Appendices

Appendix II

The Infrastructure Model

The infrastructure calculations for the Infrastructure Outlook 2050 have been performed with a specifically designed transmission model. As the study explores integrated gas and electricity transmission systems, the model had to provide a unified description of transport of the different energy carriers. Focus being on national-scale integration in the year 2050, i.e. on long-distance energy transmission in the far future, the level of detail of the model had to be limited. In particular, the model does not calculate real load flow distributions in the grids like they would occur in reality and which can be described using more comprehensive tools for detailed physical grid calculations[1]. Instead, the focus of our tool is rather to analyse if a certain quantity of energy can be transported in the total grid infrastructure to balance supply and demand. Therefore, it was decided that the model should not physically discriminate between the three energy carriers (electricity, hydrogen and methane) and describe transmission of all these carriers in terms of transport of energy.

Simple, intuitive approaches to transport usually involve a description in terms of transported quantities and distances over which the transport takes place. An everyday, be it somewhat outdated example is that of a person taking a parcel to the post office. To this activity a certain transport load can be assigned. If the post office is twice as far away, the transport load will be roughly twice as large. If the person takes two parcels instead of one, the transport load will also be roughly twice as large. In general, the transport load T can be written as a linear product of the transported quantity Q and the transport distance L over which Q is transported:

(1) $T = Q.L$

Despite the fact that this basic definition ignores potential economies of scale, the notion of transport load is widely used in e.g. the transport and logistics sector, where “ton miles” or “passenger miles” are a measure of performance of a company. In the more generally applicable mathematical transportation theory developed by Monge and Kantorovich[2], T is referred to as the *transport moment*.

In a first approximation, the linear approach to transport applies to transport of energy as well. For natural gas or hydrogen the driving force of transmission is pressure. If a quantity of Q m^3/h is transported from a point of high pressure (p_{in}) to a point of low pressure (p_{out}), the loss of power can be written in terms of the pressure difference $\Delta p = p_{in} - p_{out}$:

(2) $Q.\Delta p$

Decrease of pressure with distance is generally nonlinear, especially when intermediate compression is involved (see Figure 1). Yet, for long distances in common situations where pressures do not vary too wildly, the graph

[1] For electrical grid calculations tools like Power Factory and Integral are used; for gas grid calculations MCA and Simone are well-known hydraulic tools.
[2] G. Monge, Mémoire sur la théorie des déblais et des remblais. Histoire de l’Académie Royale des Sciences de Paris, avec les Mémoires de Mathématique et de Physique pour la même année, pages 666–704, 1781; L. Kantorovich, On the translocation of masses, C.R. (Doklady) Acad. Sci. URSS (N.S.), 37:199–201, 1942.

suggests it is possible to linearize the saw-tooth shaped pressure decrease according to the red line and approximate the transport load (2) to its linear version (1).

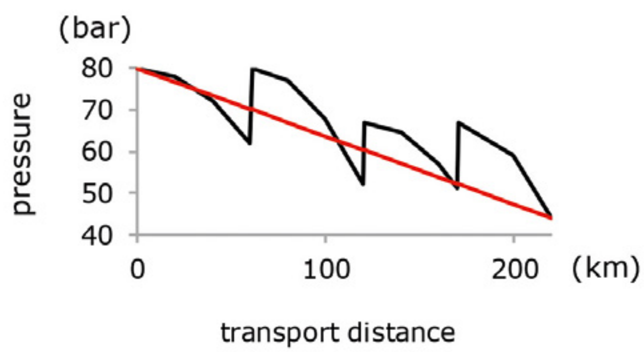


Figure 1: Pressure decrease for transport of gas in a network with intermediate compression (black line) and its linearization (red line)

For transmission of electricity, loss of power can be attributed to, among others, heat losses due to circuit impedance. The circuit of Figure 2 shows that this is generally more complicated than just considering resistive heat losses: there are nonlinear effects, involving reactive impedance from capacitors and inductors as well. In this study we assume that, to fist order, power loss can be described linearly, i.e. in terms of resistive heat losses. In this approximation, formula (1) can be used as a proxy for electrical transport load.

In the proposed linear approach to energy transmission, a network can simply be described as a graph consisting of nodes and connecting edges. For electricity, the nodes may represent transformer stations or coupling stations; for natural gas or hydrogen, the nodes can be compressor stations and coupling devices such as reducers. The edges represent power lines or gas pipelines respectively.

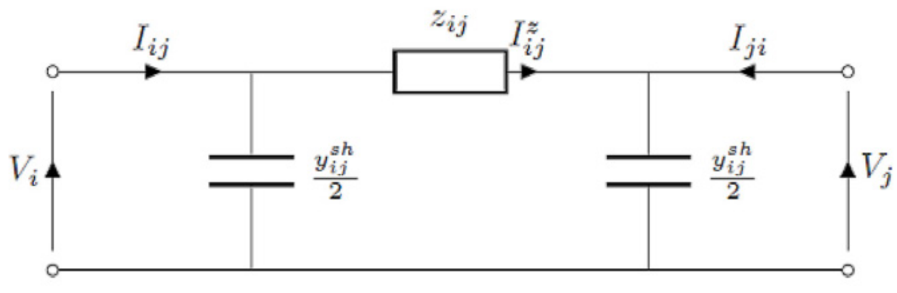


Figure 2: Equivalent circuit for medium-distance (80 – 240 km) power lines

A power line or pipeline can be characterized by its length and its maximum capacity. The length is the real distance, measured along the infrastructure, between the physical stations represented by the nodes at each end, or a calculated equivalent distance if a particular aggregation of the real network is used. The maximum capacity is the maximum flow (measured in e.g. MW) as specified by the TSO operating the (pipe)line, usually based on technical conditions and operational experience. As most (pipe)lines can be used bidirectionally, a maximum capacity will have to be specified in both directions. Particularly for gas pipelines, both numbers do not need to coincide. For electrical power lines, a reduction factor of e.g. 0.7 may apply, resulting from N-1 redundancy requirements.

The nodes of the graph do not only represent the underlying physical stations, but also specify the possible entry and exit points of the system, i.e. the points where electric power or gas enters or leaves the network. Energy is conserved at each node, i.e. the sum of all energy flows in and out (via edges, entries and exits) must be equal to zero (Kirchhoff's law, see Figure 3).

In the context of the Infrastructure Outlook 2050, the nodes and pipe(lines) together constitute an integrated network for electricity, hydrogen and

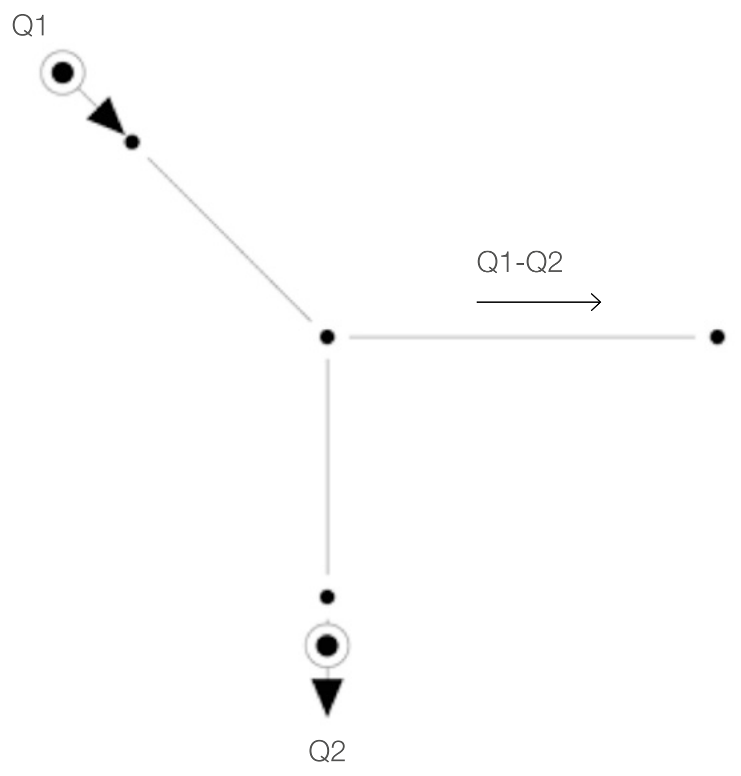


Figure 3: Kirchhoff's law representing energy conservation at node N

methane transmission on a national scale (see Figure 4). In each country, the separate networks for each of the three energy carriers are connected through power stations (converting hydrogen or methane to electricity) and electrolysis stations (converting electricity to hydrogen). A third possible connection type, between the hydrogen and methane networks, can be introduced to model the process of methanation. This connection type was used in the German part of the study.
Basically, the conversion from one carrier type to another was modelled in terms of an exit from the one system and an entry into the other system, with a fixed ratio between exit and entry reflecting the efficiency of the specific conversion type. For Outlook 2050, conversion locations and capacities were chosen beforehand for each snapshot; however, the model in principle allows for optimisation of these parameters.

The infrastructure model converts any balanced entry/exit combination into a line flow pattern, using a simple linear transport algorithm based on the transport load formula (1). For simple tree-shaped networks the transport flow pattern is uniquely determined by Kirchhoff's law. For the large-scale

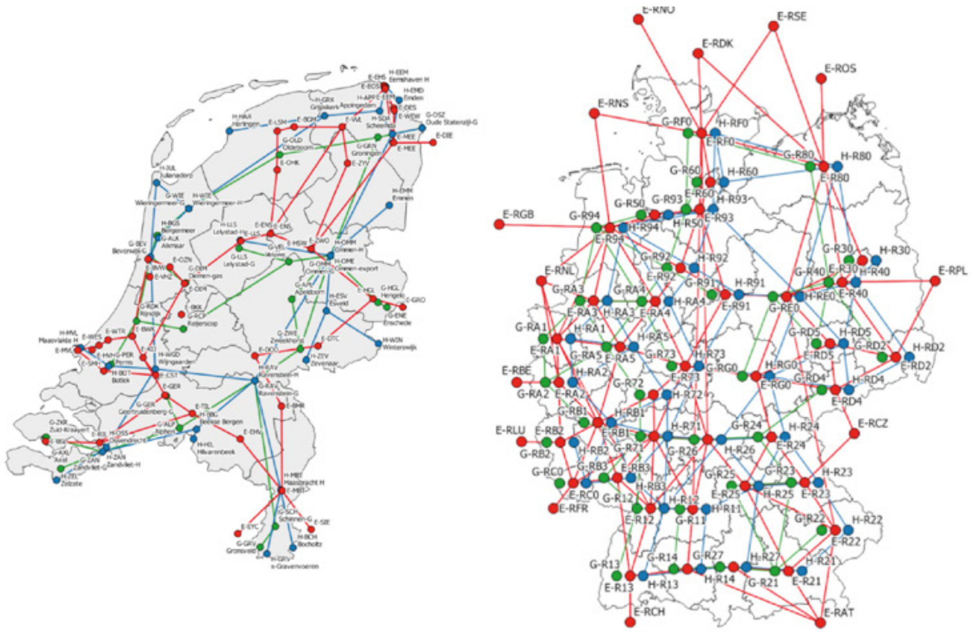


Figure 4: Coupled electricity, hydrogen and gas networks for the Netherlands (left) and Germany (right). The Dutch network is modelled according to the actual network topologies, while the German network is on a higher level of aggregation based on the 38 German NUTS-2 regions

networks of gas and electricity TSOs however, an additional degree of freedom exists due to the presence of loops. This means that, in principle, an infinite number of flow patterns can be associated with each entry/exit combination. The model has a built-in optimisation routine to find a unique, "preferred" pattern with minimal network transport load. It should be noted that this theoretically optimal solution may not be the solution chosen in day-to-day operational practice; however, it gives a good indication whether a snapshot can be accommodated by the system or not. The model is not suitable for investment decisions.

To perform the flow calculations, for each line i a load function $T_i(Q)$ is introduced:

(3) $T_i(Q) = Q.L_i$

Here, Li is the length of line i and Q is the power transported through the line. Formula (3) clearly exhibits the desirable linear behaviour for loading the line with power Q (up to its maximum capacity Q_{max}) and it is also linear in line length: a line twice as long loaded with the same power has twice the contribution to the total network load.
It is clear that flows above Q_{max} must be avoided in practice. In the model, a flow above Q_{max} would indicate that the regarded entry/exit combination causes a bottleneck and cannot be accommodated by the system.
The algorithm should always look for flow patterns without bottlenecks first and only end up with a flow pattern with overloaded lines if there is no other possibility. In the model this mechanism has been implemented by imposing a fee factor f on the transport load of a line if the flow exceeds Qmax: T(Q) → f.T(Q) if $Q > Q_{max}$. A factor of 10 or 100 usually suffices to attain the effect. In principle it is even possible here to discriminate between lines or line types (e.g. gas or electricity), but this flexibility of the model has not been used in this study. See Figure 5 for a pictorial representation of the load function of a line.

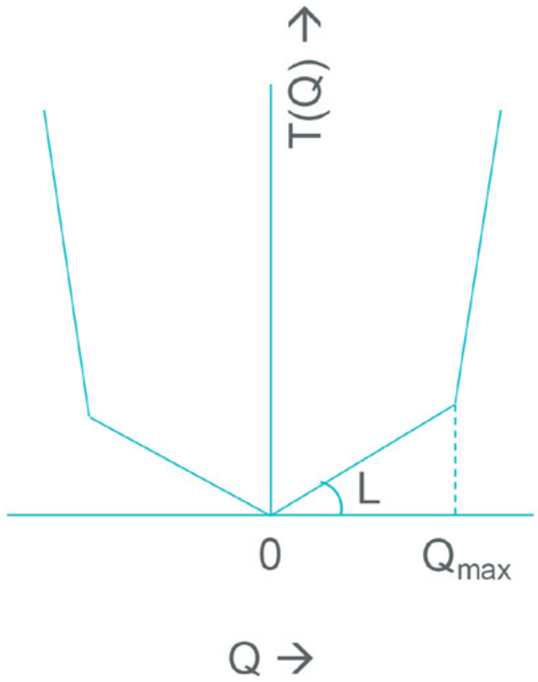


Figure 5: Piecewise linear load function of a line of length L. A longer line will have a steeper load function. The steepness ratio for Q > Qmax determines the penalty for overloading

The total network load can be found by adding the load functions of all lines for a specific flow pattern with (pipe)line flows Qi. The preferred pattern is then obtained by minimising the total network load over all possible flow patterns:

(4) $T_{pref} = \min \{ \text{sum}_i\ T_i(Q_i) \}$.

The infrastructure model was built in the piecewise linear programming environment of MCA (Multi Case Approach). Figure 6 shows a representation of the coupled networks of the Netherlands in the graphical interface of this numerical tool. MCA was originally built by Gasunie for the analysis of transport issues in gas networks, but has a wide range of applicability to all sorts of (piecewise) linear optimisation problems. As the infrastructure model used in Outlook 2050 involves linear algebra and combinatorics only, the resulting algorithm is very fast: calculating an optimised flow pattern of a snapshot typically takes less than a second, including input and output handling.

For further analysis and presentation, the output of the model was visualised as in Figure 7. The three networks, although coupled, are shown separately. The (pipe)lines are depicted with a double indication of flow intensity: the line width is proportional to its flow Q, while the line colour indicates the usage of the line in a percentage of Q_{max}; a dotted line for 0%, a green line for 0-80%, a yellow line for 80-100% and a red line for flows over 100% of Q_{max}.

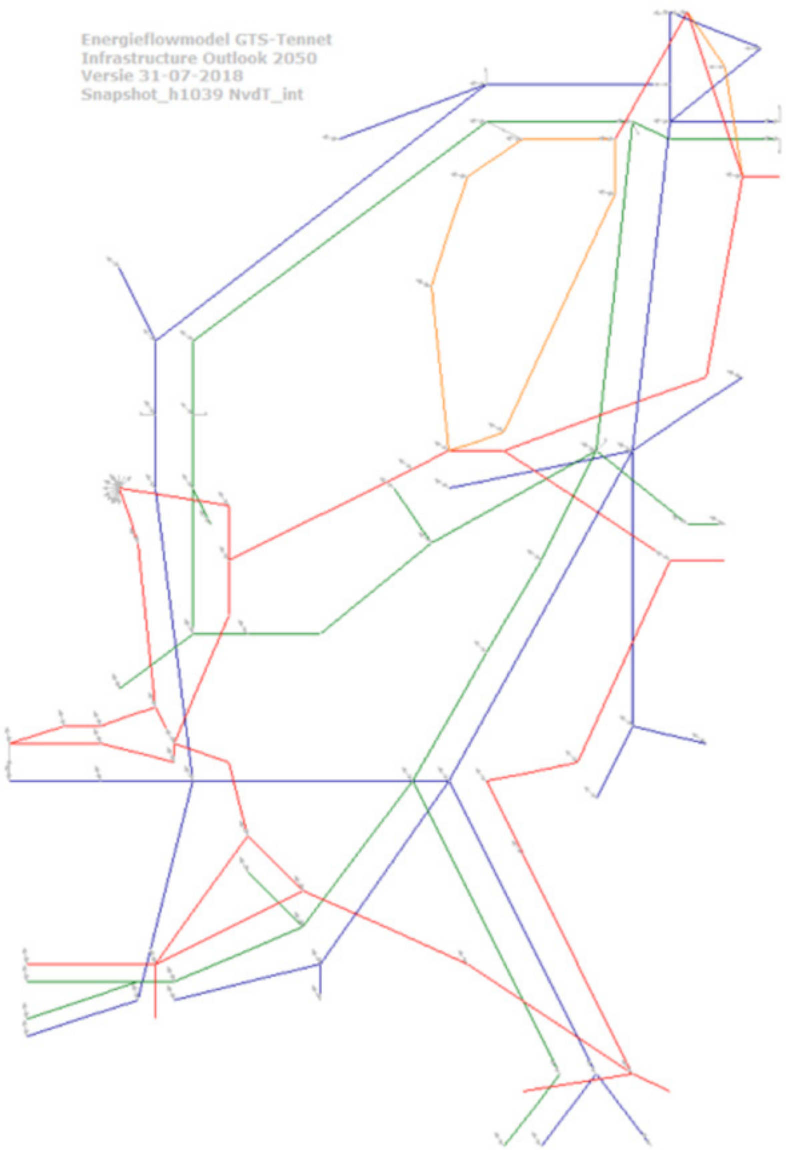


Figure 6: Combined network of the Netherlands in the graphical topological interface of MCA (red/orange = electricity; blue = hydrogen; green = methane)

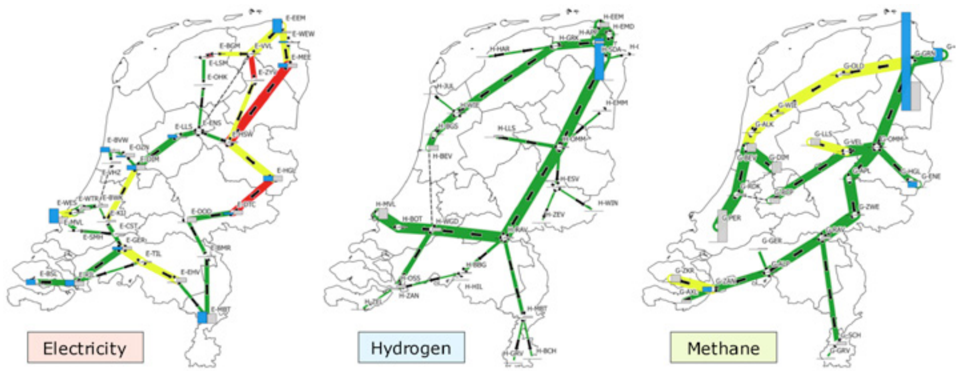


Figure 7: Intensity representation of a flow pattern for a typical snapshot (green = moderate loading; yellow = high loading; red = overloaded; line width proportional to flow)

Project documentation / appendix III

Dutch study part

Model Results Contents

Index:

Demand and Supply Curves	3-12
Storage Requirements Charge and discharge capacities	13-16
Storage Requirements: Storage Volumes	17-20
Infrastructure Calculations: operating envelope snapshots	21-29
Infrastructure Calculations electrolyser excursions	30-34
Infrastructure Calculations transit excursions	35-37
Infrastructure Calculations Conclusions	38

Demand and supply curves

- Derived from ETM model
- Used for selection of snapshots

Snapshot definition and considerations

General definition „snapshot“: Situation („hour“) with a specific (regional) occurrence 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

* (Operating envelope: Frame wherein a system can be operated safely)

Operating envelope snapshots

- 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)
- Flex options balance the gap between supply and demand
- **Three main corners of the operating envelope** were identified:
  A. High RES supply and high (final) demand
  B. High RES supply and low (final) demand
  C. Low RES supply and high (final) demand

The three main corners (snapshots)

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

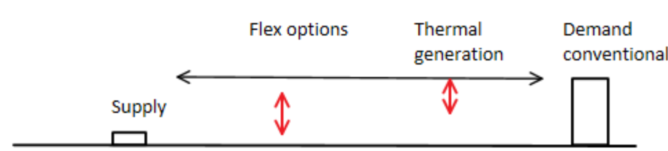
># GW

Low demand
conventional

Case: High RES WIND and low conventional demand

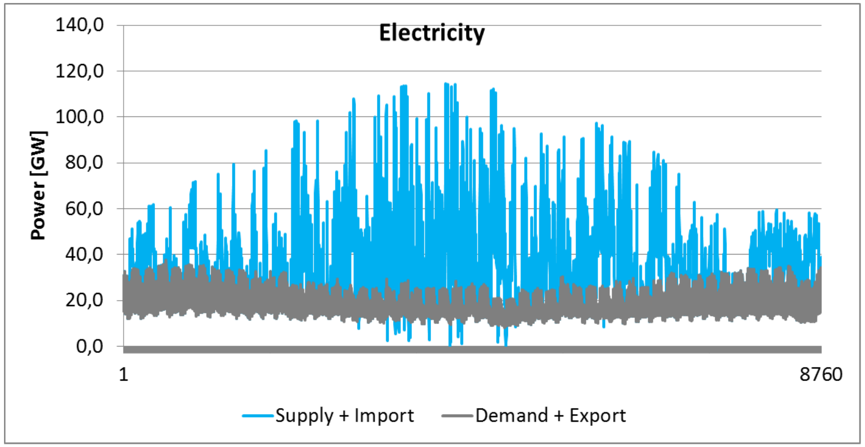
Situation C:

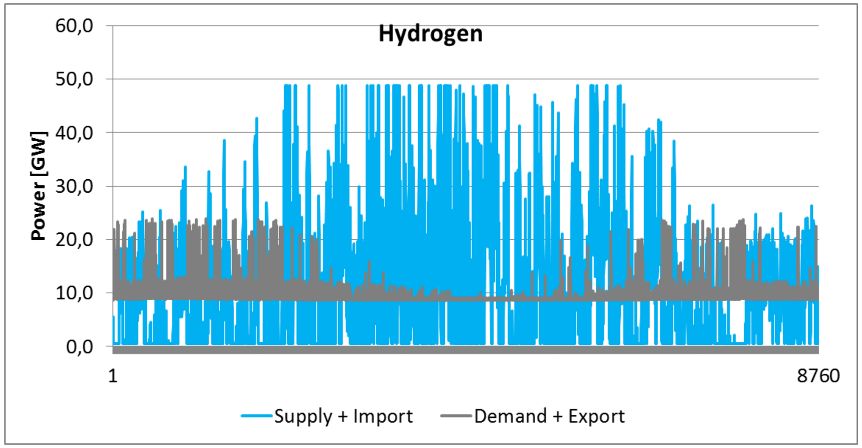
- Low wind and/or solar supply
- High final demand
- *NOTE: thus could result in a need for back-up power plants*

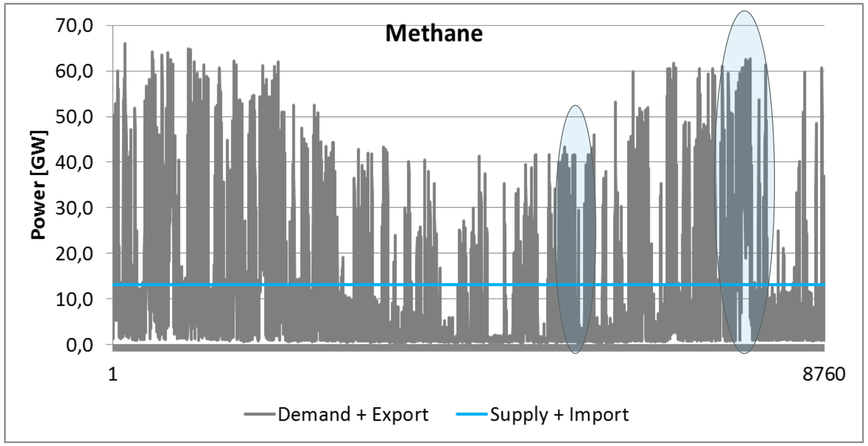


Regional scenario NL

Supply and Demand







- Electricity: High volatility of RES dominated supply (seasonality due to solar PV) and large imbalances with demand
- ➢ Significant need for flexibility options

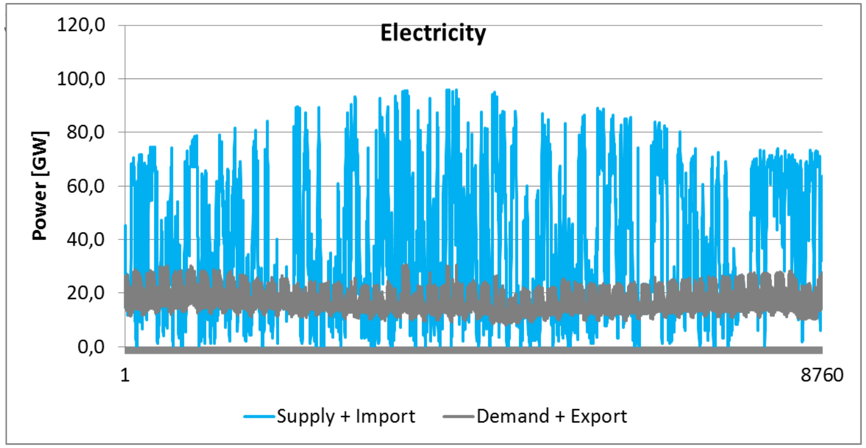
- Hydrogen: Supply predominantly power-to-H2
- Methane: Peak demand determined by both low temperature heating and gas power plants

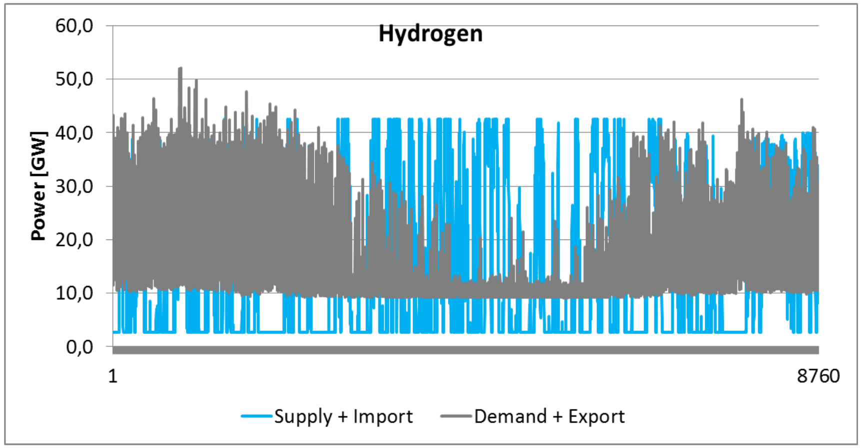
Supply = Total supply to the system including imports
Demand = Total demand from the system including exports

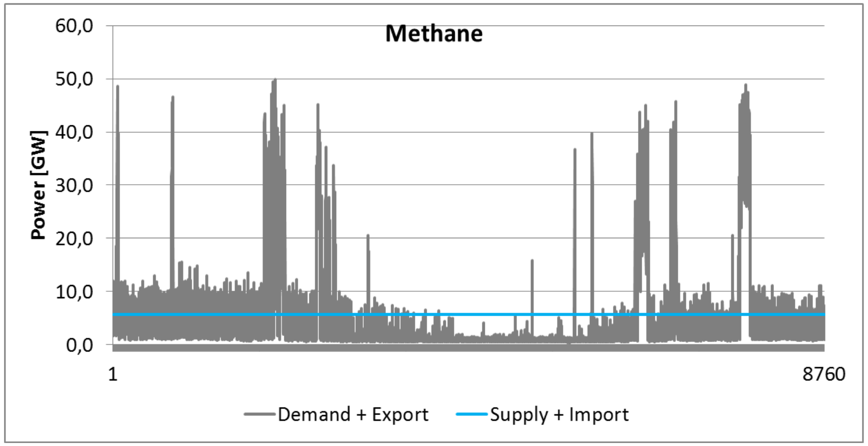
Regional Scenario NL

- **Significant mismatch between electrical supply and demand** due to high installed capacity and volatile infeed of wind and solar
- For a large part of the year the **supply to the electrical system exceeds the demand**
- To fully integrate the RES infeed, a **combination of power-to-hydrogen („base flexibility“) and battery storage („peak flexibility“)** is used
- The high capacity of solar PV leads to **significant supply peaks especially in the summer** and triggers the need for „peak flexibility“
- In situations with low RES infeed, **batteries (short term availability) and conventional generation (long-term availability) are used as back-up** to meet electrical demand
- The use of gas power plants causes significant peaks in the gas demand
- The **supply to the hydrogen system is mostly driven by RES** and therefore shows a high volatility

