Appendices

Table of contents

Appendix I

Methodology overview (NL)

Infrastructure Outlook 2050

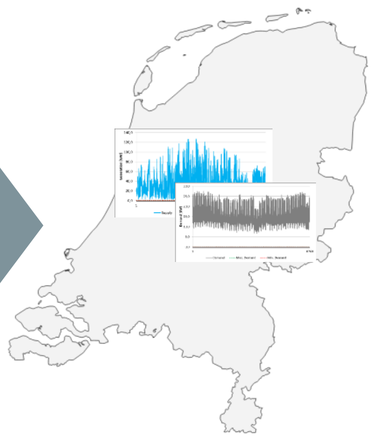
gasunie crossing borders in energy
TenneT Taking power further

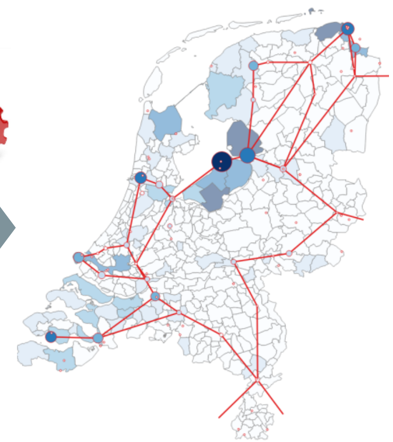
Methodology overview (NL)

Scenario A

Scenario B

…





Scenario framework

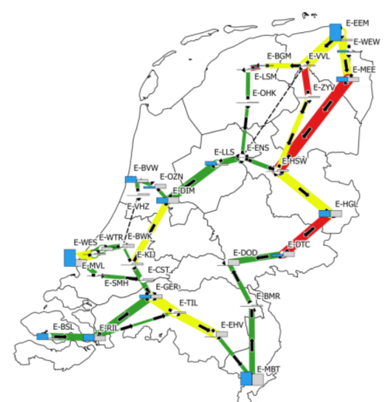
Energy system calculations

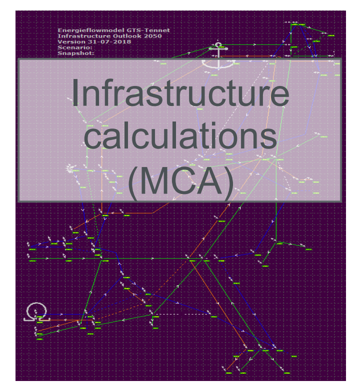
Regionalization and selection of snap shots

Linking to combined grid model

Steps:

1. Scenario framework (2050)
2. Energy system calculations
3. Regionalization and selection of snap shots
4. Infrastructure analysis
5. Visualization & analysis of results





Visualization & analysis of results

Infrastructure analysis

Methodology overview - explanation

- For 3 possible end situations of a decarbonized Dutch energy system in 2050 - *local, national and international*, the annual energy figures for electricity and gas are derived. The scenarios differ in socio-cultural and political factors influencing the energy transition.
- These annual energy figures are post-processed to include temporal (hourly) and spatial (municipality) distributions, and mapping on to the nearest grid node. *The modelled infrastructure includes the electricity and Methane grid. The Methane grid is split in to two parts – one to transport hydrogen and the other to transport green gas.*
- Then from all 3 scenario's those hours are selected and analysed that give a high load on the electricity and gas infrastructure. Three specific situations have been identified to be most critical:
    - High RES supply (solar and/or wind) and high (final) demand
    - High RES supply (solar and/or wind) and low (final) demand
    - Low RES supply and high (final) demand
- Next to these so called '*base cases*' a number of sensitivities have been analysed to assess the impact of electrolyser locations (power-to-gas(h2)), of more severe winter conditions, and of transit and loop flows from international energy transport.

Scenario framework

Scenarios: Overall framework

'National'
- Aim for energy independence relying mostly on **centralised** RES supply
- Mostly central supply of **wind**
- Strong support of power-to-gas and batteries as flexibility options
- **Limited energy exchange** with other countries allowed

NvdT 'national' (NL)
FNB 'Strom und Grünes Gas(DE)

min. **-95% CO_2 emissions** until 2050*

'International'
- Globally oriented policy with focus on **international energy exchange** No strong support of extensive RES supply increase
- 'Business as usual'

NvdT 'international' (NL)
dena 'Technologiemix 95%'(DE)

'Local'
- Strong aim for energy independence relying on **centralised** RES supply
- Mostly decentral supply of **solar**
- Strong support of power-to-gas and batteries as flexibility options
- **No energy exchange** with neighbouring countries

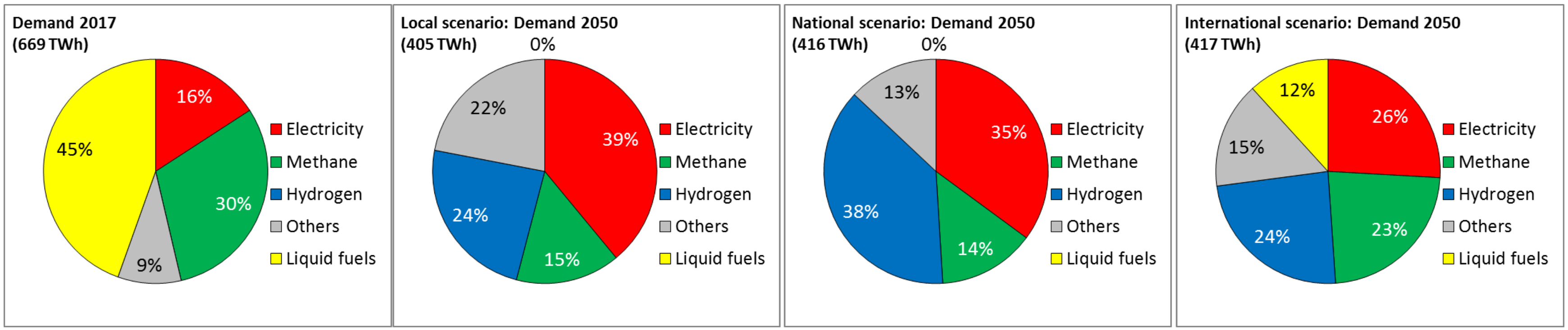
NvdT 'regional' (NL)
Enervis 'Optimiertes System' (DE)

*(Based on agreed european reduction goal between reference year 1990 and 2050)

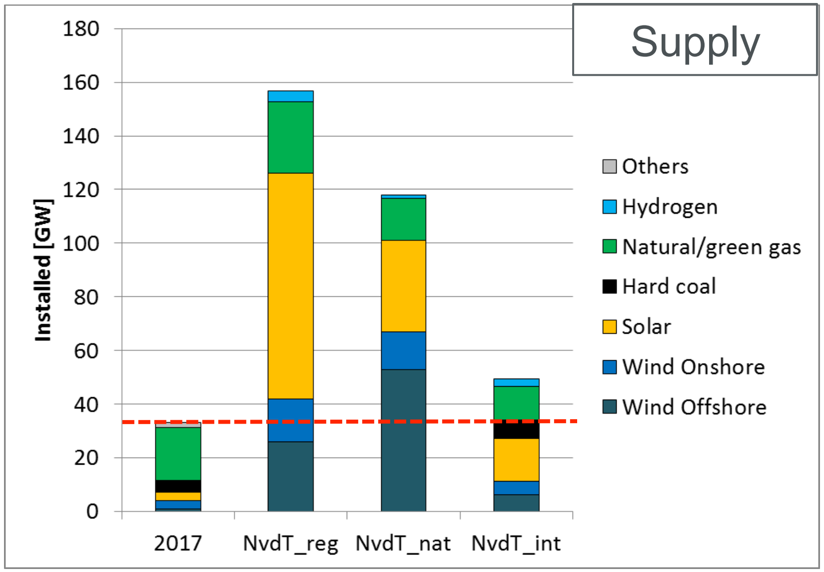
Scenarios: Study overview

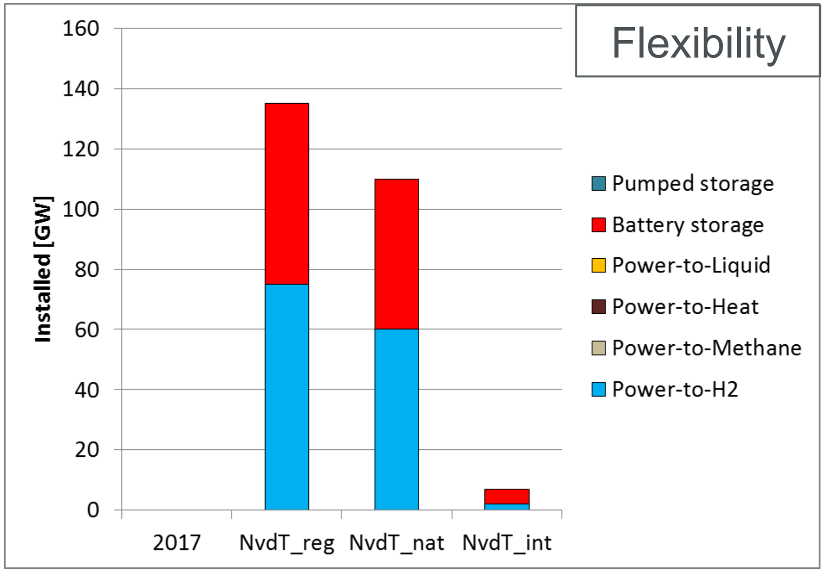
- “Net voor de toekomst” (CE Delft, 2017) → NvdT: local, national, international
- “Erneuerbare Gase - ein Systemupdate der Energiewende“ (Enervis, 2017) → Enervis
- „Leitstudie integrierte Energiewende“ (dena, 2018) → dena
- „Der Wert der Gasinfrastruktur für die Energiewende in Deutschland“ (Frontier Economics, 2017) → FNB

Scenario framework (NL): Final energy demand (2017 and three 2050-scenarios)



Scenario framework (NL): Scenario numbers





Local:
- Supply dominated by decentral solar PV
- Significant amount of PtH2 and batteries

National:
- Supply dominated by wind offshore
- Significant amount of PtH2 and batteries

International:
- Mix of renewable and fossil supply
- Almost no domestic flexibility options available and focus on import/export of energy

gasunie crossing borders in energy

TenneT Taking power further

Scenarios: Concrete dataset for 2050 (NL)

Category	Unit	2017*	NvdT_reg	NvdT_nat	NvdT_int
Supply					
Wind Offshore	GW	1	26	53	6
Wind Onshore		3	16	14	5
Solar		3	84	34	16
Hard coal		5	0	0	7
Natural/green gas		20	27	16	13
Hydrogen		0	4	1	3
Others		2	0	0	0
Sum of supply		**33**	**157**	**118**	**49**
Demand					
Households	TWh	**102**	**59**	**79**	**84**
Electricity		23	40	32	31
Methane		79	15	12	26
Hydrogen		0	5	36	27
Service sector		**69**	**36**	**46**	**50**
Electricity		33	32	32	32
Methane		36	3	5	8
Hydrogen		0	0	10	11
Industry		**121**	**113**	**112**	**55**
Electricity		30	50	50	23
Methane		91	4	4	7
Hydrogen		0	58	58	25
Transport		**2**	**40**	**41**	**48**
Electricity		2	25	19	13
Methane		1	0	0	13
Hydrogen		0	15	23	23
Agriculture		**23**	**11**	**11**	**11**
Electricity		9	11	11	11
Methane		14	0	0	0
Hydrogen		0	0	0	0
Other demand		**24**	**102**	**31**	**66**
Electricity		24	12	12	12
Methane		0	86	18	49
Hydrogen		0	4	1	5
Sum of demand		**341**	**360**	**321**	**314**
Flexibility					
Power-to-H2	GW	0	75	60	2
Power-to-Methane		0	0	0	0
Power-to-Heat		0	0	0	0
Power-to-Liquid		0	0	0	0
Battery storage		0	60	50	5
Pumped storage		0	0	0	0
Sum of flexibilty		**0**	**135**	**110**	**7**

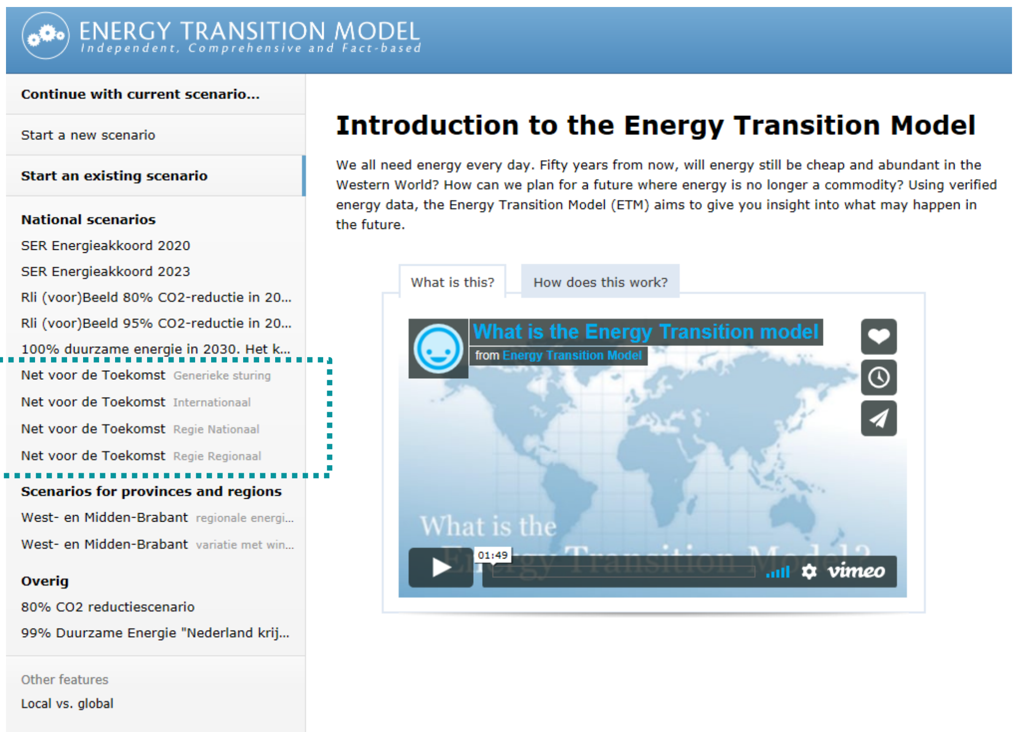
Energy system calculations (NL)

gasunie crossing borders in energy

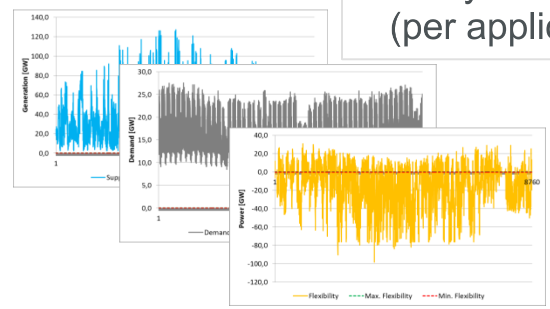
TenneT Taking power further

Energy system calculations (NL): “Energy Transition Model” (ETM)

