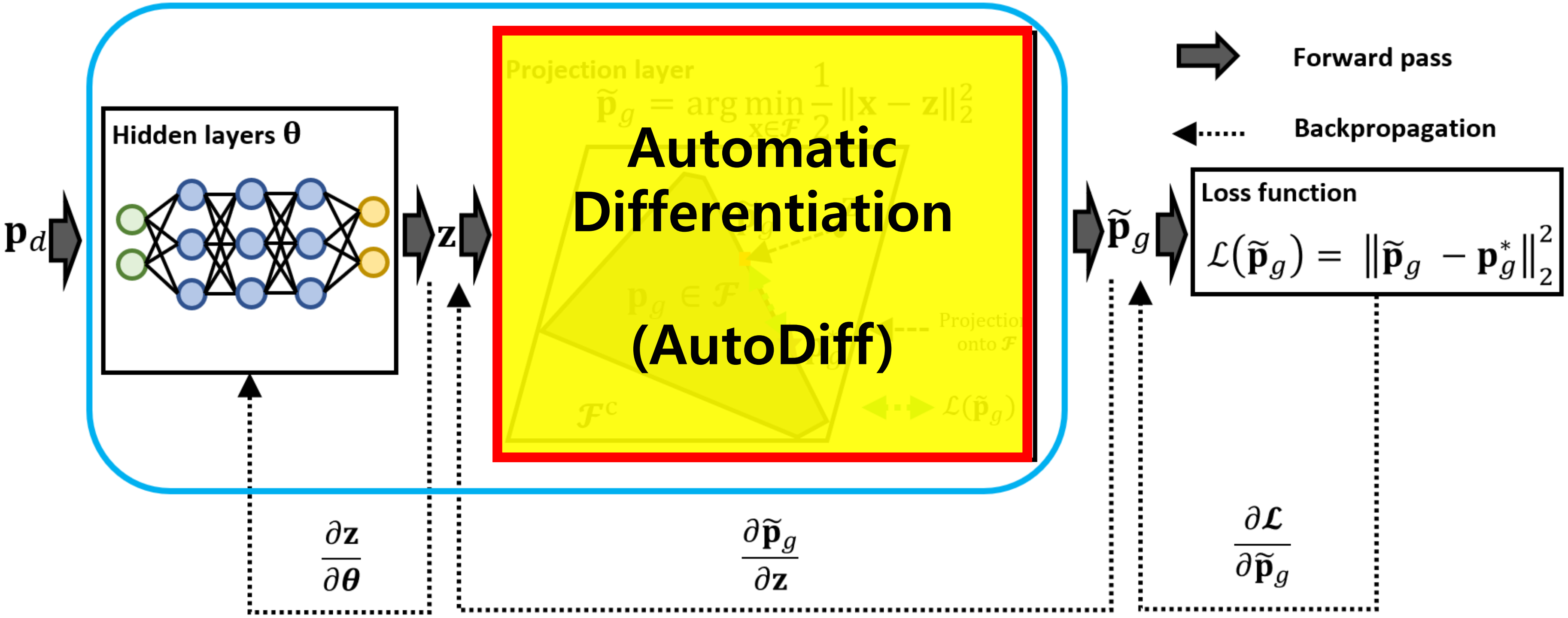
Unsupervised

Learn how to solve OPF without the need of pre-solved OPF solutions

Trustworthy AI using Implicit Layer



- Energy AI = Smart Grid + AI
  - Blackbox AI
  - Explainable AI (XAI)
  - Safety-Critical AI using **Physics Informed NN (PINN)**



M. Kim and H. Kim, Projection-aware Deep Neural Network for DC Optimal Power Flow Without Constraint Violations, *IEEE SmartGridComm, pp.1-6, Oct. 2022*