National scenario NL







- High volatility of the (RES dominated) electrical supply and mismatch with demand
- High need for flexibility options to balance electrical system
- Supply to hydrogen system predominantly driven by hydrogen conversion (PtH2)
- Significant increase in gas demand when power plants (natural / green gas) running

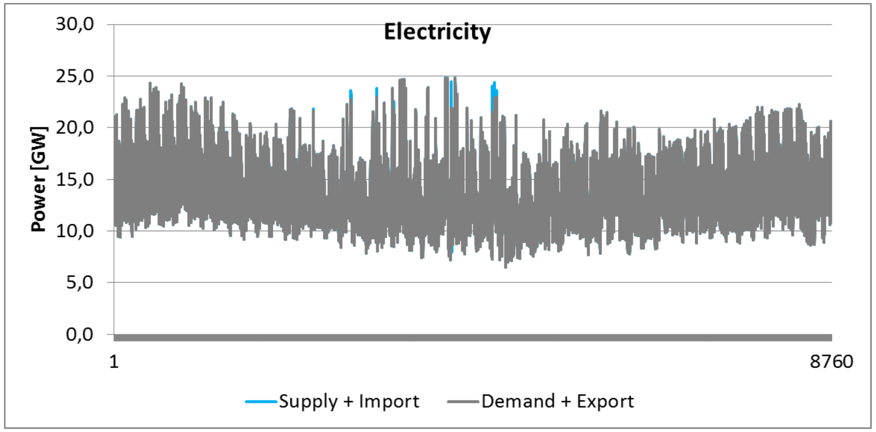
Supply = Total supply to the system including imports
Demand = Total demand from the system including exports

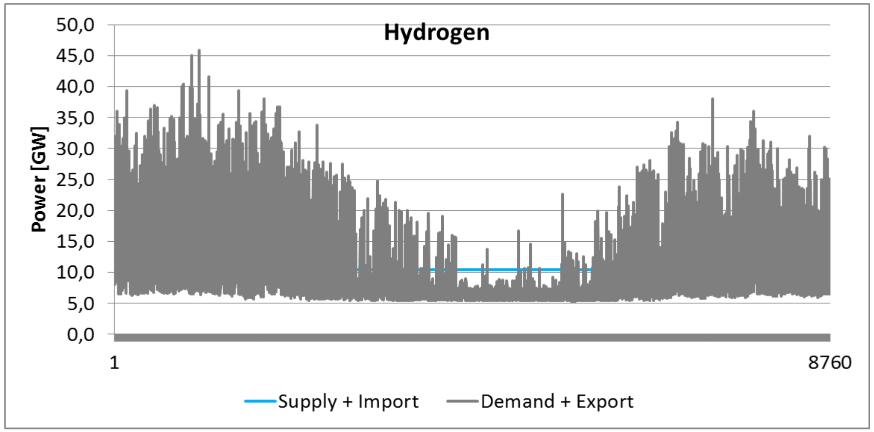
National Scenario NL

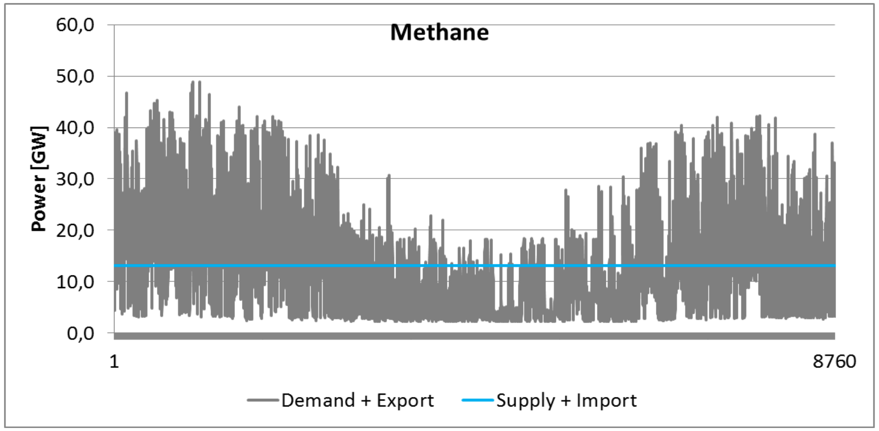
- **Significant mismatch between electrical supply and demand** due to high installed capacity and volatile infeed of wind and solar
- For a large part of the year the **supply to the electrical system exceeds the demand**
- To fill the gap and fully integrate the RES infeed, a combination of power-to-hydrogen („base flexibility"), power-to-heat and battery storage („peak flexibility") is used
- The high capacity of wind offshore with a less volatile infeed behaviour causes a „flatter" flexibility curve compared to the solar dominated decentral scenario.
- In situations with low RES infeed, **batteries (short term availability) and conventional generation (long-term availability) are used as back-up** to meet electrical demand
- The use of gas power plants causes significant peaks in the gas demand
- The **supply to the hydrogen system is mostly driven by RES** and therefore shows a high volatility

International Scenario-NL

Supply and Demand







- High match between supply and demand in the electricity system
- …

Supply = Total supply to the system including imports
Demand = Total demand from the system including exports

International Scenario NL

Supply and Demand main findings

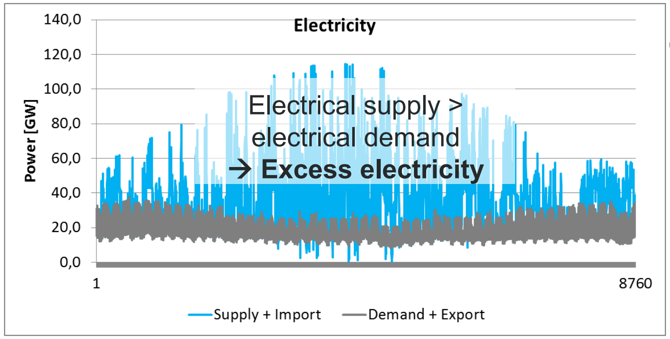
- **High match between electrical supply and demand** as result of relatively low RES and high conventional („steerable“) capacity
- Almost no need for domestic electrical flexibility, instead **balancing of system through imports and exports**
- As a direct result from the electrical supply structure, the volaitility of supply and storage use in the hydrogen system is less volatile

Storage requirements

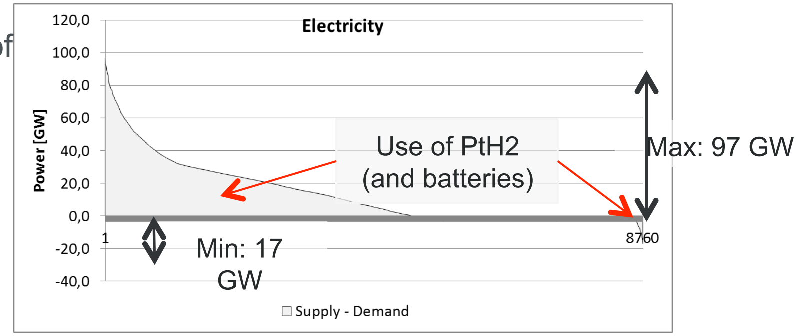
- Derived from ETM model
- Charge and discharge capacities (GW)

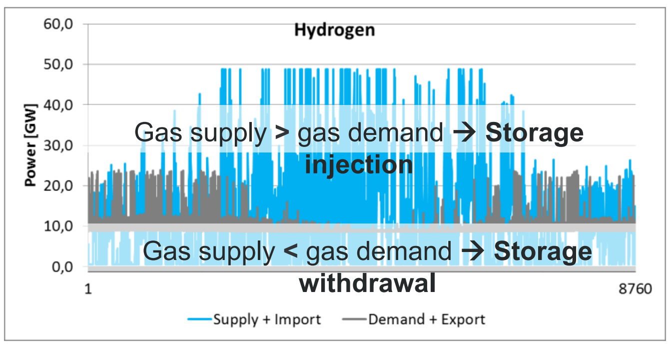
Regional Scenario NL

Charge and Discharge capacities (GW)

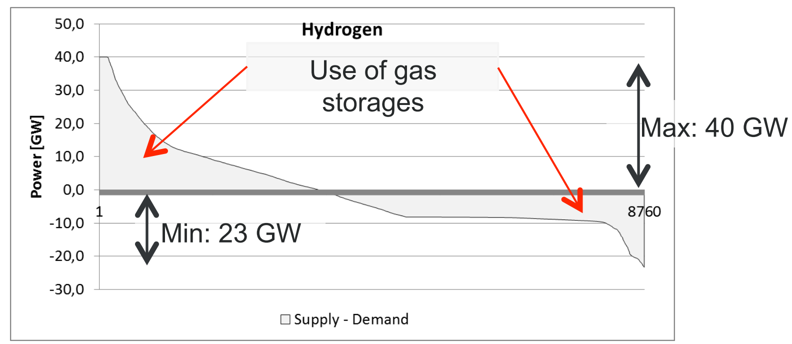


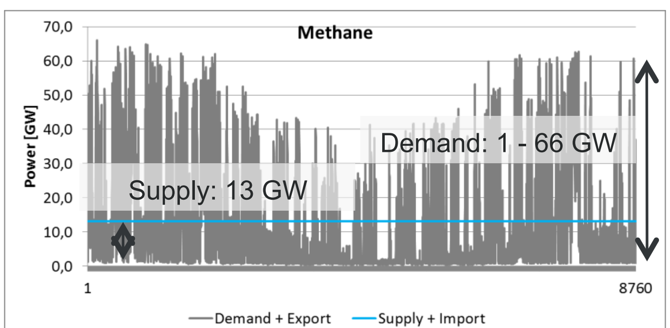
Conversion of excess electricity to hydrogen

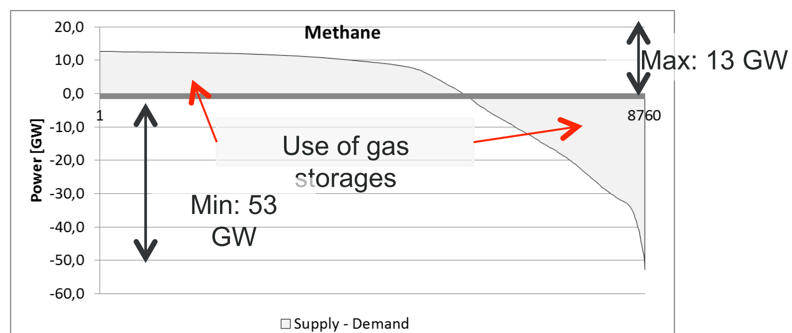




Balancing through gas storages

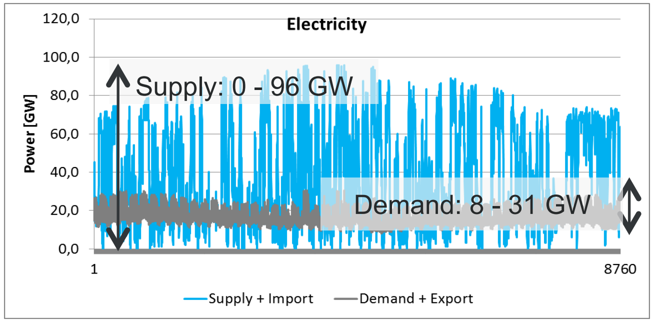


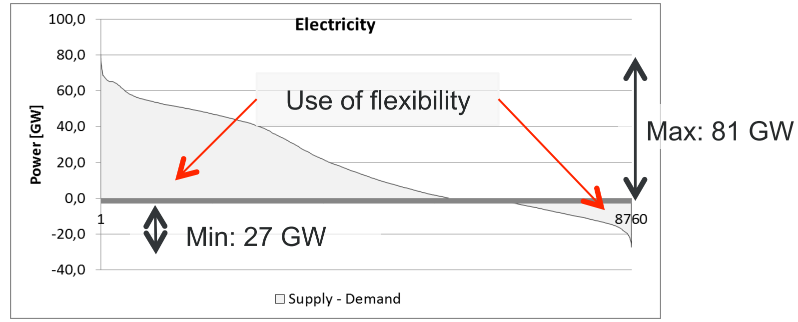


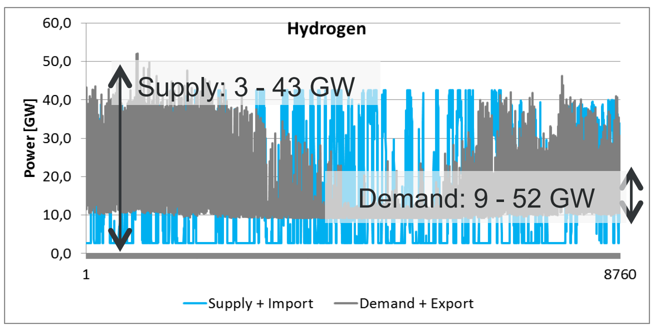


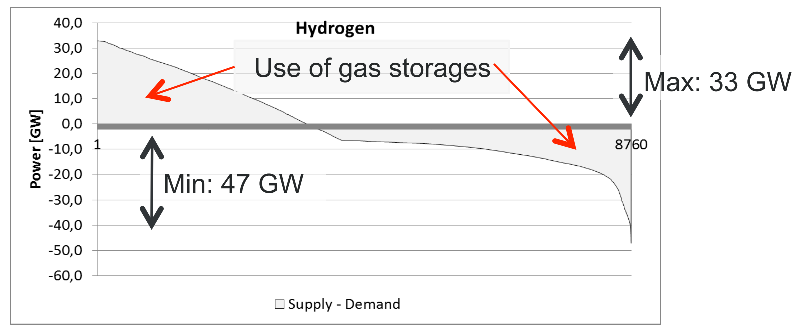
National Scenario NL

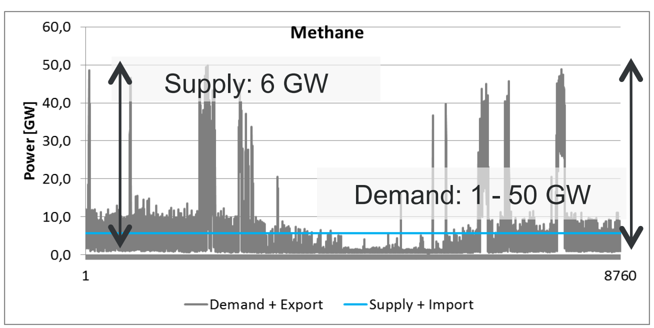
Charge and Discharge capacities (GW)

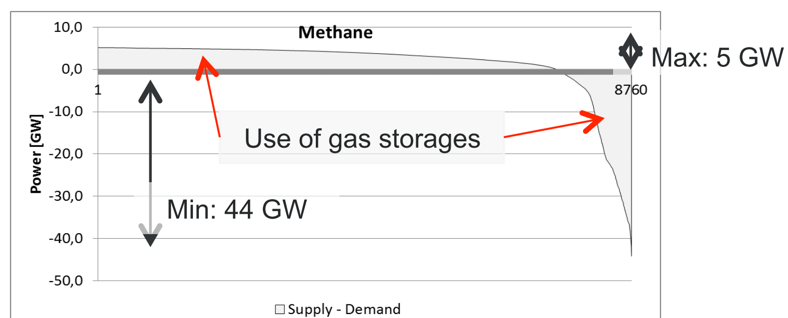










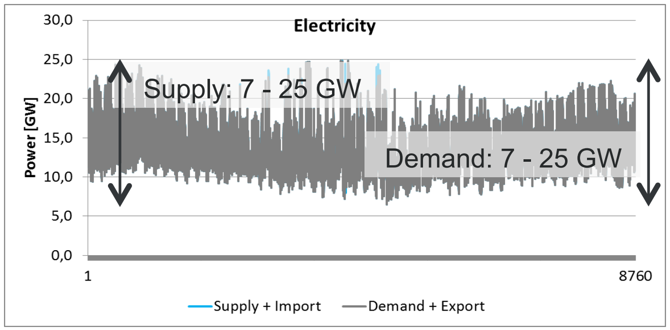


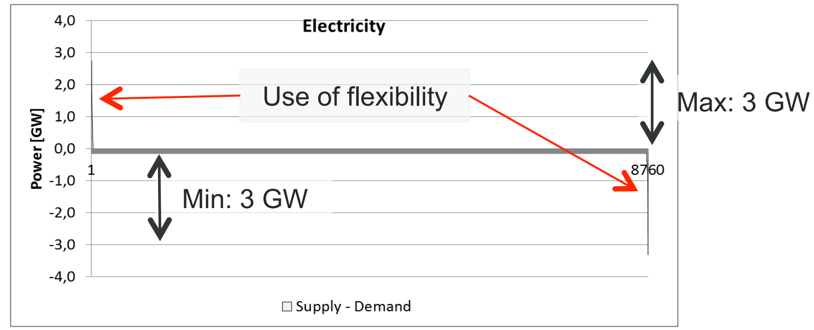
gasunie crossing borders in energy

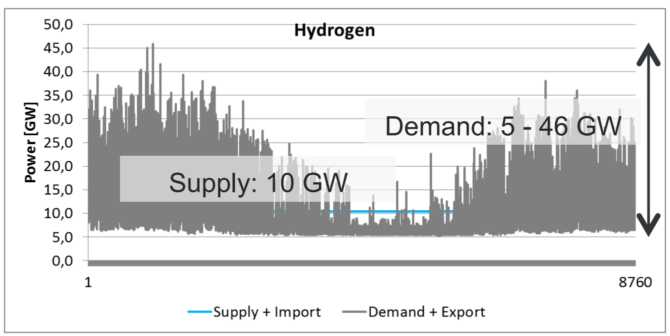
TenneT Taking power further

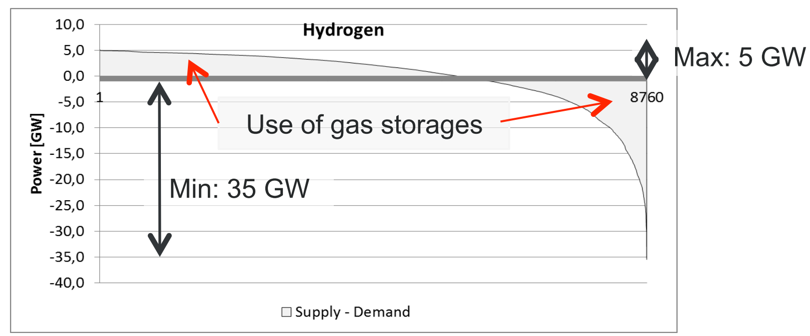
International Scenario NL

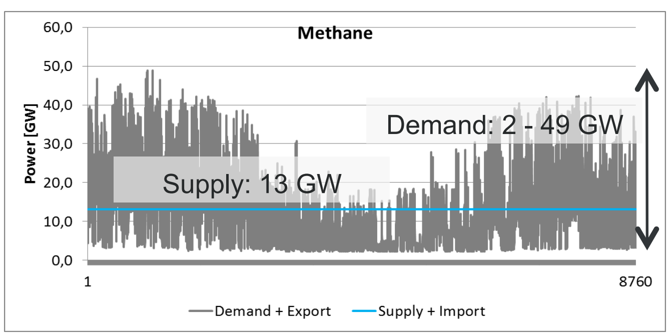
Charge and Discharge capacities (GW)

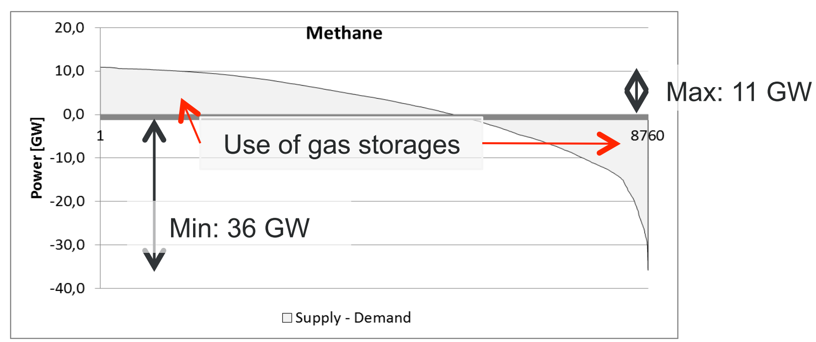










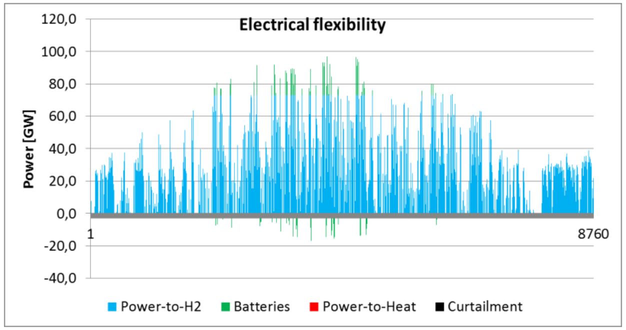


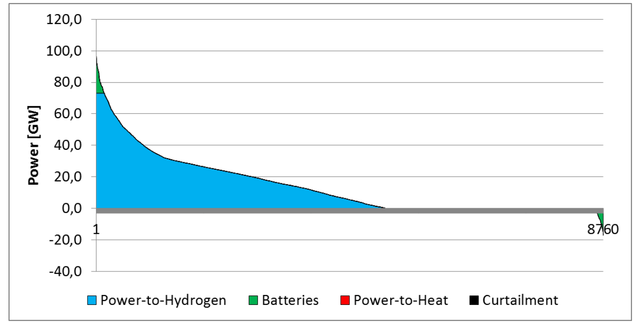
Storage requirements

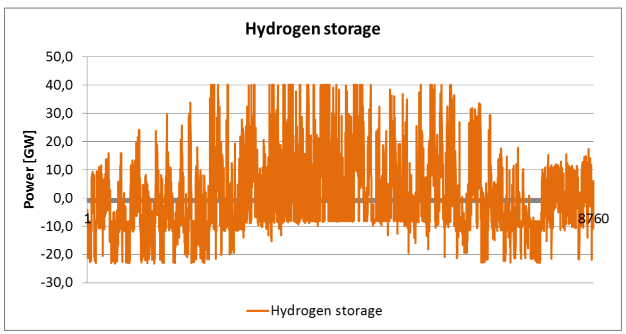
- Derived from ETM model
- Storage volumes (TWh)

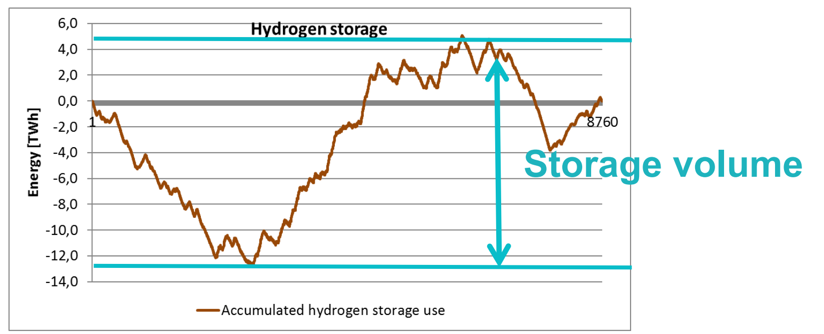
Decentral scenario NL

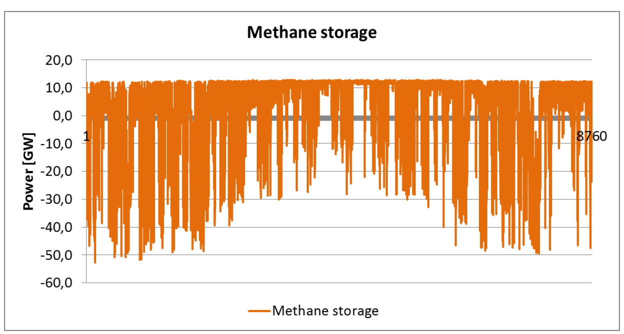
Storage volumes (TWh)

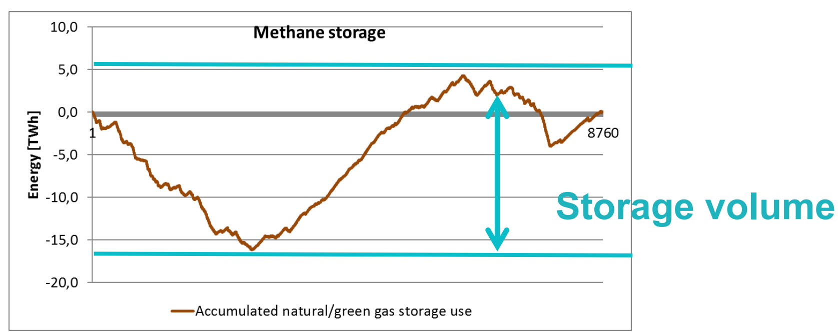






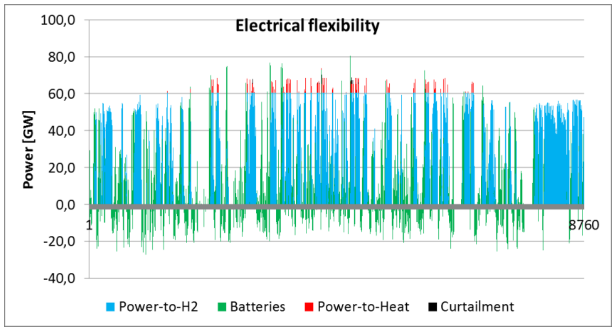


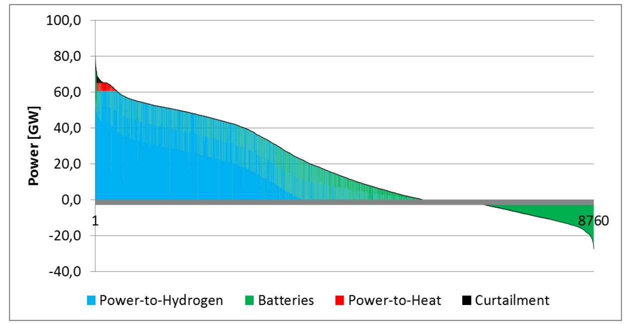


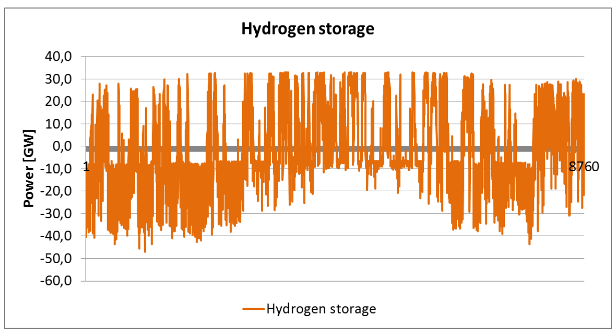


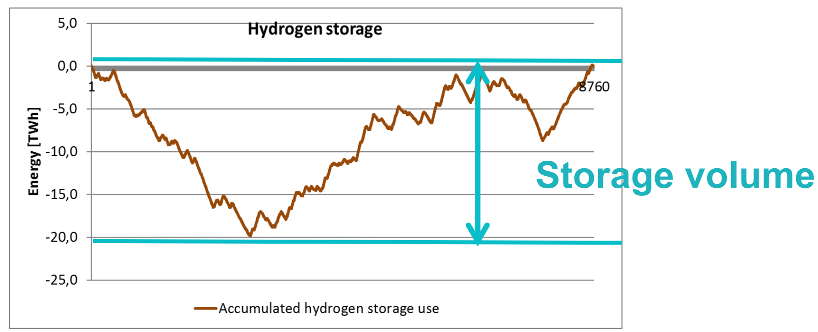
National Scenario NL

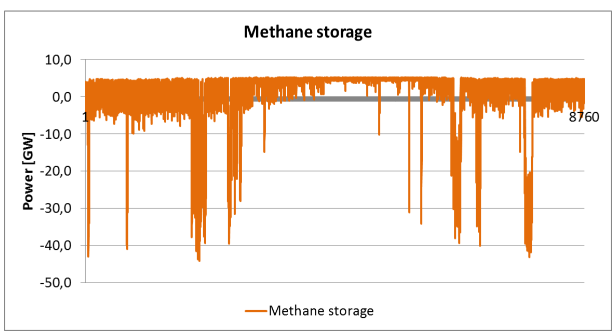
Storage volumes (TWh)