NvdT-scenarios applied to ETM



Hourly time series (per application)



Analysis, filtering and snapshot selection

Energy system calculations (NL): “Energy Transition Model” (ETM)

Link: https://pro.energytransitionmodel.com/

Main model features:

- Model to determine total energy generation, demand and interrelations between both on a national level
- Comprehensive possibilities to define scenarios
- Simplified merit-order model to determine hourly dispatch of generation units and flexibility options
- Instant calculation of target figures related to energy use (e.g. CO_2-emissions, costs, share of RES,…)
- Data export and graphical analysis functionalities

Energy system calculations: “Merit order” of flexibility options

Pump storage
- Storage of energy in water reservoirs
- Short term storage of energy

↓

Power-to-H2
- Conversion of electricity to hydrogen
- Long term storage of energy

↓

Power to Heat
- Conversion of electricity to heat
- Short term storage of energy

↓

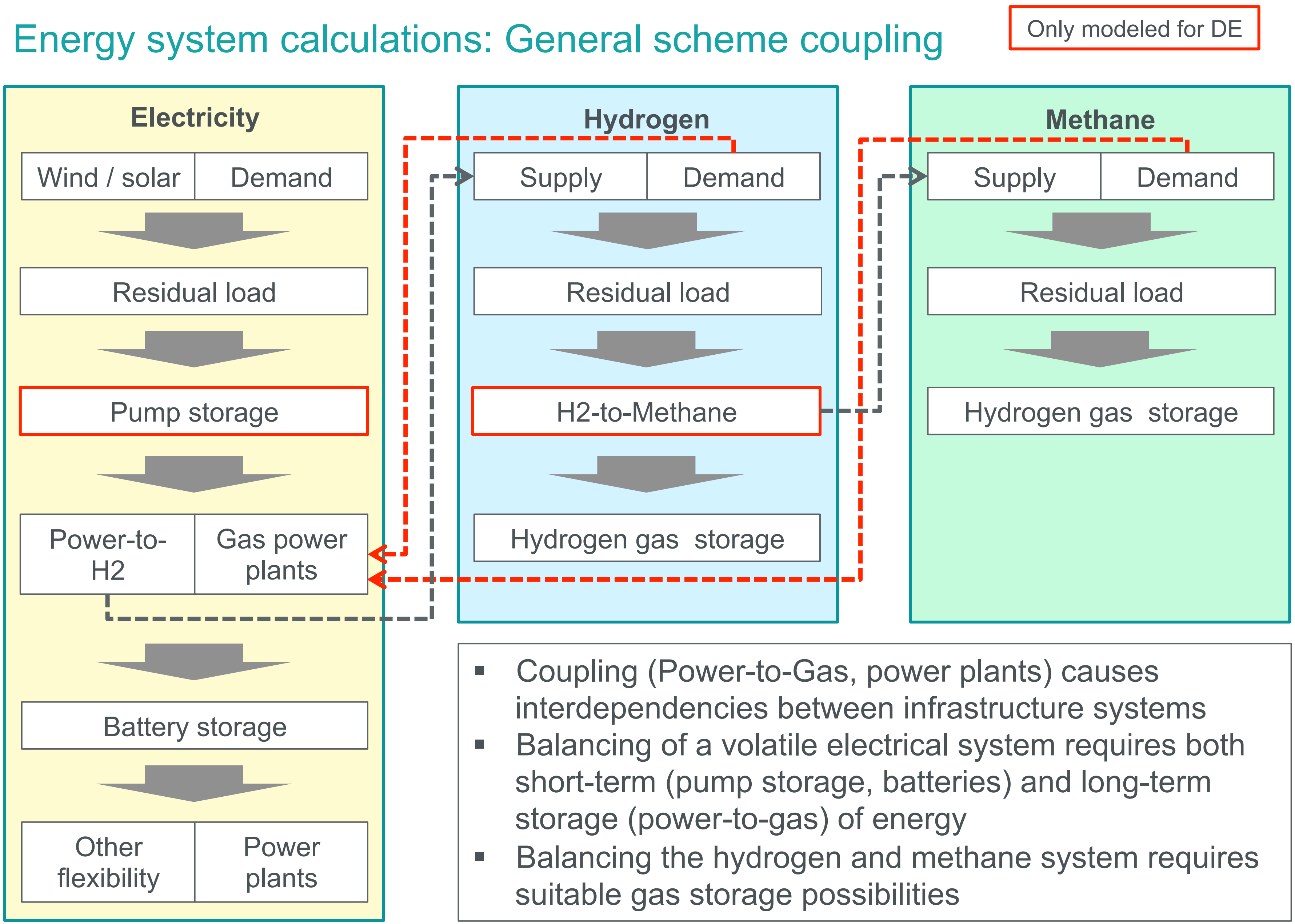
Battery storage
- Direct storage of electricity in batteries
- Short term storage of energy

↓

Curtailment
- Shuttoff of supply
- No integration of RES generation

gasunie crossing borders in energy | TenneT Taking power further

Energy system calculations: General scheme coupling



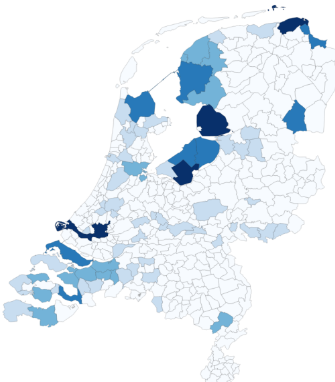
- Coupling (Power-to-Gas, power plants) causes interdependencies between infrastructure systems
- Balancing of a volatile electrical system requires both short-term (pump storage, batteries) and long-term storage (power-to-gas) of energy
- Balancing the hydrogen and methane system requires suitable gas storage possibilities

Regionalization of scenario data (NL)

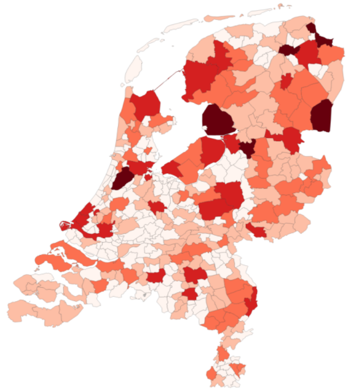
Regionalization (NL): Base assumptions for distribution keys

Category	Distribution key (per mun.)	Source
Wind onshore	Installed capacities wind onshore 2017 + provincial goals for 2020	Klimaatmonitor.nl, rvo.nl
Wind offshore	Foreseeable wind offshore connection capacities	TenneT
Solar PV	Installed capacities solar 017	Klimaatmonitor.nl
Hard coal	Installed capacities hard coal 2017	TenneT power plant list
Natural gas	Installed capacities natural gas 2017	TenneT power plant list
Green gas	Installed capacities natural gas 2017	TenneT power plant list
Hydrogen	Installed capacities natural gas 2017	TenneT power plant list
Other		
Household demand / battery storages households	Number of households	Klimaatmonitor.nl
Buildings demand	Energy demand of buildings 2017	Klimaatmonitor.nl
Industry demand / Power-to-Heat	Energy demand of industry 2017	Klimaatmonitor.nl
Agriculture demand	Energy demand agriculture 2017	Klimaatmonitor.nl
Transport demand / battery storages vehicles	Number of vehicles	Klimaatmonitor.nl
Other demand		
Power-to-H2	*Variable*	
Storage (hydrogen/methane)	Suitable geographical locations	GasUnie
Import / Export	Import / export capacities of interconnectors	TenneT, GasUnie
Green gas / hydrogen production	Installed capacities biomass 2017	Klimaatmonitor.nl

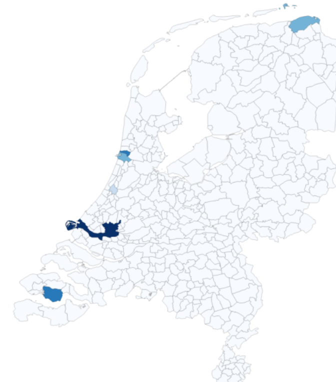
Regionalization (NL): Base assumptions for distribution keys



Wind onshore

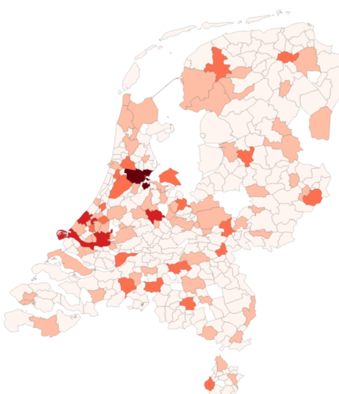


Solar PV

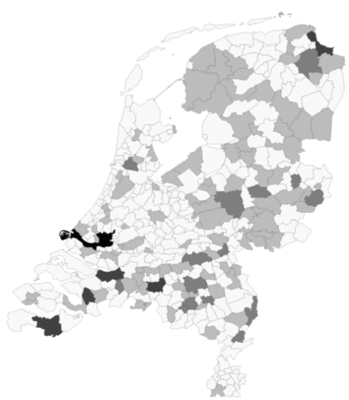


Wind offshore

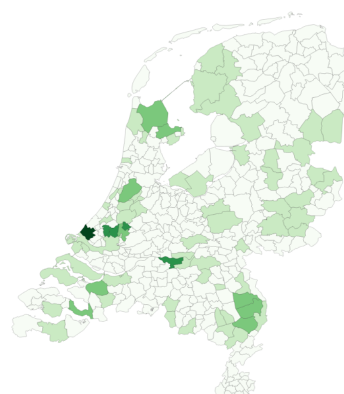
Gas power plants



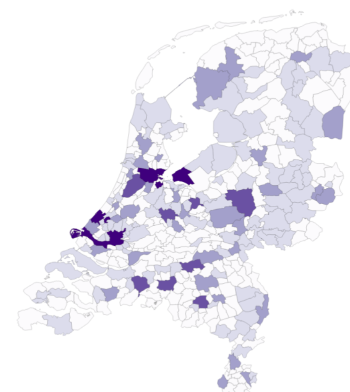
Household demand / batteries



Industry demand / PtHeat



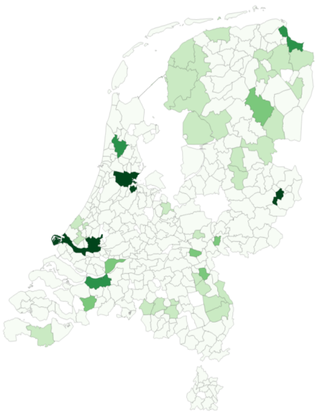
Agriculture demand



Transport demand / batteries

Regionalization (NL): Base assumptions for distribution keys

Import / Export (E)



Green gas / green hydrogen

Import / Export (G, H)

Storage (G, H)

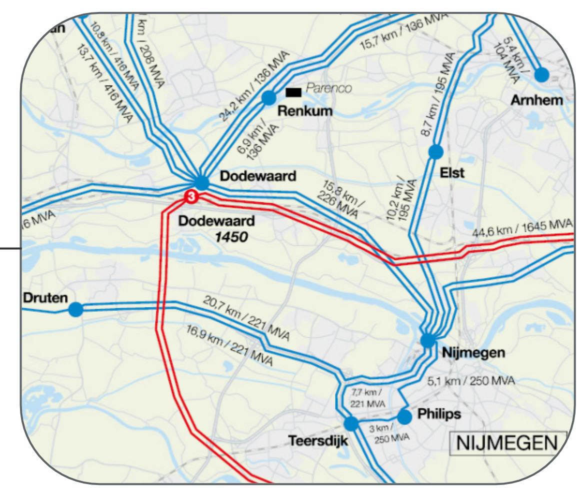
gasunie crossing borders in energy — TenneT Taking power further

Regionalization (NL): Linking of municipalities to grid nodes

Electrical grid:

Linking of municipalities to 220/380kV grid nodes:

- Filtering of grid nodes
- „Nearest neighbour“ approach considering underlying 110kV/150kV infrastructure
- Manual validation / adjustment using real grid map

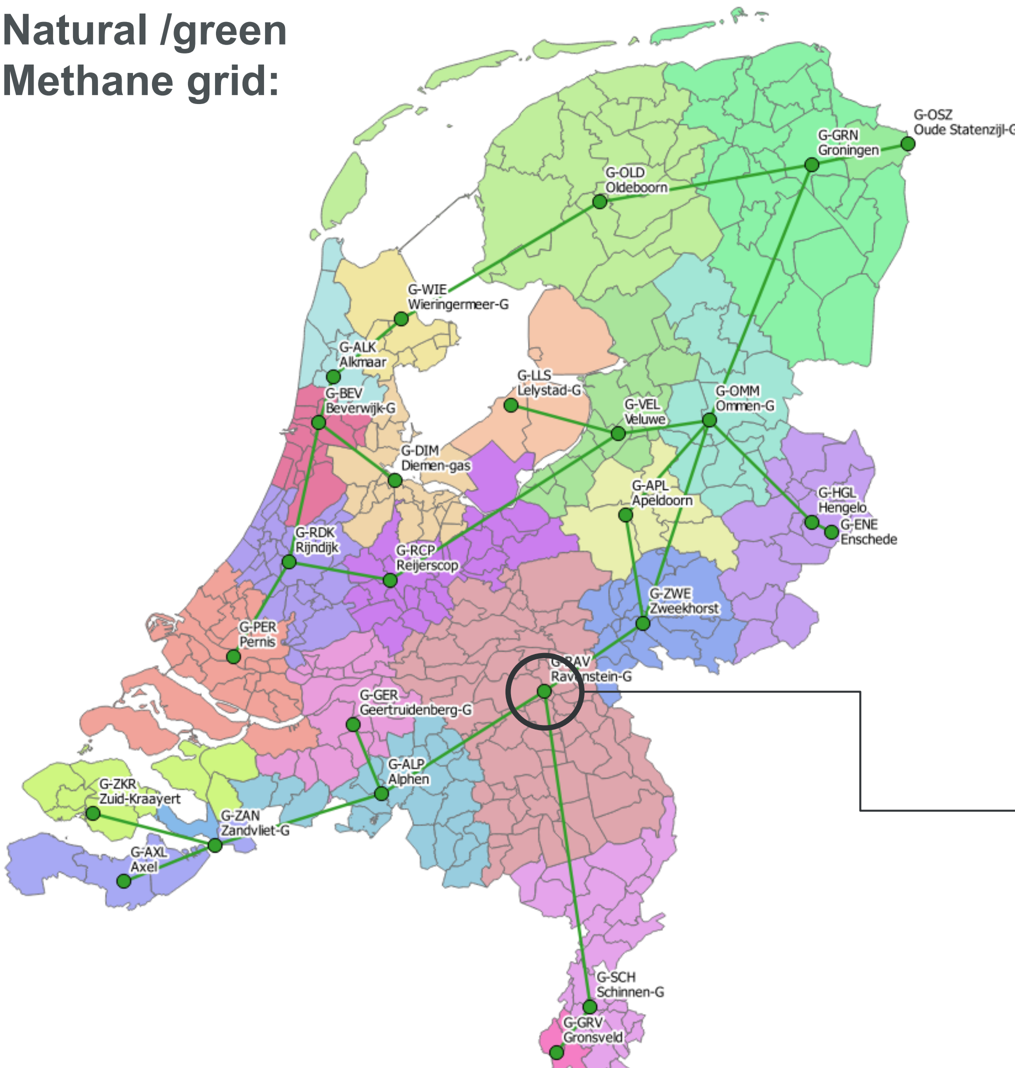


gasunie
crossing borders in energy

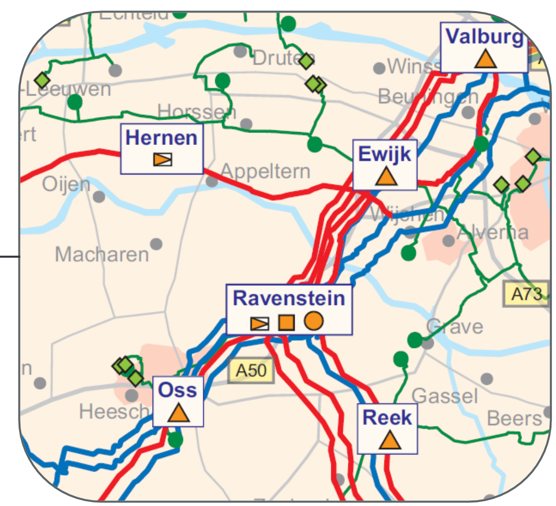
TenneT
Taking power further

Regionalization (NL): Linking of municipalities to grid nodes

Natural /green Methane grid:



Linking of municipalities to Methane grid nodes:
- Filtering of grid nodes
- „Nearest neighbour“ approach
- Manual validation / adjustment using real grid map

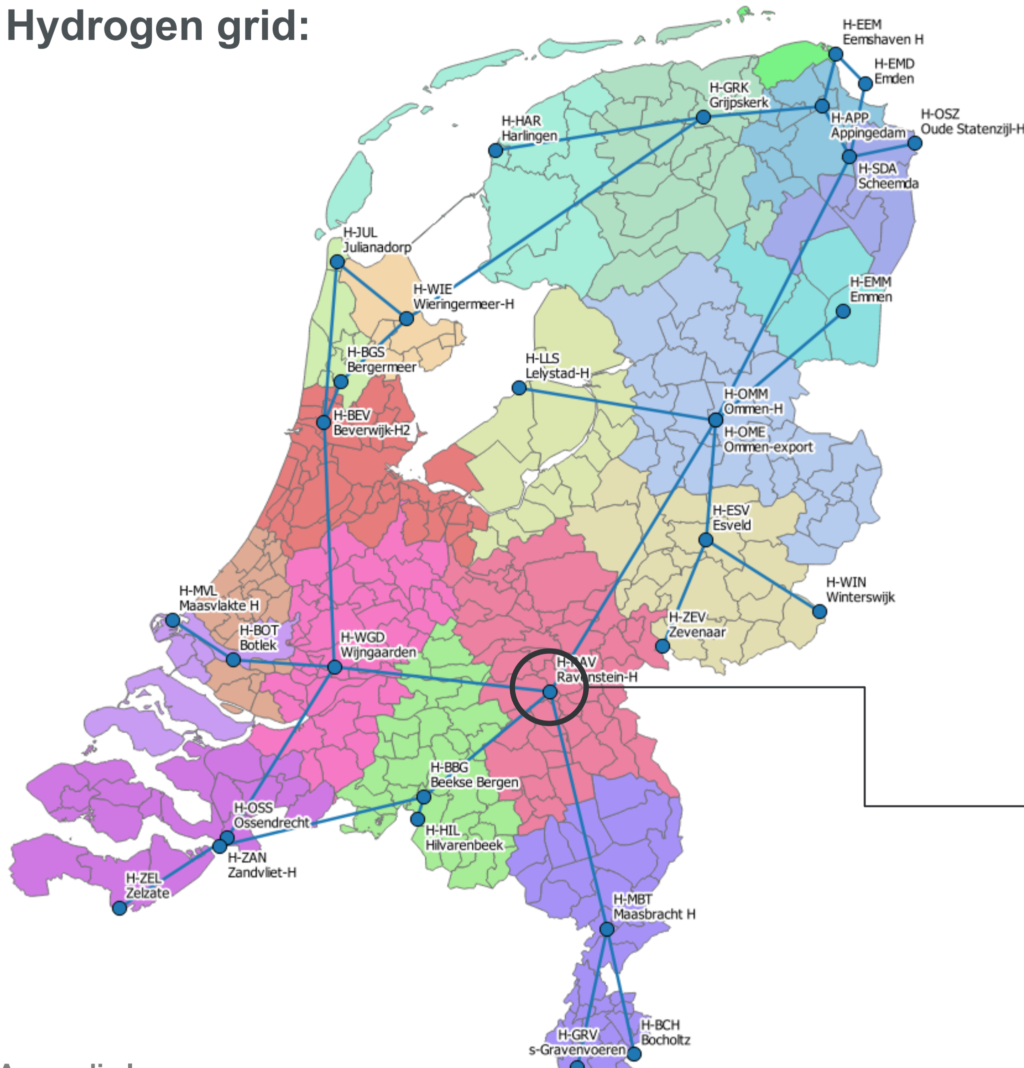


gasunie crossing borders in energy

TenneT Taking power further

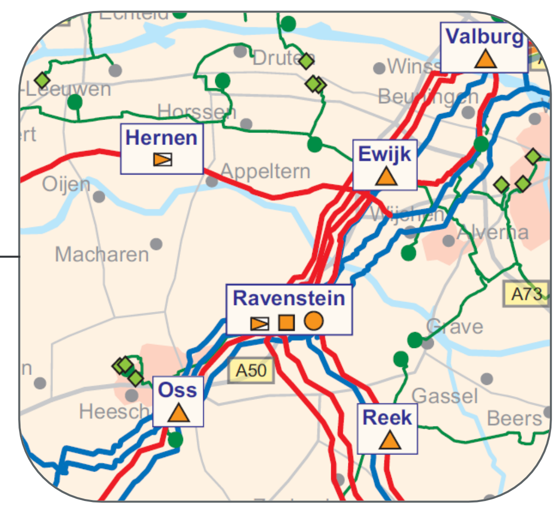
Regionalization (NL): Linking of municipalities to grid nodes

Hydrogen grid:



Linking of municipalities to Methane grid nodes:

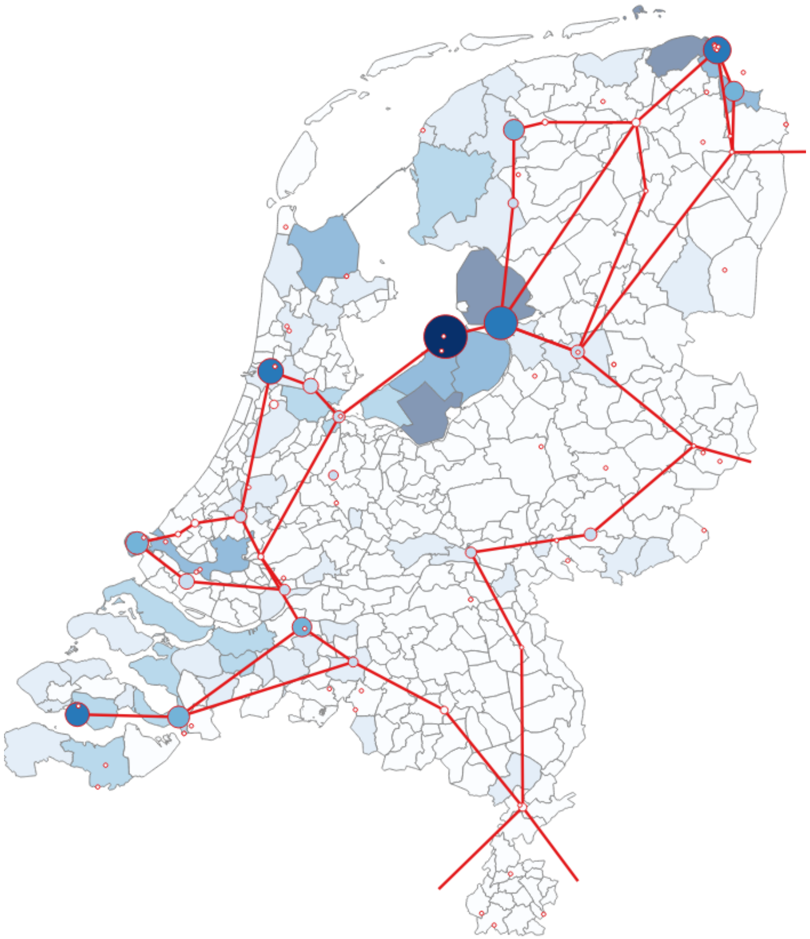
- Filtering of grid nodes
- „Nearest neighbour“ approach
- Manual validation / adjustment using real grid map



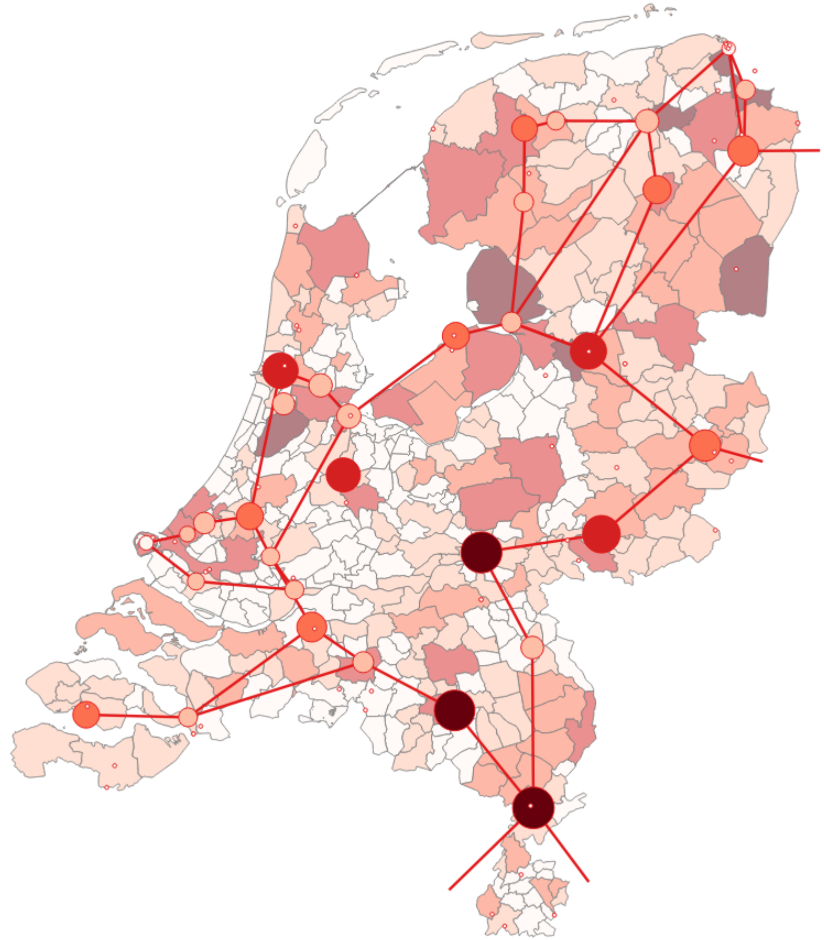
gasunie crossing borders in energy

TenneT Taking power further

Regionalization (NL): Exemplaric results



Wind onshore



Solar PV

Snapshot selection

Snapshot definition and considerations

General definition „snapshot“: Situation („hour“) with a specific (regional) occurance of supply, demand, use of flexibility options and exchange with neighbouring countries

Considerations for selecting snapshots:

- The **operating envelope** of the infrastructure: What are the maximum capacities the infrastructure should meet?
- The **transport momentum** of energy**:** Are transport of large quantities of energy across long distances foreseen that result in a high load on the infrastructure?
- The **regional distribution** of energy**:** Do future projected supply and demand locations combine with existing (and foreseen extension of) infrastructure?
- The **choice and (regional) locations for flexibility options** (especially electrolyzers) determines to an extent the load on the electrical or gas infrastructure
- The selection is **scenario dependent** due to different assumptions about supply, demand, flexibility and exchange possibilities
- Additional sensitivities based on selected base snapshots allow to investigate impacts of singular changes in scenario assumptions

Snapshot selection: operating envelop

- The operating envelope determines the **(max) capacity requirements of the infrastructure**
- Supply, consisting of a high share of intermittent RES should meet demand (in this analysis matched on a hourly basis)

- **Three main corners of the operating envelope** were identified:
  1. High RES supply and high (final) demand
  2. High RES supply and low (final) demand
  3. Low RES supply and high (final) demand

- Flex options balance the gap between supply and demand
- Furthermore, we can distinguish offshore wind, onshore wind and solar RES For each a different set of flex options could be selected

HIGH
RES

Flex options:
Demand management
Battery
Conversion
Export
Curtailment

GW

High demand
conventional

Example

gasunie crossing borders in energy
TenneT Taking power further

Snapshot selection: Infrastructure operating envelop

Situation A:
- High wind and/or solar supply
- High final demand

HIGH
RES

Flex options:
Demand management
Battery
Conversion
Export
Curtailment

GW

High demand
conventional

Situation B:
- High wind and/or solar supply
- Low final demand
- *NOTE: The need for flexibility options could be larger compared to situation 1*

HIGH
RES

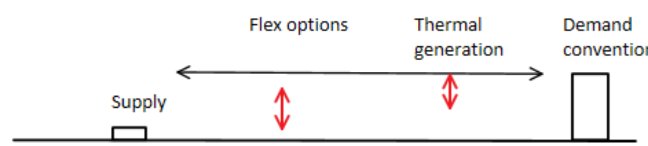
Flex options:
Demand management
Battery
Conversion p-2-h2
Export
Curtailment

># GW

Low demand
conventional

Case: High RES WIND and low conventional demand

Situation C:
- Low wind and/or solar supply
- High final demand
- *NOTE: thus could result in a need for back-up power plants*



→ Selection of suitable „snapshot hours“ that fullfill the defined criteria

Modeling limitations and points for improvement

Energy system modeling (ETM):

- Only rudimental consideration of energy exchange with neighbouring countries
- Only one national weather year pattern for RES infeed and demand
- Simplified determination of power plant dispatch (merit order) without consideration of further „real world“ boundary conditions

Regionalization:

- Fixed distribution keys for supply, demand, flexibility and exchange categories mostly based on today‘s distribution and according to statistical data

Infrastructure modeling & calculations:

- Underlying energy infrastructure not modeled (electrical grid < 220kV, Methane grid < 40 bar)
- Linear optimization scheme to determine grid power flows not fully reflecting real world flow patterns (but providing rough indication if power can be transported)

Appendix I

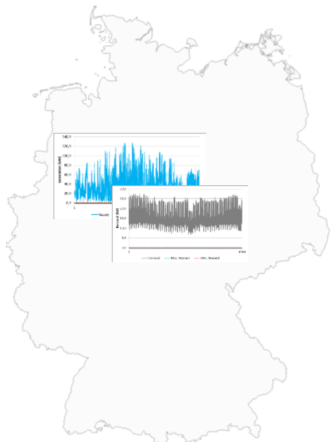
Methodology overview (DE)

Methodology overview (DE)

Scenario A

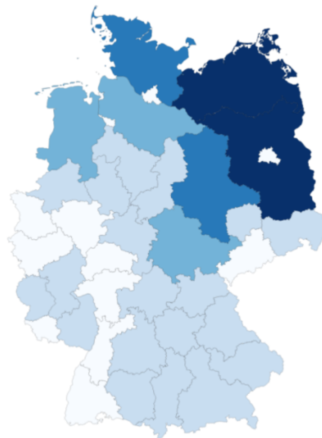
Scenario B

…



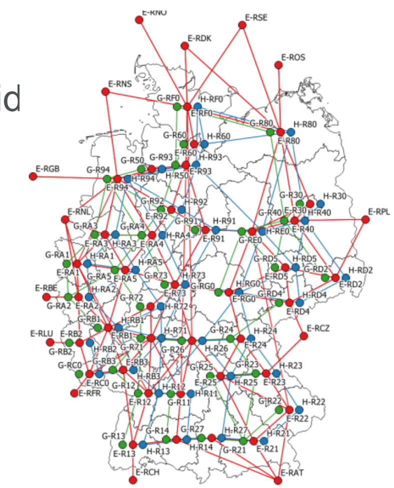
Energy system calculations (IAEW)

Snapshot selection

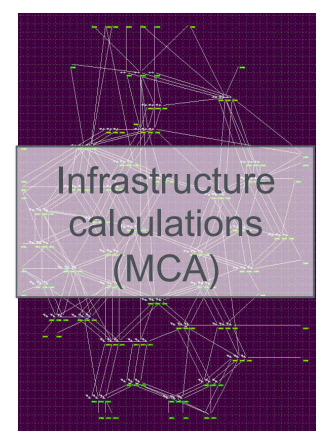


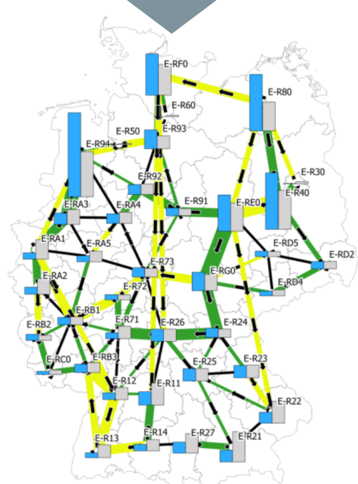
Regionalization of scenario data

Linking to grid model



Combined grid model (electricity/ hydrogen/methane)





Visualization & analysis

Steps:

1. Definition of scenarios (2050)
2. Energy system calculations
3. Selection of snapshots
4. Regionalization of scenario data
5. Linking to grid infrastructure
6. Power flow calculations
7. Data analysis and visualization

Methodology overview - explanation

- For 3 possible end situations of a decarbonized German energy system in 2050 - *local, national and international*, the annual energy figures for electricity and gas are derived. The scenarios differ in socio-cultural and political factors influencing the energy transition.
- These annual energy figures are post-processed to include temporal (hourly) and spatial (municipality) distributions, and mapping on to the nearest grid node. *The modelled infrastructure includes the electricity and Gas grid. The Gas grid is split in to two parts – one to transport hydrogen and the other to transport green methane.*
- Then from all 3 scenario's those hours are selected and analysed that give a high load on the electricity and gas infrastructure. Three specific situations have been identified to be most critical:
  - High RES supply (solar and/or wind) and high (final) demand
  - High RES supply (solar and/or wind) and low (final) demand
  - Low RES supply and high (final) demand
- Beside the *'base case'* setup the sensitivity of the load on the different grids to the location of the electrolyser (P2Gas(H2) has been studied

Scenario framework

gasunie crossing borders in energy | TenneT Taking power further

Scenarios: Overall framework

'National'

- Aim for energy independence relying mostly on **centralised** RES supply
- Mostly central supply of **wind**
- Strong support of power-to-gas and batteries as flexibility options
- **Limited energy exchange** with other countries allowed

NvdT 'national' (NL)
FNB 'Strom und Grünes Gas(DE)

min. **-95% CO_2 emissions** until 2050*

'International'

- Globally oriented policy with focus on **international energy exchange** No strong support of extensive RES supply increase
- 'Business as usual'

NvdT 'international' (NL)
dena 'Technologiemix 95%'(DE)

'Local'

- Strong aim for energy independence relying on **centralised** RES supply
- Mostly decentral supply of **solar**
- Strong support of power-to-gas and batteries as flexibility options
- **No energy exchange** with neighbouring countries

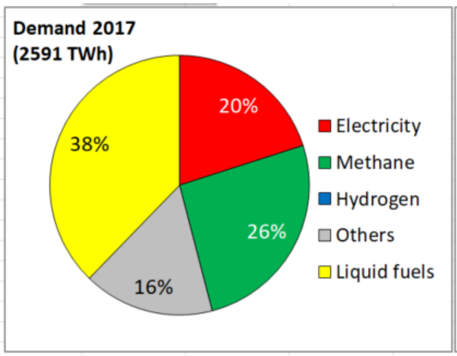
NvdT 'regional' (NL)
Enervis 'Optimiertes System' (DE)

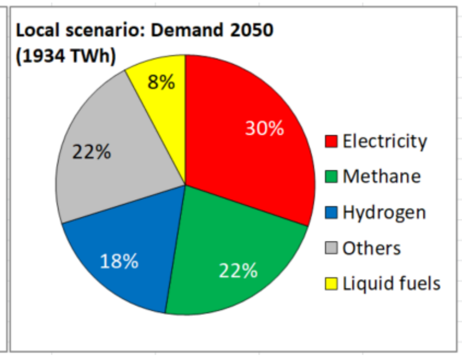
*(Based on agreed european reduction goal between reference year 1990 and 2050)

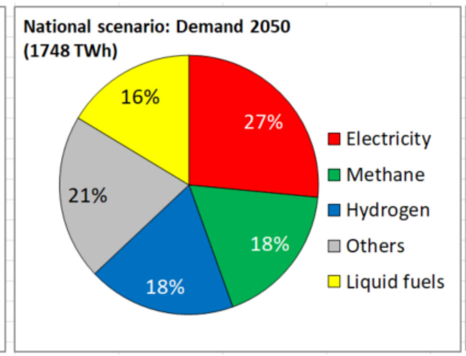
Scenarios: Study overview

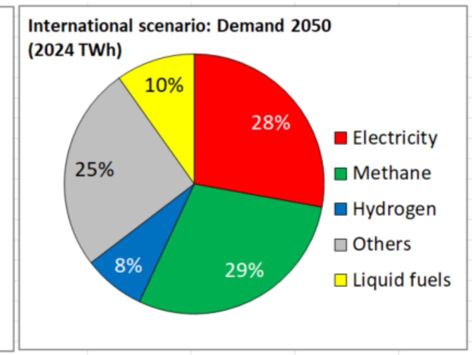
- “Net voor de toekomst” (CE Delft, 2017) → NvdT: local, national, international
- “Erneuerbare Gase - ein Systemupdate der Energiewende“ (Enervis, 2017) → Enervis
- „Leitstudie integrierte Energiewende“ (dena, 2018) → dena
- „Der Wert der Gasinfrastruktur für die Energiewende in Deutschland“ (Frontier Economics, 2017) → FNB

Scenario framework (DE): Final energy demand (2017 and three 2050-scenarios)





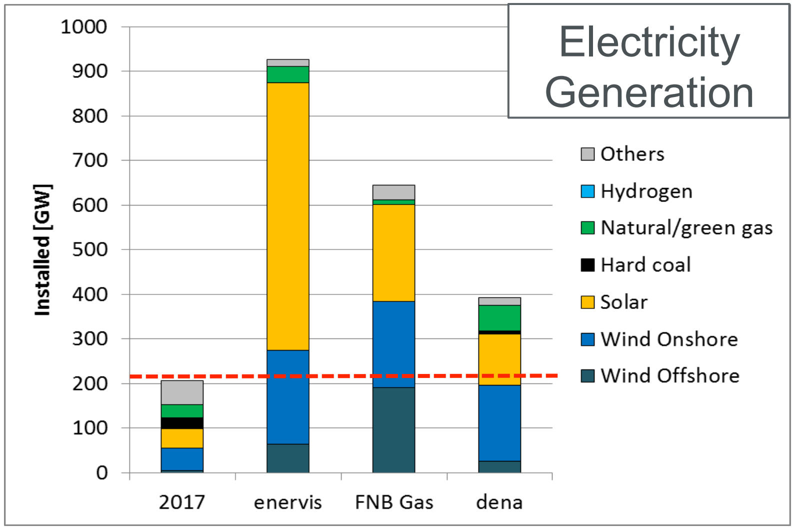


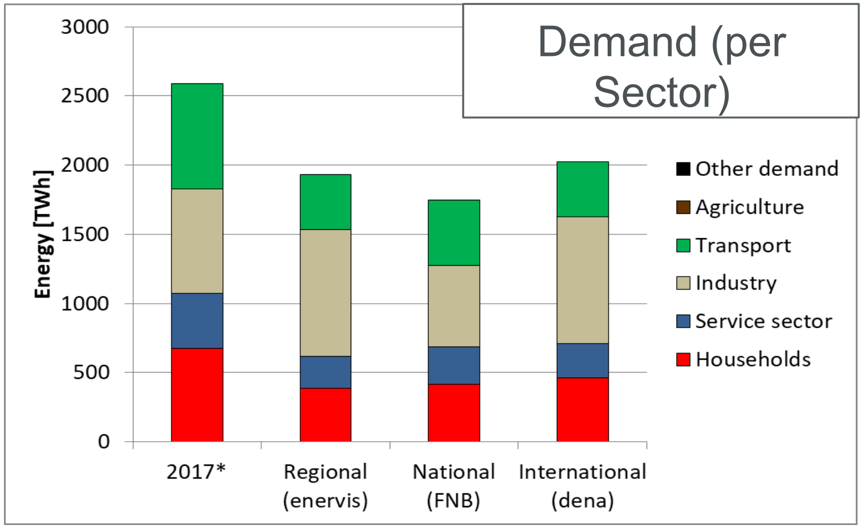


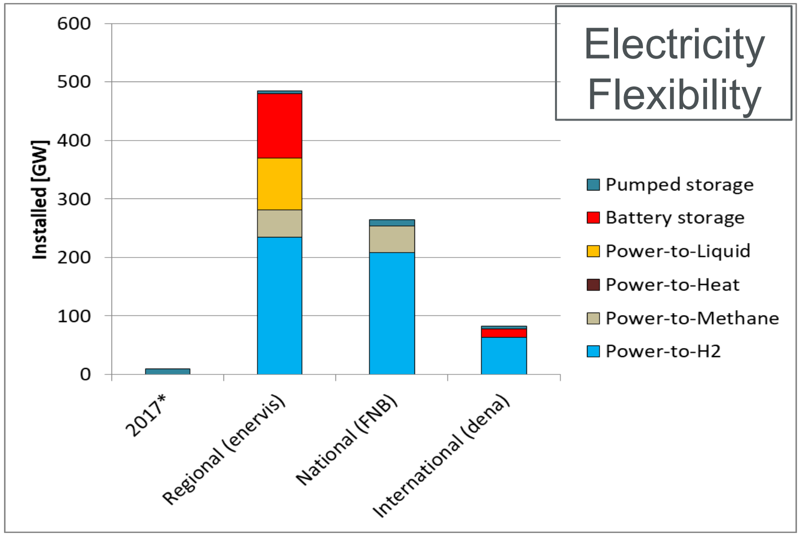
Category others: Includes coal, biomass and district heating
Category liquids: Includes oil and power-to-liquid

*(Source: BMWi, Zahlen und Fakten Energiedaten)

Scenario framework (DE): Scenario numbers







Local (Enervis):
- Supply dominated by decentral solar PV
- Very high amount of PtH2 and batteries

National (FNB):
- Supply mix of wind offshore, onshore and solar
- High amount of PtH2 and batteries
- Import of green liquid fuels

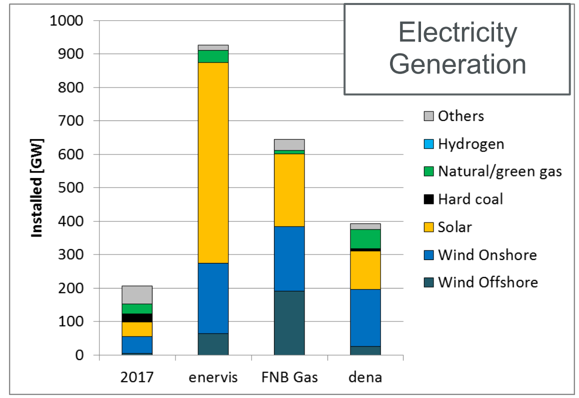
International (dena):
- Conservative increase of RES, gas still part of generation
- Almost no domestic flexibility options available and focus on import/export of energy

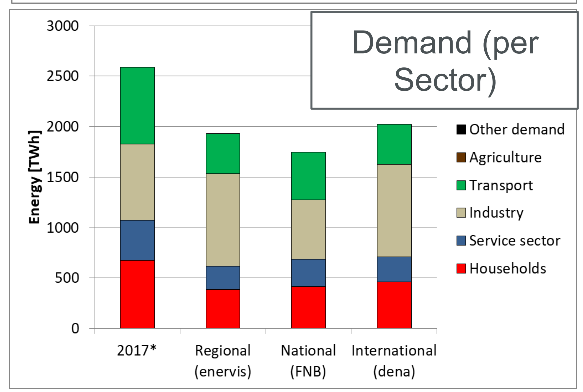
Infrastructure Outlook 2050

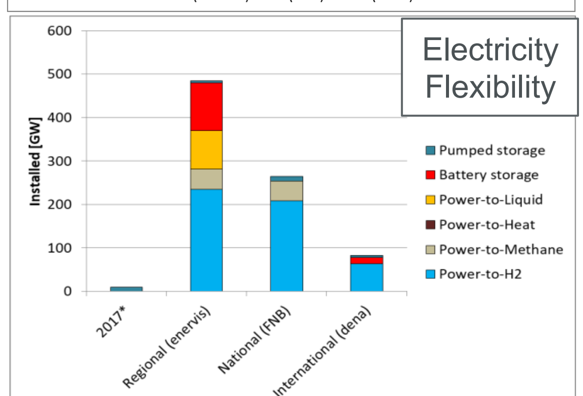
gasunie crossing borders in energy | TenneT Taking power further