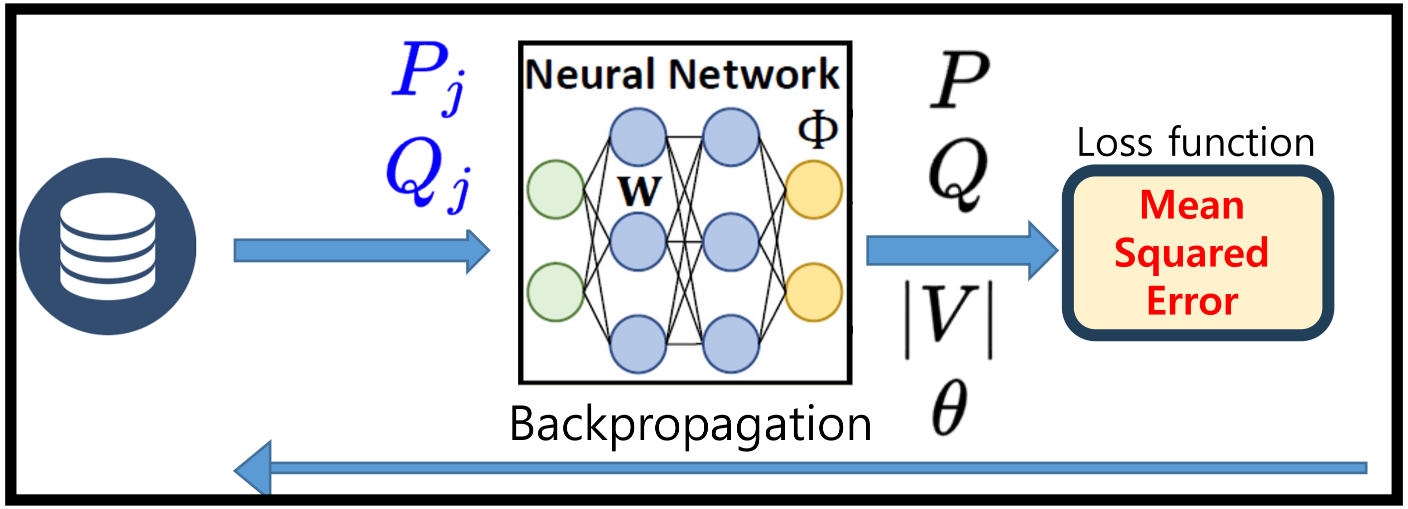
TRUSTWORTHY AI FOR POWER SYSTEMS

DTU

Organized by Prof. SPYROS CHATZIVASILEIADIS (http://www.chatziva.com/pscc2024.html)

Learning to Solve Optimal Power Flow (SL)

Supervised Learning



Pros:

- **Significantly faster than solvers.**

Cons:

- **Need optimal solutions as labels.**
- **Obtaining feasible solutions is hard.**

AC-OPF Problem

$$\min_{P_i, Q_i, V_i, \forall i \in \mathcal{G}} \quad \sum_{i \in \mathcal{G}} C_i(P_i)$$

subject to

Inequality constraints

$$\underline{P}_i \le P_i \le \overline{P}_i, \forall i \in \mathcal{G},$$
$$\underline{Q}_i \le Q_i \le \overline{Q}_i,$$
$$|\underline{V}_i| \le |V_i| \le |\overline{V}_i|,$$
$$|V_i(V_i^* - V_j^*)Y_{ij}^*| \le \overline{S}_{ij}, \forall (i,j) \in \mathcal{E},$$

Equality constraints

$$P_i = \sum_{(i,j) \in \mathcal{E}} \mathrm{Re}(V_i(V_i^* - V_j^*)Y_{ij}^*),$$
$$Q_i = \sum_{(i,j) \in \mathcal{E}} \mathrm{Im}(V_i(V_i^* - V_j^*)Y_{ij}^*),$$

Learning to Solve Optimal Power Flow (LDF)

☐ Problem Formulation

$$\min_{\mathbf{y}\in\mathbb{R}^n} f_{\mathbf{d}}(\mathbf{y}),$$
$$\text{s.t.} \quad g_{\mathbf{d}}(\mathbf{y}) \leq \mathbf{0}, \quad h_{\mathbf{d}}(\mathbf{y}) = \mathbf{0},$$

☐ Lagrange Function

$$\mathcal{L}(\mathbf{y}, \boldsymbol{\lambda}, \boldsymbol{\mu}) = f_{\mathbf{d}}(\mathbf{y}) + \boldsymbol{\lambda}^{\intercal} R(g_{\mathbf{d}}(\mathbf{y})) + \boldsymbol{\mu}^{\intercal} S(h_{\mathbf{d}}(\mathbf{y}))$$

- $f_{\mathbf{d}}(\mathbf{y})$: Cost function
- $\boldsymbol{\lambda}^{\intercal} R(g_{\mathbf{d}}(\mathbf{y}))$: Violation degree of inequality constraints
- $\boldsymbol{\mu}^{\intercal} S(h_{\mathbf{d}}(\mathbf{y}))$: Violation degree of equality constraints

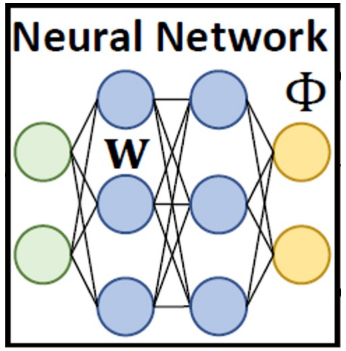
where $R(g_{\mathbf{d}}(\cdot)) = \max\{g_{\mathbf{d}}(\cdot), 0\}$, and $S(h_{\mathbf{d}}(\cdot)) = |h_{\mathbf{d}}(\cdot)|$.