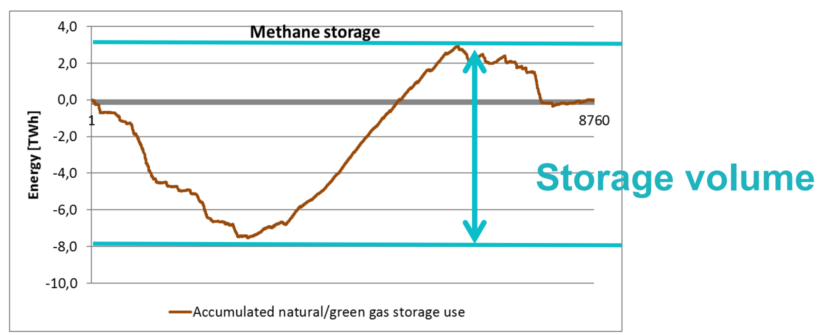






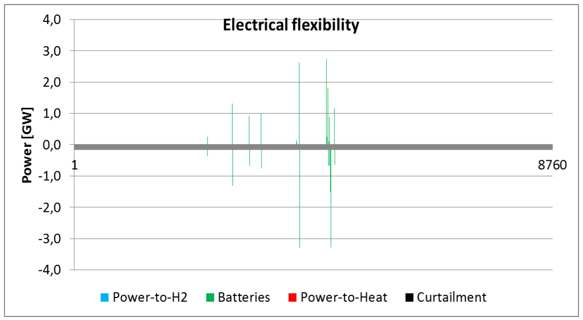


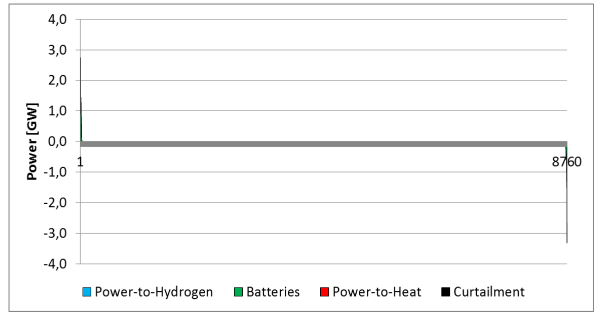


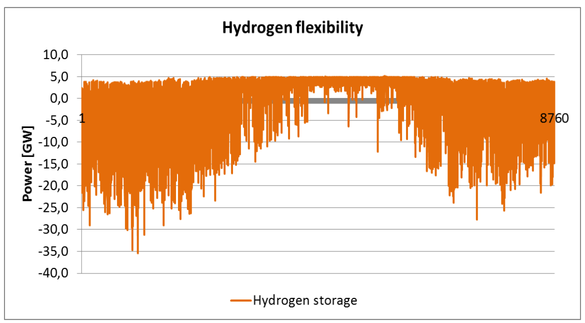


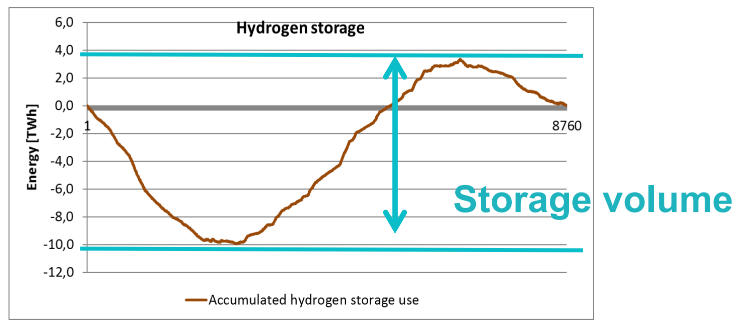
International Scenario NL

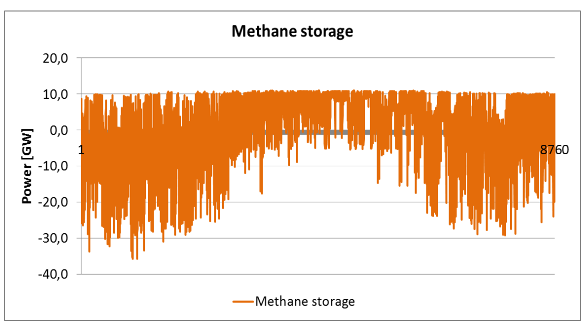
Storage volumes (TWh)

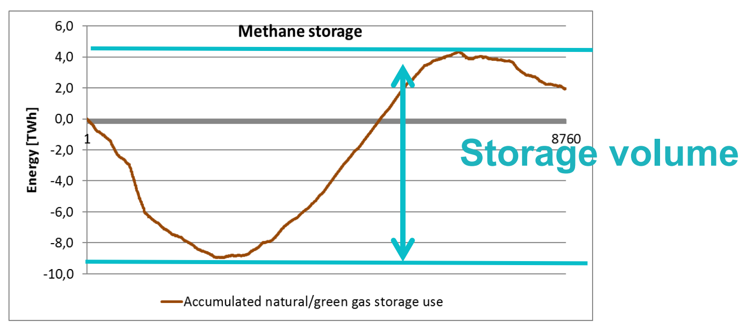












Infrastructure Calculations

- Selection of operating envelope snapshots

gasunie crossing borders in energy
TenneT Taking power further

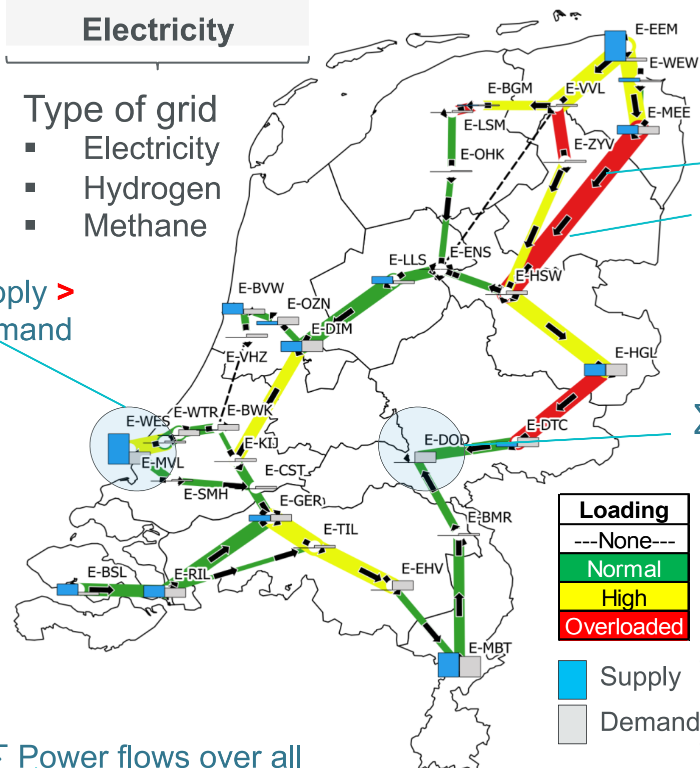
Infrastructure Calculations: Introduction

Infrastructure calculations (NL): Explanation of map visualization

Electricity

Type of grid
- Electricity
- Hydrogen
- Methane

∑ Supply > ∑ Demand



Flow direction

Line overloaded

∑ Demand > ∑ Supply

Colour indicates relative loading of lines compared to max. line capacities
- Normal: Loading between 0% and 75%
- High: Loading between 75% and 100%
- Overloaded:Loading above 100%

Supply: Sum of all supply elements
Demand: Sum of all demand elements

= ∑ Power flows over all lines

Power flow = 1,3 TWkm
Rel. usage = 0 TWkm

= ∑ (Power flow – max. capacity of overloaded lines)

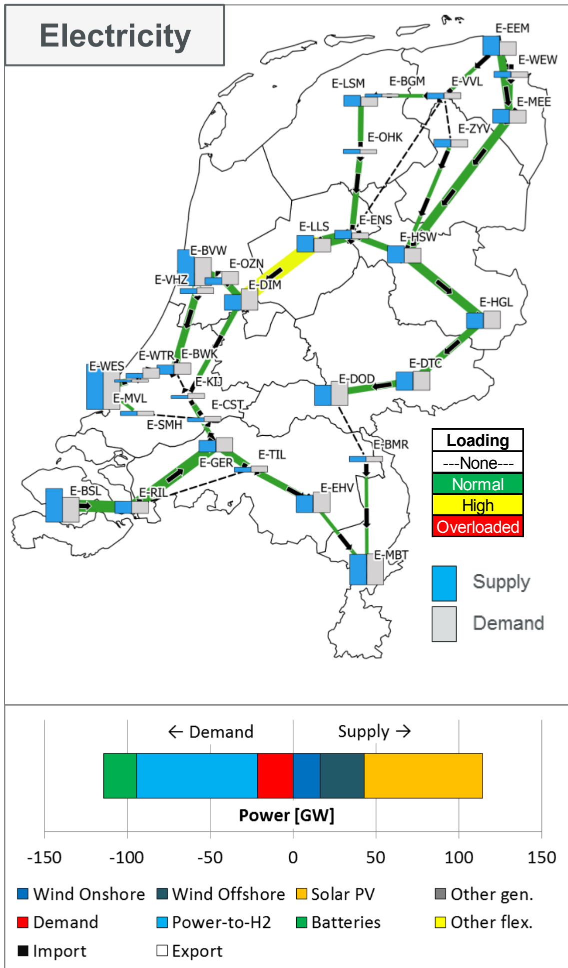
gasunie crossing borders in energy

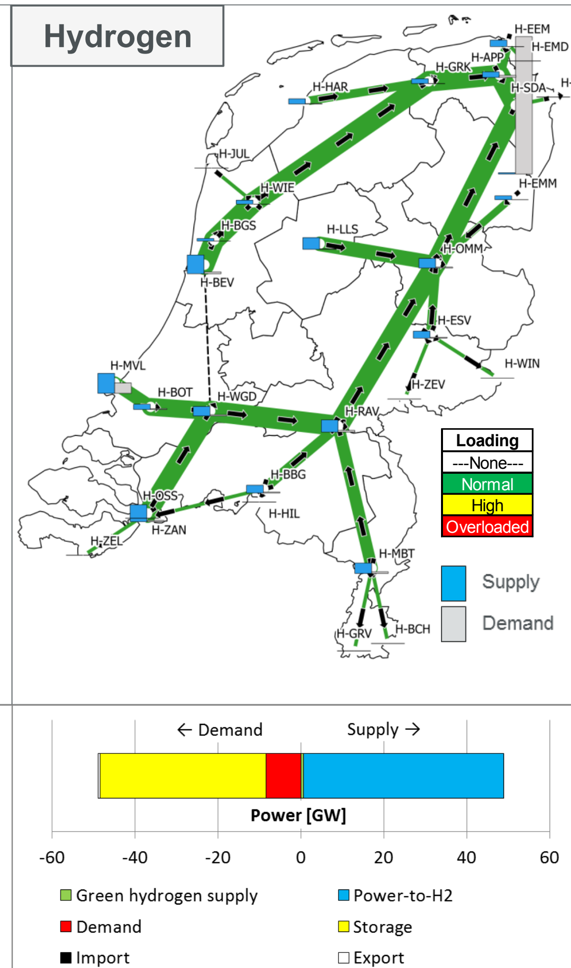
TenneT Taking power further

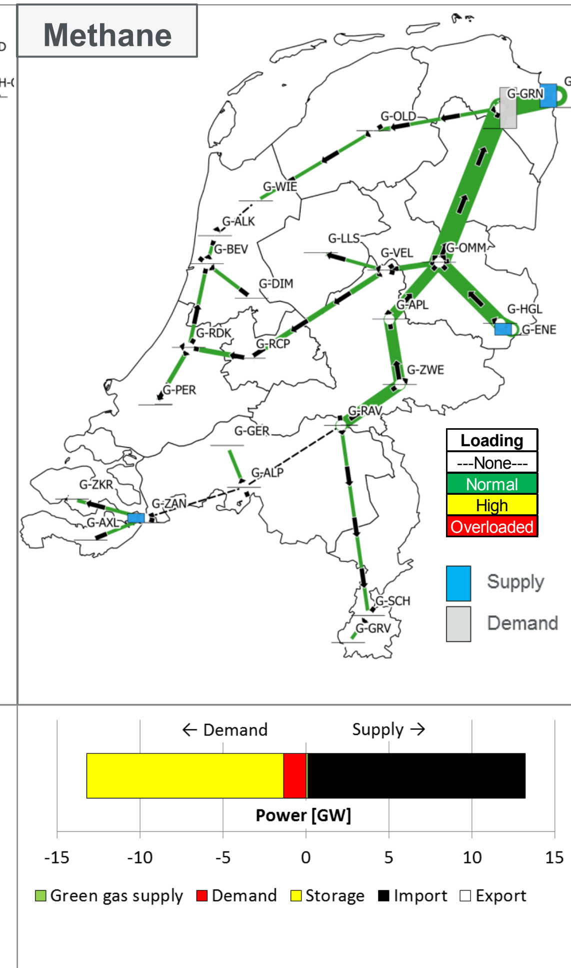
Regional Scenario NL

Operating Envelope Snapshot Hour 4044

High RES + high electrical demand



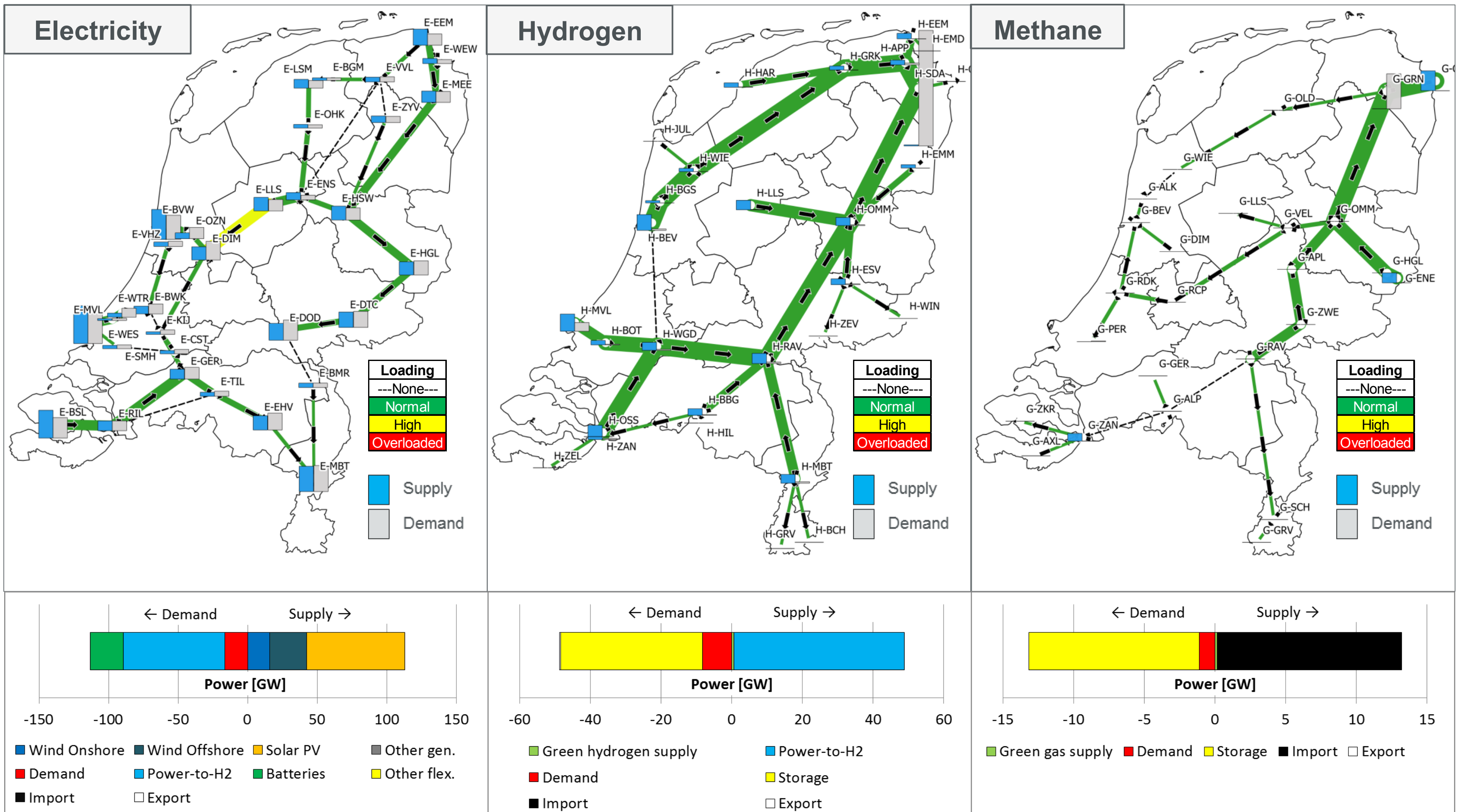




Regional Scenario NL

High RES + low electrical demand

Operating Envelope Snapshot Hour 4116



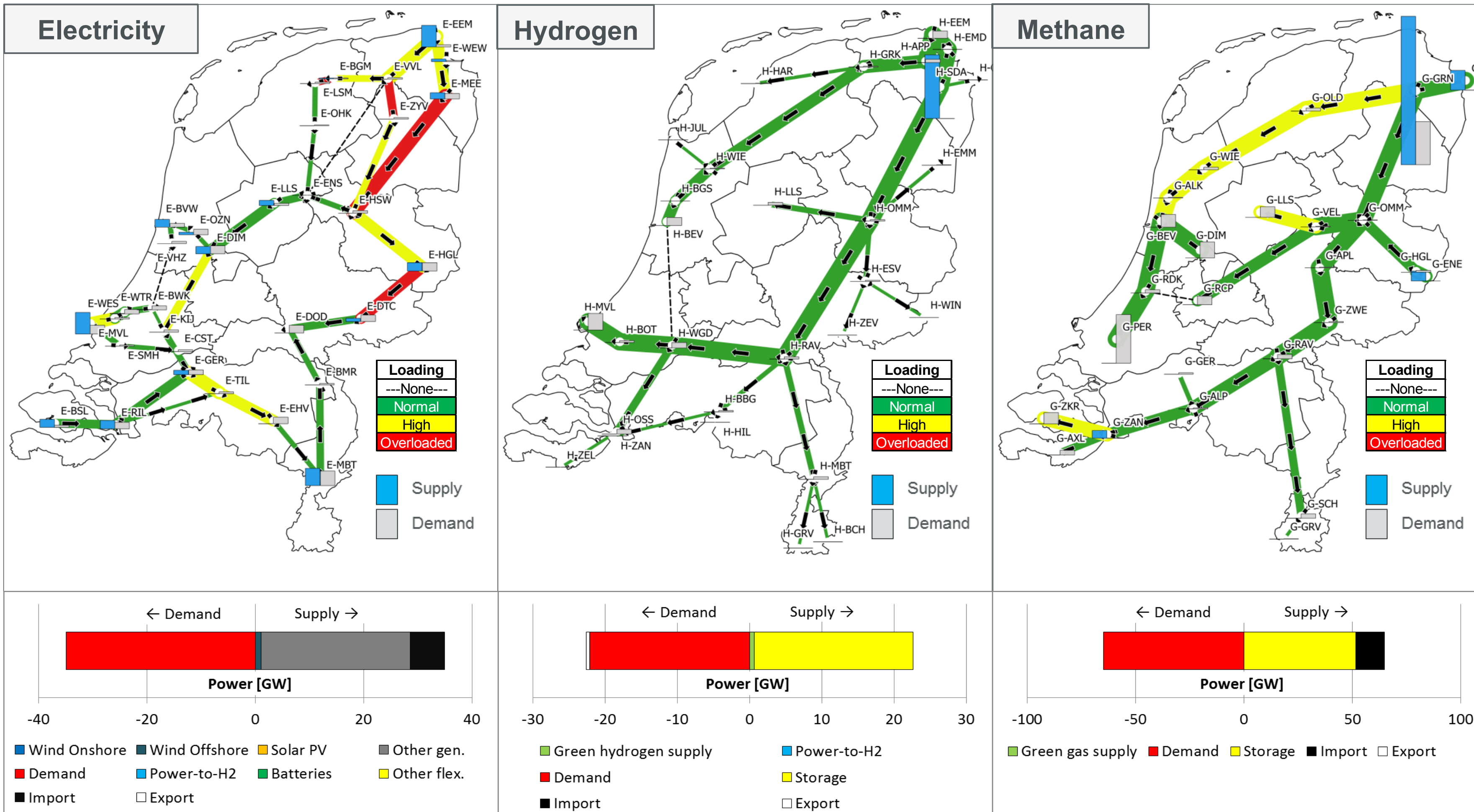
gasunie crossing borders in energy

TenneT Taking power further

Regional Scenario NL

Operating Envelope Snapshot Hour 954

Low RES + high electrical demand + high conv. supply



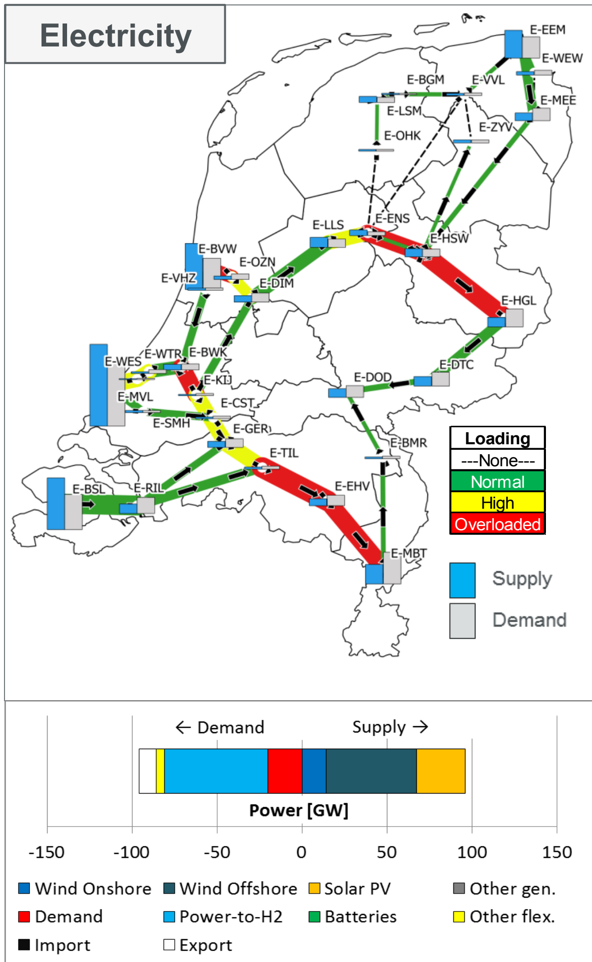
gasunie crossing borders in energy

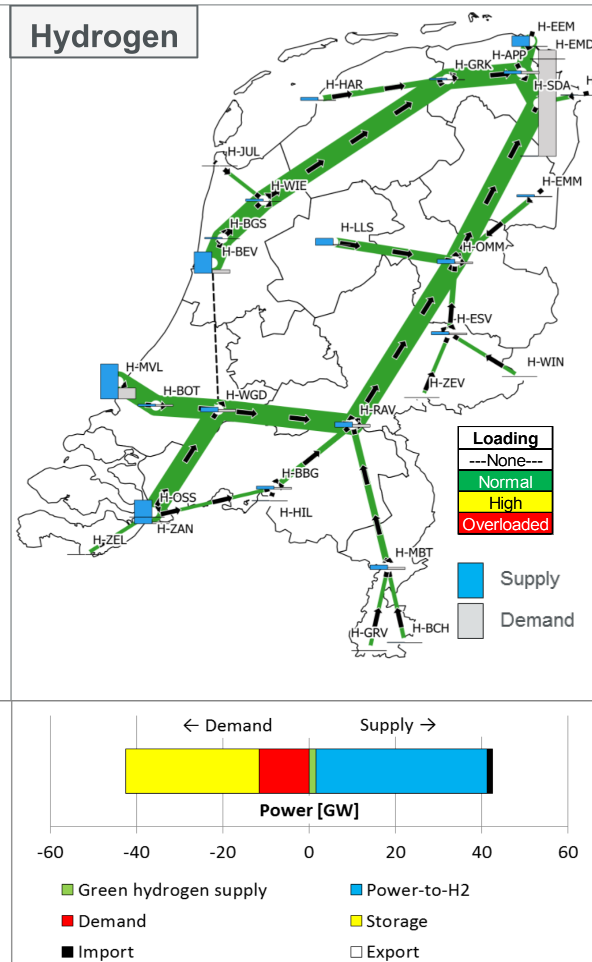
TenneT Taking power further

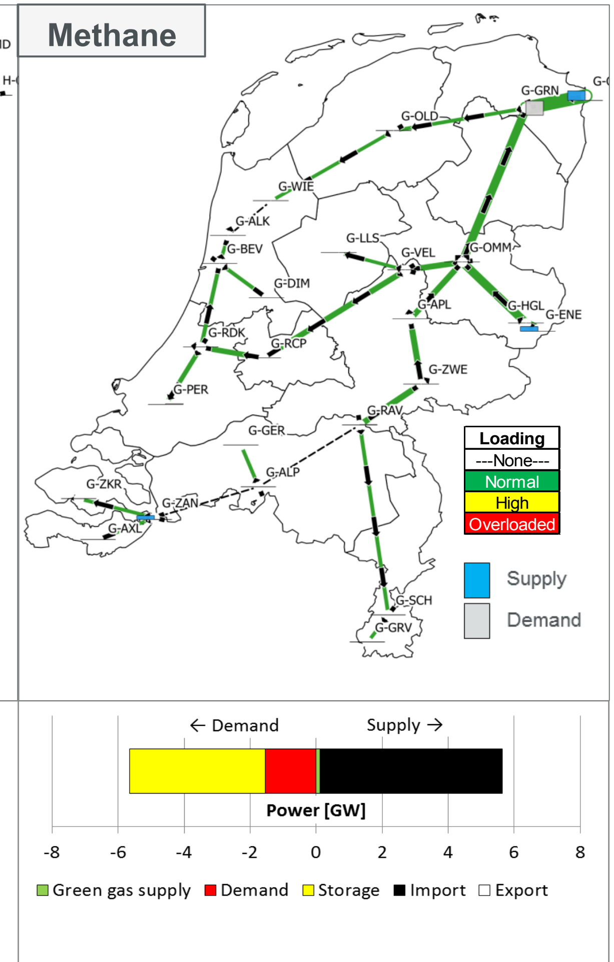
National Scenario NL

High RES + high total electrical demand

Operating Envelope Snapshot Hour 4044







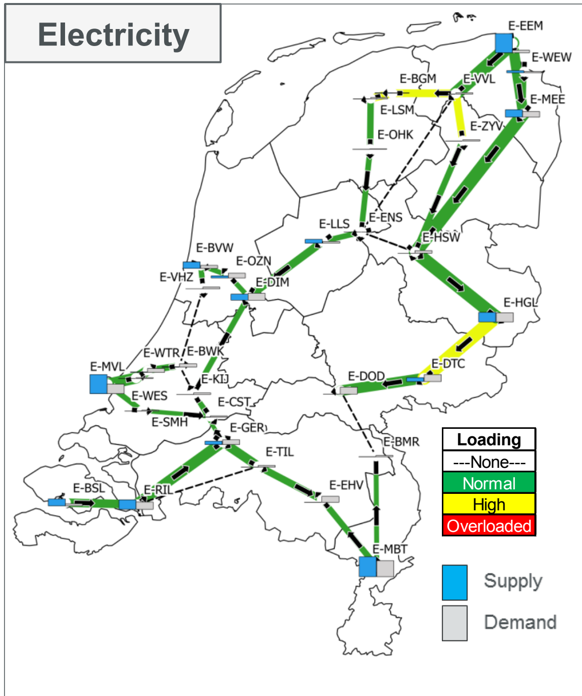
gasunie crossing borders in energy

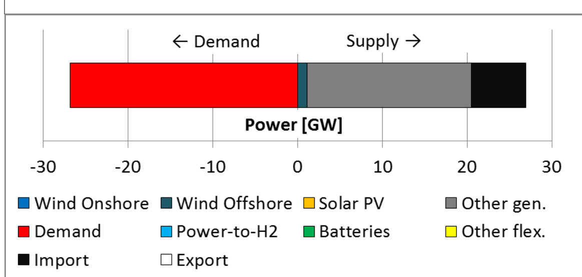
TenneT Taking power further

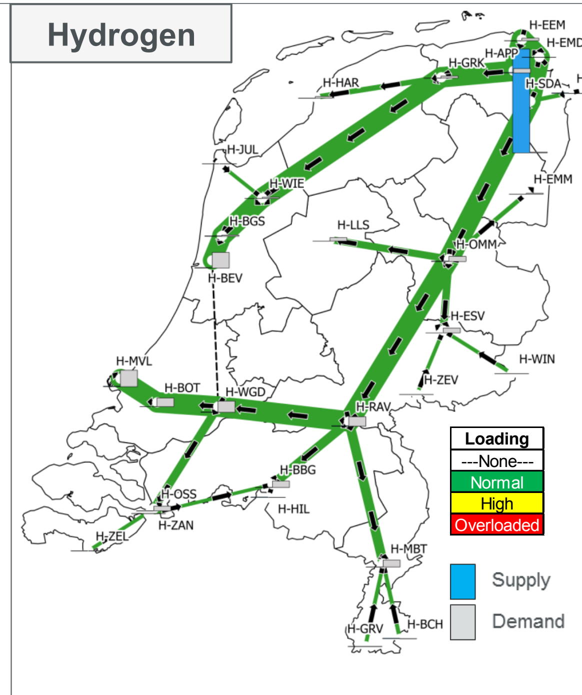
National Scenario NL

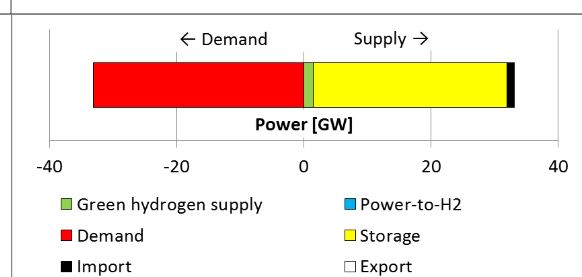
Low RES + high electrical demand + conv. generation