Scenarios: Concrete dataset for 2050 (DE)

Category	Unit	2017*	Regional (enervis)	National (FNB)	International (dena)
Supply					
Wind Offshore	GW	5	64	191	26
Wind Onshore		51	210	193	171
Solar		42	600	218	114
Hard coal		25	0	0	7
Methane		30	36	10	57
Hydrogen		0	0	0	0
Others		54	17	33	18
Sum of supply		**207**	**927**	**645**	**393**
Demand					
Households	**TWh**	**675**	**390**	**418**	**463**
Electricity		129	118	111	128
Methane		273	74	149	100
Hydrogen		0	0	0	0
Others		143	197	157	206
Liquid fuels		129	0	0	29
Service sector		**401**	**227**	**272**	**245**
Electricity		147	116	152	111
Methane		133	32	59	42
Hydrogen		0	0	0	0
Others		40	79	62	80
Liquid fuels		81	0	0	12
Industry		**750**	**915**	**582**	**918**
Electricity		232	239	168	239
Methane		263	326	107	395
Hydrogen		0	200	166	64
Others		236	150	142	191
Liquid fuels		19	0	0	29
Transport		**765**	**403**	**476**	**399**
Electricity		12	111	33	86
Methane		1	0	0	52
Hydrogen		0	142	157	92
Others		4	0	0	40
Liquid fuels		748	150	286	129
Agriculture		**0**	**0**	**0**	**0**
Other demand		**0**	**0**	**0**	**0**
Sum of demand		**2591**	**1934**	**1748**	**2024**
Flexibility					
Power-to-H2	GW	0	235	208	63
Power-to-Methane		0	46	46	0
Power-to-Heat		0	0	0	0
Power-to-Liquid		0	89	0	0
Battery storage		0	110	0	15
Pumped storage		10	5	10	5
Sum of flexibilty		**10**	**485**	**264**	**83**







* Data source: BMWi, Zahlen und Fakten Energiedaten

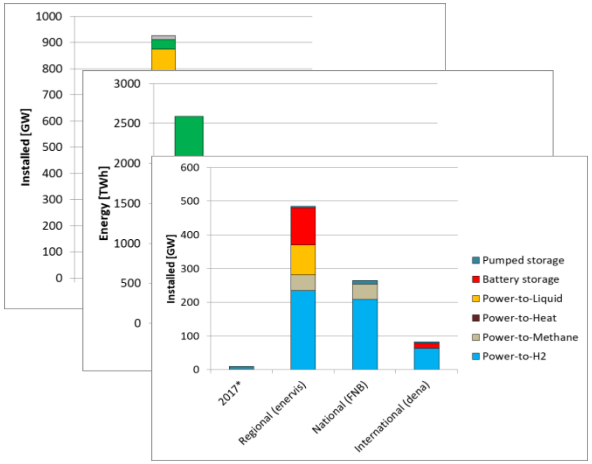
Energy system calculations (DE)

gasunie crossing borders in energy

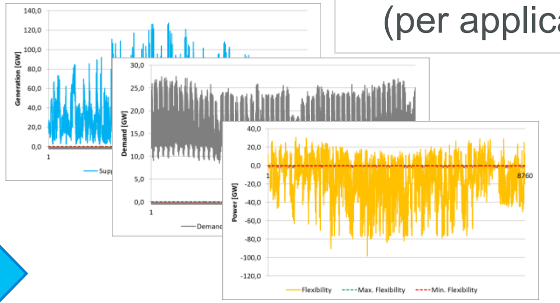
TenneT Taking power further

Energy system calculations (DE): ETM and Modelling IAEW

Scenarios (Enervis, FNB, Dena)



Time-series



Hourly time series (per application)

Analysis, filtering and snapshot selection

Energy system calculations (DE): ETM and Modelling IAEW

ETM used for:

- Check of scenario data
- Calculation/Check of target figures related to energy use (e.g. CO_2-emissions, costs, share of RES,…)

Modelling IAEW

- Generation of Time-Series based on IAEW Know-How
- Generation Time-Series for different weather-regions
- Regionalization of Time-Series

Energy system calculations: “Merit order” of flexibility options

Pump storage
- Storage of energy in water reservoirs
- Short term storage of energy

↓

Power-to-H2
- Conversion of electricity to hydrogen
- Long term storage of energy

↓

Power to Heat
- Conversion of electricity to heat
- Short term storage of energy

↓

Battery storage
- Direct storage of electricity in batteries
- Short term storage of energy

↓

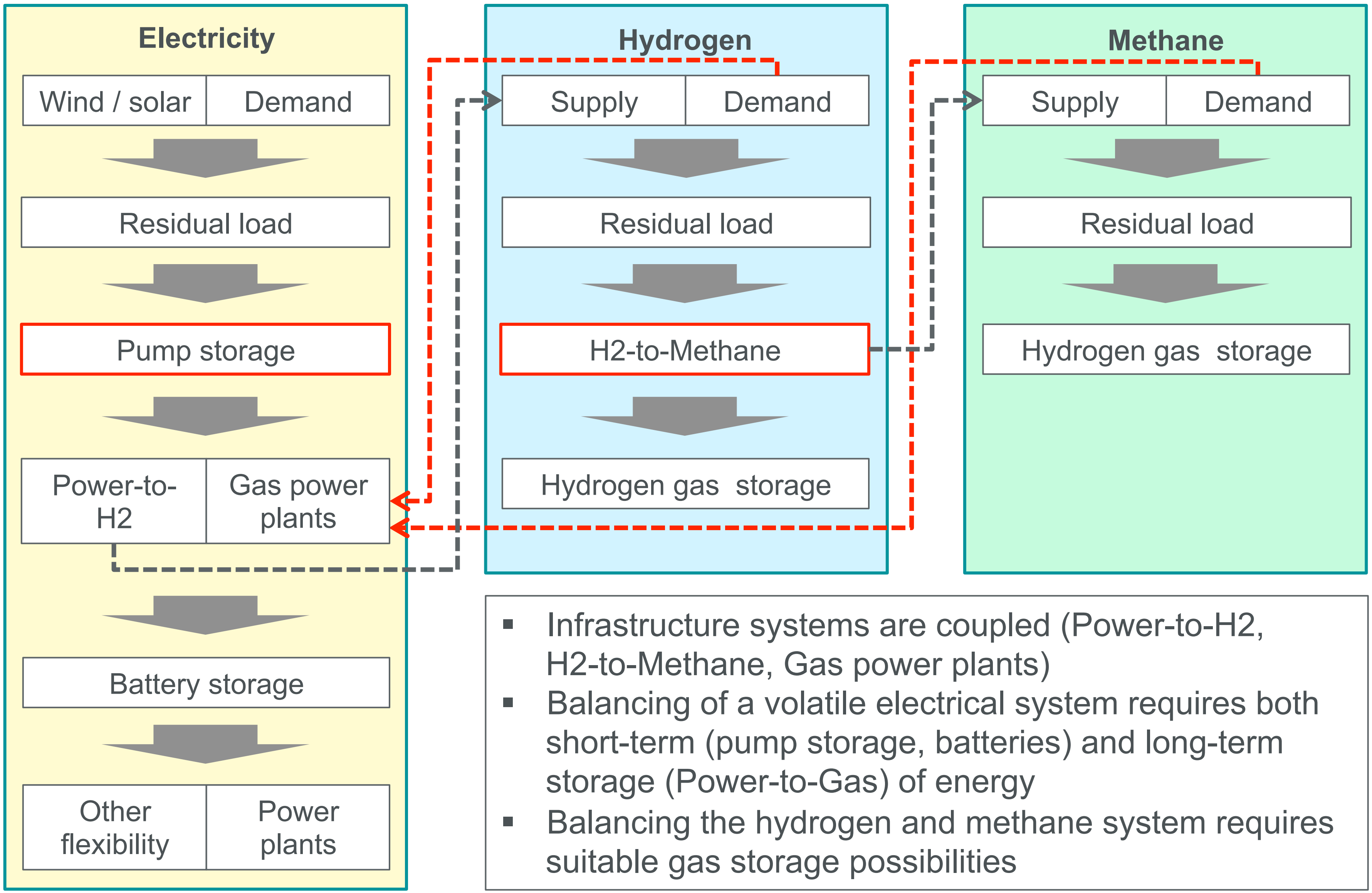
Export/Curtailment
- Export or finaly Shuttoff of supply
- No integration of RES generation

gasunie crossing borders in energy

TenneT Taking power further

Energy system calculations: General scheme coupling

Only modeled for DE



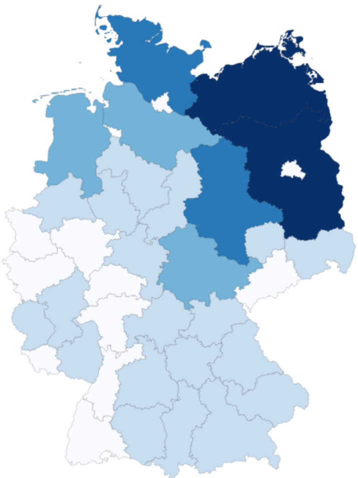
- Infrastructure systems are coupled (Power-to-H2, H2-to-Methane, Gas power plants)
- Balancing of a volatile electrical system requires both short-term (pump storage, batteries) and long-term storage (Power-to-Gas) of energy
- Balancing the hydrogen and methane system requires suitable gas storage possibilities

Regionalization of scenario data (DE)

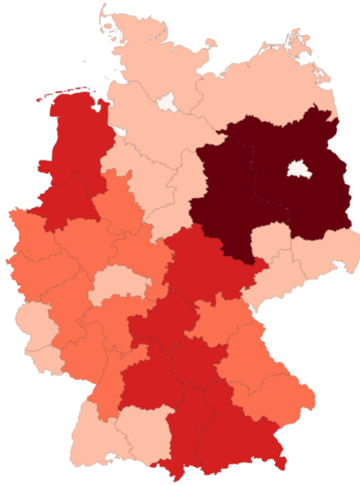
Regionalization (DE): Base assumptions for distribution keys

Category	Distribution key (NUTS-2)	Source
Wind onshore	Potential analysis, regionalized time series	IAEW Aachen
Wind offshore	Distribution of NEP 2030 (2017)	TenneT
Solar PV	Currently installed capacities, regionalized time series	IAEW Aachen
Hard coal	Currently installed capacities	IAEW Aachen
Natural gas	Currently installed capacities (gas)	IAEW Aachen
Green gas	Currently installed capacities (gas)	IAEW Aachen
Hydrogen	Not modeled	Not modeled
Other	Currently installed capacities (hydro, biomass)	TenneT
Household demand	Population	IAEW Aachen
Buildings demand	Employment service sector (GHD)	IAEW Aachen
Industry demand	Employment industry (metal, chemistry, paper, oil)	IAEW Aachen
Transport demand	Number of vehicles	IAEW Aachen
Heat buildings	Number of buildings	IAEW Aachen
Power-to-Gas	Installed capacities of wind and solar (->Sensitivity)	IAEW Aachen
Storage (hydrogen/methane)	Current installed capacities/ WGV	GASUNIE
Import / Export	Import / export capacities of interconnectors	TenneT, GASUNIE
Green gas production	Currently installed capacities (biomass)	TenneT
H2-to-CH4	Based on the distribution of bio-methane production	GASUNIE

Regionalization (DE): Base assumptions for distribution keys

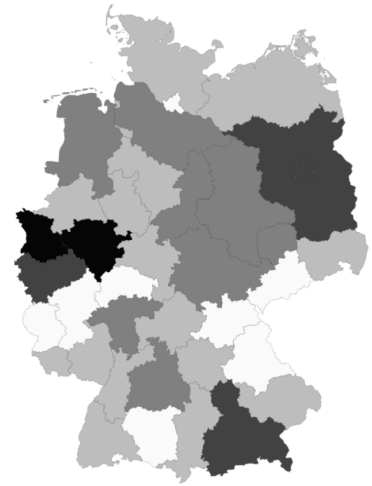


Wind onshore*

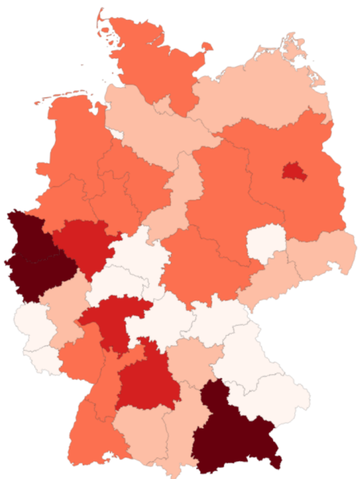


Solar PV*

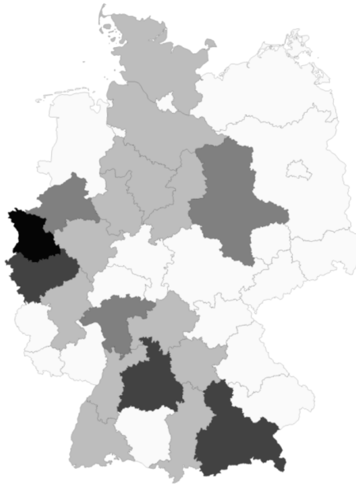
Wind offshore



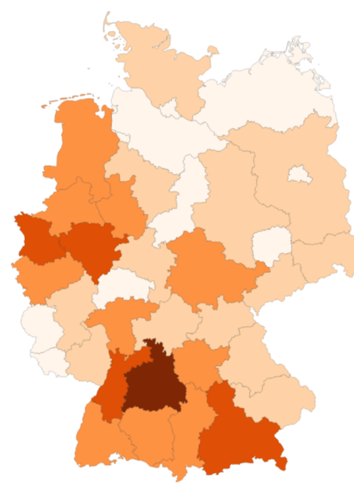
Gas power plants



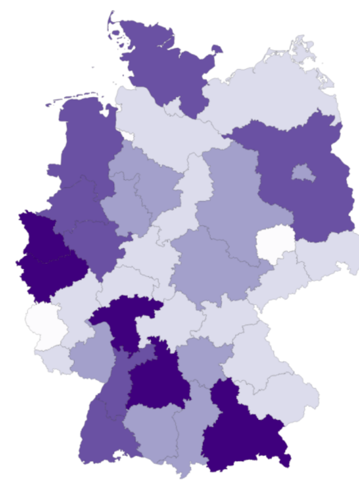
Household demand



Industry demand

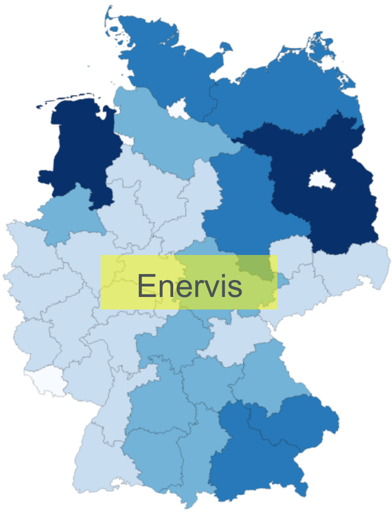


Buildings demand

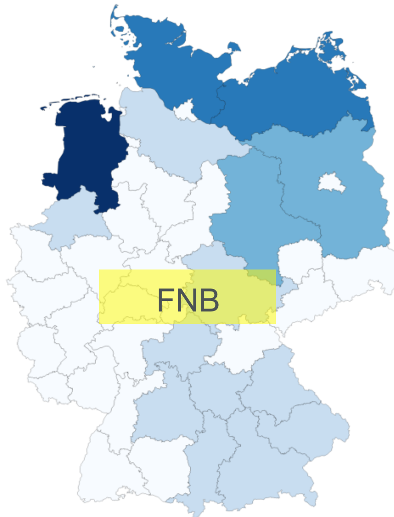


Transport demand

Regionalization (DE): Base assumptions for distribution keys

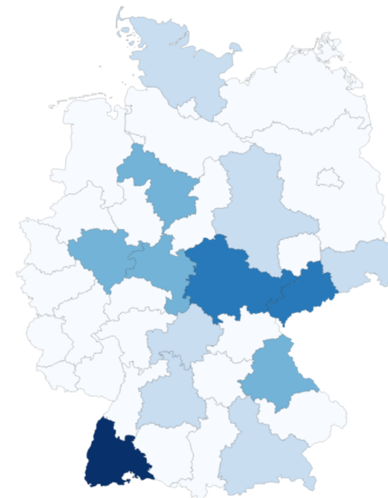


Power-to-H2 (E, H)