Learning to Solve Optimal Power Flow (LDF)

Unsupervised + Lagrange Dual

P_j (d)

Q_j



Backpropagation

P (y)

Q

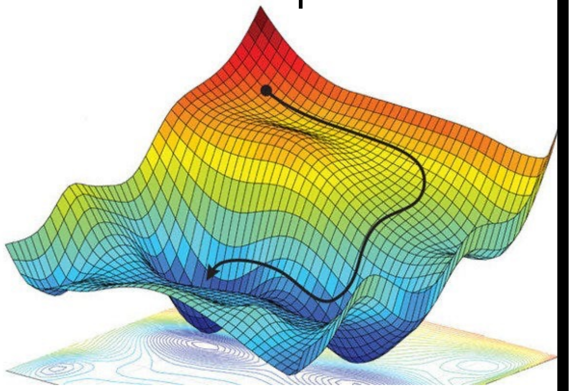
$|V|$

θ

Loss function

Cost
+ Ineq. viol
+ eq. viol

Nonconvex Optimization



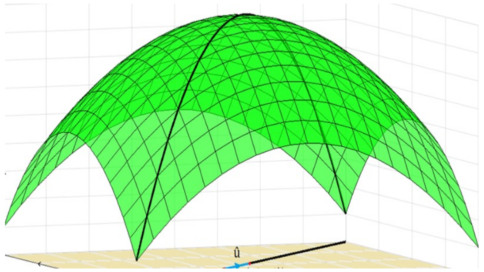
Feasibility of equality constraints is not guaranteed!

Inequality Constraints

$$\boldsymbol{\lambda} \leftarrow \boldsymbol{\lambda} + \rho \nabla_{\boldsymbol{\lambda}} \mathcal{L}(\mathbf{y}^*, \boldsymbol{\lambda}, \boldsymbol{\mu})$$

Equality Constraints

$$\boldsymbol{\mu} \leftarrow \boldsymbol{\mu} + s \nabla_{\boldsymbol{\mu}} \mathcal{L}(\mathbf{y}^*, \boldsymbol{\lambda}, \boldsymbol{\mu})$$



Lagrange Dual Function

PENN: Embedding Implicit Layer

☐ Reformulated Constrained Optimization

$$\min_{\mathbf{x}\in\mathbb{R}^{n-n_{eq}}} f_{\mathbf{d}}\left(\begin{bmatrix}\mathbf{x}\\ \Psi_h(\mathbf{x})\end{bmatrix}\right),$$
$$\text{s.t.} \quad g_{\mathbf{d}}\left(\begin{bmatrix}\mathbf{x}\\ \Psi_h(\mathbf{x})\end{bmatrix}\right) \le 0.$$

We don't need to consider about equality constraints

$$h_{\mathbf{d}}(\mathbf{y}) = h_{\mathbf{d}}\left(\begin{bmatrix}\mathbf{x}\\ \mathbf{z}\end{bmatrix}\right) = h_{\mathbf{d}}\left(\begin{bmatrix}\mathbf{x}\\ \Psi_h(\mathbf{x})\end{bmatrix}\right) = \mathbf{0}$$

☐ Lagrange Function

$$\mathcal{L}_e(\mathbf{x}, \boldsymbol{\lambda}) = f_{\mathbf{d}}\left(\begin{bmatrix}\mathbf{x}\\ \Psi_h(\mathbf{x})\end{bmatrix}\right) + \boldsymbol{\lambda}^\intercal R\left(g_{\mathbf{d}}\left(\begin{bmatrix}\mathbf{x}\\ \Psi_h(\mathbf{x})\end{bmatrix}\right)\right).$$