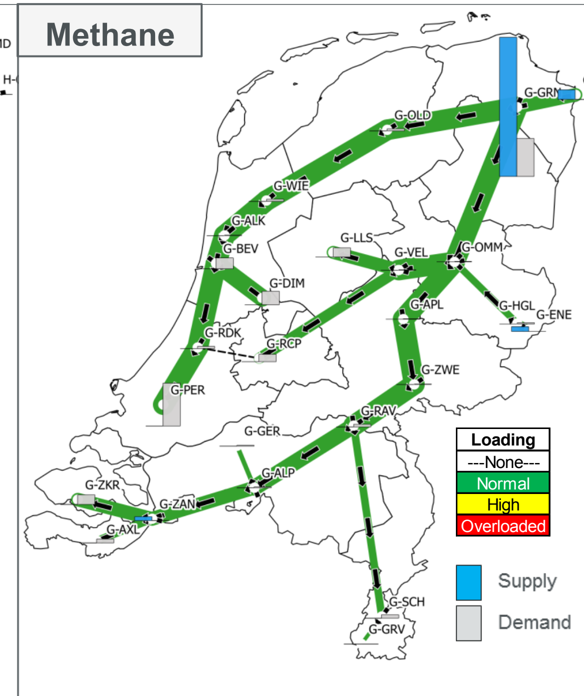
Operating Envelope Snapshot Hour 7746

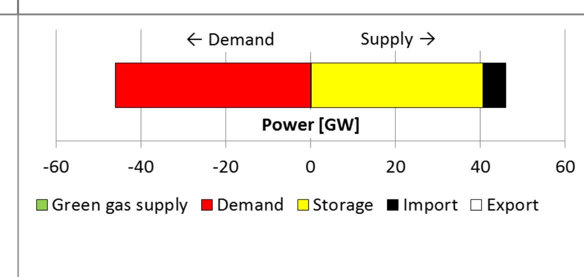












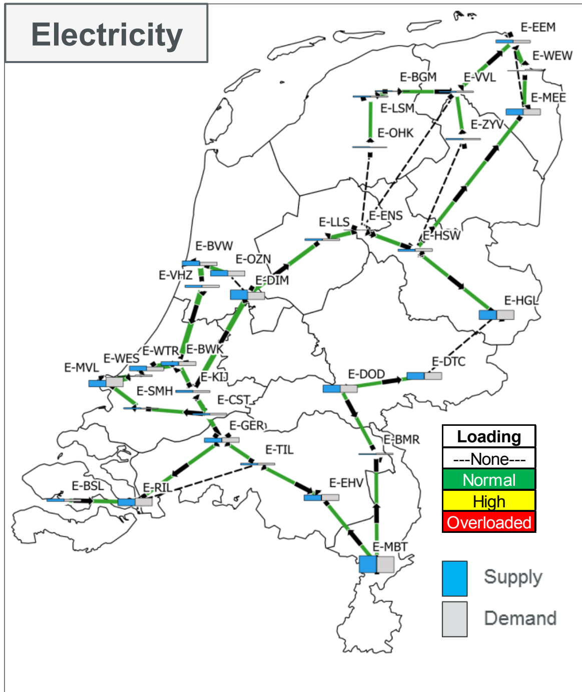
gasunie crossing borders in energy

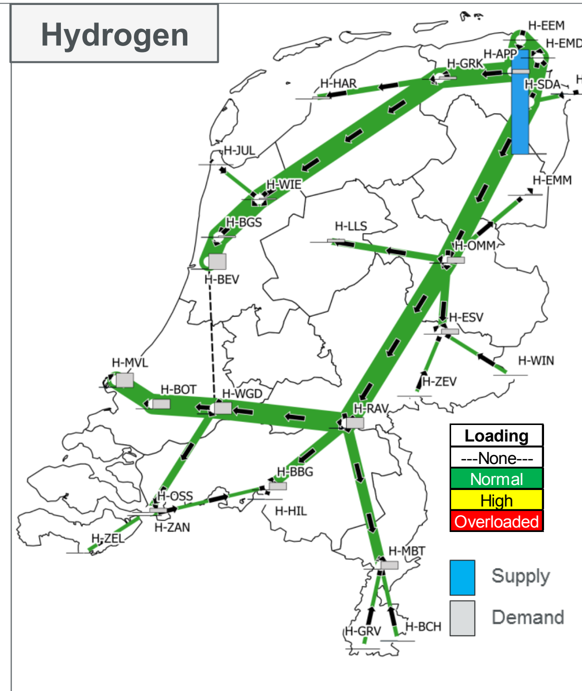
TenneT Taking power further

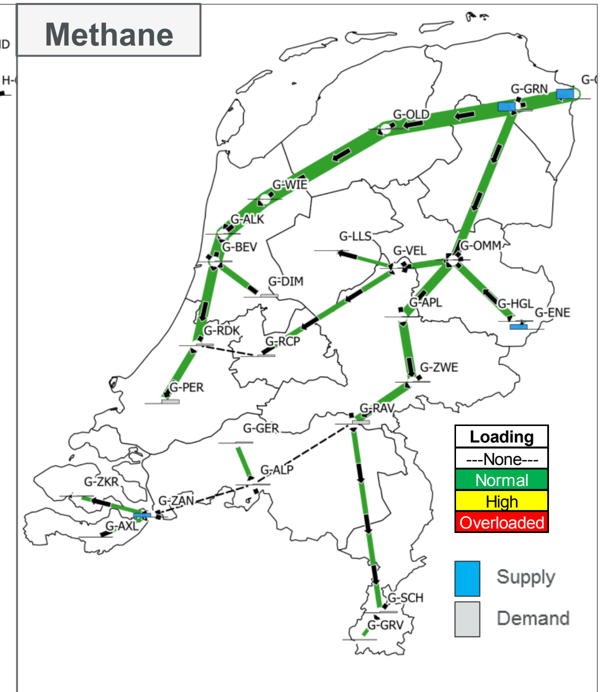
National Scenario NL

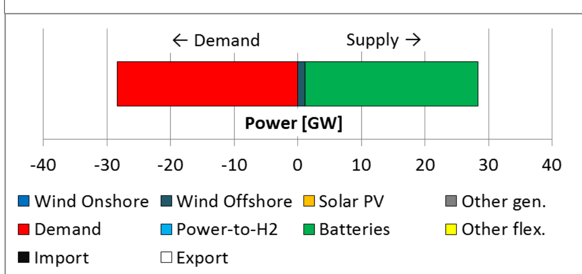
Low RES + high electrical demand + battery decharging

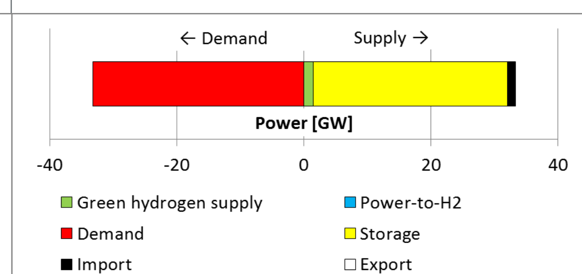
Operating Envelope Snapshot Hour 1022 excursion battery discharging

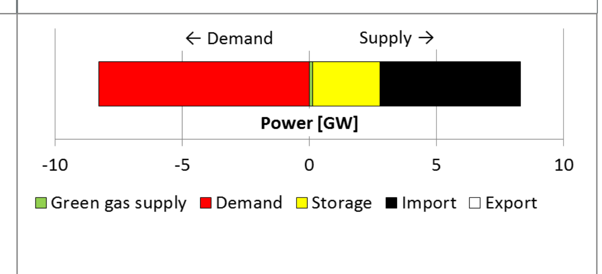












Conclusions from envelope snapshots

- **High RES and high demand**
  - Regional Scenario: No bottlenecks, because electrolyses near supply shifts load from electrical to hydrogen grid
  - National Scenario: Bottlenecks in the electricity grid, but optimisation of location of electrolysers will solve the issue because the power not supplied is relatively low
- **High RES and low demand**
  - Regional and National scenarios; No bottlenecks found
- **Low RES and high demand**
  - Up to 28 GW demand (National) no bottlenecks are found
  - At 35 GW (regional) relative small bottlenecks in the electrical grid occur because of supply load by power plants (assumed on existing locations). High load in hydrogen grid as well to supply these power plants
  - Use of batteries can alleviate bottlenecks in electrical grid

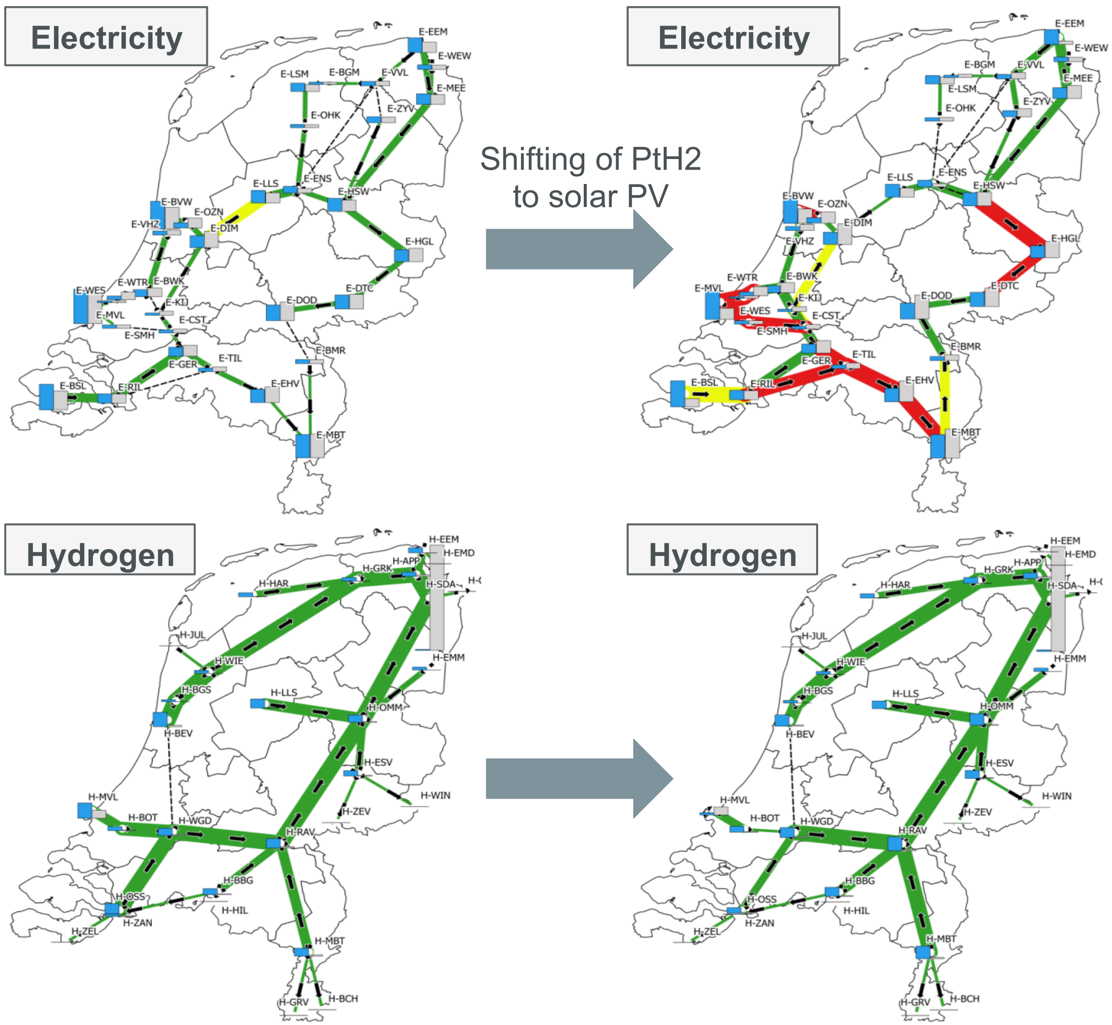
Infrastructure Calculations

- Two types of electrolyser excursions

Regional Scenario NL

High RES + high electrical demand

Hour 4044 **concentrating electrolysers near solar**



- Localizing PtH2 solely at solar PV locations increases compared to the base case (PtH2 near all RES locations) the total transport in the electrical grid due to a higher remaining excess power by wind onshore and offshore
- Direction of power flows mainly from west to south-east
- Rather small effect on the hydrogen grid flows, main direction remains towards gas storages in the north

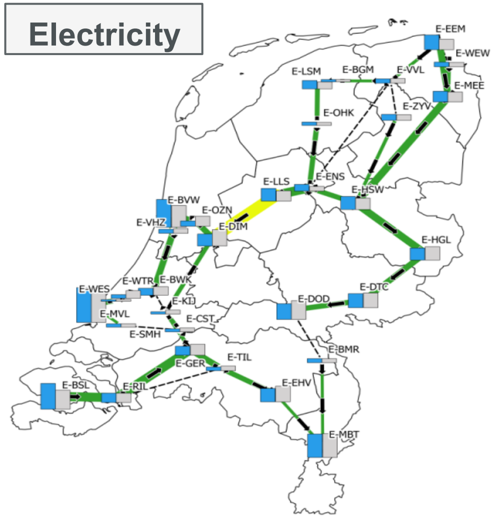
gasunie crossing borders in energy | TenneT Taking power further

Regional Scenario NL

High RES + high electrical demand

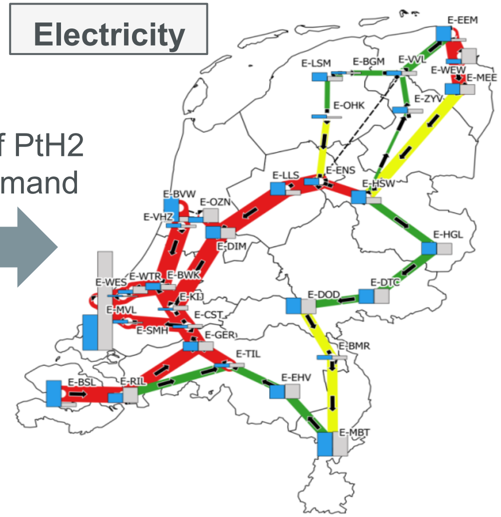
Hour 4044 concentrating electrolysers near solar

Electricity

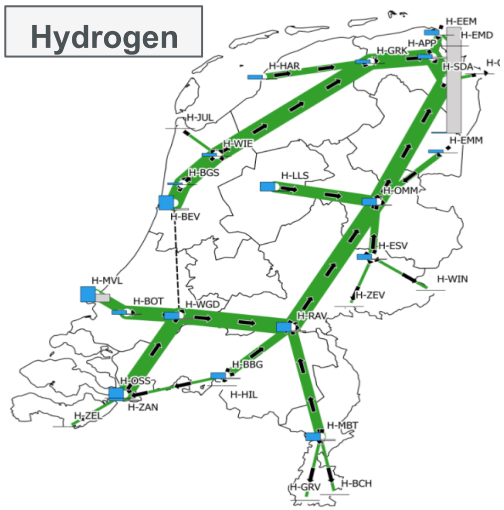


Shifting of PtH2 to gas demand

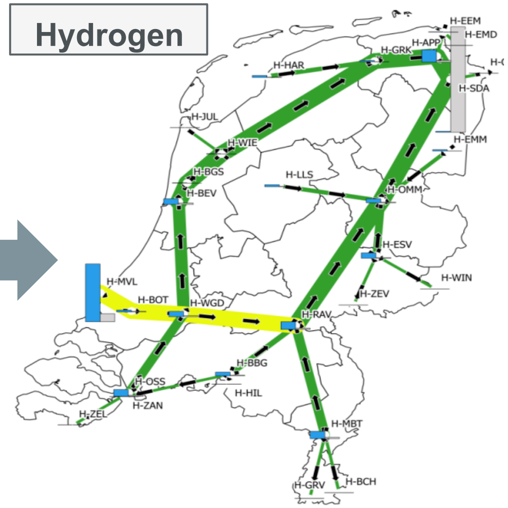
Electricity



Hydrogen



Hydrogen



- Localizing PtH2 at gas demand locations increases the total transport in the electrical grid due to an increased transport distance between RES supply and electrical demand
- Direction of power flows towards high demand locations

- Regionally increased hydrogen grid flows (from west to east), main direction remains towards gas storages in the north

gasunie crossing borders in energy

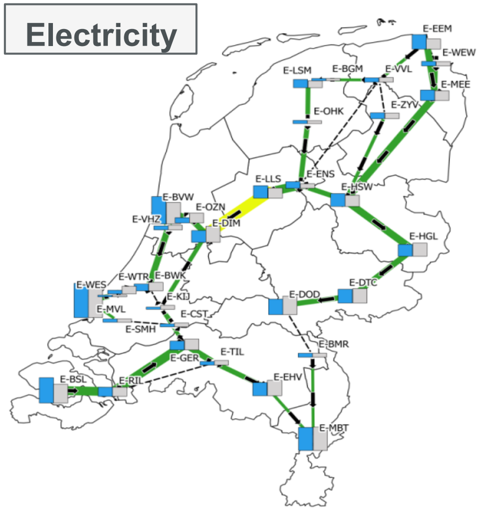
TenneT Taking power further

Regional Scenario NL

High RES + high electrical demand

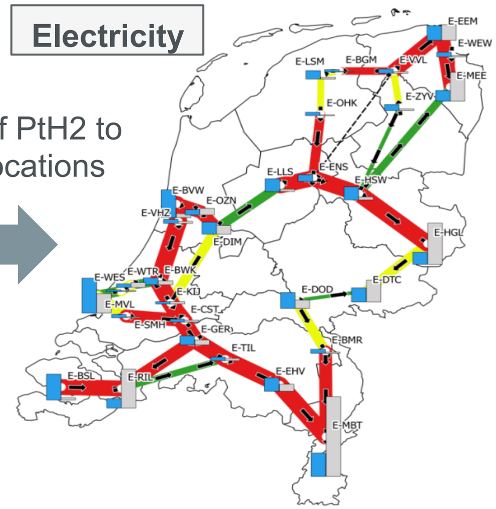
Hour 4044 concentrating electrolysers near system borders

Electricity

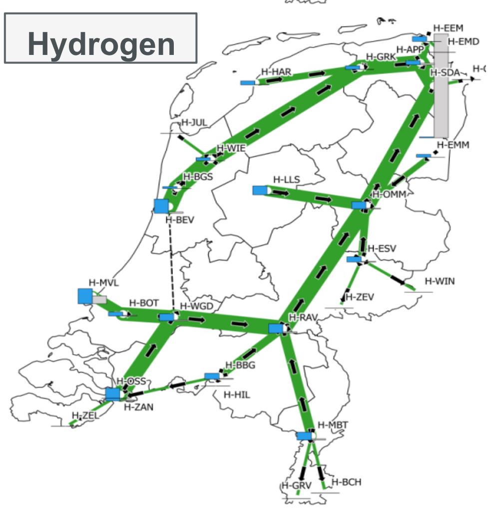


Shifting of PtH2 to export locations

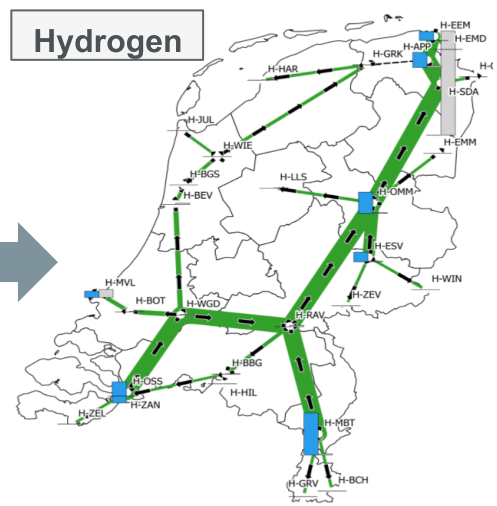
Electricity



Hydrogen



Hydrogen



- Localizing PtH2 at the <u>borders of the system</u> leads to a high transport distance between RES supply and electrical demand and a very high transport in the electrical grid
- Direction of power flows mainly towards export nodes
- Still no bottlenecks in hydrogen grid as result of high assumed north-south transport capacities

gasunie crossing borders in energy

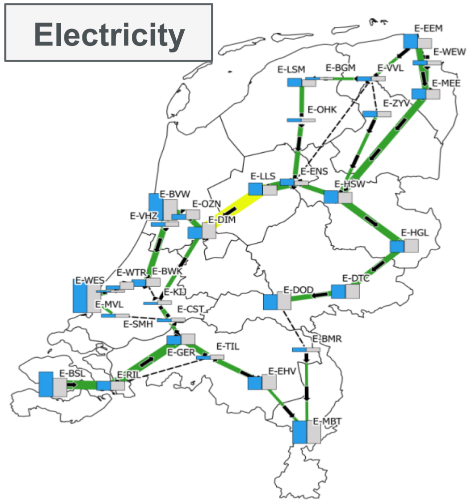
TenneT Taking power further

Regional Scenario NL

High RES + high electrical demand

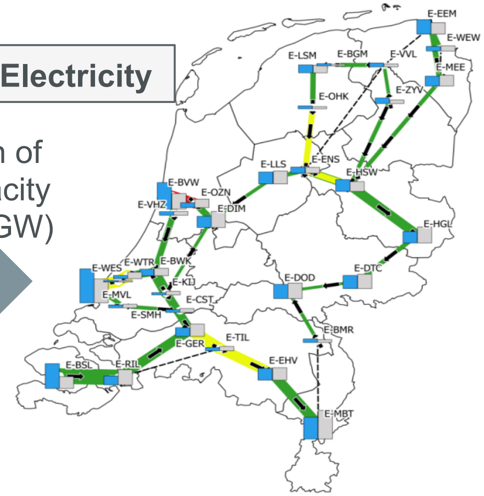
Hour 4044 **Reduction of electrolyzer capacity (75GW -> 25GW)**

Electricity

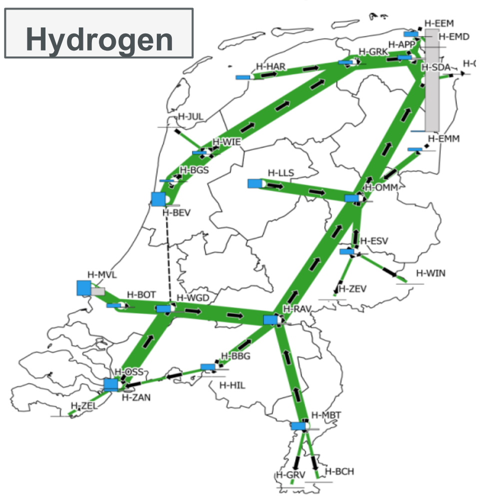


Reduction of PtH2 capacity (75 -> 25 GW)

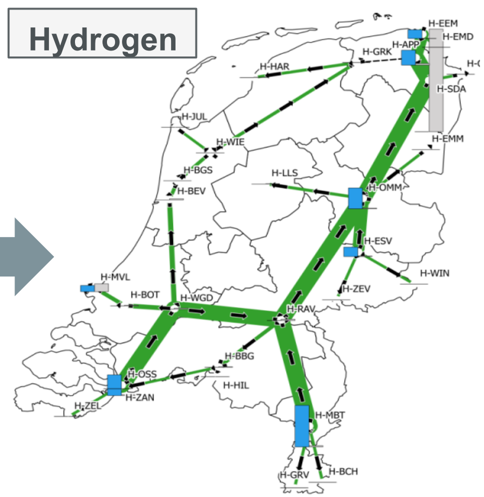
Electricity



Hydrogen



Hydrogen



- Reducing the PtH2 capacity from 75 GW to 25 GW means shifting of flexibility from RES locations more to battery locations (household demand) and higher transport distances of electrical power
- In total decreased transport of hydrogen since compared to the base case more power is now transported as electricity

gasunie crossing borders in energy

TenneT Taking power further

Infrastructure Calculations

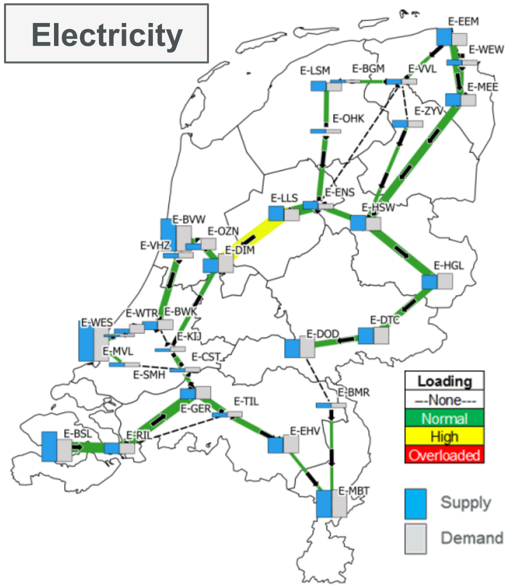
- Transit excursions

Regional Scenario

High RES + high electrical demand

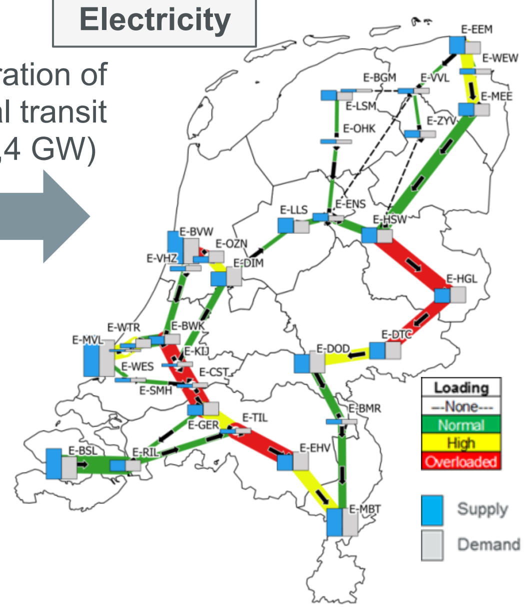
Hour 4044 **transit flows (North+East -> South+West**

Electricity



Consideration of additional transit flows (6,4 GW)

