Case Study 1:
Multi-modal pan-European energy concepts for achieving CO_2 emission reduction goals

with perfect foresight, considering sector coupling of electricity, heating and cooling, mobility, and fuels / gas, and coupling to gas grids

by D. Most, L. Wyrwoll, I. Yueksel-Erguen, 20 May '21

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Demonstration of the Workflow from Investment Pathway to Market Model to Electric and Gas Grid Analysis

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pathway 2020 … 2050

MIM

1 **Multi-Modal Investment**

- Transition pathway
- Sector coupling
- Including energy vectors of all energy relevant sectors
- Technology neutral optimization
- Aggregated spatial resolution
- Linear optimization

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focus year 2040

DMEM

2 **European Unit Commitment**

- Single year optimization
- Disaggregation of ① energy mix scenario
- High spatial resolution
- Lagrangian relaxation

3 **Transmission Grid Operation**

- Powerflow
- Congestion management
- Detailed European grid model
- Consideration of sector coupling technologies

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GNO

4 **Gas Grid Operation**

- European gas entry-exit network
- Detailed grid model for Germany
- Nomination validation
- Coupling with electricity grid: consideration of P2G and gas power plants

provide optimal energy mix, investments and retirements along the pathway

detailed bottom-up modelling for further analysis of single years including market model and (re-)dispatching

evaluate operation of gas grid

Multimodal Investment Model (MIM) representing the integrated pan-European energy system

"What will the optimal future energy mix look like?
How can we reach that goal with a cost-effective investment pathway?
What impact has sector coupling on the future generation fleet,
e.g., the potential role of emerging technologies like power-to-heat, eMobility and power-to-gas?"

- Multimodal investment model (MIM): in nutshell
- Overview Scenarios modelled + exemplary detailed results
- Key results of the study

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An integrated multimodal optimization approach enables consideration of sector coupling, including demands from multiple energy vectors and cross-sector flexibility from implemented technologies

Multimodal Investment and Operation Model (MIM) of the integrated pan-European Energy System – Pathway Optimization

Fixed Input (incl. projections)

- Demand patterns in terms of useful energy [1)] required
- Technology specific data and parameters
- Regional data and distribution patterns
- Optional: CO_2 emission reduction target

1) Important: We use technology neutral useful energy demand as input to the classic approach of using final energy consumption (e.g. electricity) of a technology group. This empowers the optimizer to choose freely between all available technologies & energy modes.

Investment Model - Optimization

Multi modal multi-regional energy system analysis

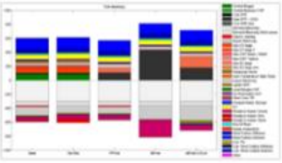
- Optimization by solving a very large 'Linear Problem'
- Target function: minimize OPEX & CAPEX
- Side constraint CO_2 emission restriction
- Ensure security of supply on hourly basis

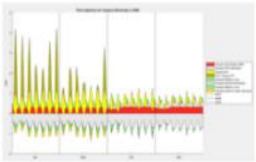
Demand & generation (+ weather) patterns | Regional data & distribution patterns | Technology specific parameters

Output

Cost optimized energy system till 2050

- Capacities for each technology
- Dispatch of generation & storage
- Energy flow
- Marginal costs
- Transition pathway using 5-year periods (simulate operation at 1 year per interval)


Load / generation overview


Energy flow time series


Energy flow diagram

Pathway 2020 – 2050
Annual Investments
Hourly Dispatch
33 Countries

Multimodal Approach / Sectors:

- **Electricity (+ interconnection grid)**
- **Heating & Cooling**
- **Mobility**
- **Fuels/Gas (+ associated processes)**

Including, e.g.,
Over 100 technology classes
Wind Offshore Hubs + connection
H_2 pseudo transport grid
P2G, Fuel Synthesis & Refinery

Over 100 technology classes are implemented in the MIM model building a meshed representation of the Pan European Energy System

El. Generation - Utility & Industry
- Steam PP Coal/Gas/Oil/Lignite
- Gas Turbine SCPP Oil / Gas / H_2
- Combined Cycle CCPP Gas / H_2
- Nuclear PP
- CHP Engine or Fuel Cell (large)
- Hydro Run-of-River
- Hydro Lake w/ reservoir
- Solar PV (large farms)
- Wind Onshore
- Wind Offshore
- Biomass PP / Biogas CHP
- MSW PP (exergetic utilization)
- MSW incineration (w/o energy gen)
- Solar thermal (large)

El. Generation - decentral
- Rooftop PV (small, roof-top)
- Micro CHP (Gas, Biogas)
- Micro CHP w/ Fuel cells (e.g. SOFC)

Electricity Transport Grids
- Interconnections (NTC, cross-border)
- North & Baltic Sea Hubs (NTC Links)

Simplified Electricity Transport Grids
- Transmission (per region, simplified)
- Distribution (per region, simplified)

Mobility
- Classic Mobility (Rail / Ship / Air)
- Classic Cars / Public Bus / Coaches
- Classic Trucks light / heavy / long distance
- Fuel Cell Electric Cars / Trucks / Rail / Bus
- E-Mobility
  - eCar, eBus, eCoach
  - eTruck light / heavy / LD catenary hybrids

Mobility Demands
- Passenger in p*km Road / Air / Ship / Rail
- Freight in t*km Road / Air / Ship / Rail

Heating/Cooling – temperature levels
- LT <100 °C
- MT 100°C .. 150°C
- HT 150°C .. 500°C
- VHT >500°C
- Cooling 0° .. 15 °C
- Freezing <0°C

Cooling - central / decentral
- Compression Chiller Cooling / Freezing
- Compression Chiller HVAC
- Absorption Chiller 1 & 2 stage (large)

Simplified Cooling Grid
- District Cooling (per region, simplified)

Heating - decentral
- Small Boiler Gas/ Oil / Coal / Biomass
- Small Electric Rods
- Micro CHP Engine Gas / Biogas
- Micro CHP Fuel Cell Gas / H_2
- Heat Pumps small (Air / Water)
- District Heating LT
- Solar Thermal (roof-top size)

Heating / Cooling Efficiency Optimization
- Building Insulation (save heating)
- Building Energy management (save cooling)

Heating - central
- Furnace VHT Gas/ Oil / Coal / Biomass / H_2
- Large Boiler Gas/ Oil / Coal / Biomass / H_2
- Arc Furnace (electric) VHT
- Heating rod (electric) LT / MT / HT
- Heat Pump (LT / MT)
- (Deep) Geothermal Heat
- District Heating MT
- Solar Thermal (large)

Simplified Heating Grid
- District Heating (per region, simplified)

Heating & Cooling Demands
Central exogenous / industry
Decentral exogenous / residential

Gas/Fuel Conversion
- Electrolysis (H_2)
- P2Gas w/ CO_2 capture (syn. CH_4)
- P2X w/ CO_2 capture (syn. Liq. Fuel, CH_3OH)
- SMR, Coke Oven (Syngas)
- NH_3 simplified synthesis classic / e-based
  CH_3OH simplified synthesis classic / e-based
- Liquid fuel from Refineries incl. H_2 demand
- H_2 Liquefaction

Industry Demand correlated to Fuel/Gas
- Chemical Industry H_2 Demand
- NH_3 CH_3OH Demand Industry
- MSW incineration

Gas Transport Grids
- H_2 Pseudo Grid (NTC, cross-border)

Simplified Gas Transport Grids
- Mix Gas / H_2 (per region, simplified)