Cost function

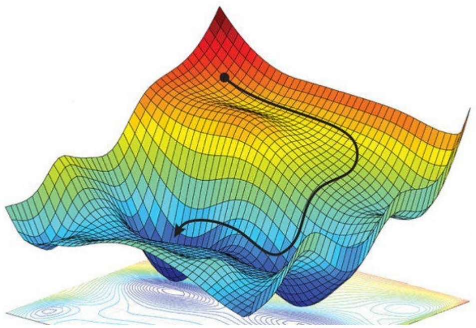
Violation degree of inequality constraints

DeepLDE

Unsupervised + Implicit Layer + Lagrange Dual

P_j (d) → **Reparameterization Memoization Generalization** → P_i (x) $|V_i|$ → Equality Constraints **AutoDiff** (Equation Embedding $h_d(\mathbf{y}) = 0$ where $\mathbf{y} = \begin{bmatrix}\mathbf{x} \\ \Psi_h(\mathbf{x})\end{bmatrix}$) → (y) P Q $|V|$ θ → Loss function: **Cost + Ineq. viol**

Nonconvex Optimization

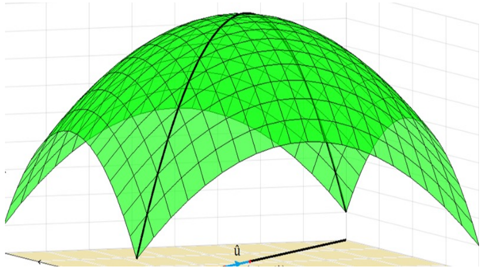


Backpropagation through equations (automatic differentiation)

Feasibility of equality constraints is always guaranteed!

Inequality Constraints

$$\boldsymbol{\lambda} \leftarrow \boldsymbol{\lambda} + \rho \sum_{\mathbf{d}\in\mathcal{D}} R\left(g_{\mathbf{d}}\left(\begin{bmatrix}\boldsymbol{\Phi}(\mathbf{w},\mathbf{d}) \\ \Psi_h(\boldsymbol{\Phi}(\mathbf{w},\mathbf{d}))\end{bmatrix}\right)\right)$$



Lagrange Dual Function

DeepLDE Results

☐ IEEE 57, 118 Bus Systems

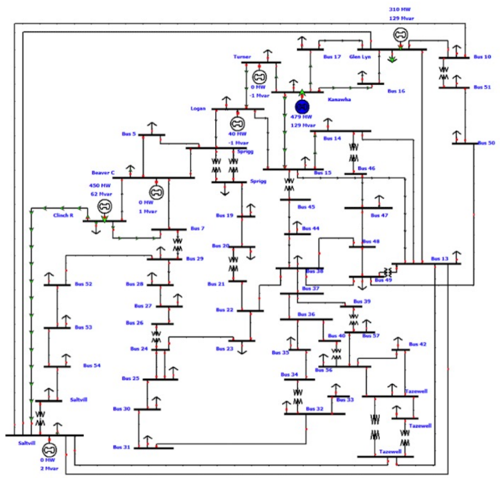
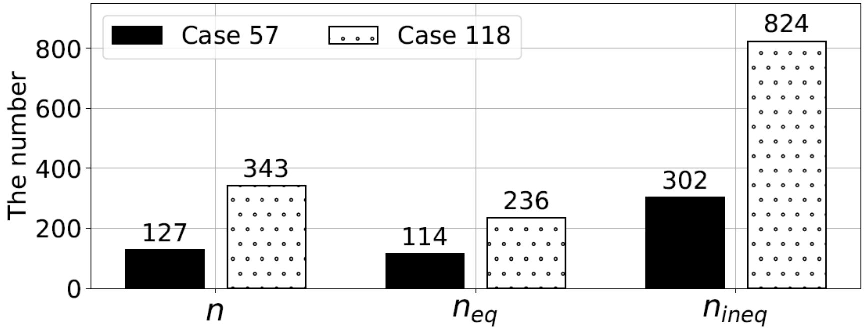