Electricity



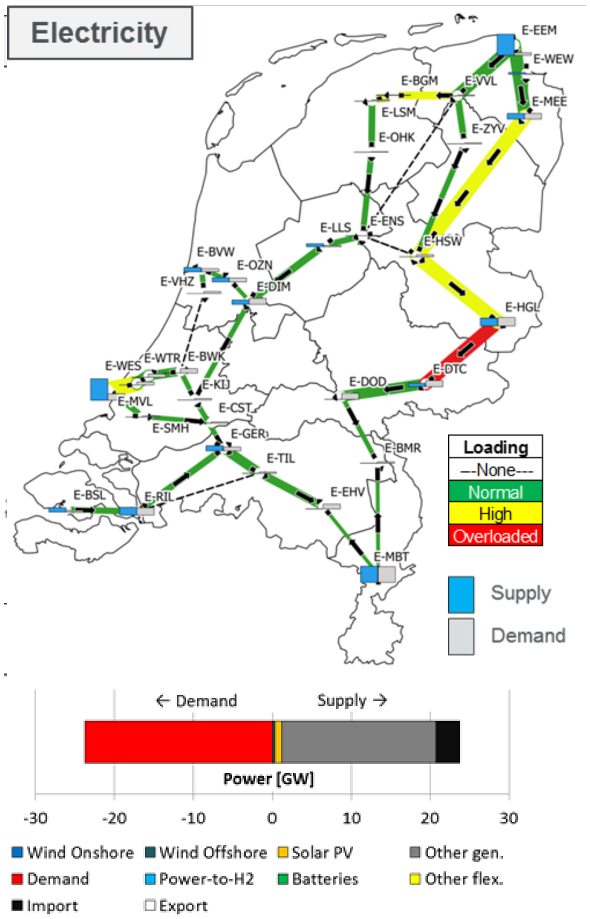
<u>Assuming international transit flows</u> with a north south direction and determined by the maximum export possibilities to the south leads to a higher loading and less available capacity of the electrical grid for domestic energy transports

gasunie crossing borders in energy | TenneT Taking power further

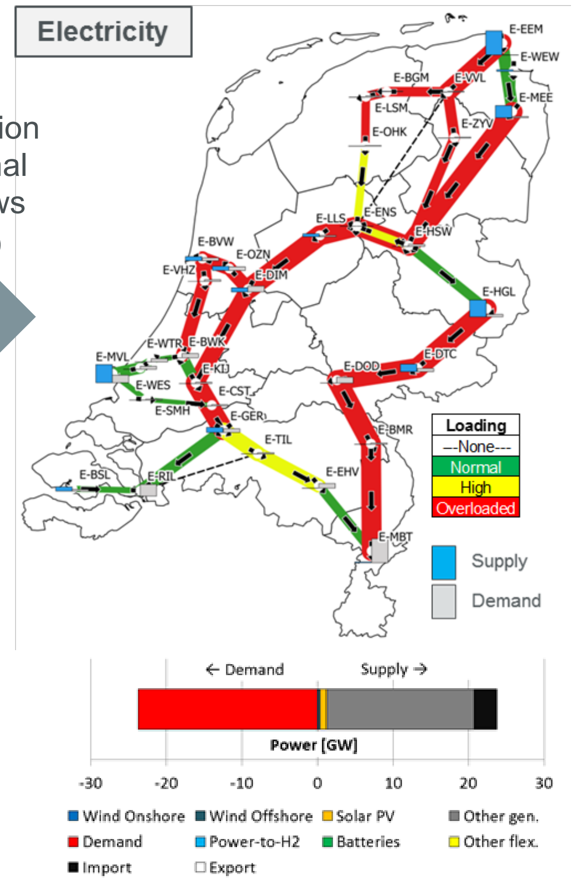
International scenario

Low RES + high electrical demand + high conv. supply

Hour 489 transit flows (North+East -> South+West)



Consideration of additional transit flows (10 GW)



Assuming international transit flows with a north south direction and determined by the maximum export possibilities to the south leads to a higher loading and less available capacity of the electrical grid for domestic energy transports

Conclusions infrastructure calculations

- The **locational choice of flexibility options** (PtG, batteries, PtHeat) strongly determines the energy transport in the particular infrastructure(s)
- Locating **PtG near RES supply** reduces the loading of the electrical and increases the use of the hydrogen grid infrastructure (shifting of power between infrastructures)
- The **assumed gas grid seems able to cope with all occuring transport needs**
- **Battery storages located near (household) demand** have a grid benefical impact
- Very high amounts of wind offshore could be critical to the electrical infrastructure due to a relatively high transport momentum
- Situations with both low RES infeed and high electrical demand could lead to critical power flows due to congestions in the grid between gas power plants and demand, at least in cases where batteries can not feed energy back into the grid
- International flows can have an significant influence on the need for (electrical) infrastructure

Project documentation / appendix III

German study part

Model Results Contents

Index:

Demand and Supply Curves	3-12
Storage Requirements Charge and discharge capacities	13-16
Storage Requirements: Storage Volumes	17-20
Infrastructure Calculations: Regional Szenario (Enervis)	21-33
Infrastructure Calculations: National Szenario (FNB)	34-41
Infrastructure Calculations: International Szenario (dena)	42-49
Infrastructure Calculations: Sensitivity electrolyser	50-62

Demand and supply curves

- Derived from ETM model and simulation by IAEW
- Used for selection of snapshots

Snapshot definition and considerations

General definition „snapshot“: Situation („hour“) with a specific (regional) occurrence 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 electrolysers and H2-to-CH4 plants) determines to an extent the load on the electrical and 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

* (Operating envelope: Frame wherein a system can be operated safely)

Operating envelope snapshots

- 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)
- Flex options balance the gap between supply and demand
- **Three main corners of the operating envelope** were identified:
  A. High RES supply and high (final) demand
  B. High RES supply and low (final) demand
  C. Low RES supply and high (final) demand

The three main corners (snapshots)

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

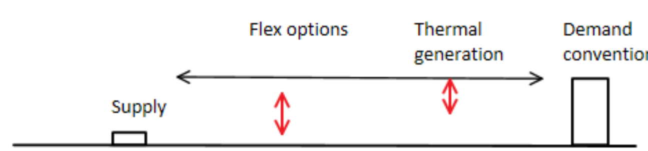
Flex options:
Demand management
Battery
Conversion p-2-h2
Export
Curtailment

># GW

Low demand
conventional

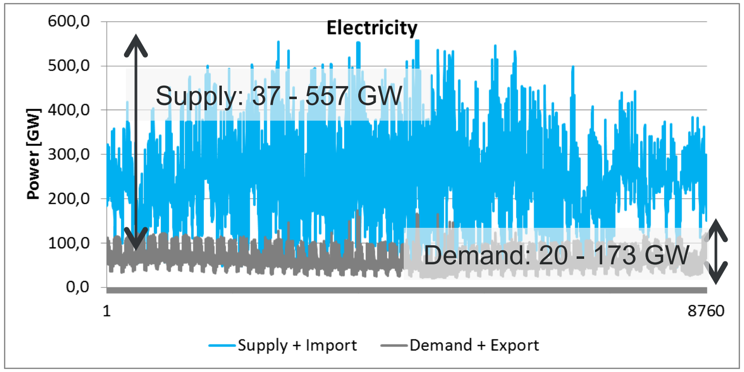
Case: High RES WIND and low conventional demand

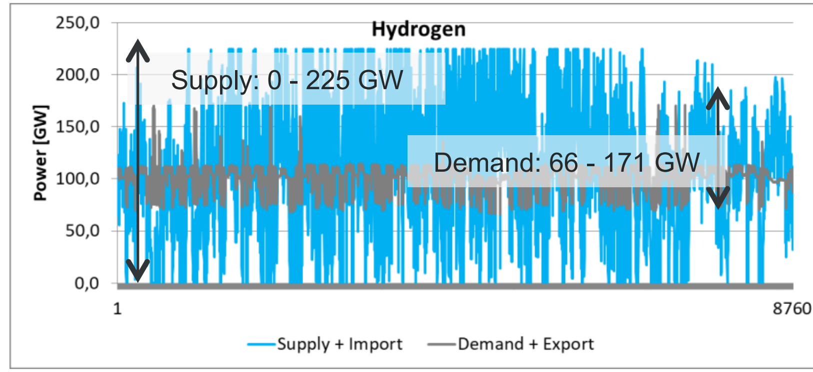
Situation C:
- Low wind and/or solar supply
- High final demand
- *NOTE: thus could result in a need for back-up power plants*

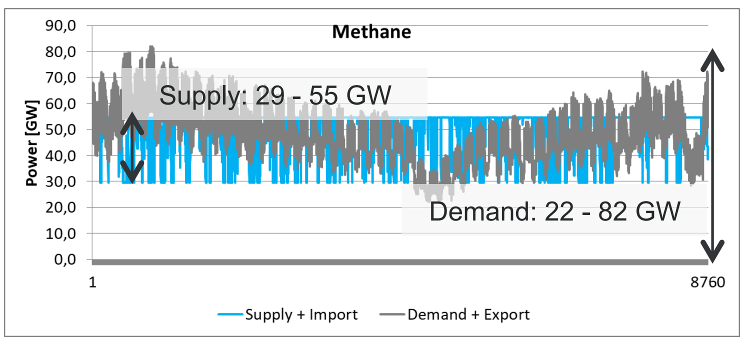


Regional scenario DE

Supply and Demand







Supply = Total supply to the system including imports
Demand = Total demand from the system including exports

- Electricity: High volatility of RES dominated supply (seasonality due to solar PV) and large imbalances with demand
- ➢ Significant need for flexibility options
- Hydrogen: Supply volatility from power-to-H2. Demand stable (industry) except for peaks from gas power plants
- Methane: Stable supply by optimization of the methaninzation process (H2->CH4). Demand strongly temperature depending (heating demand).

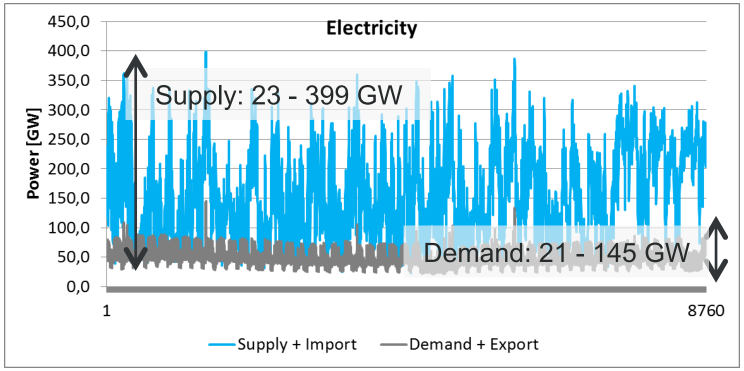
Regional Scenario DE

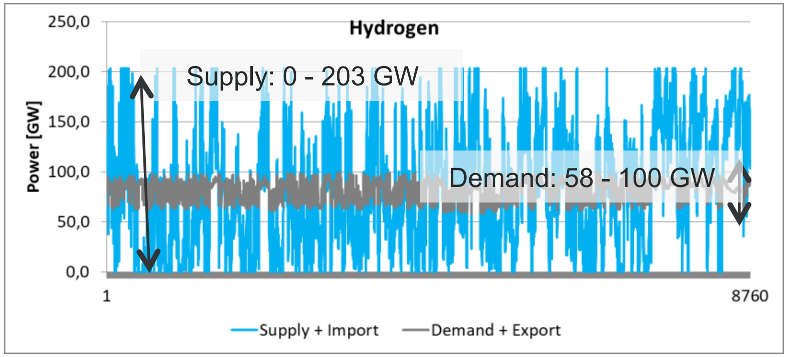
Supply and Demand main findings

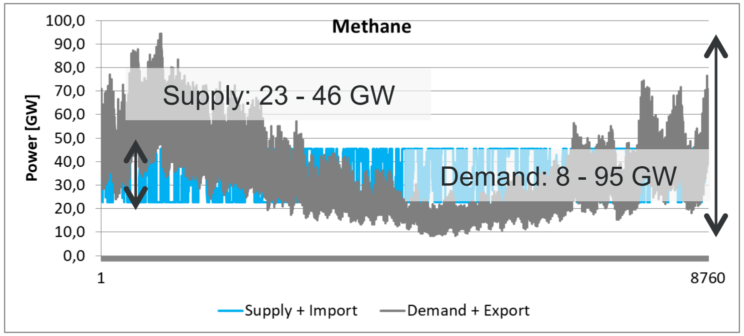
- **Significant mismatch between electrical supply and demand** due to high installed capacity and volatile infeed of wind and solar
- To fully integrate the RES infeed, a **combination of power-to-hydrogen („base flexibility“) and battery storage („peak flexibility“)** is used
- The high capacity of solar PV leads to **significant supply peaks and a strong seasonality (summer vs. winter)** and triggers the need for peak- **and** long-term flexibility (from P2G in combination with hydrogen storages)
- In situations with low RES infeed, **batteries (short term availability) and conventional generation (long-term availability) are used** to meet the electrical demand. Storages (Hydrogen and Methane) cover the lake of supply from P2Gas.
- The use of gas power plants causes significant peaks in the gas demand (hydrogen)
- The **supply to the hydrogen system is driven by RES** and therefore shows a high volatility
- The supply to the methane system is kept relatively stable (-> high utilization hours for methaneization-plants)

National scenario DE

Supply and Demand







- Electricity: High volatility of RES dominated supply (seasonality due to solar PV) and large imbalances with demand
  - ➢ Significant need for flexibility options
- Hydrogen: Supply volatility from power-to-H2. Demand stable (industry) except for peaks from gas power plants
- Methane: Stable supply by optimization of the methaneinzation process (H2->CH4). Demand strongly temperature depending (heating demand).

Supply = Total supply to the system including imports
Demand = Total demand from the system including exports

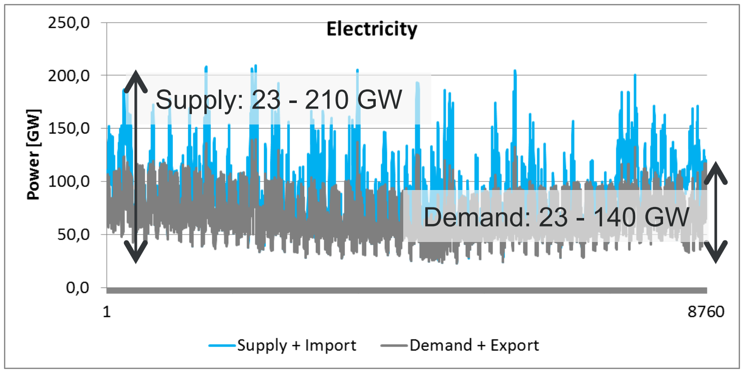
National Scenario DE

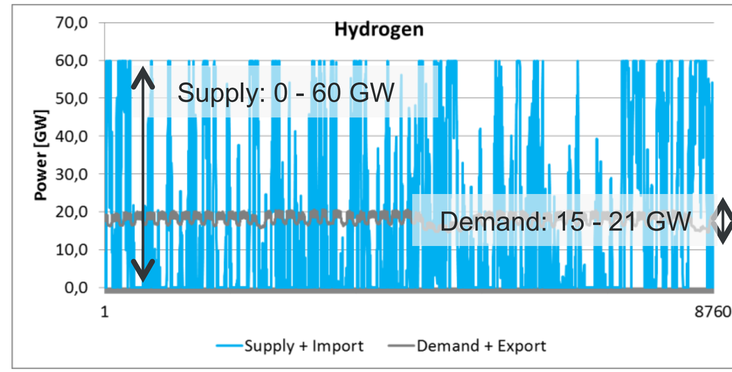
Supply and Demand main findings

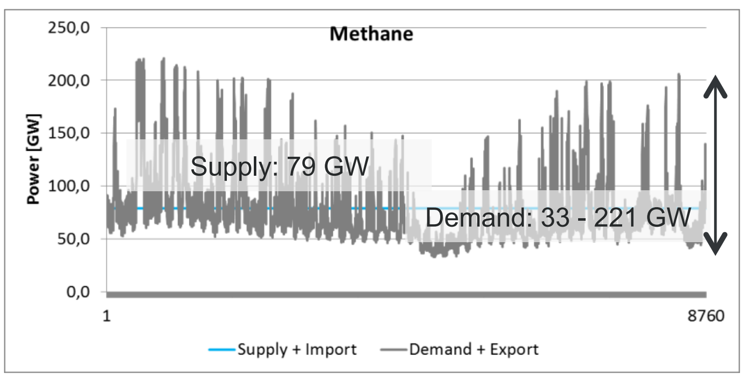
- Behaviour on the overall demand/supply view comparable to Regional Scenario
- Main Difference in different RES Supply structure (higher Wind (Onshore/Offshore) and less PV)
- Import of significant amounts of green liquid fuels

International Scenario-NL

Supply and Demand (original dena figures)







Supply = Total supply to the system including imports
Demand = Total demand from the system including exports

- Electricity: Installed RES capacities much smaller compared to Regional and National since high import of (renewable) Methane. Flexibility by (some) P2Gas / battery
- Hydrogen: Supply volatile (RES). Demand stable (Industry)
- Methane: No link to Hydrogen system via Methaneization. Temperature dependend demand (heating) with peaks from gas-power-plants

International Scenario NL

Supply and Demand main findings

- **Closer match between electrical supply and demand** as result of relatively low RES and high conventional/thermal („dispatch-able“) capacity
- Methane and Hydrogen System are independent - no link between the systems via methaneization
- The design of the DENA scenario can be challenged at some decisions:

  The Hydrogen market is relatively small – especially it could be expected, that a larger part of industry demand and demand from gas-power-plants can be covered by hydrogen.

  All gas imports are seen as imports of (renewable) Methane – this would imply an intense use of the methaneization process in exporting countries to provide the methane. There is a strong optimization potential to shift the market (demand/supply) to the hydrogen system.

  The hydrogen storages have to provide short- and long-term flexibility for the volatile supply from RES.

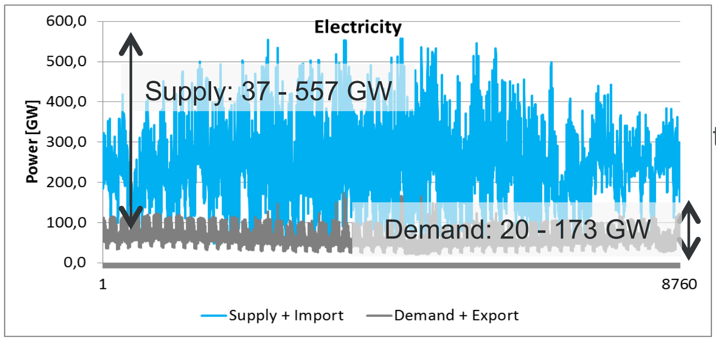
  Methane storages have to provide long-term flexibility (seasonality) to cover the strongly temperature dependent (heating) demand, but have to cover as well short-term demand from power-plants -> the flexibility requirement could be reduced, if a share of power-plants would be covered by hydrogen.
- In the simulations of the International/DENA scenario we have shifted a part of the demand (mainly power-plants and industry) and some import-volumes to the hydrogen system

Storage requirements

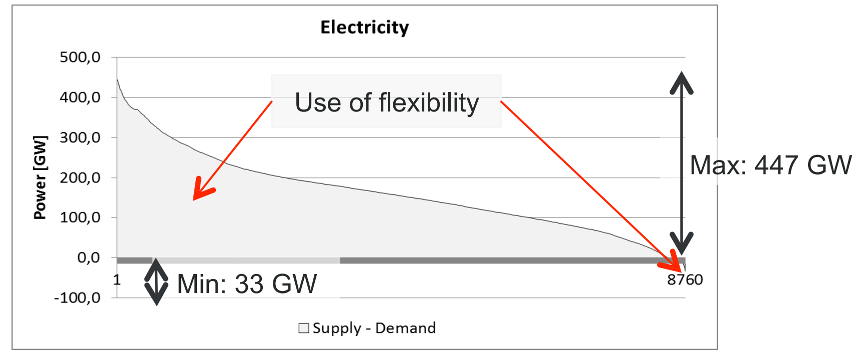
- Derived from ETM model and simulation from IAEW
- Charge and discharge capacities (GW)

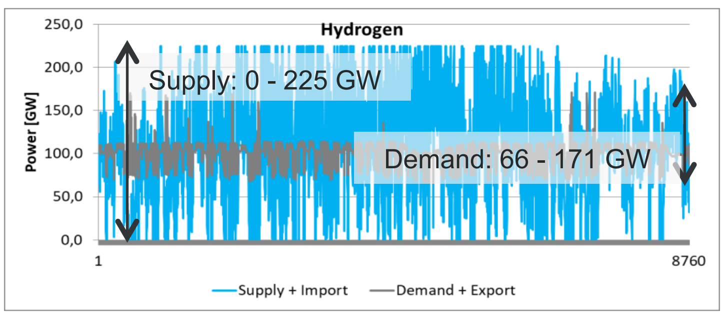
Regional Scenario DE

Charge and Discharge capacities (GW)

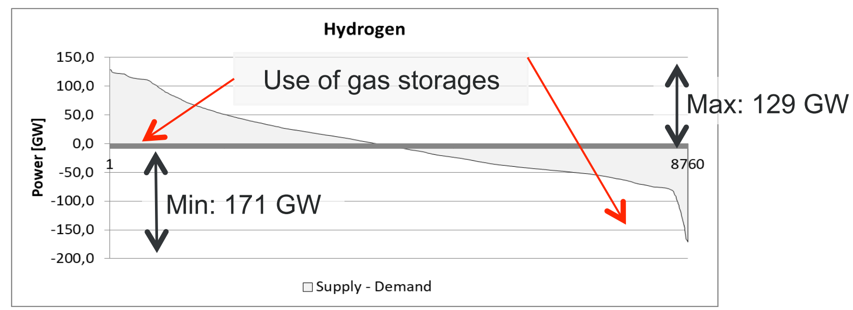


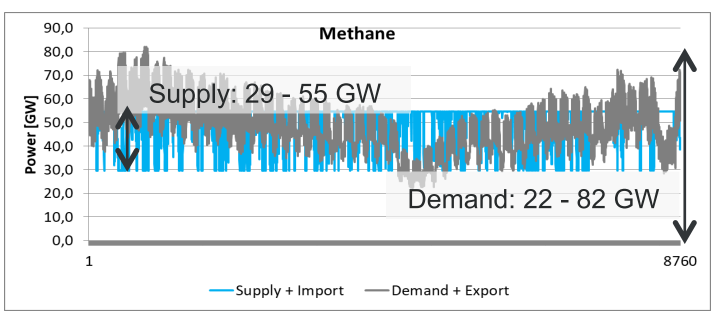
Flexible electricity demand through Power-to-hydrogen

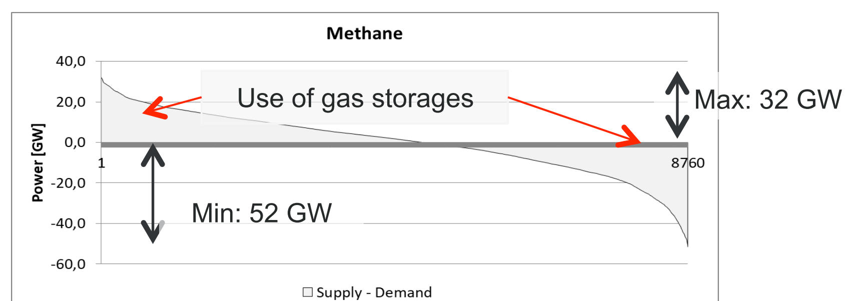




Balancing through gas storages

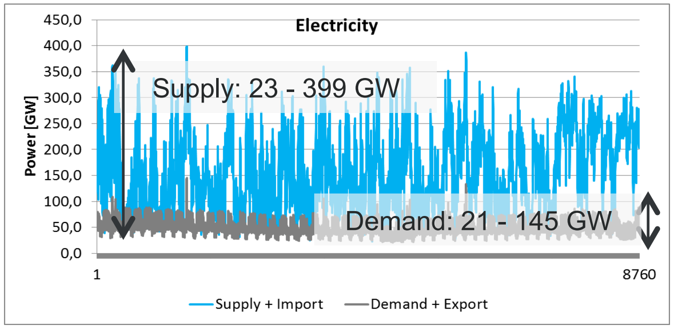


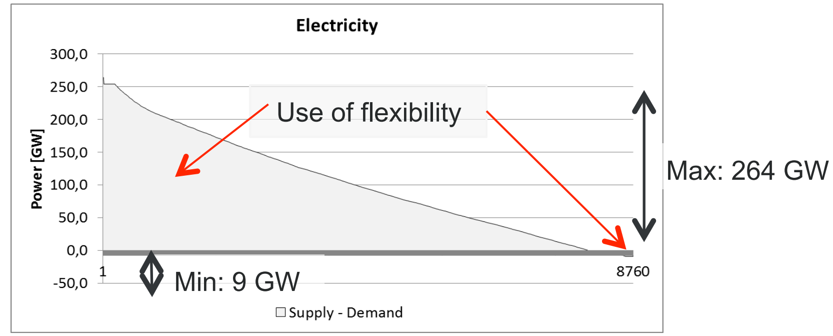


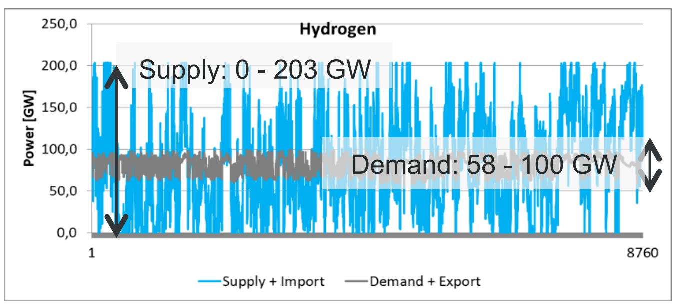


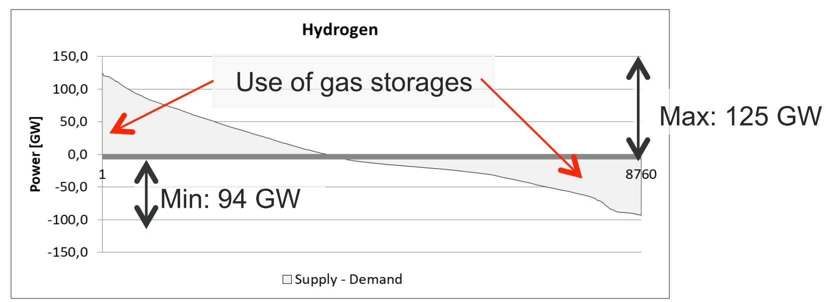
National Scenario DE

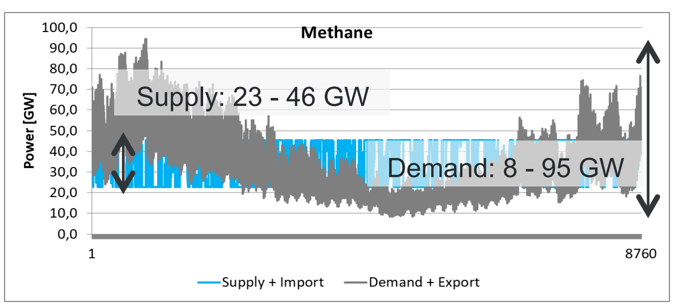
Charge and Discharge capacities (GW)