Storages
- Pumped Hydro (pure / mixed)
- Batteries (large, decentral)
- Home Batterie for Rooftop PV
- Heat Storage HT / MT / LT (small, large)
- Cold Storage H_2O, Ice (small, large)
- NG Storage unlimited in pipeline & cavern
- H_2 Storage in Cavern / Tanks & Vessels

Scenarios analyzed using the MIM approach
Finding: The utilization of small PV triggers two manifestations, a world dominated by either central units or by small decentral prosumers

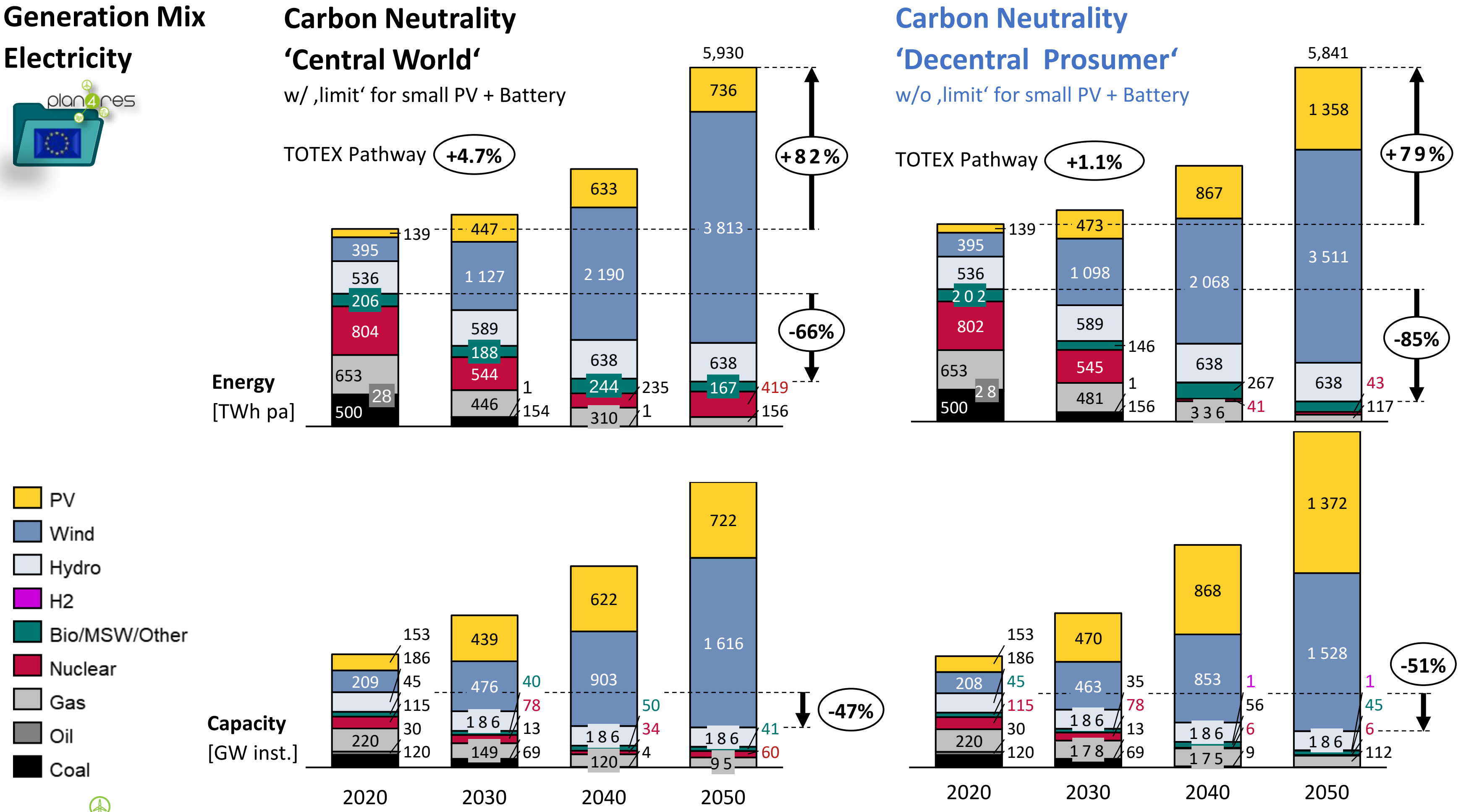
Add. TOTEX	Scenarios
BAU +0.0%	**0) Business as Usual** → -60% CO_2 emissions simply from refurbishments and trends in technologies & costs
+3.0%	**1) COP21 Reduction Targets (-90% @ 2050 -55% @ 2030)** w/ Central World assumption → feasible within projected ETS scheme 25, 33, 55, 90 €/t_{CO2}
	Carbon Neutrality (-98% @ 2050 -55% @ 2030): → feasible within projected ETS scheme 25, 33, 55, 90 €/t_{CO2} and at moderate costs
	Level of utilization of small PV potential as trigger point to the electric system:
+4.7%	**2) Central World (CW) w/ limit of small PV potential** → reduction of Gas PP, NPPs to $^1/_3$ → an energy system dominated by large units and central storages
+1.1%	**3) Decentral Prosumer (DP) w/o limit for small PV potential** 180% of limit as stated by a) → small PV x2, no NPP, Gas PP as reserve only → lots of small decentral prosumers, e.g. rooftop PV + Battery, but reduced base of large units
+1.5%	**4) CN DP „National Supply" with limited cross-border grid extension** (TYNDP BE2027 & today's electricity exchange) → cross-border exchange ensures security of supply → further limitation: model is infeasible
+16%	**5) CN CW „H_2 Mobility" - enforced 'Min 30% FCEV in Road Traffic policy'** → disruption in passenger road traffic (resulting ~70% FCEV cars in 2050), but not in freight transport

Limit for rooftop PV
~740 TWh a)
based on PV modules
(feasible ?)

(no limit for large PV Farms)

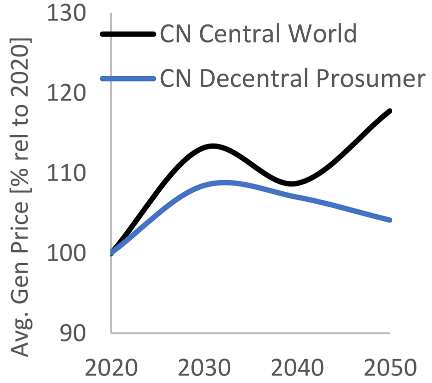
a) Basing on data from (Bódis, Kougias, Jäger-Waldau, Taylor, & Szabó, 2019) a conservative potential of roof-top PV is estimated to ~ 740 TWh pa

A massive installations of small PV + home battery promotes residential self supply enabling Carbon Neutrality at a lower costs, but without NPPs and with large gas power plants only as reserve