Figure 4. IEEE 57 bus system



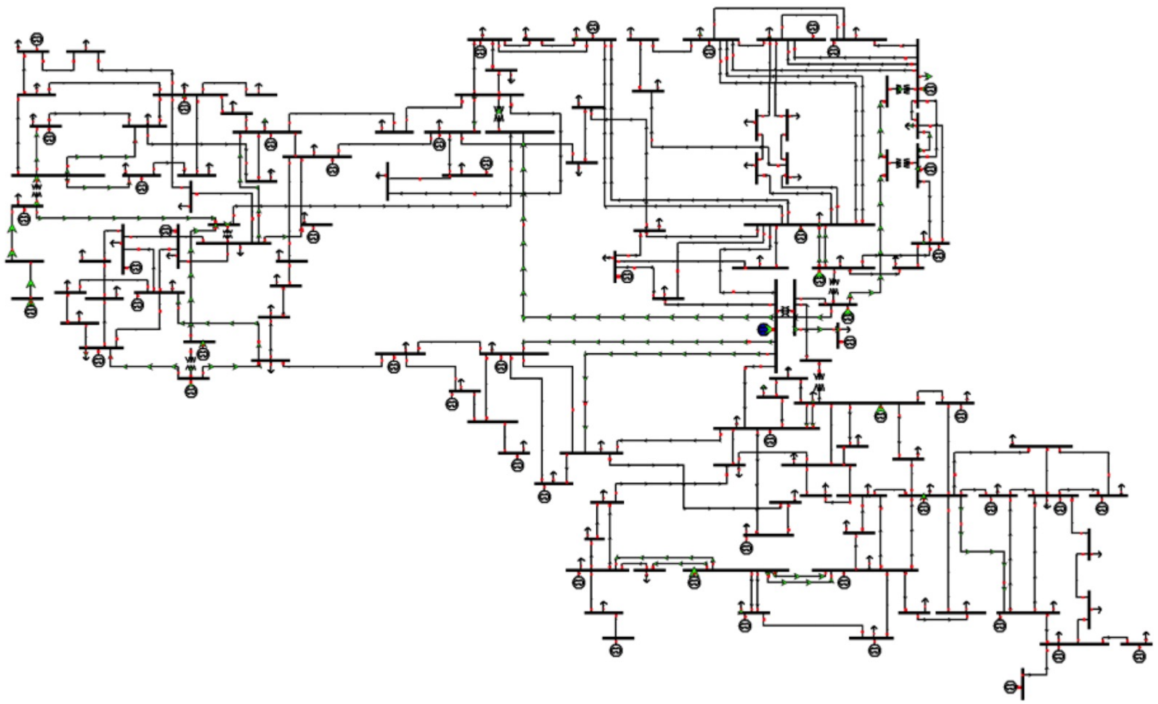