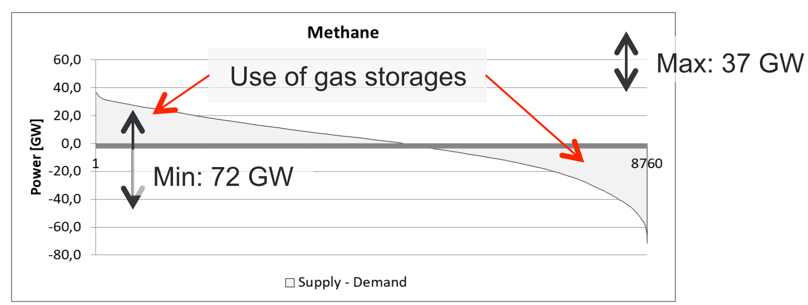






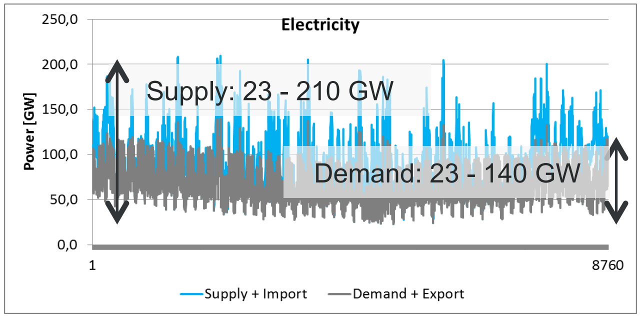


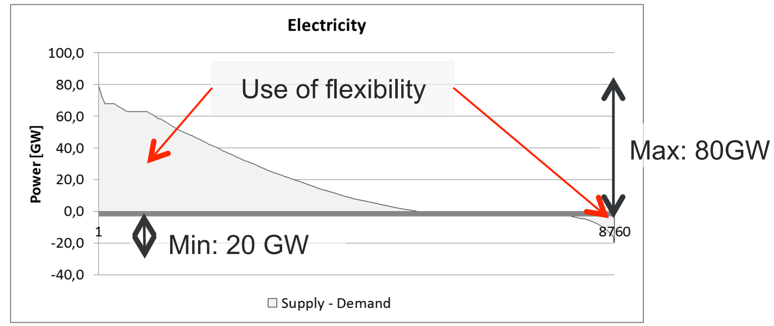


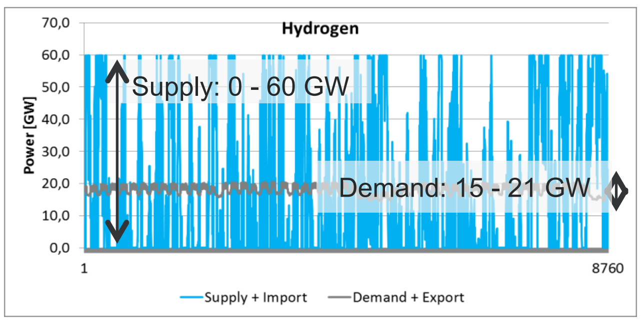


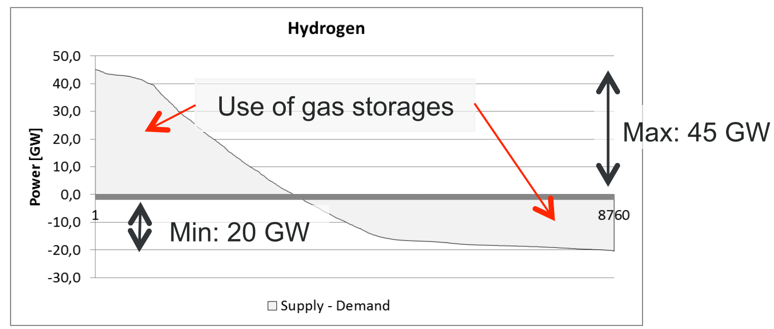
International Scenario DE

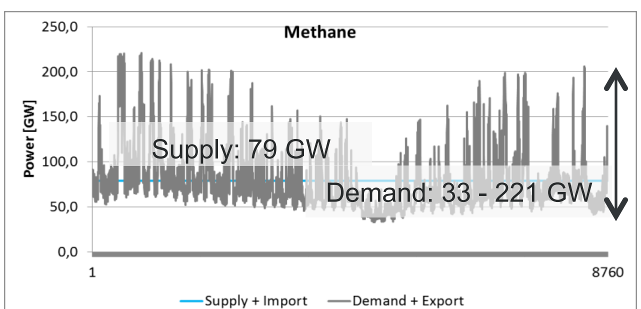
Charge and Discharge capacities (GW) – dena original

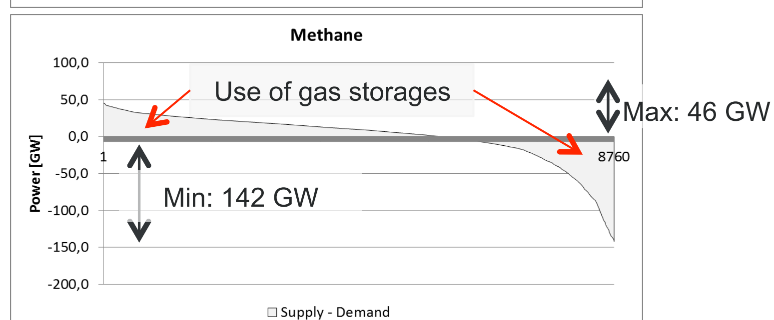










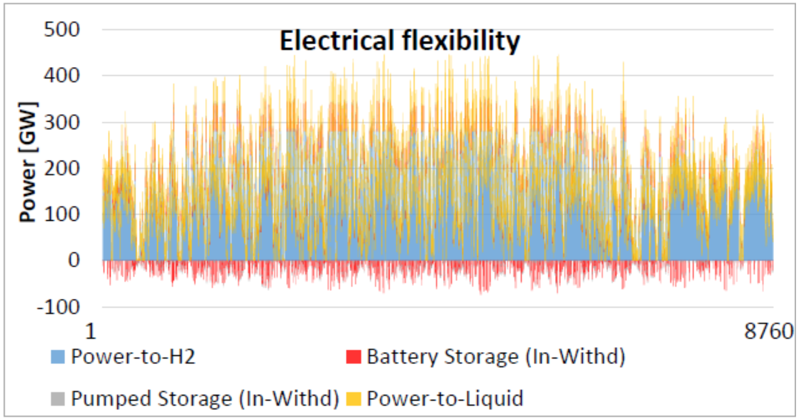


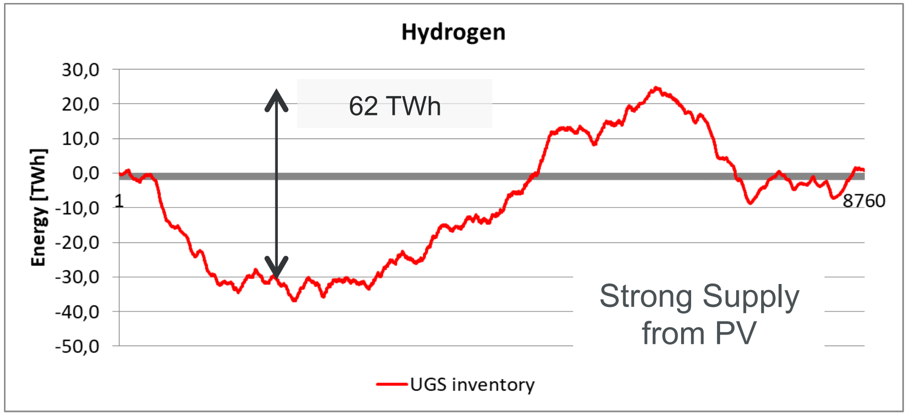
Storage requirements

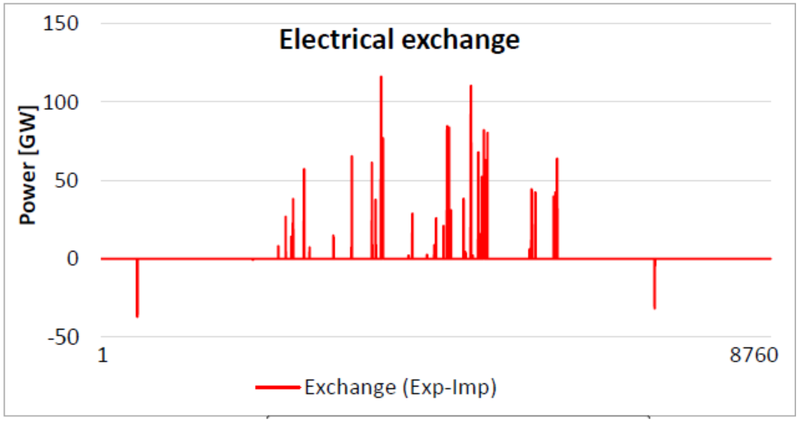
- Derived from ETM model and simulation from IAEW
- Storage volumes (TWh)

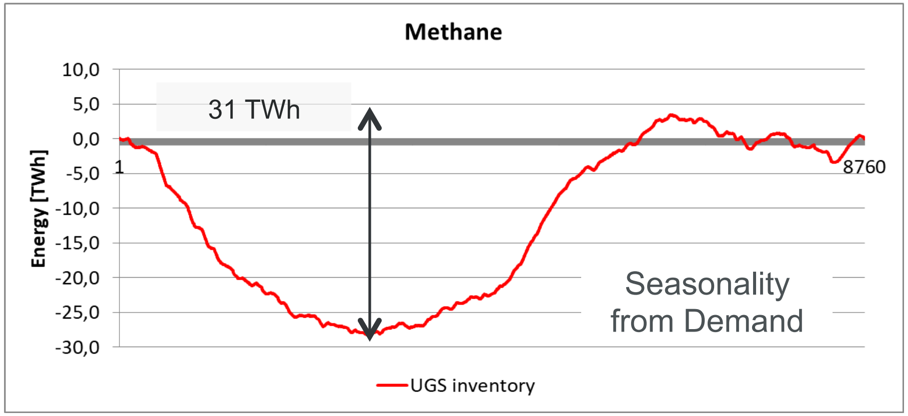
Decentral scenario DE

Storage volumes (TWh)



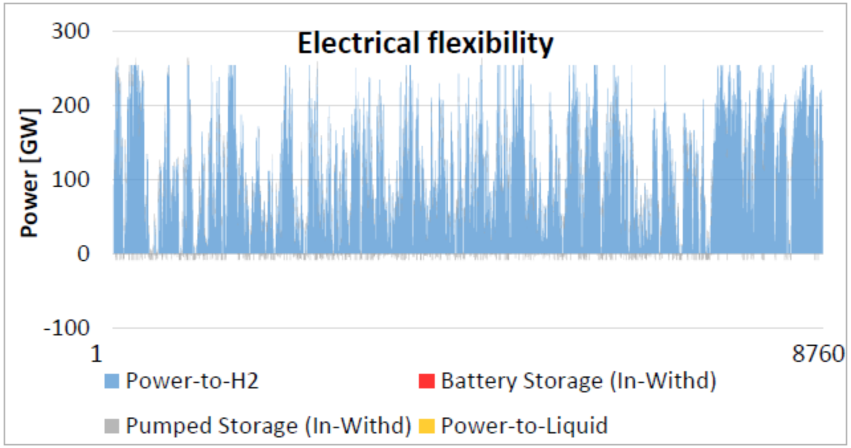


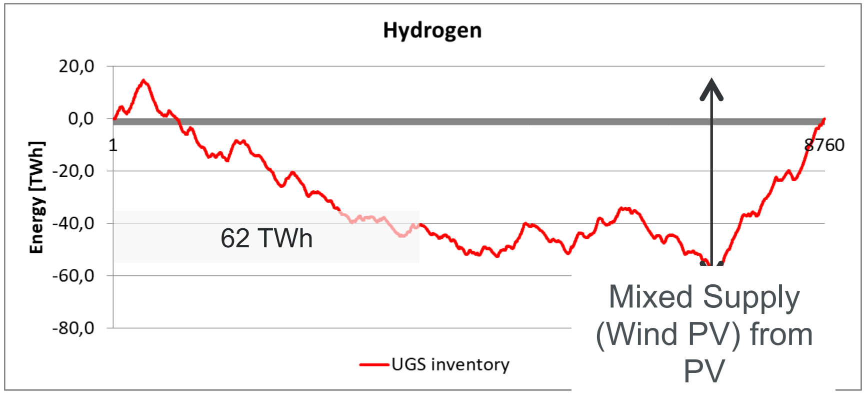


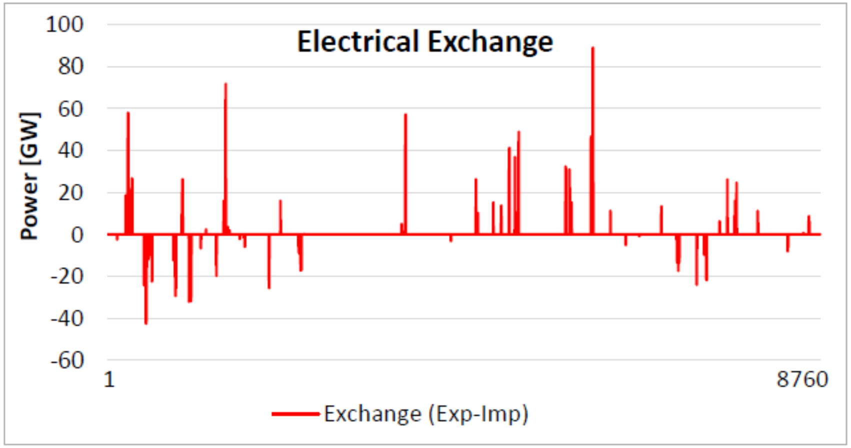


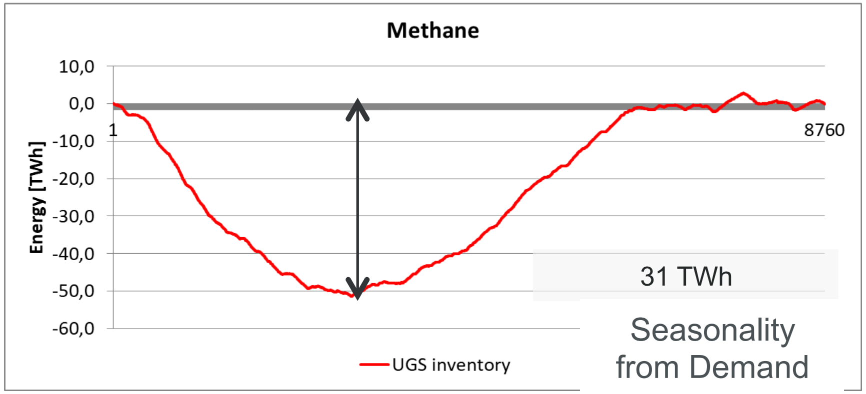
National Scenario DE

Storage volumes (TWh)



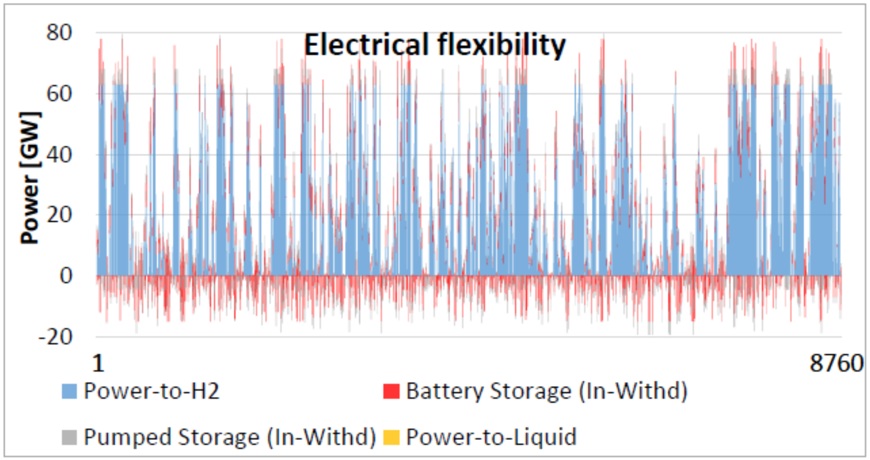


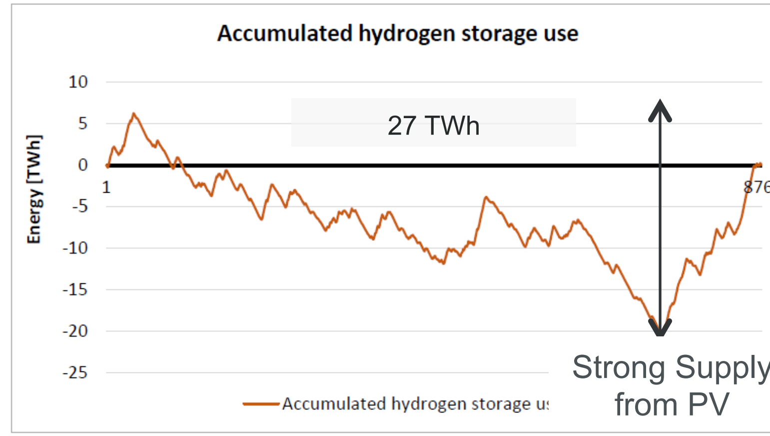


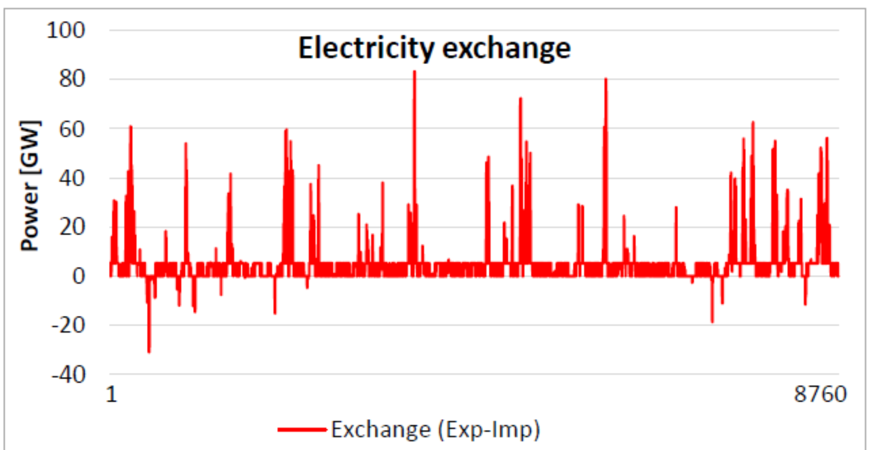


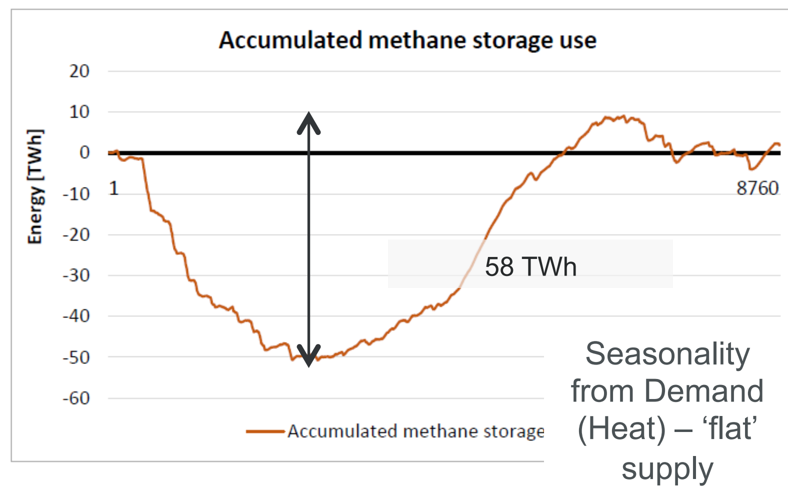
International Scenario DE

Storage volumes (TWh) (original dena figures)









Infrastructure Calculations

- Regional Szenario (Enervis)

gasunie crossing borders in energy

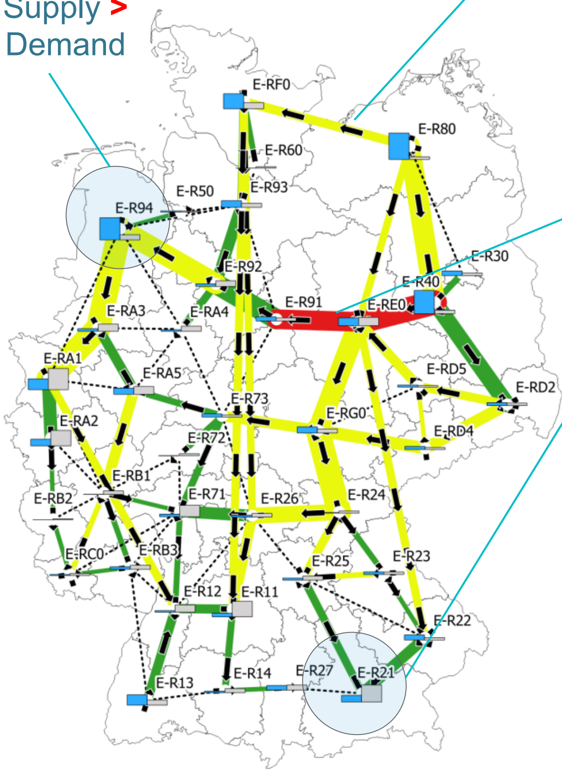
TenneT Taking power further

Infrastructure Calculations: Introduction

Infrastructure calculations (DE): Map visualization (e.g. Electricity)

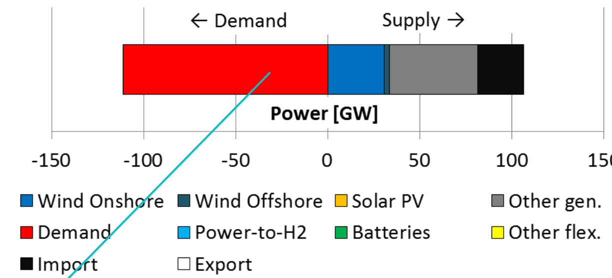
∑ Supply > ∑ Demand

Flow direction



Line overloaded

∑ Demand > ∑ Supply



Composition of Demand vs. Supply

Loading
---None---
Normal
High
Overloaded

Color indicates relative loading of lines compared to max. line capacities

- Normal: Loading between 0% and 75%
- High: Loading between 75% and 100%
- Overloaded: Loading above 100%

Supply

Demand

Supply: Sum of all supply elements
Demand: Sum of all demand elements

Infrastructure calculations (DE): Overview snapshot **base cases**

Scenario	Snapshot hour	Description
Enervis	4526	Max RES + high total demand (incl. flexibility)
Enervis	1450	High Wind - High Conventional
Enervis	916	High Wind - Low Conventional
Enervis	4358	High Solar - High Conventional
Enervis	5126	High Solar - Low Conventional
Enervis	474	No RES + high total demand
Enervis	474	Low RES + high electrical demand
Enervis	474	Low RES + maximum total demand (excl. flexibility)
Enervis	4953	Maximum hydrogen storage charging
Enervis	8174	Maximum hydrogen storage decharging
Enervis	4943	Maximum natural/green gas storage charging
Enervis	473	Maximum natural/green gas storage decharging

gasunie crossing borders in energy

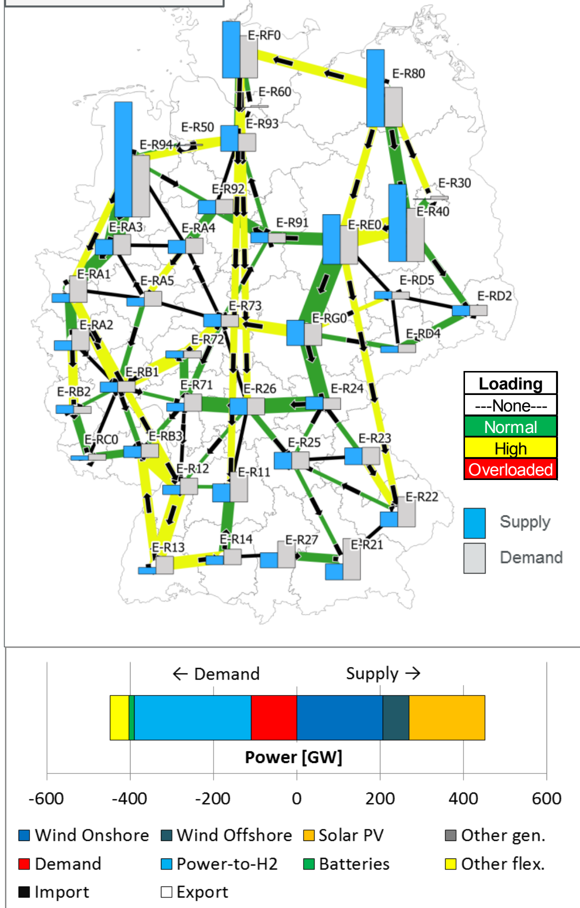
TenneT Taking power further

Infrastructure calculations (DE)

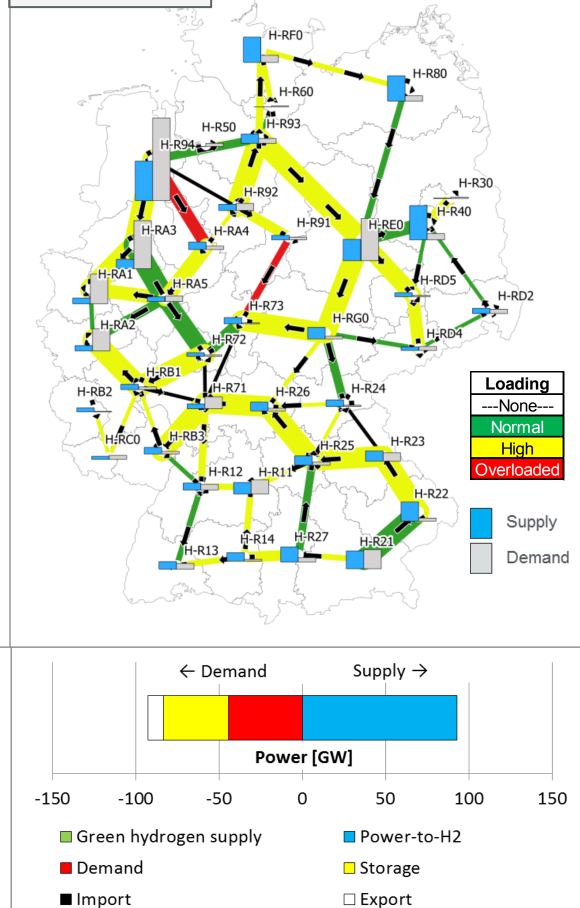
High RES + low electrical demand

Base cases (Enervis_1450)