The level of how much small PV we can utilize maybe a trigger point

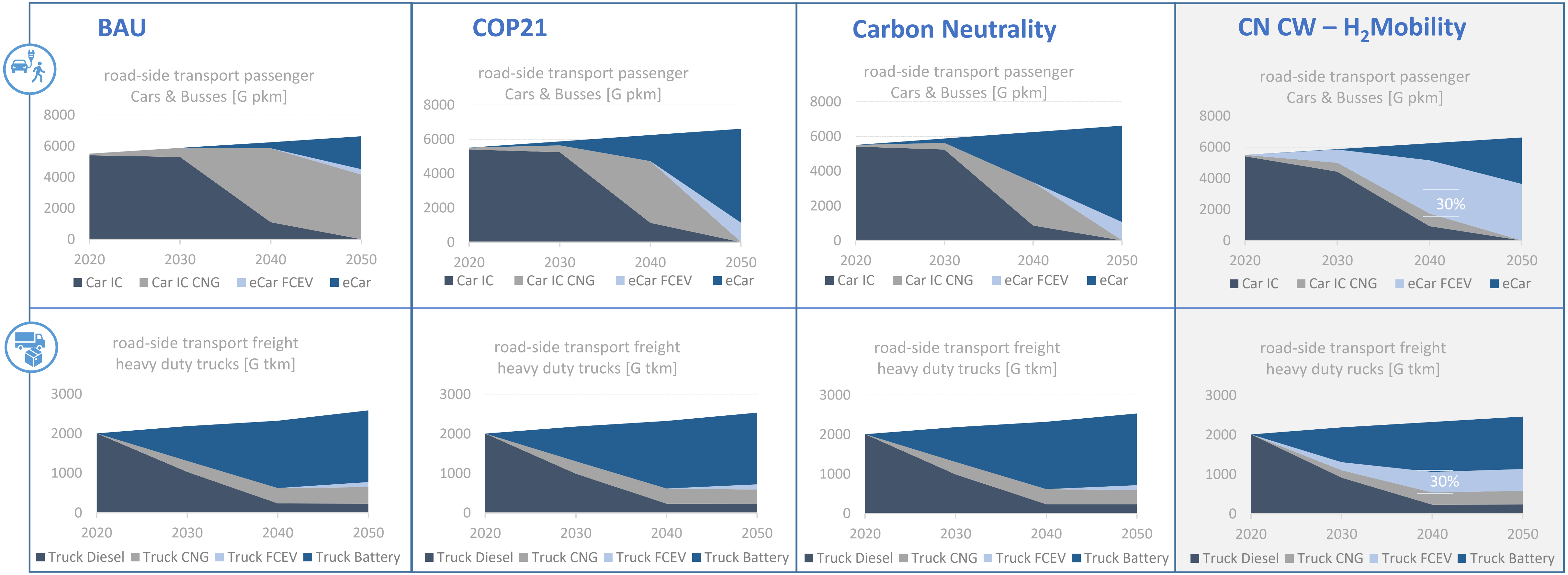
CN Central World: need for NPPs may lead to higher el. generation costs in 2050



With increasing carbon reduction targets the trend to eMobility gets more robust; enforced min shares in H_2 Mobility can trigger a disruption in passenger transport, but at much higher costs

Transition of roadside mobility – shares in transport volume [G pkm resp. G tkm]

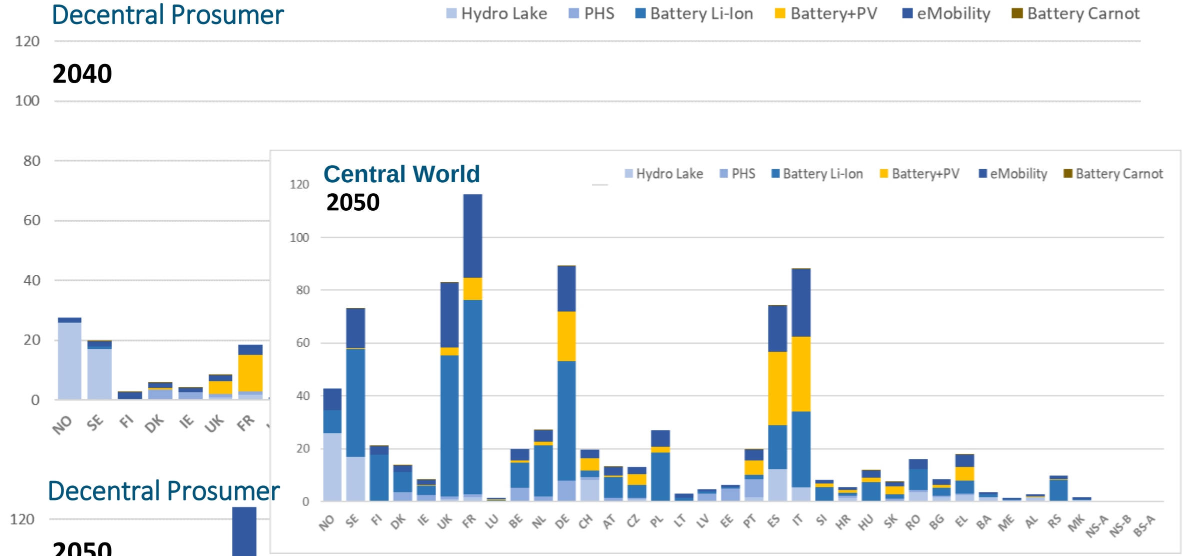
enforced min share 30% FCEV

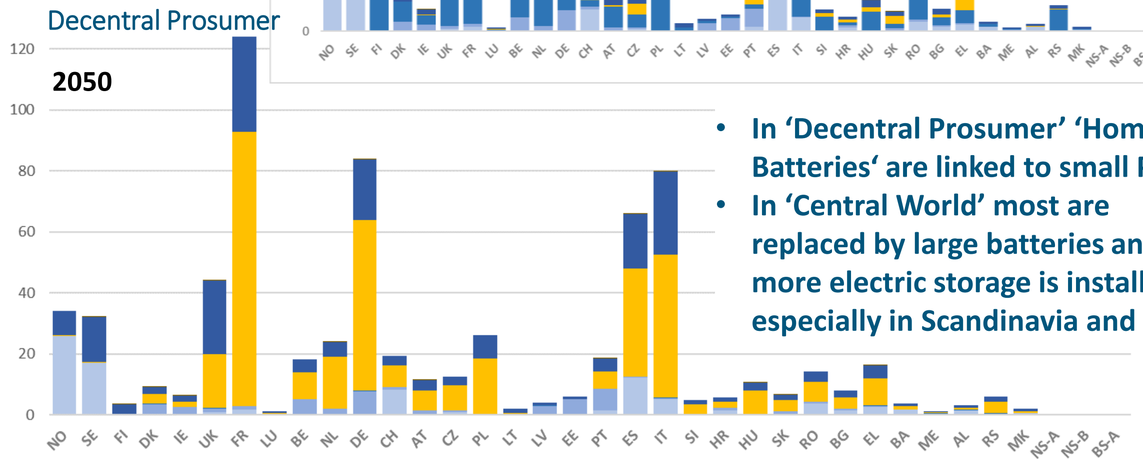


Regional developments of storages support the implementation of RES, mainly electric batteries, only from 2050 on some Power-To-Gas

Regional Development Storage Option Batteries

Electric Storage Capacity [GW]