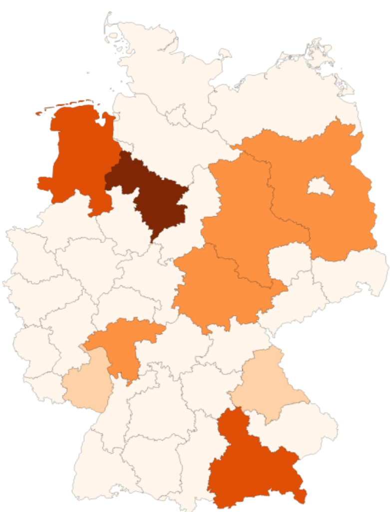


Power-to-H2 (E, H)

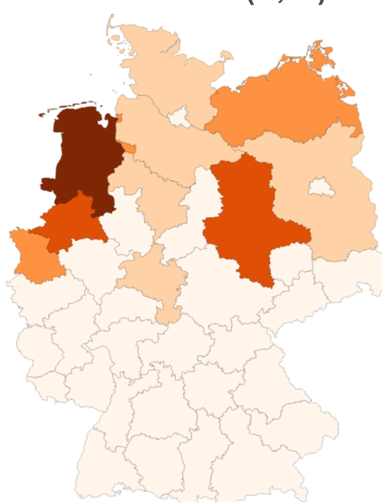
Power-to-H2 (E, H)



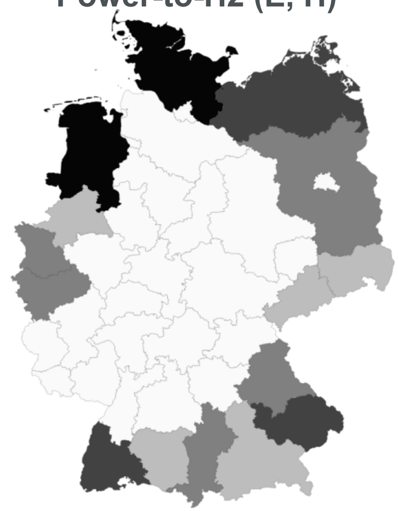
Pump storage (E)



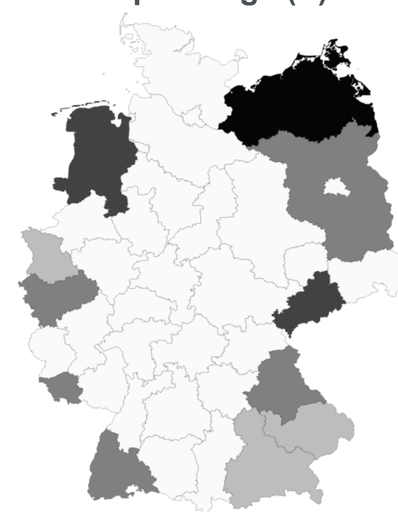
Gas storage (G)



Gas storage (H)

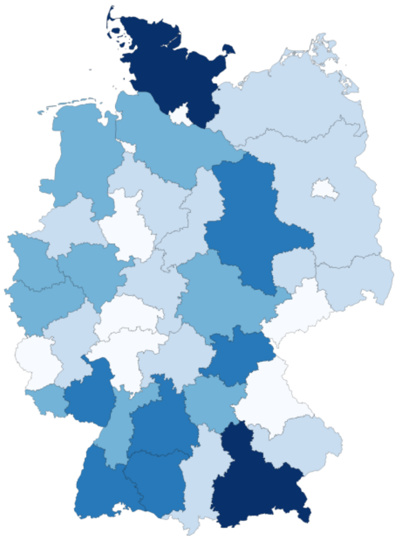


Import / Export (E)



Import / Export (G, H)

Regionalization (DE): Base assumptions for distribution keys



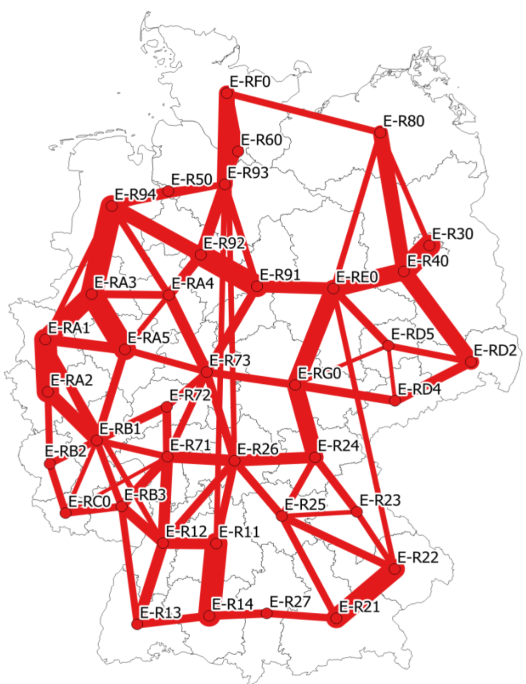
H2-to-CH4 (G)

Infrastructure modeling (DE)

gasunie crossing borders in energy

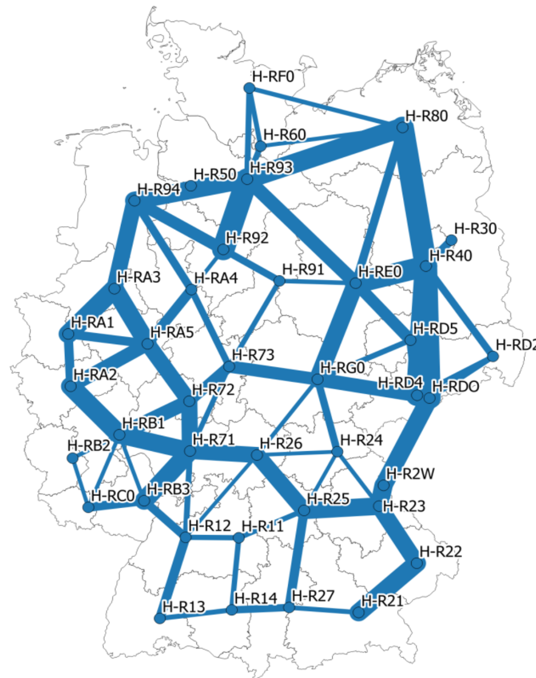
TenneT Taking power further

Infrastructure modeling (DE): Assumed topologies



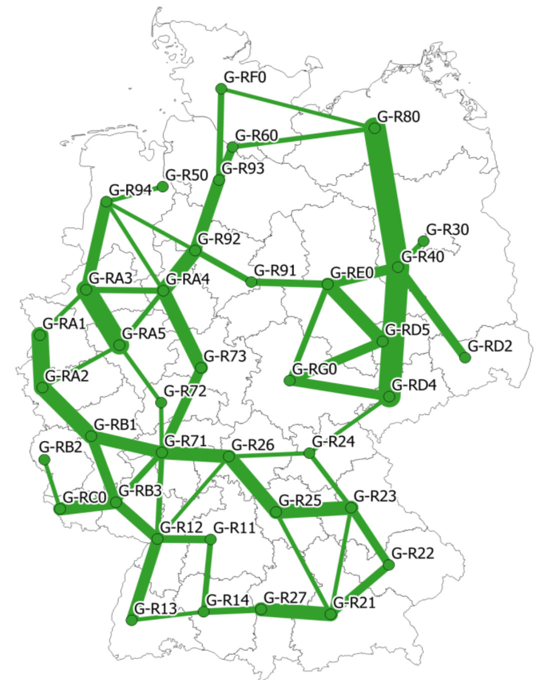
Electrical grid

- 220/380kV grid considered
- Today's grid + additional certain grid expansion measures until 2030 (confirmed grid development plan 2017)
- Flow calculations with **70% of line capacities** to estimate „n-1" operation



Hydrogen grid

- Based on today's natural gas grid
- Including Expansions of NEP2018
- Gas grid split into hydrogen and methane grid
- Hydrogen grid 'designed' as a strong back-bone

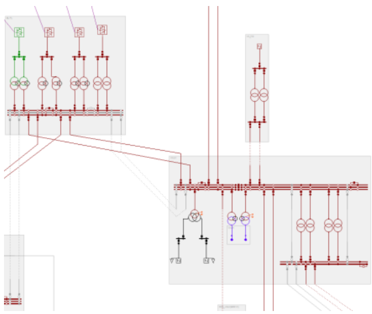


Methane grid

- Methane grid 'designed' to satisfy transport to end-customer (heat demand)

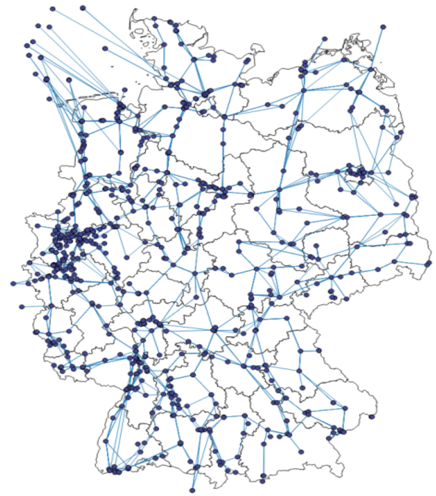
Remark: Line thickness indicates amount of maximum transport capacity

Infrastructure modeling (DE): Methodology (electricity)



Electrical grid model (Officially confirmed grid for 2030, German grid development plan 2017)

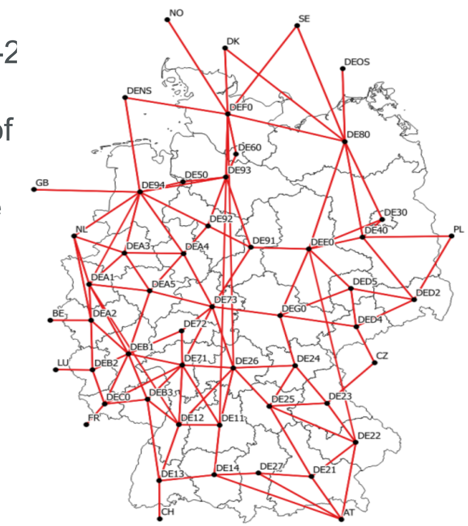
Filtering of relevant grid nodes



Electrical 220/380kV grid (> 800 grid nodes)

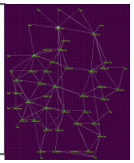
Geographical data on grid node locations

Linking of grid nodes to NUTS-2 regions and determination of connections between these



Simplified grid infrastructure (38 + 13 nodes)

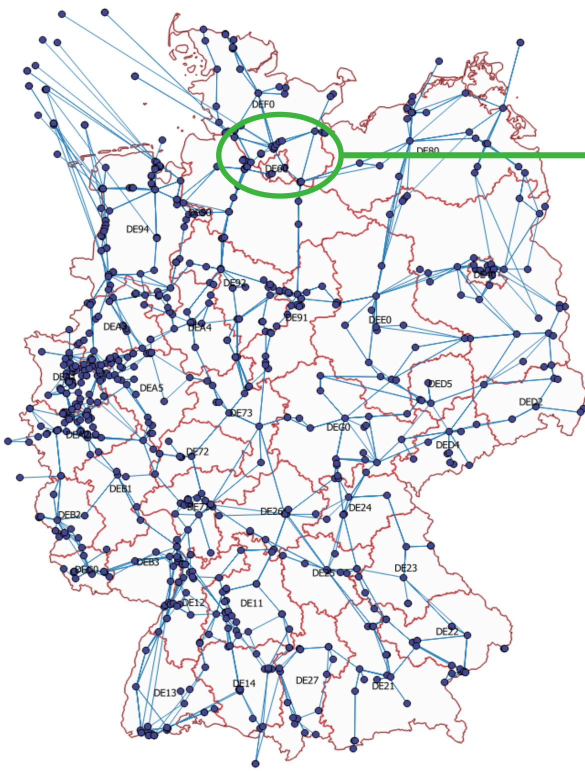
Infrastructure / grid model (MCA tool)

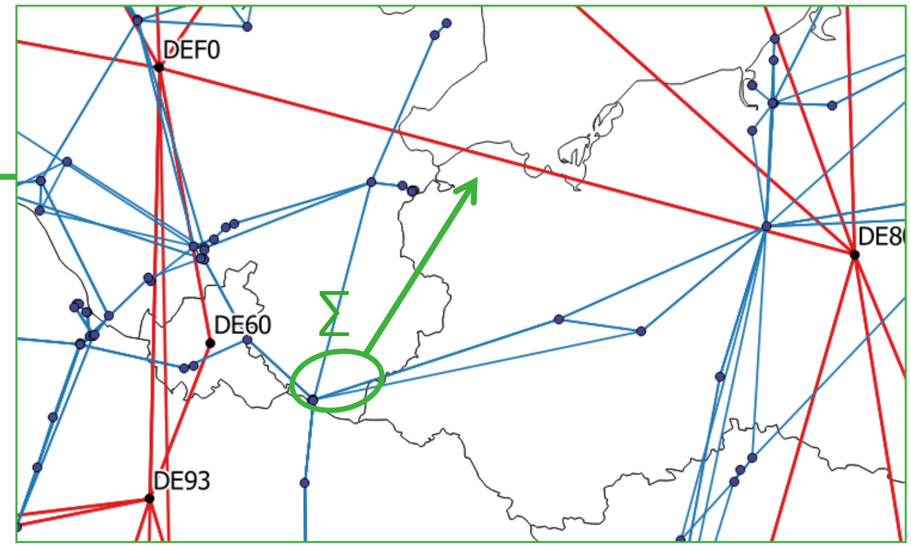


gasunie crossing borders in energy

TenneT Taking power further

Infrastructure modeling (DE): Methodology (electricity)