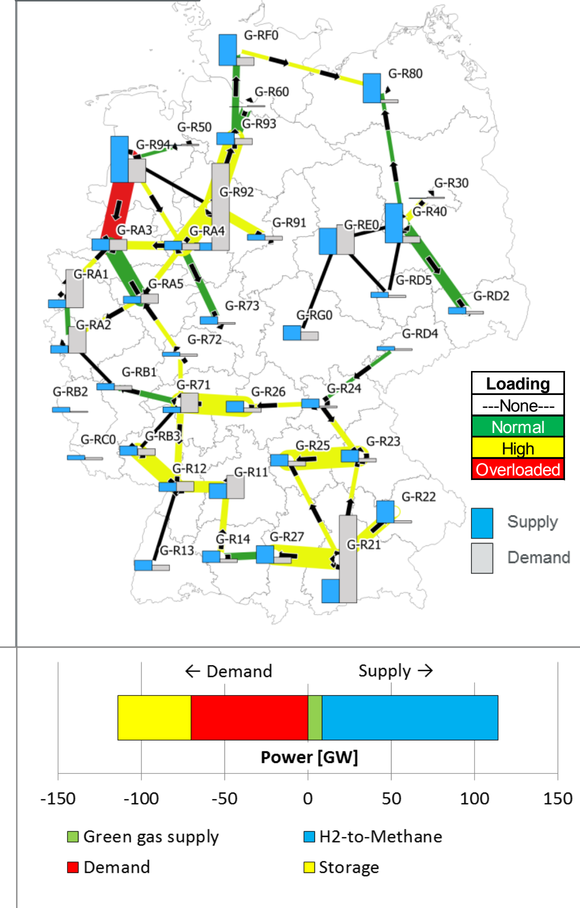
Electricity



Hydrogen



Methane



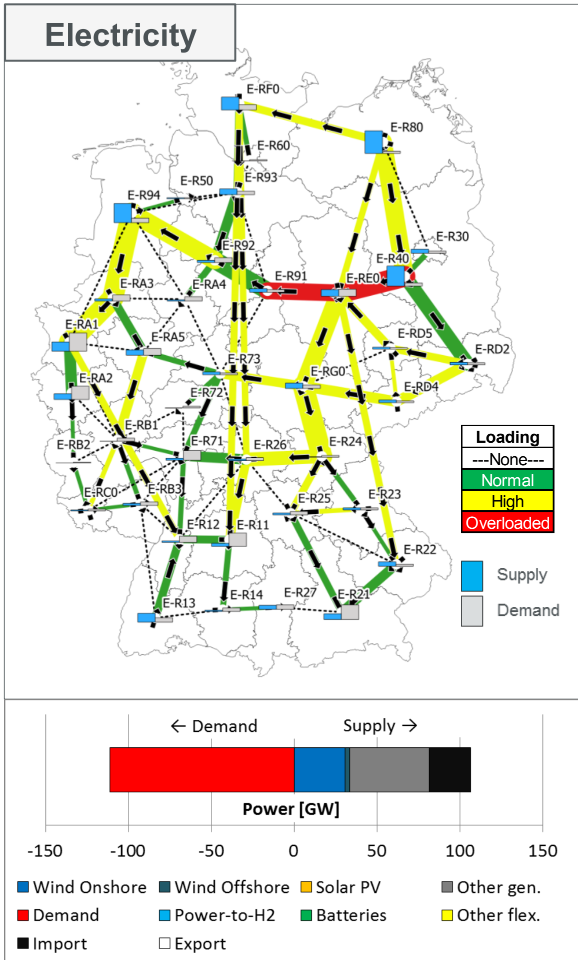
gasunie crossing borders in energy

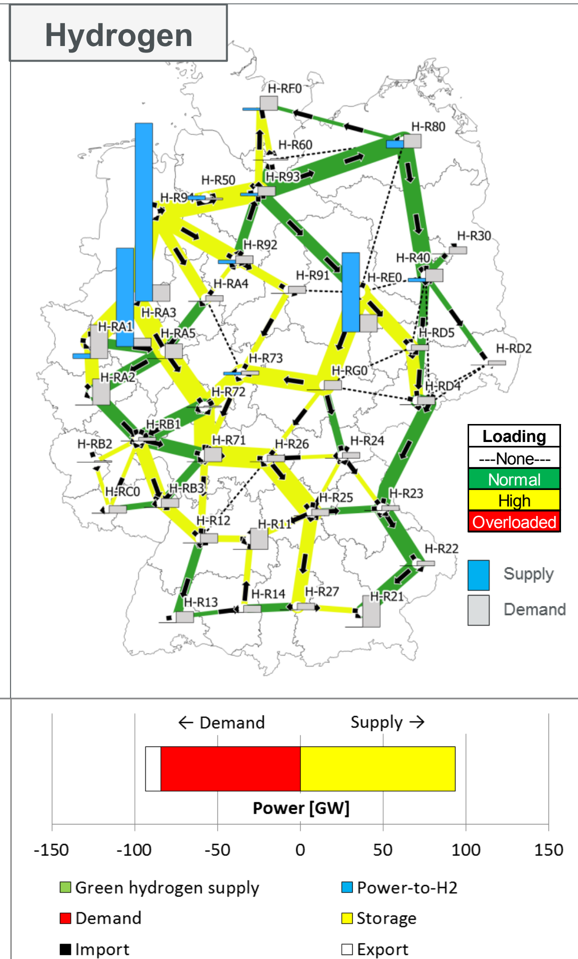
TenneT Taking power further

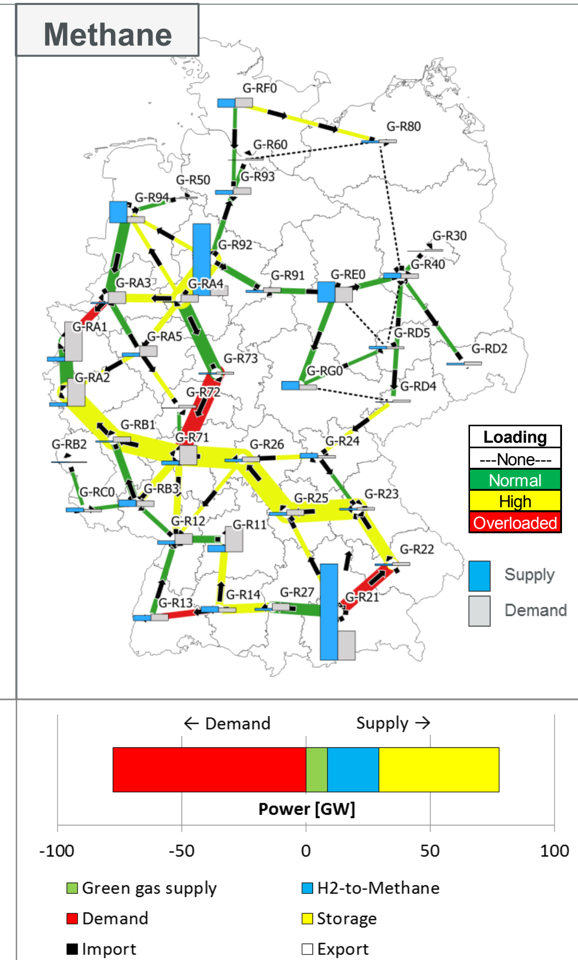
Infrastructure calculations (DE)

Base cases (Enervis_473)

High RES + low electrical demand





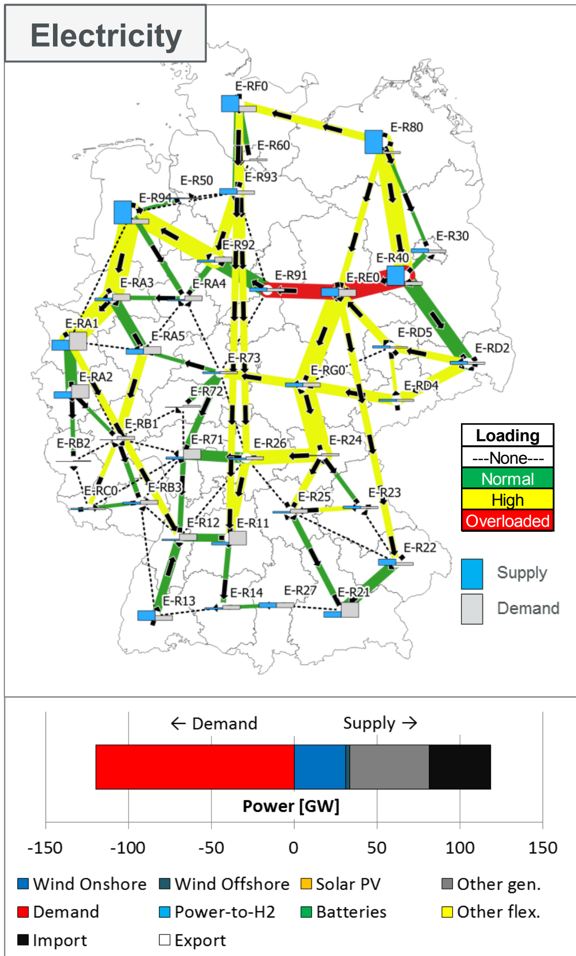


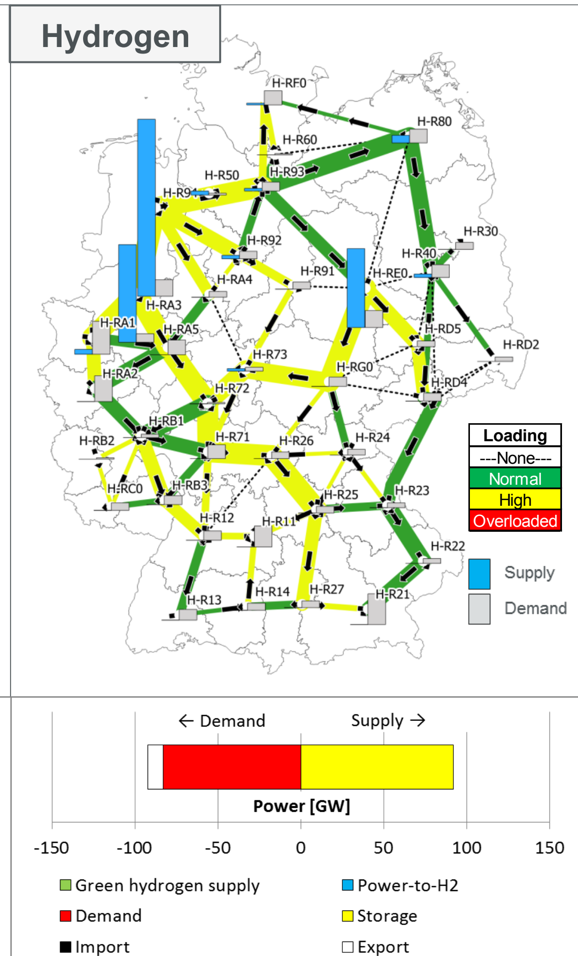
gasunie crossing borders in energy — TenneT Taking power further

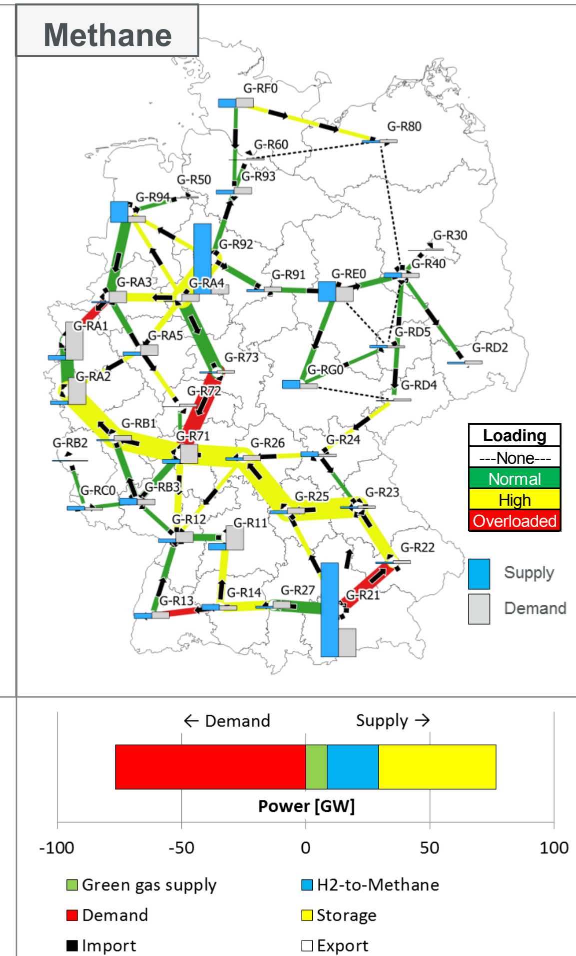
Infrastructure calculations (DE)

Base cases (Enervis_474)

High RES + low electrical demand







Infrastructure Outlook 2050

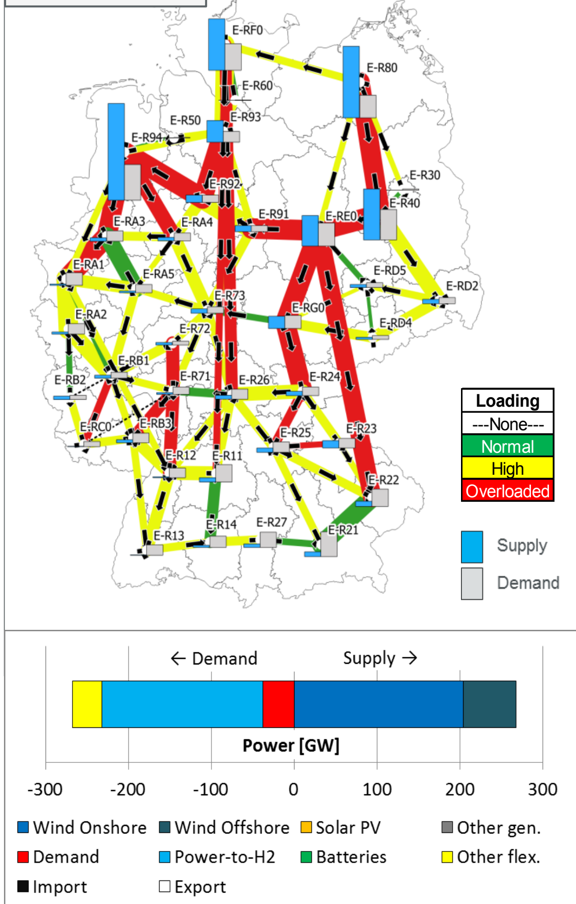
gasunie crossing borders in energy | TenneT Taking power further

Infrastructure calculations (DE)

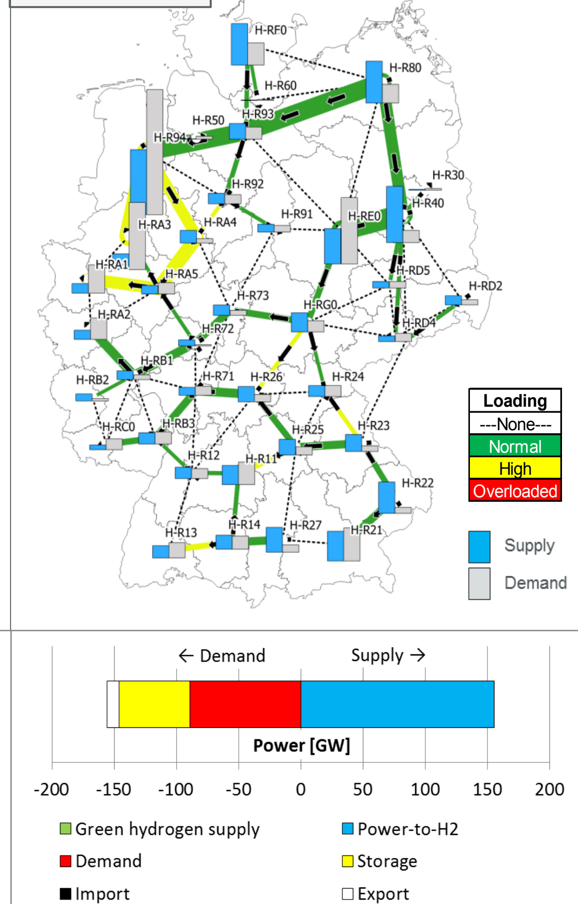
High RES + low electrical demand

Base cases (Enervis_916)

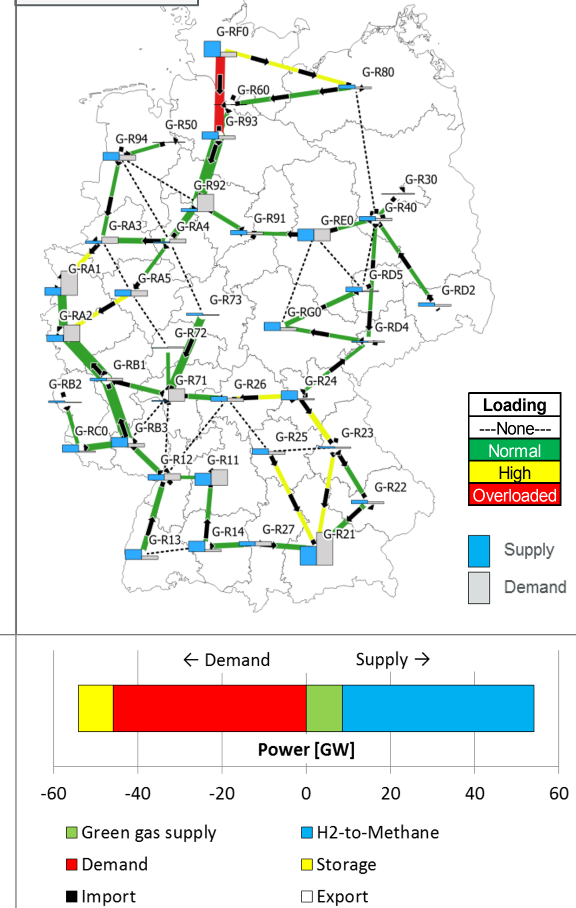
Electricity



Hydrogen



Methane



gasunie crossing borders in energy

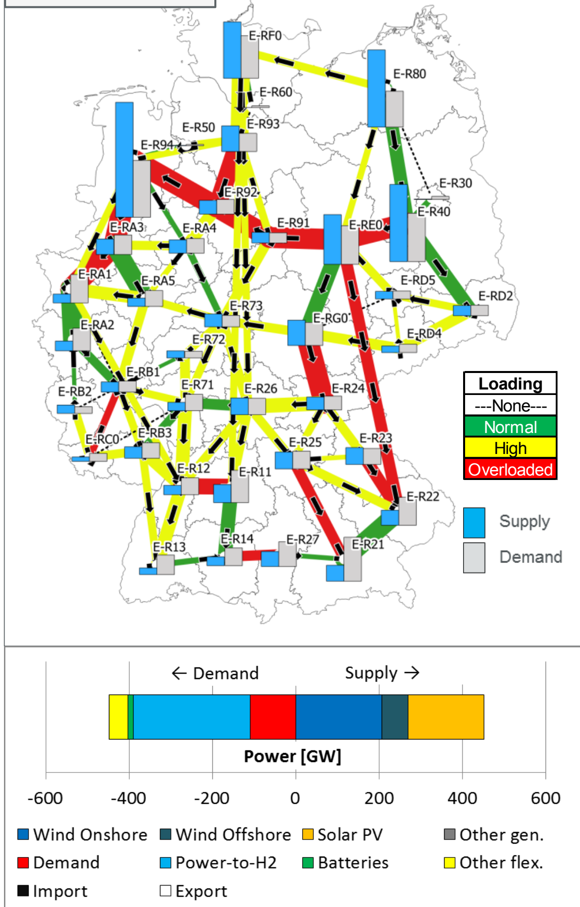
TenneT Taking power further

Infrastructure calculations (DE)

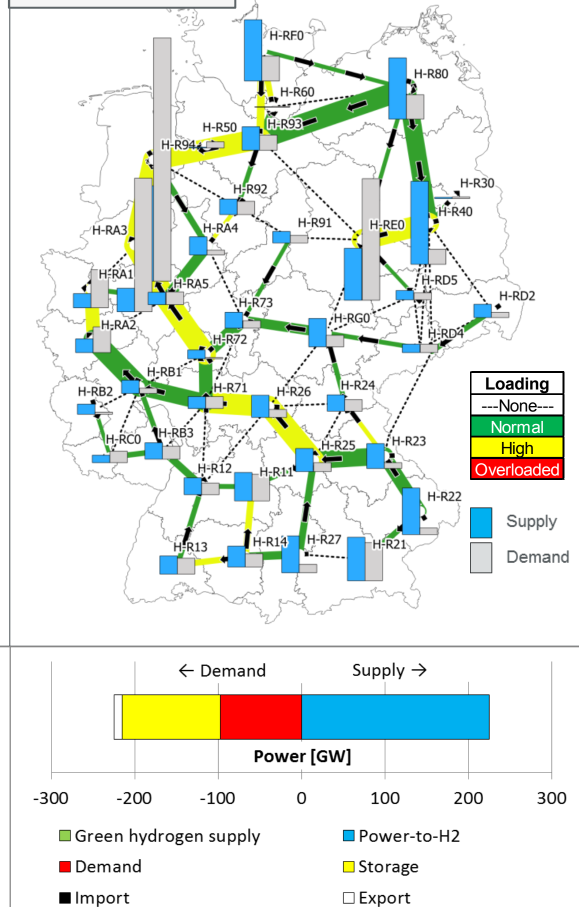
Base cases (Enervis_1450)

High RES + low electrical demand

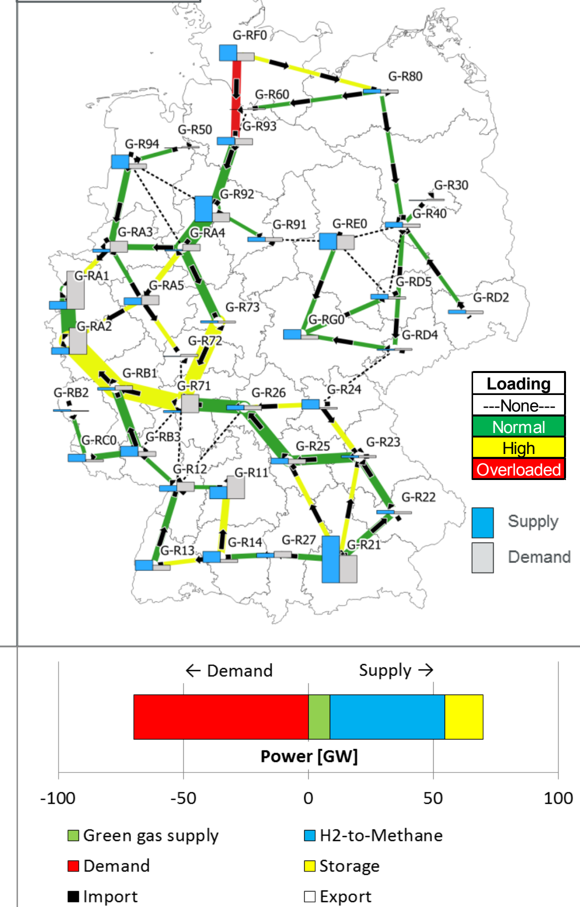
Electricity



Hydrogen



Methane



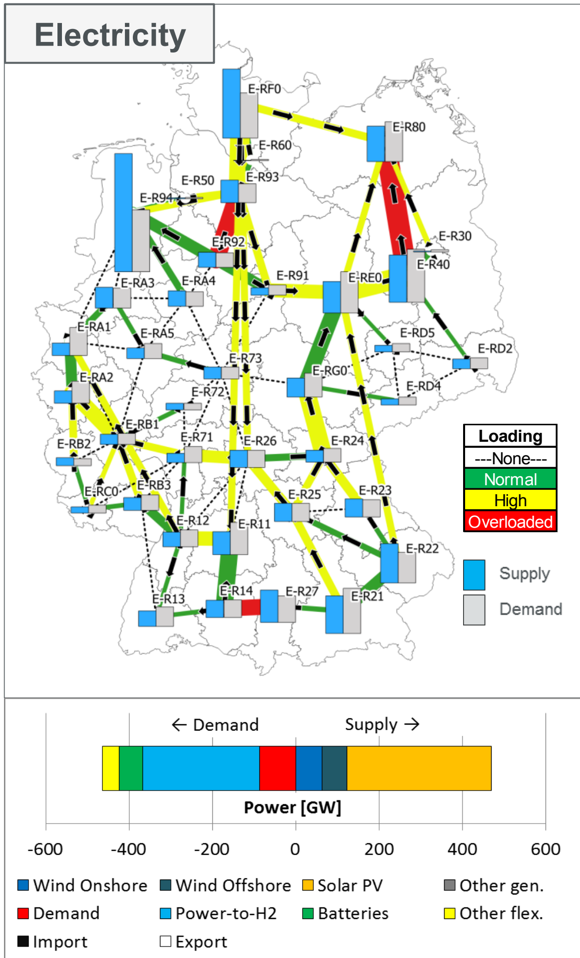
gasunie crossing borders in energy

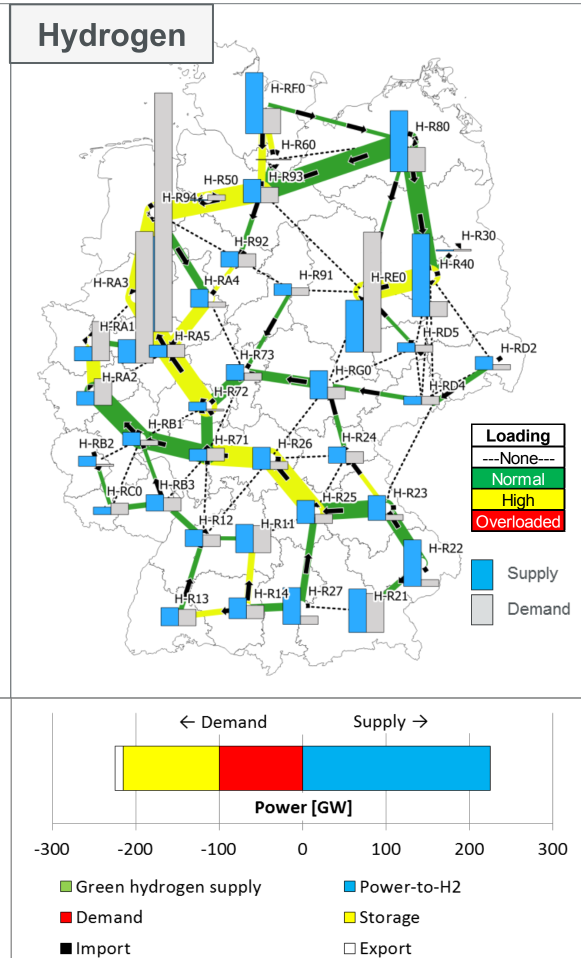
TenneT Taking power further

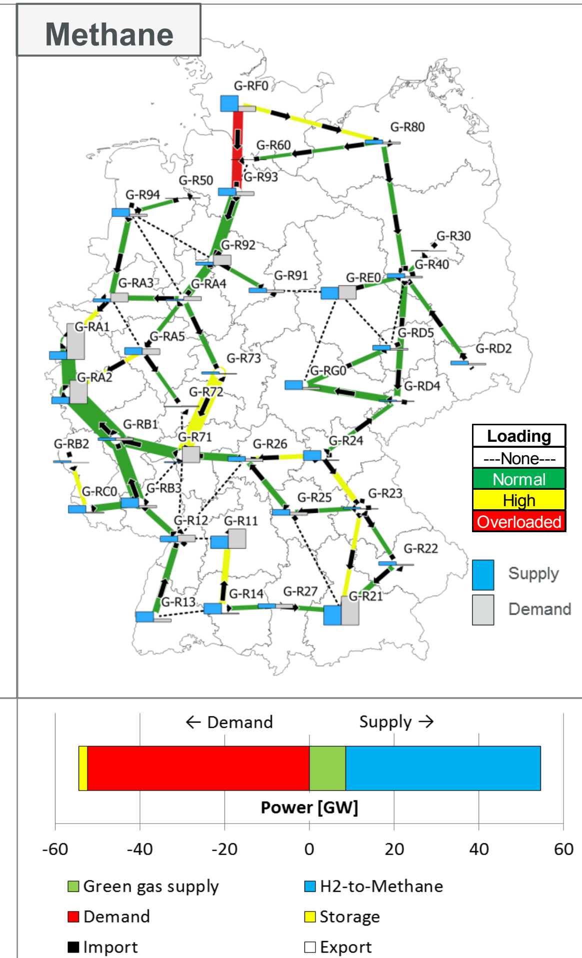
Infrastructure calculations (DE)

Base cases (Enervis_4358)

High RES + low electrical demand



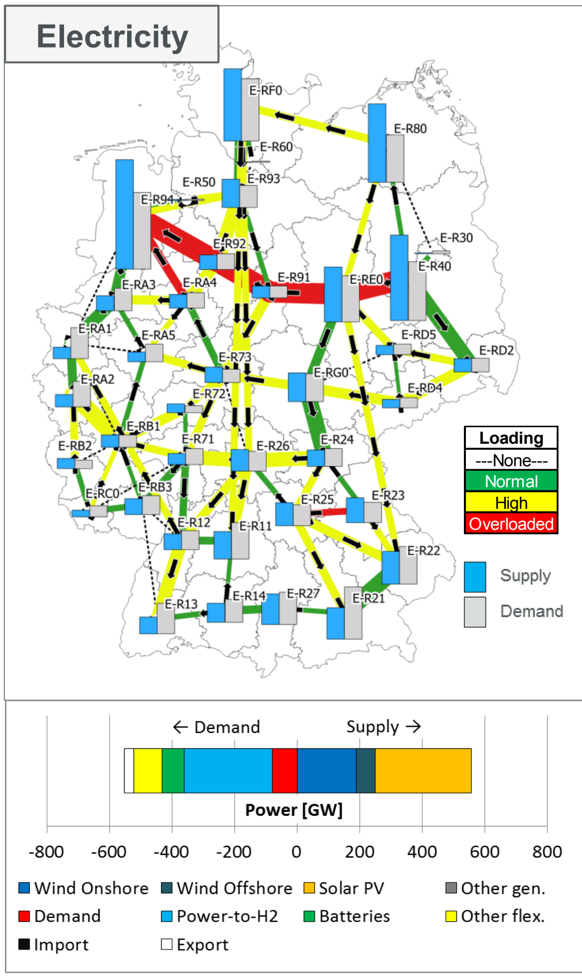


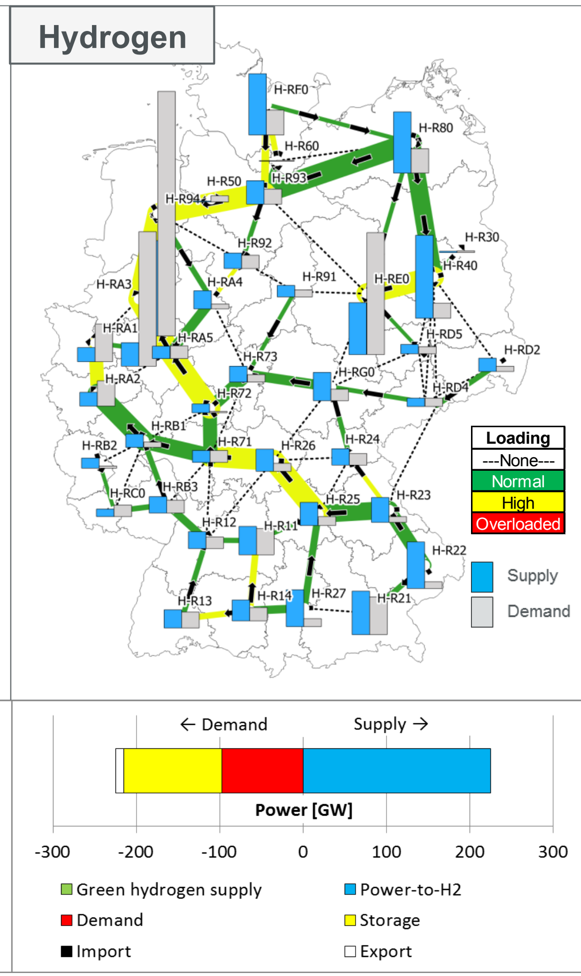


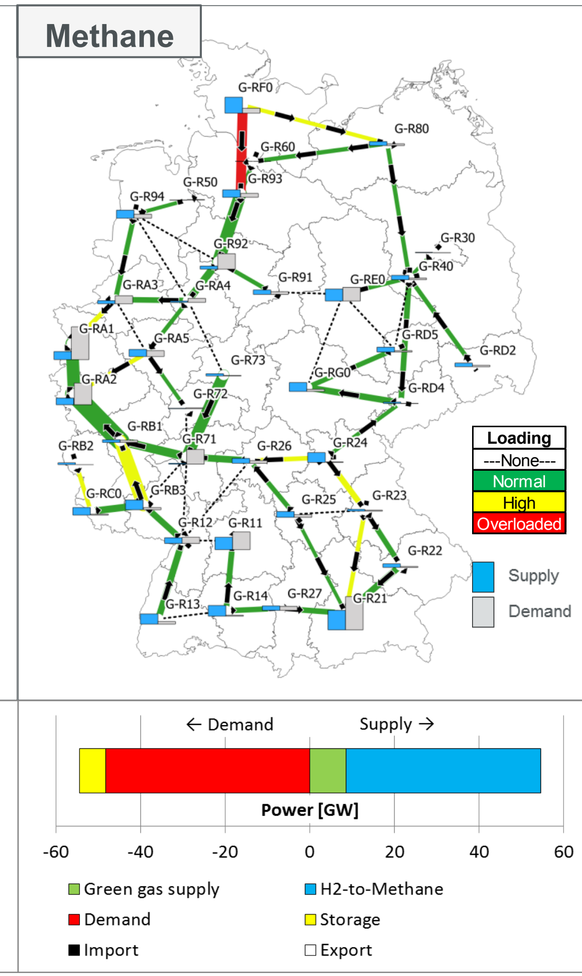
Infrastructure calculations (DE)