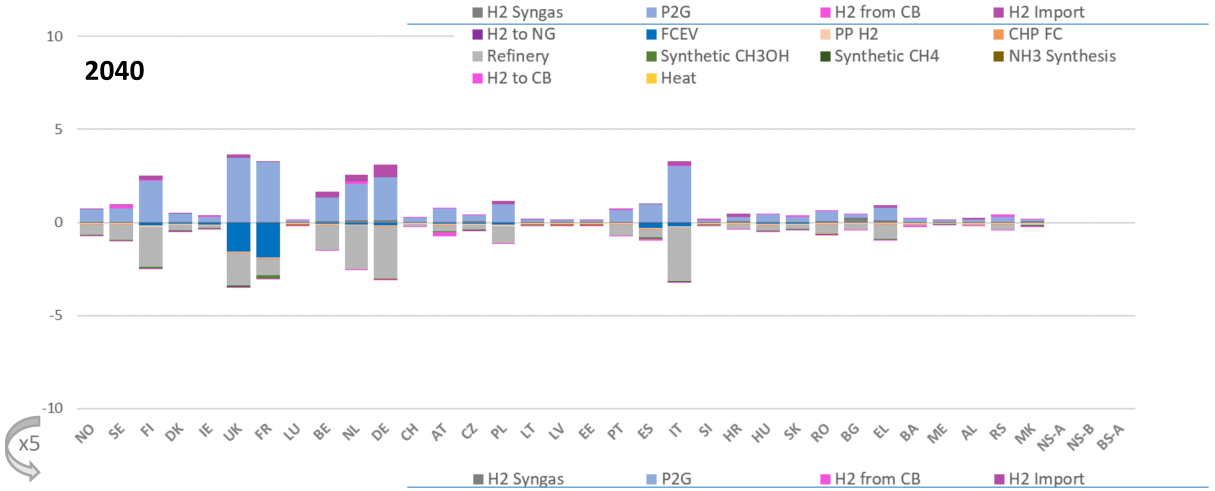


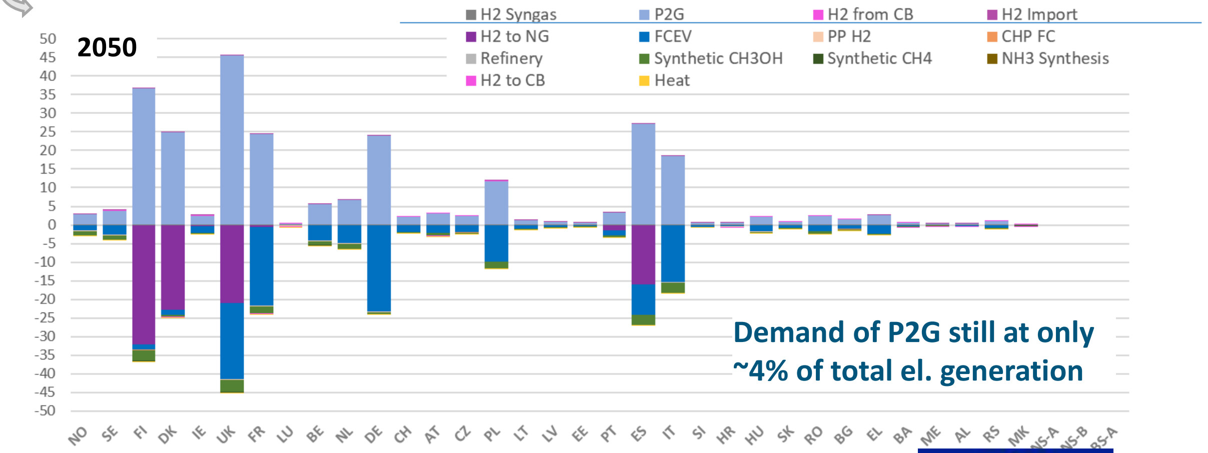


- In 'Decentral Prosumer' 'Home Batteries' are linked to small PV
- In 'Central World' most are replaced by large batteries and more electric storage is installed especially in Scandinavia and UK

Regional Development of Storage Option Power-To-Gas

Hydrogen Generation and Usage [$TWh_{H2,LHV}$ pa]





Demand of P2G still at only ~4% of total el. generation

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Integrated Multimodal Investment Model (MIM)
Key results

We developed

- ❑ *A **MIM approach representing the integrated pan-European Energy system***
- considering sector coupling of the sectors electricity, heating, cooling, mobility, gas/fuels
- technology open multimodal optimization approach with perfect foresight

We analyzed several scenarios

- ❑ **BAU** leads already to -60%; **COP21** targets will be feasible within projected ETS penalty scheme
- ❑ **Carbon Neutrality** will be feasible, too

The level of small PV we can utilize maybe a trigger point leading either to

➢ **Central World**	higher costs	(large units + NPP)
➢ **Decentral Prosumers**	lower costs	(small PV + Battery, limited large units, but w/o NPP)

robust trends are

- Steady ramp-up of RES; new electricity hubs pop up, e.g. in the North and Baltic Sea, IT, ES, UK
- Power-to-heat and eMobility get dominant; → savings in overall primary energy demand
- Electric demand increases to 180% of 2020
- Lots of storage, providing flexibility by decoupling generation & demand
- Some Power-to-gas only in 2040+ plus synthetic gas and imports of green H_2
- Sensitivity (enforced) Hydrogen Mobility is more cost intensive

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Disaggregated Multi-Energy Model (DMEM) for a European market and electrical grid analysis

“How can a multi-energy scenario be implemented in detail considering market and grid operation with high spatial resolution?”

- Disaggregated Multi-Energy Model (DMEM): how it works in nutshell
- Results of market and grid simulation of a carbon neutral scenario for 2040 from MIM
- Key results of the study

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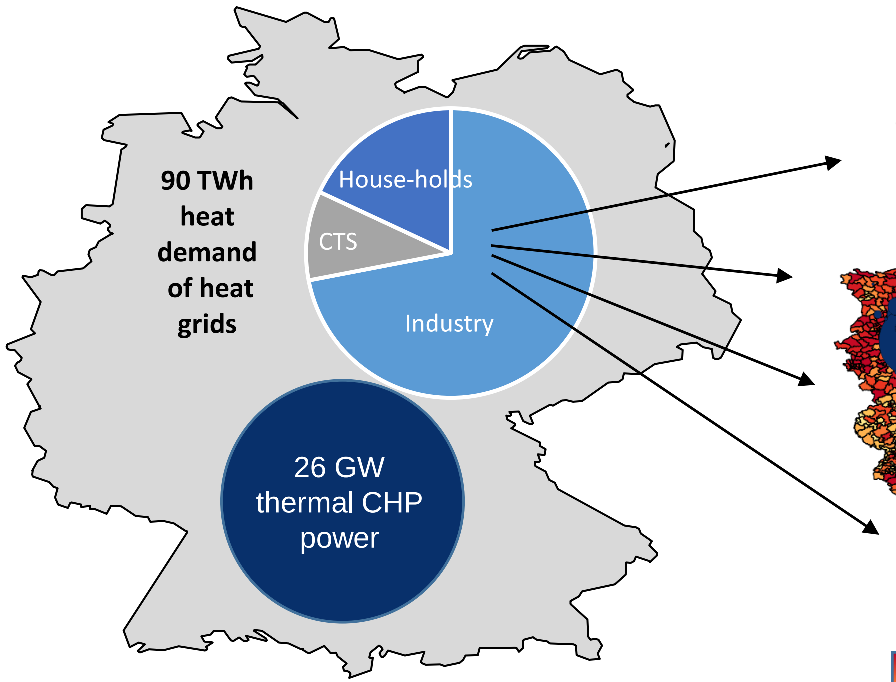
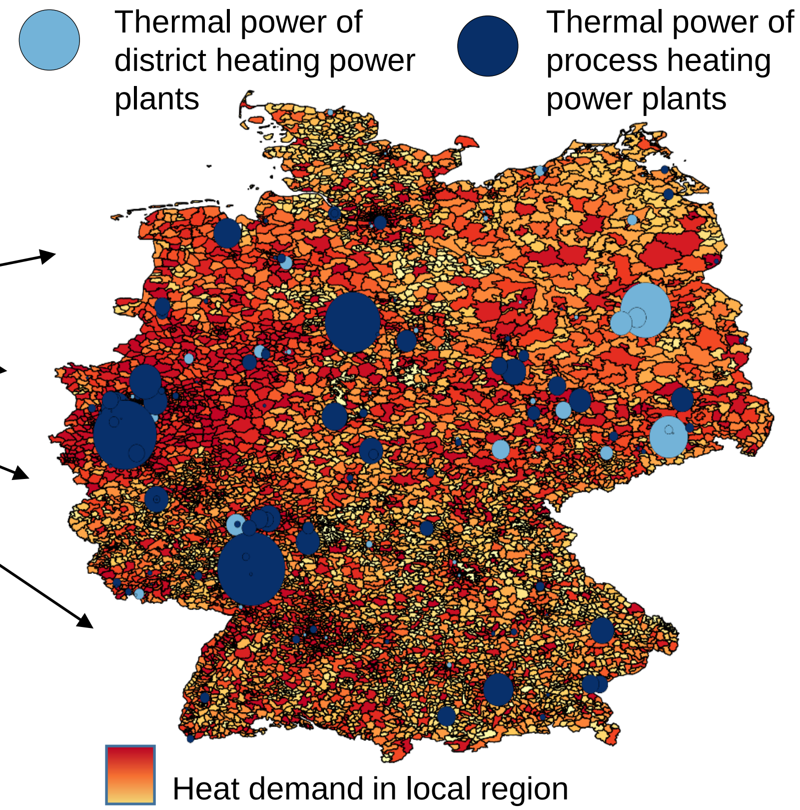
Spatial resolution of heating supply