- Electrical power flows are in reality mainly dependent on impedance of lines
- MCA tool uses **capacity and length** of lines to determine flow patterns

- **Capacities:** Summing up of line capacities to achieve equivalent transmission capacity of edge
  (e.g. 2 x 1 GW line cap. = 2 GW)
- **Edge length**: Average of corresponding line lengths and division through number of lines

Ce Capacity of edge e
Ci = Capacity of line i
n = number of lines

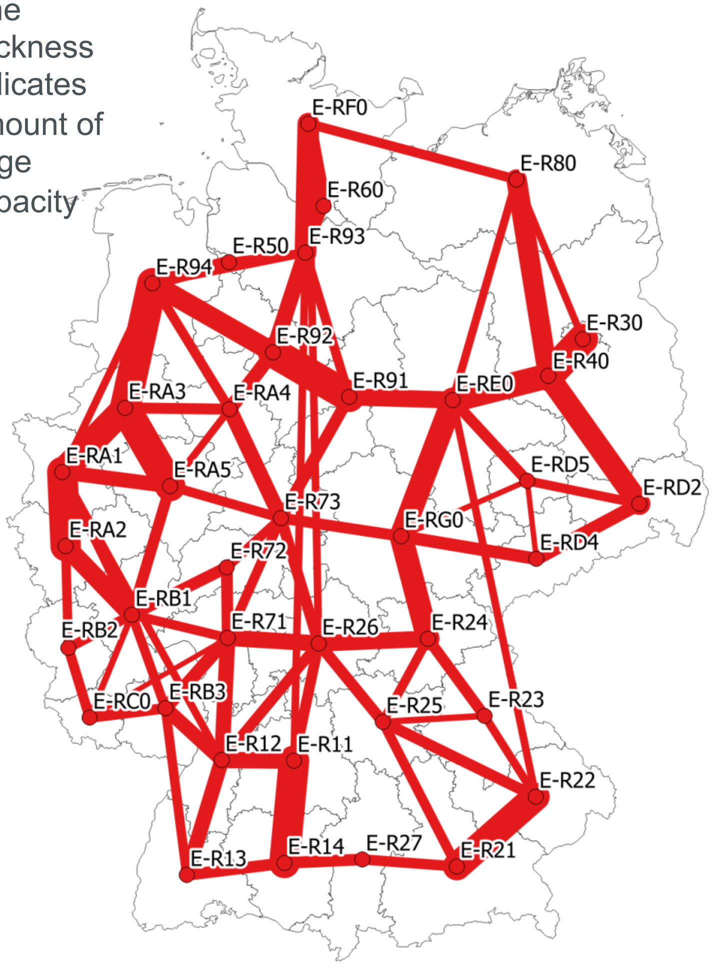
Le = Weighted length of edge e
Li = Length of line i
n = number of lines

gasunie crossing borders in energy

TenneT Taking power further

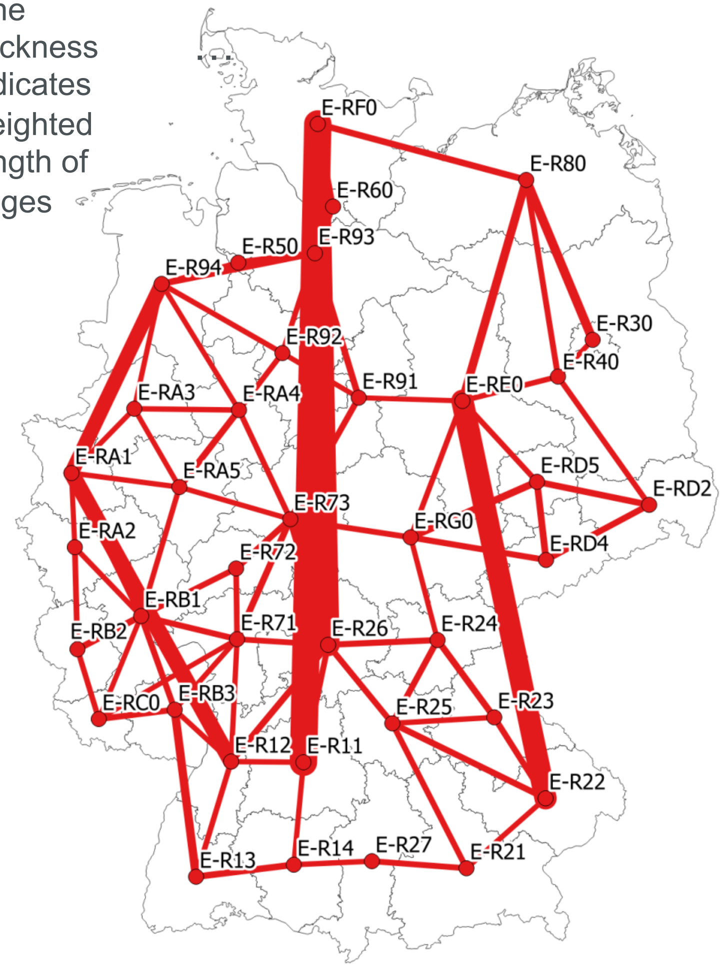
Infrastructure modeling (DE): Methodology (electricity)

Line thickness indicates amount of edge capacity



Line capacities (2030)

Line thickness indicates weighted length of edges



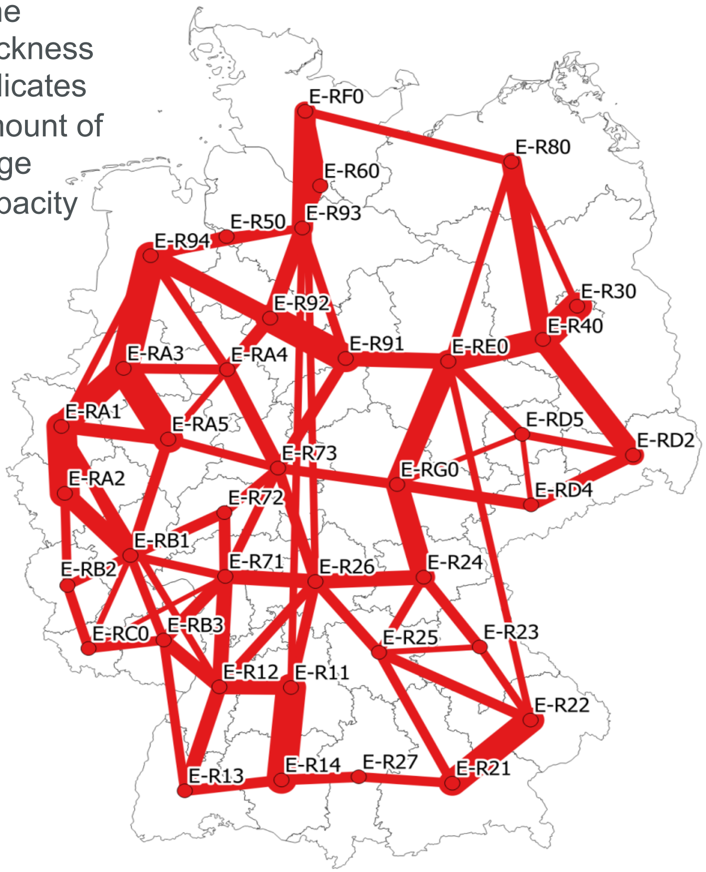
Weighted lengths (2030)

gasunie crossing borders in energy

TenneT Taking power further

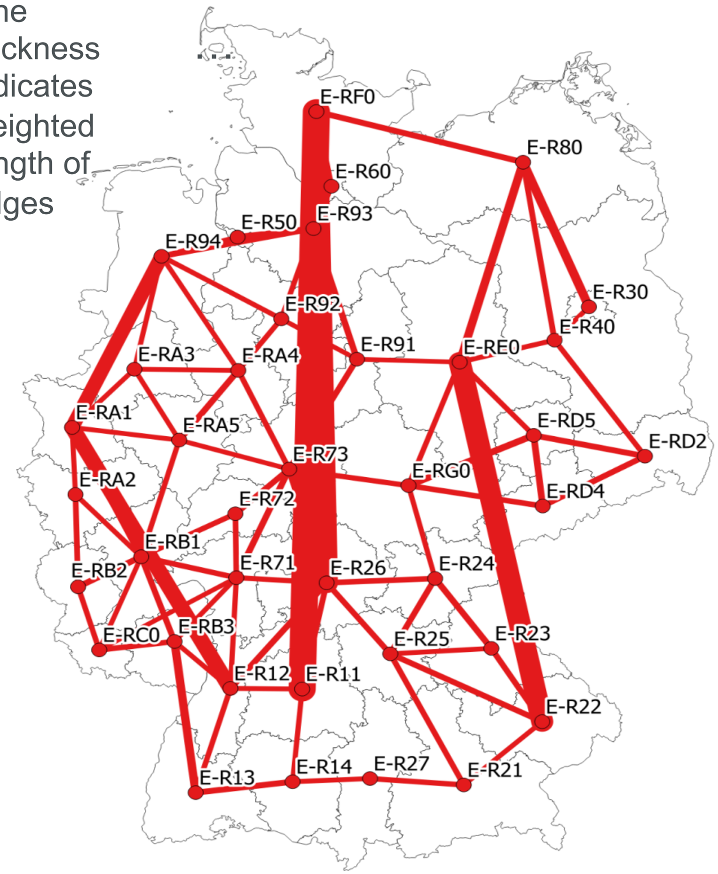
Infrastructure modeling (DE): Methodology (electricity)

Line thickness indicates amount of edge capacity



Line capacities (2030)

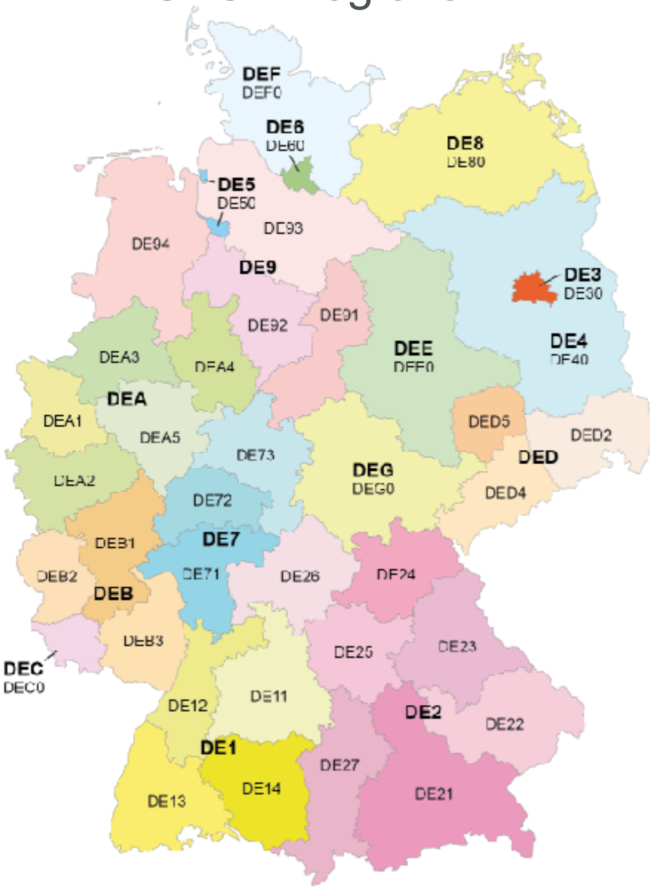
Line thickness indicates weighted length of edges



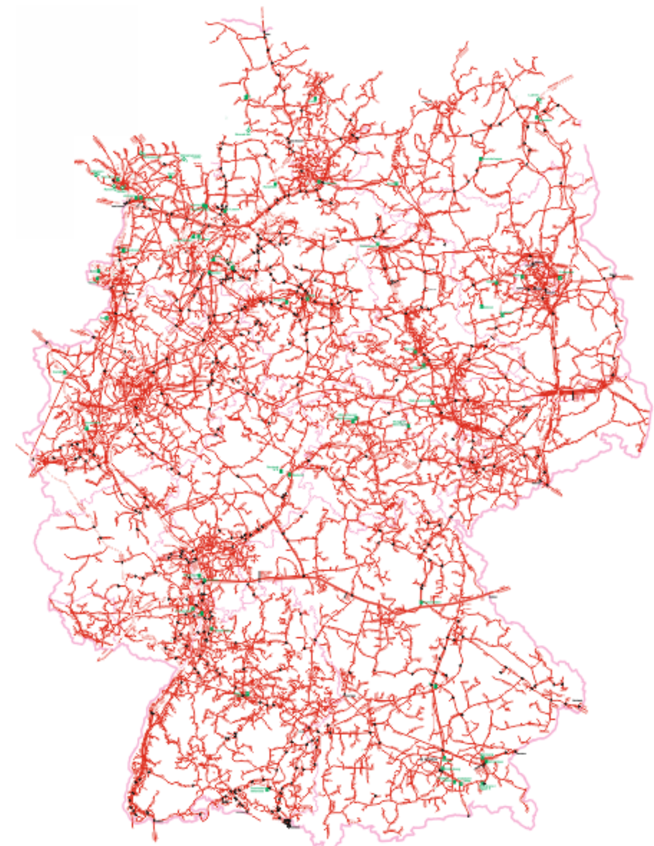
Weighted lengths (2030)

Infrastructure modeling (DE): Methodology (gas)