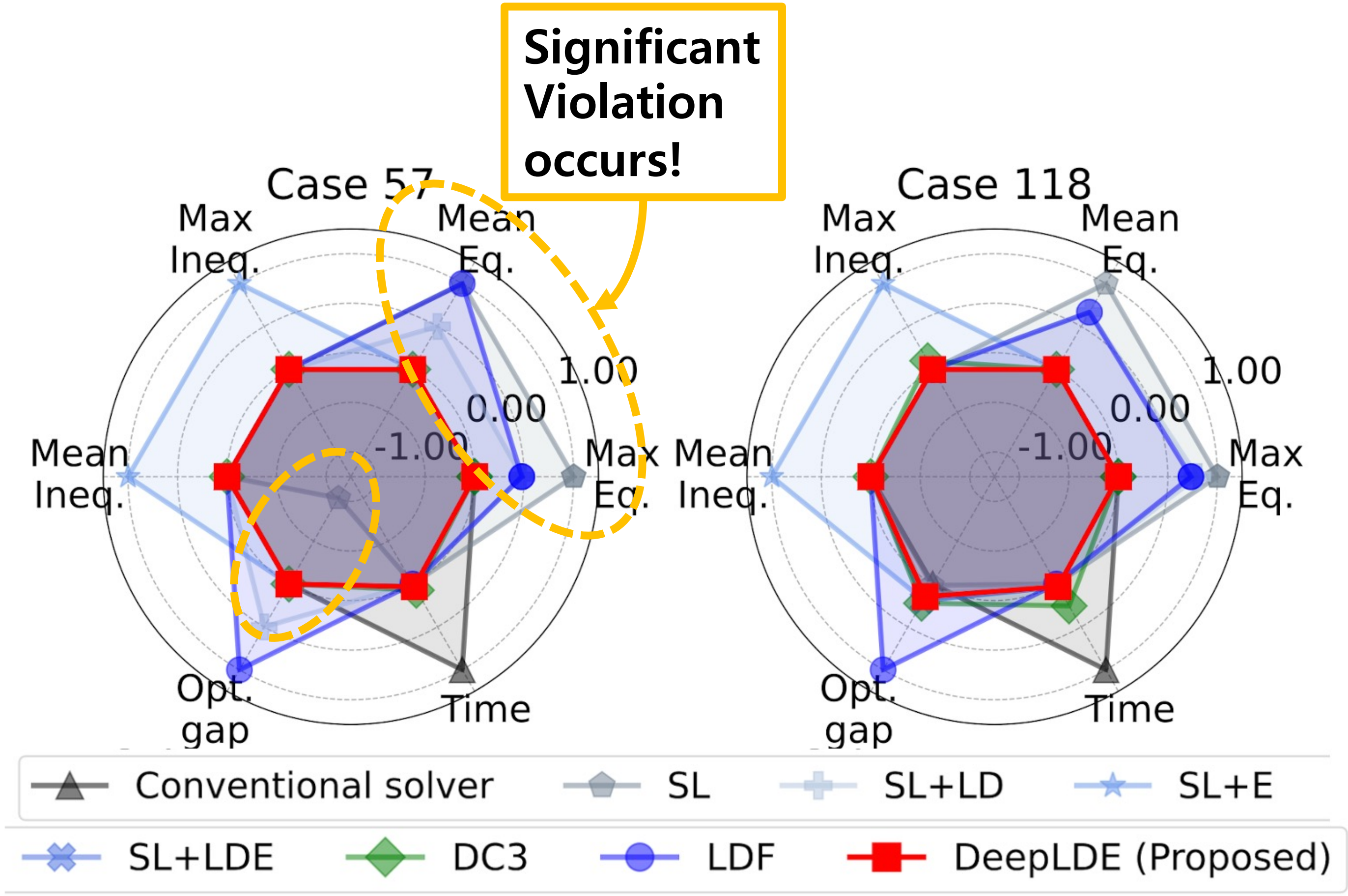
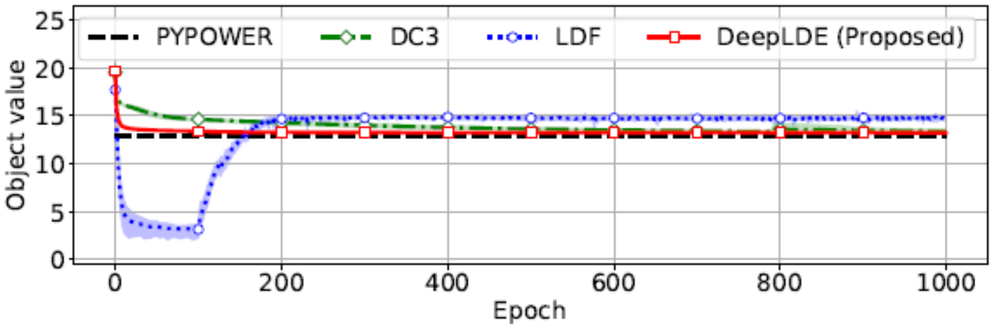