- ❑ Modelling decentral energy supply requires high spatial resolution due to local constraints
- ❑ Heat supply technologies are allocated according to demand based on spatial data
- ➢ **Local perspective necessary to determine optimized heating supply in combination with electricity supply**

Aggregated perspective

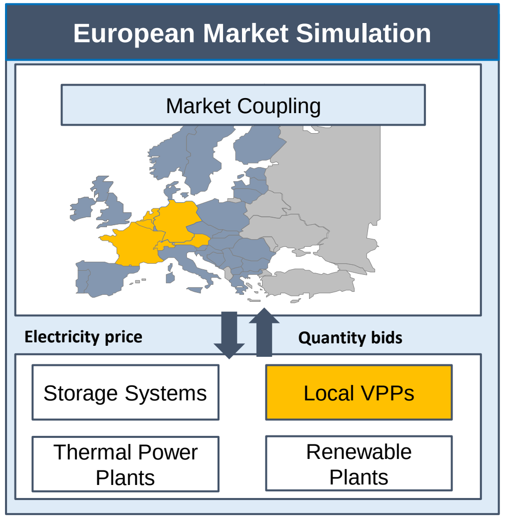


Local perspective

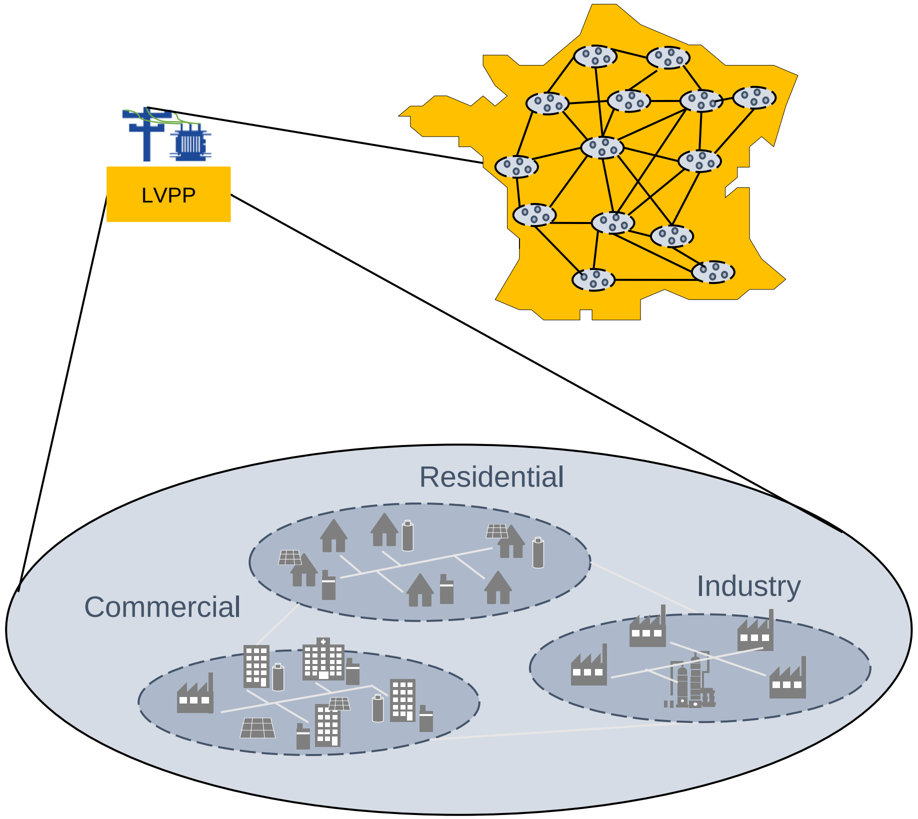


Integration of decentral electricity suppliers

- ❑ Market integration of distributed technologies possible within market simulation
- ❑ Aggregation of flexible technologies (electric vehicles, CHPs, power-to-heat, etc…) as local virtual power plants (LVPPs)
- ❑ **Integration of LVPPs as into the market simulation enables evaluation of different operation modes:**
  - **Maximize own consumption**
  - **Market-driven operation**