NUTS2 Regions



VGE MAP 2010 + Information NEP

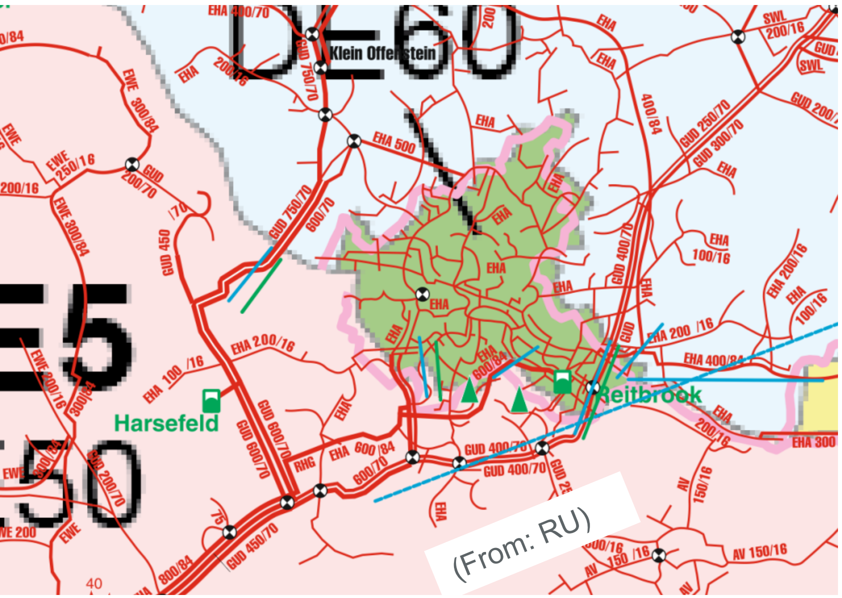


- Merged the NUTS2 Regions with a gas infrastructure map „manually“
- Focus on the connection between the borders

gasunie crossing borders in energy — TenneT Taking power further

Infrastructure modeling (DE): Methodology (gas)

Example: Hamburg



- Examination of the boundaries between the NUTS2 regions
- Considered Pipelines: max. Pressure > 40 bar
  Diameter > 400 mm
- Categorization hydrogen / methane:
  - Focus on hydrogen
  - Loop lines methane
  - Import / Export dependent on country
    - Hydrogen: RU, NO
    - Hydrogen/Methane: NL, DK, FR, IT, AU, CH
- Interconnection points interregional modelled

Capacity assumptions: - pressure (75% of max. pressure)
- flow velocity (5 m/s)
- gas quality hydrogen ≙ 80% of high calorific gas

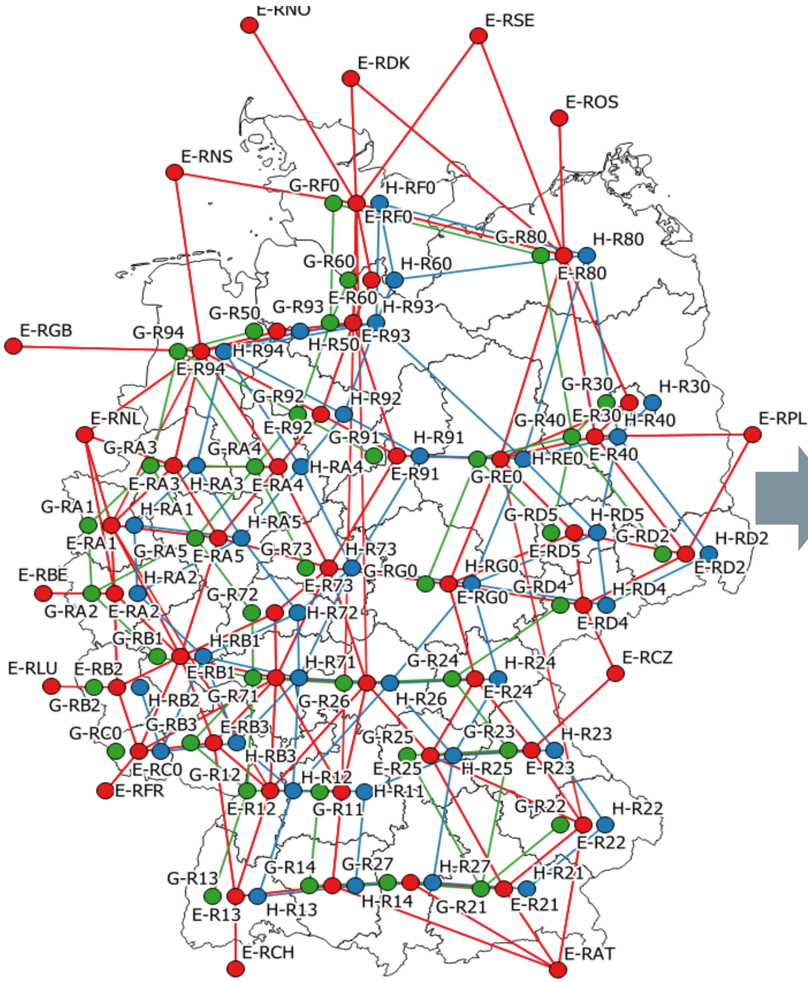
➡ Capacity only dependents on: diameter, pressure, velocity, gas quality

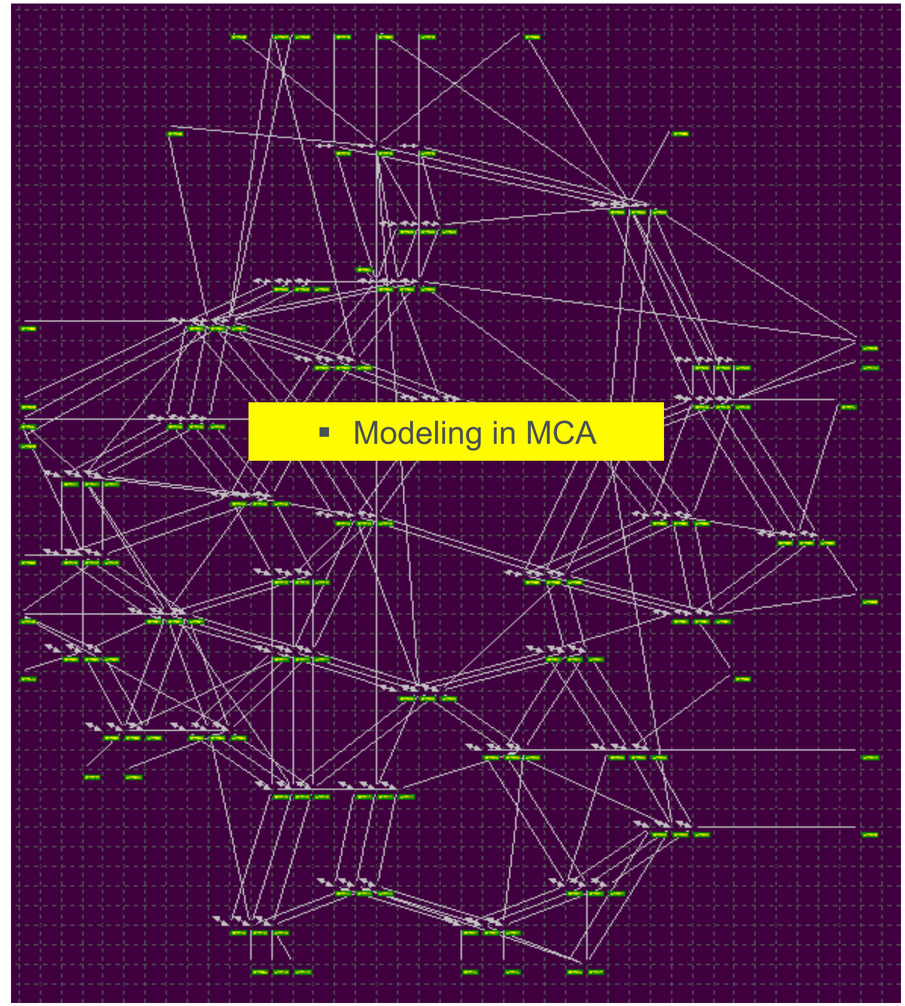
Outlook: allocation methane / hydrogen of the pipelines could be changed
implementation of GIS could automate the process

gasunie crossing borders in energy

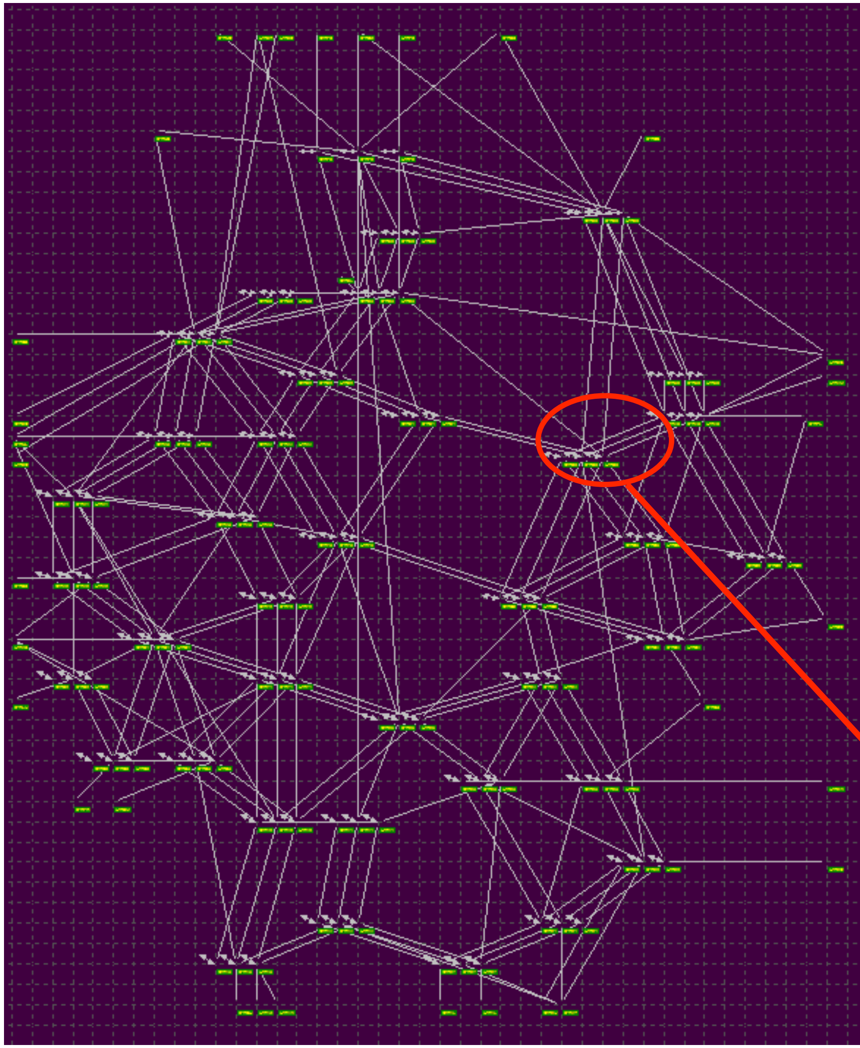
TenneT Taking power further

Infrastructure modeling (DE): Interface to MCA-tool





Infrastructure modeling (DE): Interface to MCA-tool



Standardized identifiers (IDs) for each grid node:

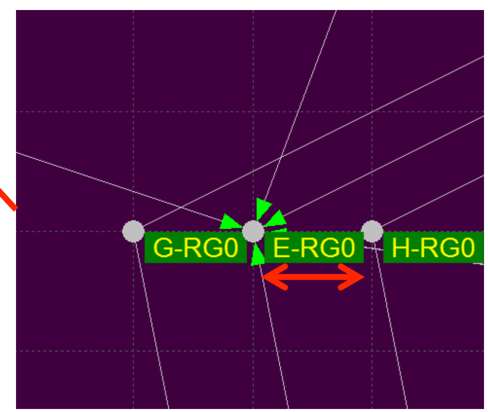
- E-RXX
- G-RXX
- H-RXX

ID of infrastructure type

ID of NUTS-2-region (e.g. „DE12“ = „12“)

Standardized identifiers (IDs) for each line between starting (X) and end point (Y):

- E-RXXRYY
- G-RXXRYY
- H-RXXRYY



Coupling of infrastructure:

- Power-to-H2
- Hydrogen / gas power plants
- H2-to-CH4

Snapshot selection

Snapshot definition and considerations

General definition „snapshot“: Situation („hour“) with a specific (regional) occurance of supply, demand, use of flexibility options and exchange with neighbouring countries

Considerations for selecting snapshots:

- The **operating envelope** of the infrastructure: What are the maximum capacities the infrastructure should meet?
- The **transport momentum** of energy**:** Are transport of large quantities of energy across long distances foreseen that result in a high load on the infrastructure?
- The **regional distribution** of energy**:** Do future projected supply and demand locations combine with existing (and foreseen extension of) infrastructure?
- The **choice and (regional) locations for flexibility options** (especially electrolyzers) determines to an extent the load on the electrical or gas infrastructure
- The selection is **scenario dependent** due to different assumptions about supply, demand, flexibility and exchange possibilities
- Additional sensitivities based on selected base snapshots allow to investigate impacts of singular changes in scenario assumptions

gasunie crossing borders in energy

TenneT Taking power further

Snapshot selection: operating envelop

- The operating envelope determines the **(max) capacity requirements of the infrastructure**
- Supply, consisting of a high share of intermittent RES should meet demand (in this analysis matched on a hourly basis)

- **Three main corners of the operating envelope** were identified:
  1. High RES supply and high (final) demand
  2. High RES supply and low (final) demand
  3. Low RES supply and high (final) demand

- Flex options balance the gap between supply and demand
- Furthermore, we can distinguish offshore wind, onshore wind and solar RES For each a different set of flex options could be selected

HIGH
RES

Flex options:
Demand management
Battery
Conversion
Export
Curtailment

GW

High demand
conventional

Example

Snapshot selection: Infrastructure operating envelop

Situation A:

- High wind and/or solar supply
- High final demand

HIGH
RES

Flex options:
Demand management
Battery
Conversion
Export
Curtailment

GW

High demand
conventional

Situation B:

- High wind and/or solar supply
- Low final demand
- *NOTE: The need for flexibility options could be larger compared to situation 1*

HIGH
RES

Flex options:
Demand management
Battery
Conversion p-2-h2
Export
Curtailment

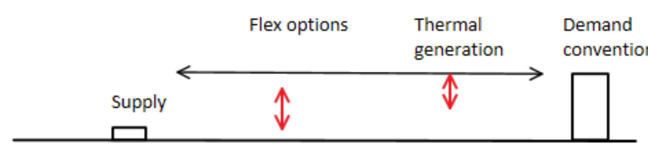
>\# GW

Low demand
conventional

Case: High RES WIND and low conventional demand

Situation C:

- Low wind and/or solar supply
- High final demand
- *NOTE: thus could result in a need for back-up power plants*



→ Selection of suitable „snapshot hours“ that fullfill the defined criteria

Modeling limitations and points for improvement

Energy system modeling (ETM):

- Only rudimental consideration of energy exchange with neighbouring countries
- Only one national weather year pattern for RES infeed and demand
- Simplified determination of power plant dispatch (merit order) without consideration of further „real world“ boundary conditions

Regionalization:

- Fixed distribution keys for supply, demand, flexibility and exchange categories mostly based on today‘s distribution and according to statistical data

Infrastructure modeling & calculations:

- Underlying energy infrastructure not modeled (electrical grid < 220kV, Methane grid < 40 bar)
- Linear optimization scheme to determine grid power flows not fully reflecting real world flow patterns (but providing rough indication if power can be transported)