Figure 5. IEEE 118 bus system

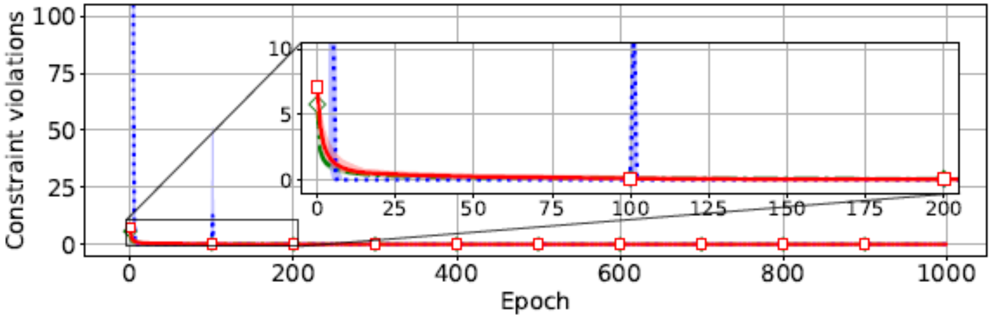
Deep**LDE** Results

- No constraint violations
- ***35*** times faster than conventional solver

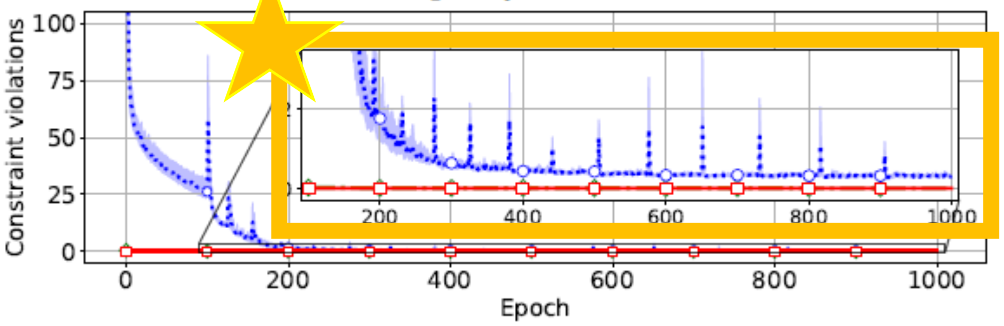




(a) Objective funtion



(b) Maximum inequality constraint violations



(c) Maximum equality constraint violations

AI Model for Korea AC-OPF: K-LDE

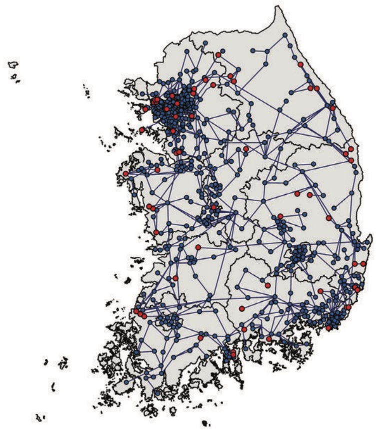
☐ KPX 85 Bus System (Jeju Island)

Solver	Cost (kWon)	Opt. gap (%)	Pg satisfaction rate	Qg Satisfaction rate	|V| satisfaction rate	Branch satisfaction rate	Active PF satisfaction rate (tol: 1e-2)	Reactive PF satisfaction rate (tol: 1e-2)	Inference time (ms)
PowerModels.jl	**836.38**	-	100%	100%	100%	100%	100%	100%	211.54
MATPOWER	**836.38**	-	100%	100%	100%	100%	100%	100%	58.32
K-LDE	837.07	0.08	**100%**	**100%**	**100%**	**100%**	**100%**	**99.04%**	**1.54**

137x faster!

Case Study of Korea Power Grid (K-LDE for KPX 4872 Bus System)

smart KPX
KOREA POWER EXCHANGE



No.	Pg	Qg	Pd	Qd	zP	zQ	Branch	N
4872-bus	180	180	2917	3033	1775	1779	6372	4872

Solver	Cost (kWon)	Opt. gap (%)	Pg satisfaction rate	Qg Satisfaction rate	|V| satisfaction rate	Branch satisfaction rate	Active PF satisfaction rate (tol: 1e-2)	Reactive PF satisfaction rate (tol: 1e-2)	Inference time (ms)
PowerModels.jl	**125,290**	-	100%	100%	100%	100%	100%	100%	4770.7
MATPOWER	**125,290**	-	100%	100%	100%	100%	100%	100%	1771.9
K-LDE+	**126,164**	**0.70**	**100%**	**98.94%**	**99.92%**	**99.96%**	**99.84%**	**99.83%**	**352.18**
LU K-LDE	**126,816**	**1.22**	**100%**	**98.42%**	**99.74%**	**99.94%**	**99.82%**	**99.82%**	**353.18**

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Concluding Remarks

Solution Perspectives

Future of AI

AI including LLM keeps advancing and Energy AI is not exception.

Safety-Critical

AI experts may not have domain knowledge about power systems.

Cost Saving

AI AC-OPF would save billions of dollars (US)

Trustworthy AI

Handling Uncertainty

Carbon Neutrality by 2050

Inverter-based generation → Increased uncertainty → Fast sensing/communication

Role of AI AC-OPF

Forecasting, Control, Optimization and their integration → AI Optimization and Self learning

Feasibility Verification

AI AC-OPF should be verified for sufficient cases.