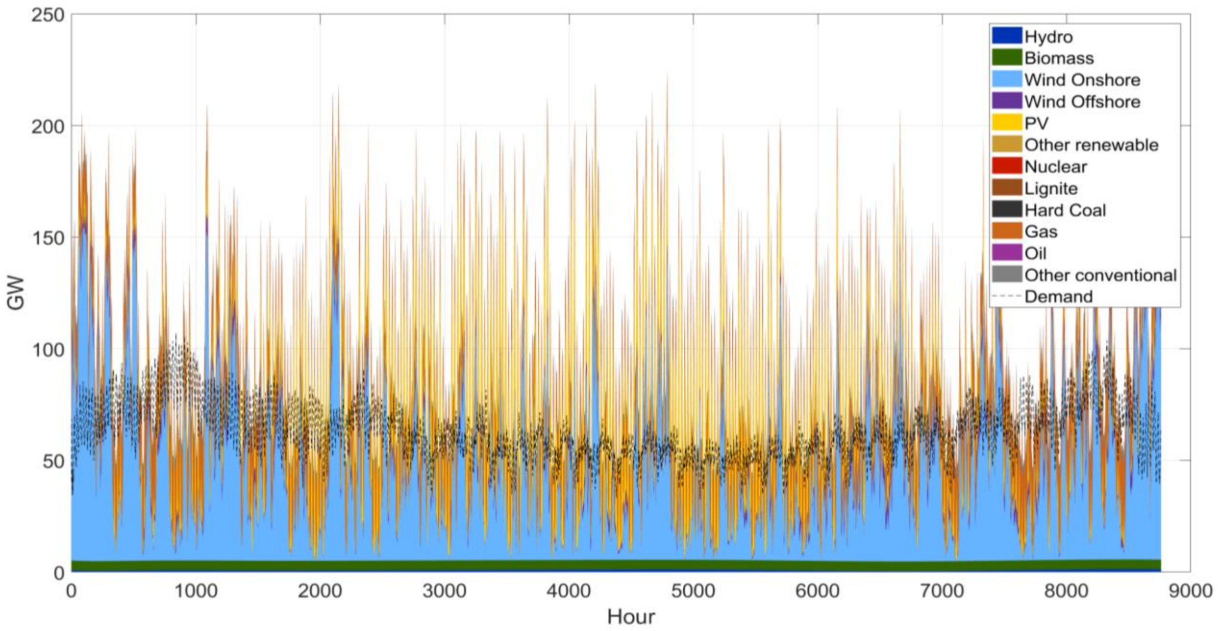


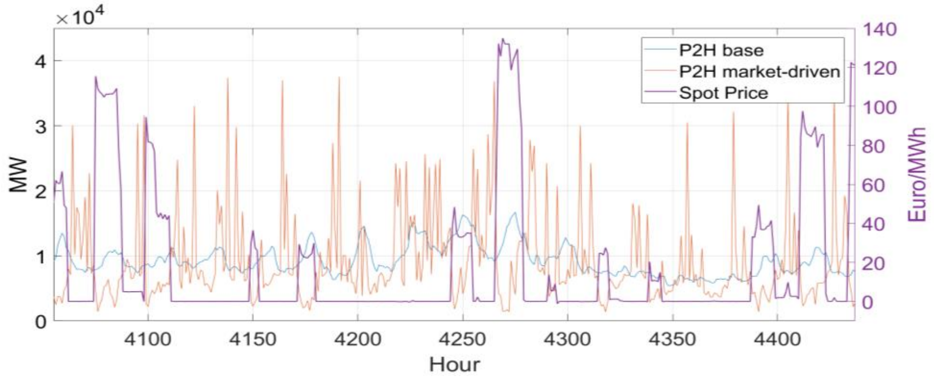
Aggregation of decentral demand and supply according to sector on substation level



Exemplary demand and generation schedules

- ❑ Electricity generation in Germany mainly dominated by volatile feed-in of wind onshore and PV
- ❑ Some hours with high surpluses
- ➢ **Flexibility for compensation needed**

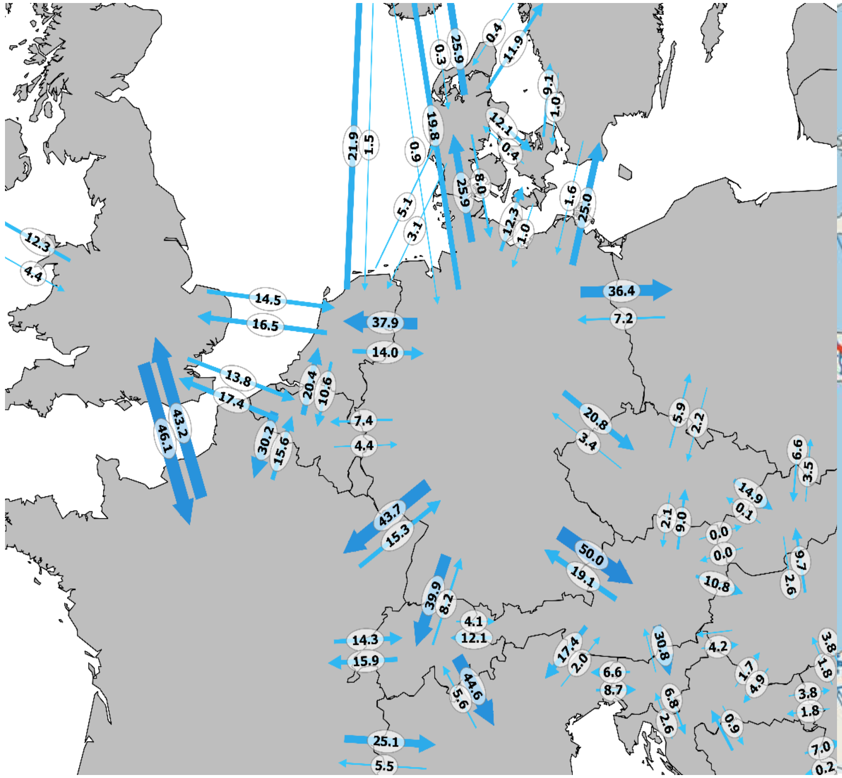


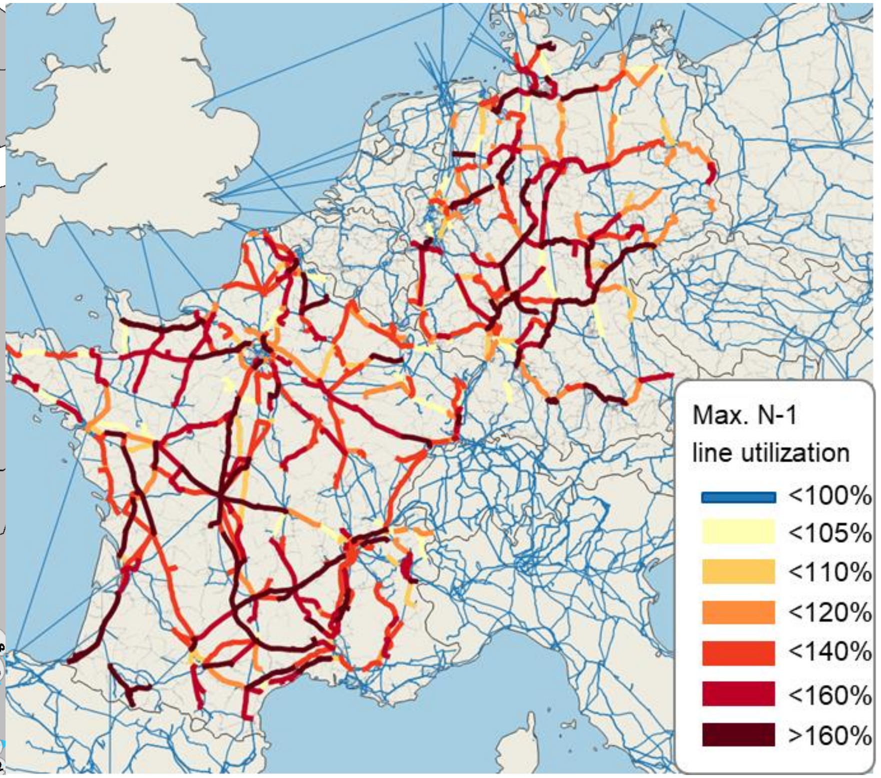


➢ **Market integration of decentral power-to-heat units can influence their schedules significantly due to price incentives**

Exchange flows and impact on the grid

- ❑ High aggregated commercial exchange flows
- ❑ Leads to high N-1 line utilization in power flow simulation
- ❑ Redispatch measures including operation of power-to-gas units
- ➢ **Redispatch costs show necessity of further grid expansion**





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Disaggregated Multi-Energy Model (DMEM)
Key results

- Modeling **detailed heating supply**
  - Including heating sector requires high spatial resolution due to local demand and supply structures
  - Local heating demand can be supplied by a mix of decentral technologies and central power plants according to local availability

- Analysis of the **Pan-European electricity market and grid**
  - An electricity supply largely based on wind and solar energy leads to a high volatility of generation
  - Market integration of small decentral suppliers and consumers, e.g. power-to-heat increases market efficiency due to price incentives
  - Further compensation through international electricity exchange, which, however, is one driver of high grid utilization

➢ **Impact on the gas grid** of gas demand and power-to-gas injection evaluated by the **GNO model**

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Gas grid analysis on pan-European Scale

"Feasibility Analysis of Market Simulation Results by Gas Grid Integration to Electricity Grid and Gas Network Optimization"

- Gas network optimization (GNO) model: how it works in nutshell
- Proof of concept study for using the GNO on pan-European scale to evaluate feasibility of gas related decisions of MIM and DMEM (including usage of power-to-gas)
- Key results of the study

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Gas Network Optimization (GNO) Model – How it works, in a nutshell

Nomination of validations (NoVa): Is the given amounts of gas flow at entries and exits technically feasible?

- A stationary gas network optimization model
- A mixed integer non-linear program (MINLP)

Input:

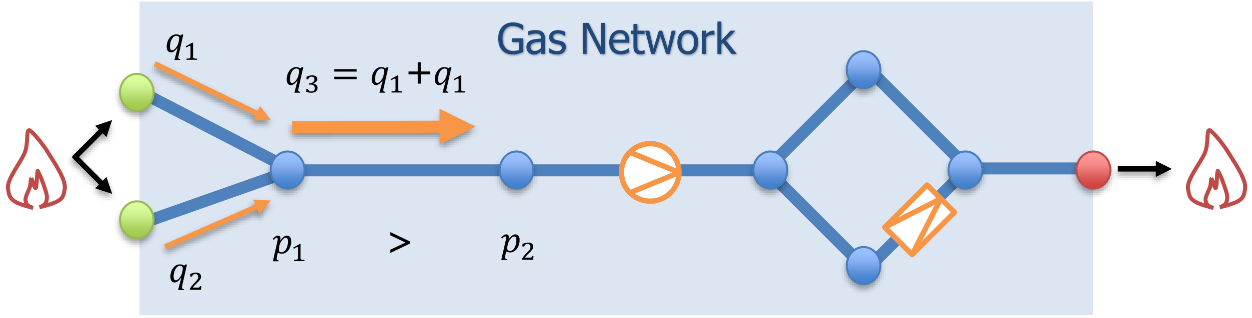
- A gas network → Graph representation
  - Pipelines, nodes, exits & entries, active components
- A Scenario: Amounts of gas flow at entries and exits

Constraints

- Mass flow is conserved at nodes
- Gas moves according to thermodynamic laws
- Gas pressure drops as it flows through pipelines
  - Weymouth Equation → non-linear equations
- Gas pressure is regulated by active components
  - Valves, control valves, compressor stations → subnetworks
  - States: bypassed, closed, active → binary variables

Output:

- Feasibility of the given scenario
- State of the network for a feasible scenario



Weymouth Equation: $\alpha(p_1^2 - p_2^2) = \beta q_3 |q_3|$

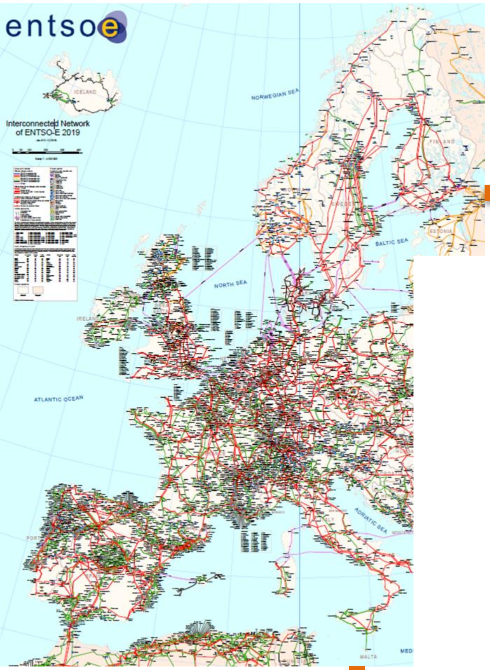
***In CS1, GNO** is used to evaluate:*

- Feasibility of gas network related decision of the DMEM TGO and MIM
- Give feedback to MIM and DMEM TGO from results of infeasibility analysis

*So, **a method for analysis to extend NoVa on a pan-European scale** is proposed and tested, by addressing the issues:*

- Spatio-temporally alignment of GNO to DMEM TGO
- Scarcely available pan-European gas transport network data - Insufficient data for the GNO

*A proof of concept study on using the GNO on **pan-European scale** to evaluate feasibility of gas related decisions of MIM and DMEM by **gas grid-electricity grid coupling***

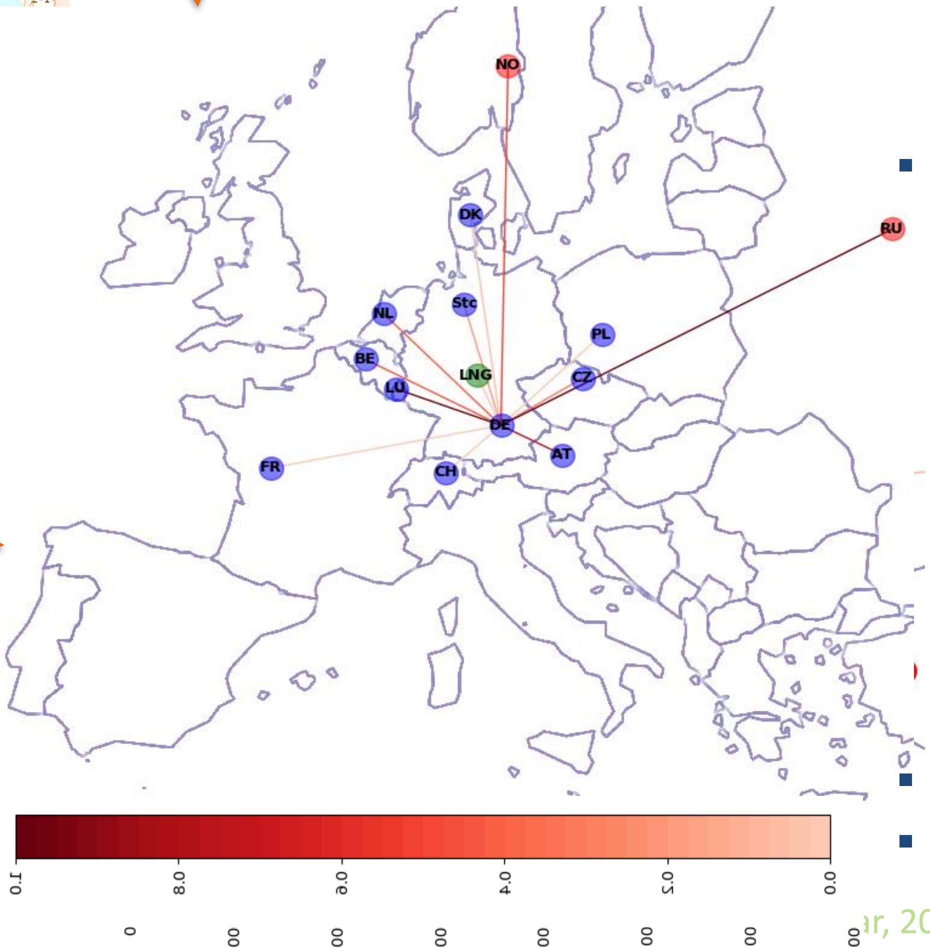


Gas demand:

- GPPs
- Household and industry
- Gas Storages

Gas supply:

- P2G
- Imported gas
- LNG
- Biogas
- National Prod.
- Gas storages



Method used for the proof of concept:

- Select a restricted region where network topology data can be constructed during project time span: Germany
  - A readily-available network topology data set for DE is corrected & improved using TSO and ENTSOG data
  - 58 compressor stations in DE are modeled from partially available public data and network topology limitations
- Use available pan-European supply /demand data & high-level gas network topology to generate valid scenarios for the restricted region (DE)
  - Replace ENTSOG data with DMEM results where applicable
  - Spatially align scenarios to postal code region-based DMEM results
  - Imply limitations from power-to-gas, if there are any power-to-gas facilities
  - Use capacitated network flow models to generate scenarios
- Evaluate feasibility of the scenarios with GNO
- Analyze infeasible scenarios and generate feedback

Step 2.1: Temporal Disaggregation of EU Gas Supply and Demand

Yearly cumulative forecasts, hourly market sim. result time series → Daily time series for a future year (2040 in this study)

- Historical physical flow data from ENTSOG is used as meta-distribution
- DMEM results are merged with forecast data

Step 2.2: Geospatial disaggregation of supply and demand forecasts

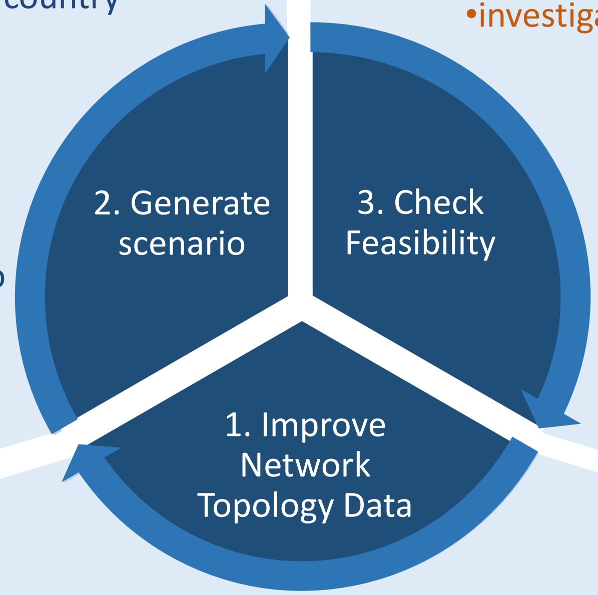
Supply and demand forecast of a single day → Physical flow entering to and flowing from each country

- Pan-European high-level entry exit network topology is used
- A capacitated network flow model is solved

Step 2.3: Dispatching disaggregated supply and demand forecasts to actual nodes of the gas network

Physical flow entering to and flowing from each country, DMEM results for each postal code region, gas storage data → A balanced scenario for Germany gas transport network

- DE gas network topology data set is used
- A capacitated network flow model is solved



Step3.1. Solve the NoVa probl

•If there is a feasible solution f
feasible solution with the deta

•Else, solve slack formulations
the slack formulation results v

Step3.2. Diagnose the infeasib

•investigate and isola

Step 1.1: Improve the LKD-EU* project Germany netwo

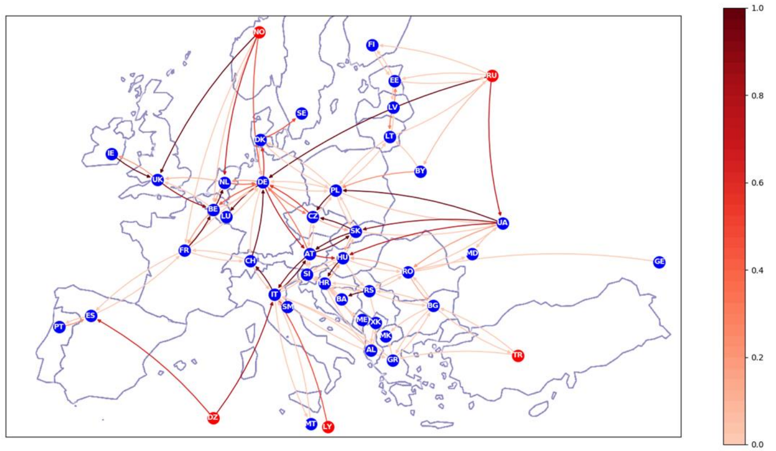
- Augment and correct the data with TSO and ENTSOG
- Add compressor station models

Step1.2. Check and correct the existing network topology data

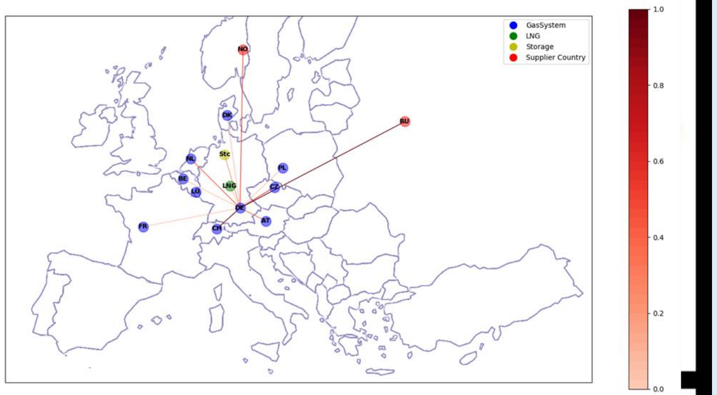
- Diagnose the root cause of the infeasibility
  - Error in base data set
  - Change in the topology in the future state of data
- Correct the data set accordingly.

*Kunz, F., Weibezahn, J., Hauser, P., H
Data Set: Electricity, Heat, and Ga
1.0.0).Zenodo. https://doi.org/10.5281

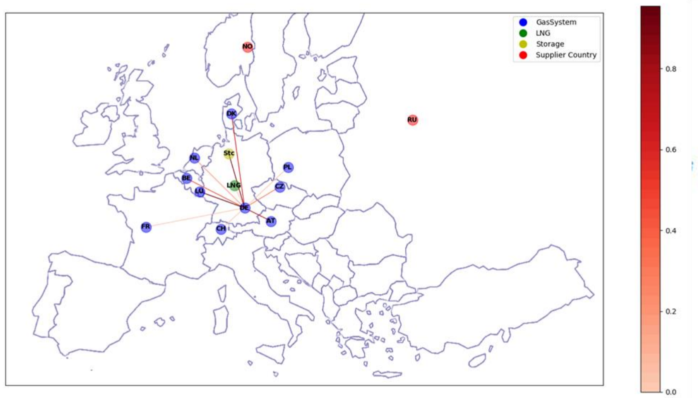
Capacity Utilization of European Gas Transport Connections



Capacity Utilization of Gas Network Connections from DE



Capacity Utilization of Gas Network Connections to DE



Key results

- We demonstrated **the proof-of-concept for integrating gas network models and electric grid transport models** by
  - proposing *a method to generate practically relevant scenarios for Germany* and evaluated those by modelling the *German gas grid in detail* embedded in the constraints of *pan-European gas network* and also in *the electric operation from dispatch and market clearing*
  - demonstrating the *feasibility* of the proposed method on *a pan-European scale*
- The proposed method is **helpful for further modeling the energy system to assess the role of gas network in energy transition**
  - e.g., as *a flexibility to electricity grid* or regarding *new technologies* like power-to-gas.
- We assembled a feasible **data set for demonstration from publicly available data sources**
  - A data set for pan-European gas supply and demand - historical data and forecasts
  - An exemplary data set for Germany for the high-pressure gas transport, which should be further improved

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Thank you for attendance
Questions to Case Study 1

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