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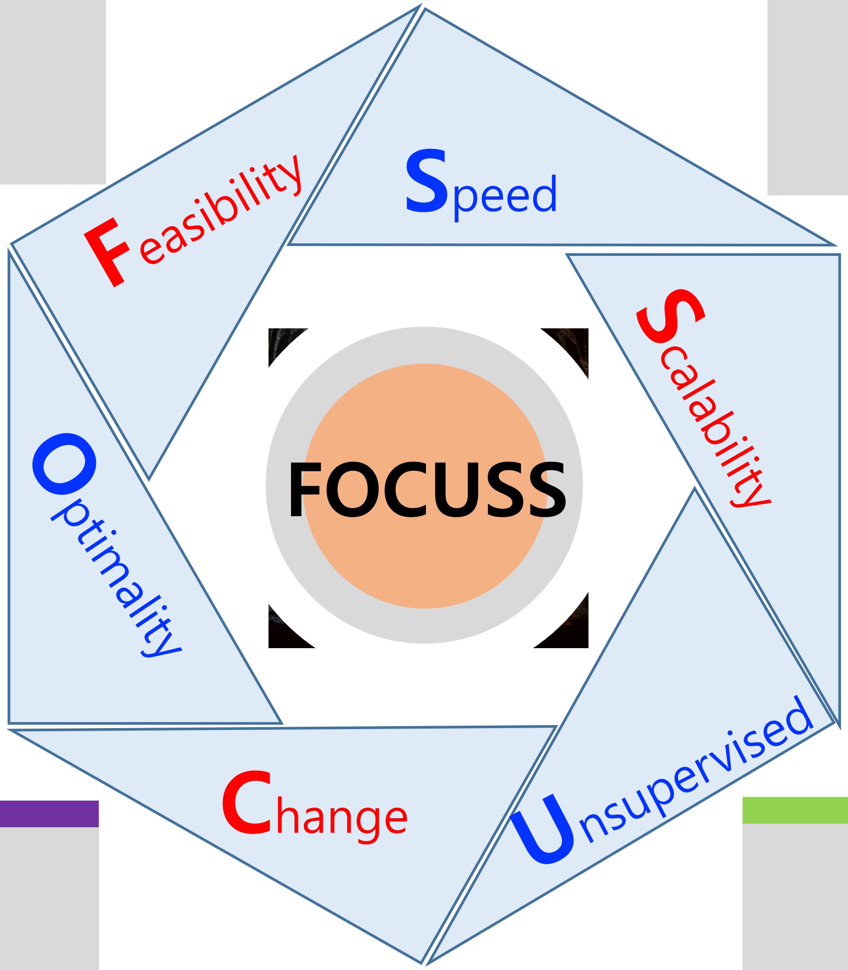
Future Work

Feasibility

Better way of solving PF equations leveraging GPU and linear algebra

Speed

Better way of solving PF equations leveraging GPU and linear algebra



Optimality

Better neural network architectures

Scalability

Towards continent-scale AI AC-OPF

Flexible to Changes

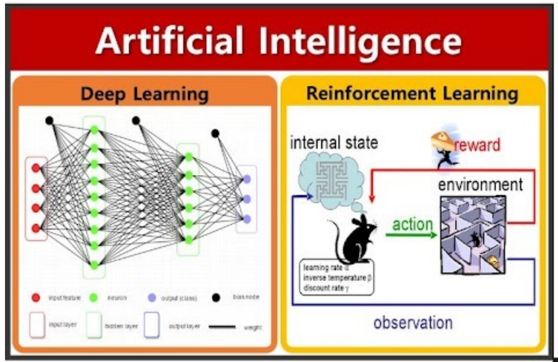
Graph neural networks

Unsupervised

can be combined with semi-supervised learning

Acknowledgements

- ☐ **KPX (Sponsor) and NICE members**

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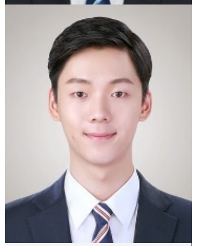

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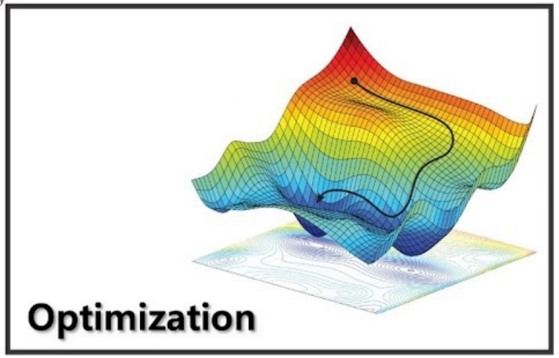






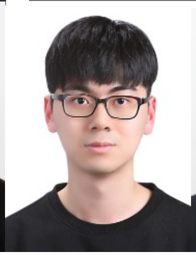
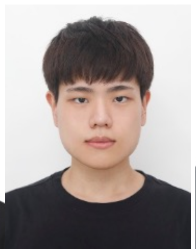






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