High RES + low electrical demand

Base cases (Enervis_4526)







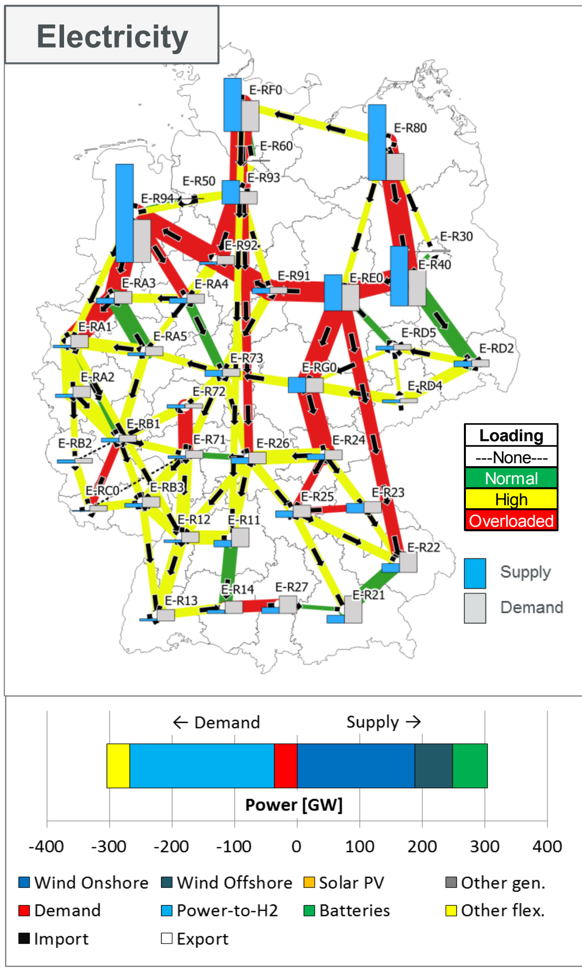
gasunie crossing borders in energy

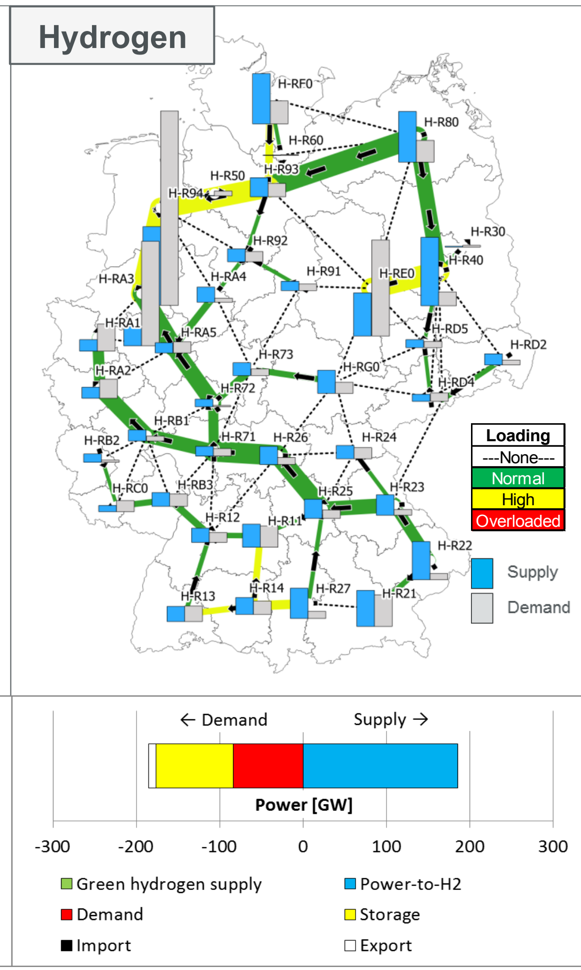
TenneT Taking power further

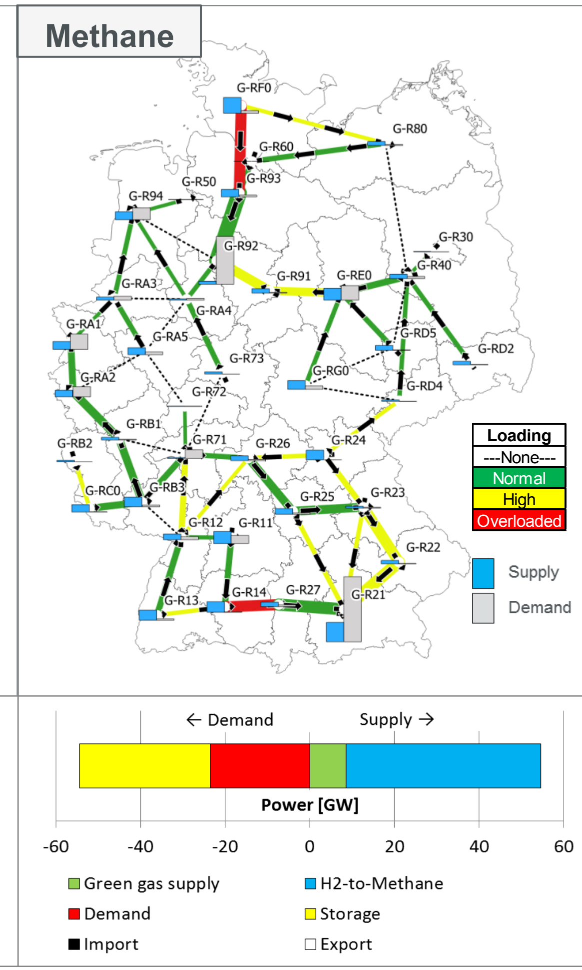
Infrastructure calculations (DE)

Base cases (Enervis_4943)

High RES + low electrical demand







gasunie crossing borders in energy

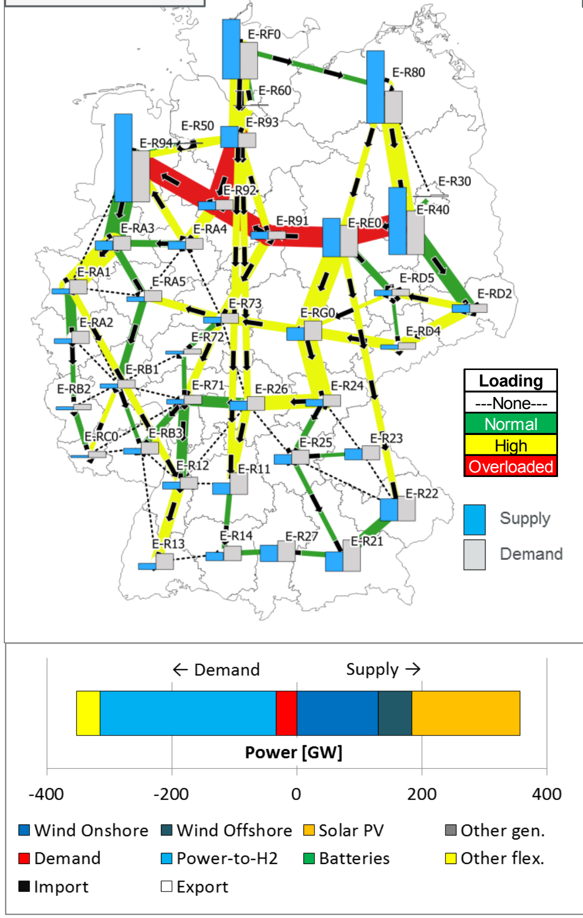
TenneT Taking power further

Infrastructure calculations (DE)

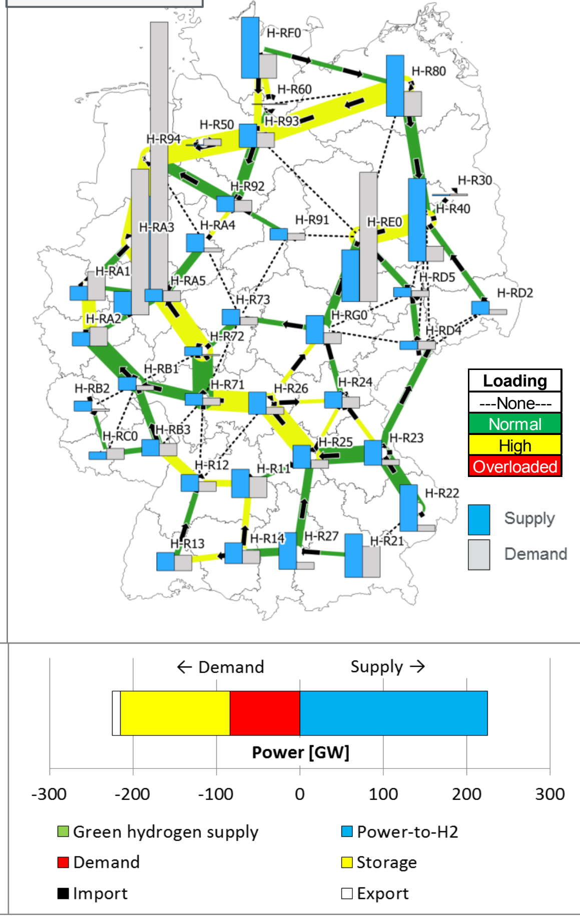
Base cases (Enervis_4953)

High RES + low electrical demand

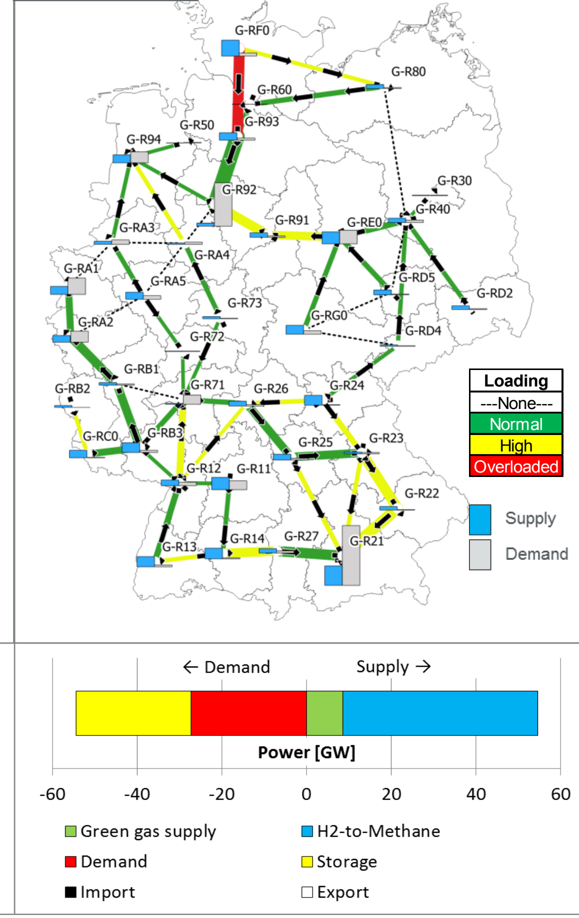
Electricity



Hydrogen



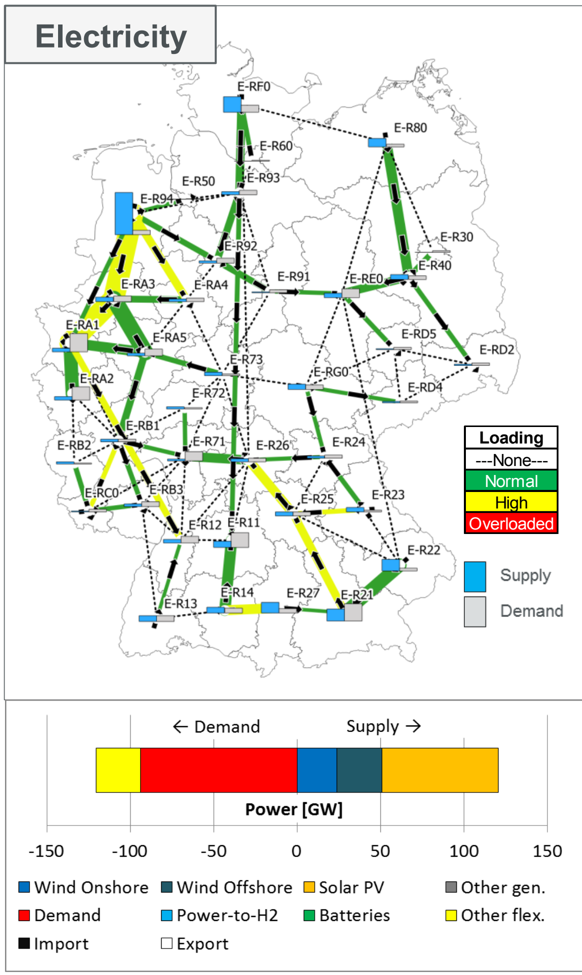
Methane

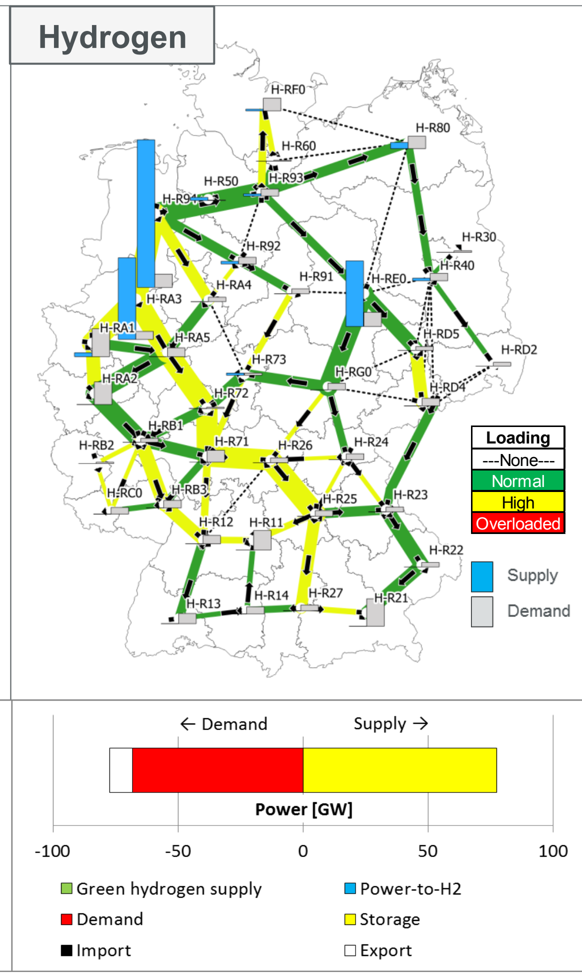


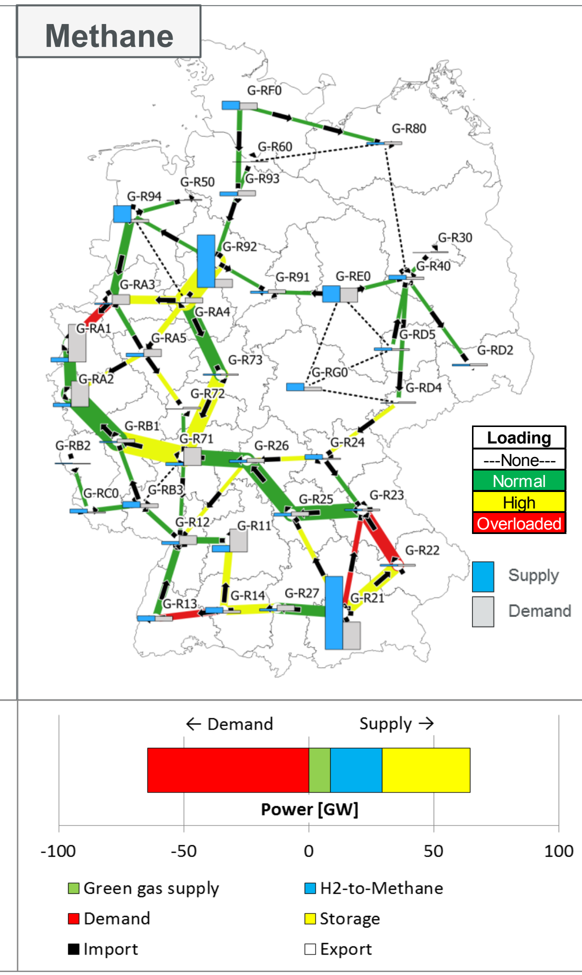
Infrastructure calculations (DE)

Base cases (Enervis_8174)

High RES + low electrical demand







Infrastructure Calculations

- National Szenario (FNB)

Infrastructure calculations (DE):

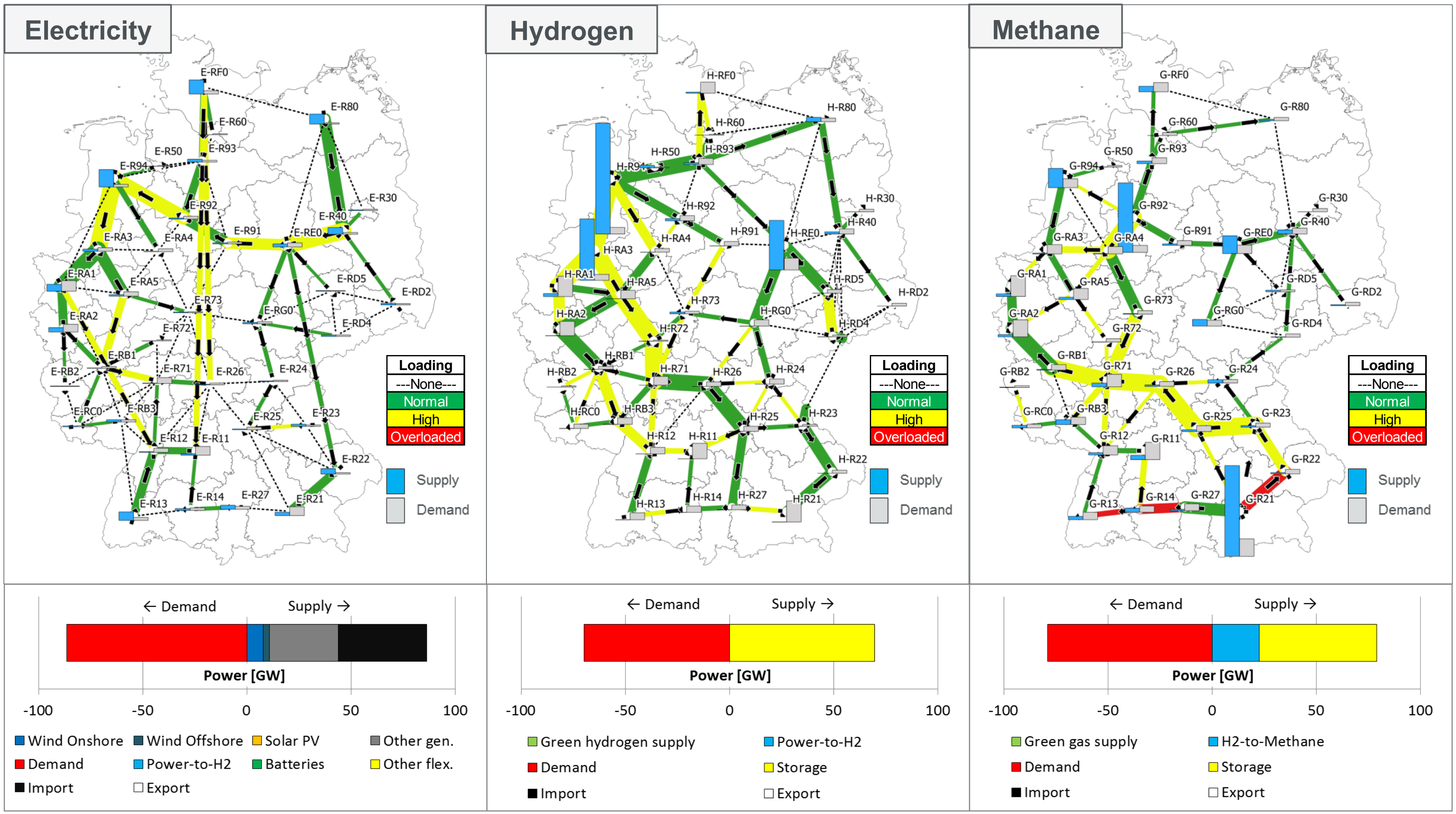
Overview snapshot base cases

Scenario	Snapshot hour	Description
FNB	1451	High wind + high total demand (incl. flexibility)
FNB	1450	High wind + high electrical demand
FNB	914	High wind + low electrical demand
FNB	914	High wind offshore + low solar PV + high Hydraulic charging
FNB	5057/914	High wind offshore + high hydraulic charging
FNB	5126	High Solar Low Demand
FNB	4358	High Solar High Demand
FNB	474	Low RES + high total demand
FNB	474	Low RES + high electrical demand

Infrastructure calculations (DE)

High RES + high electrical demand

Base cases (FNB_474)



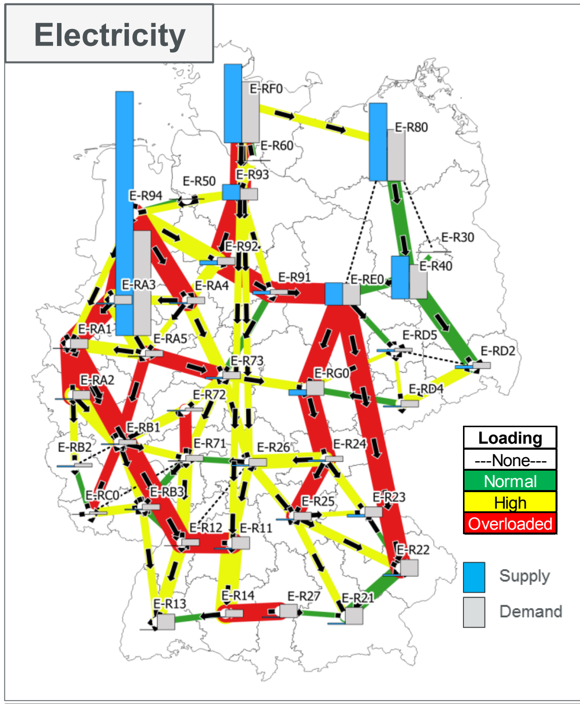
crossing borders in energy

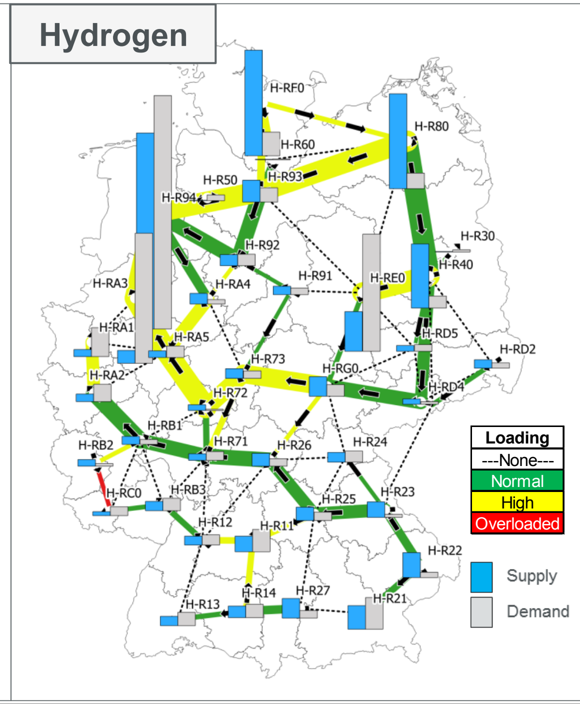
Taking power further

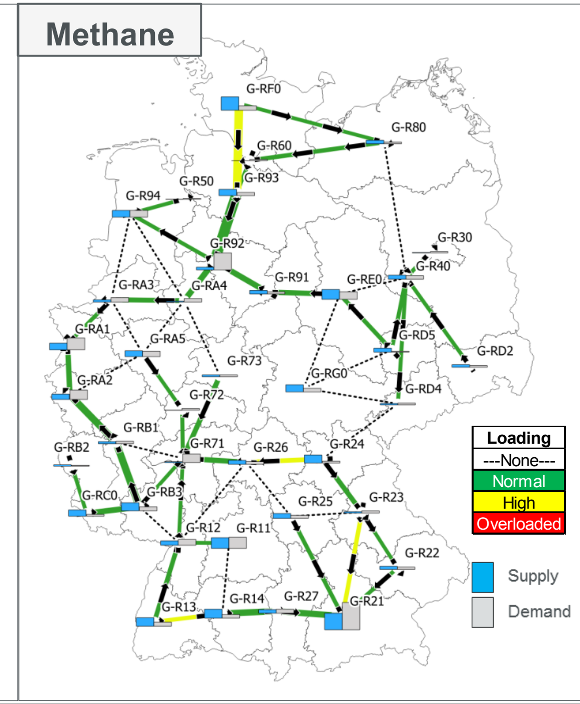
Infrastructure calculations (DE)

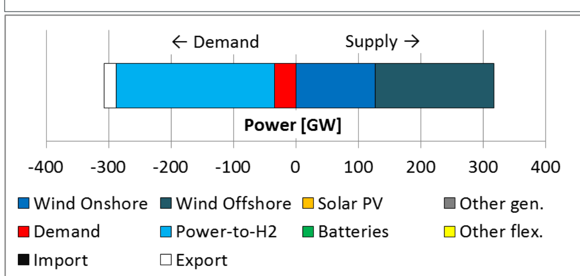
High RES + high electrical demand

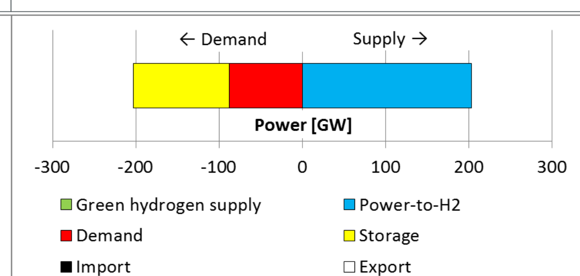
Base cases (FNB_914)

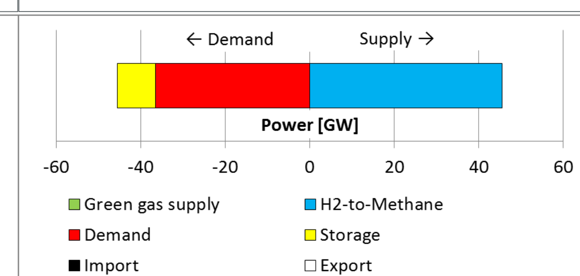












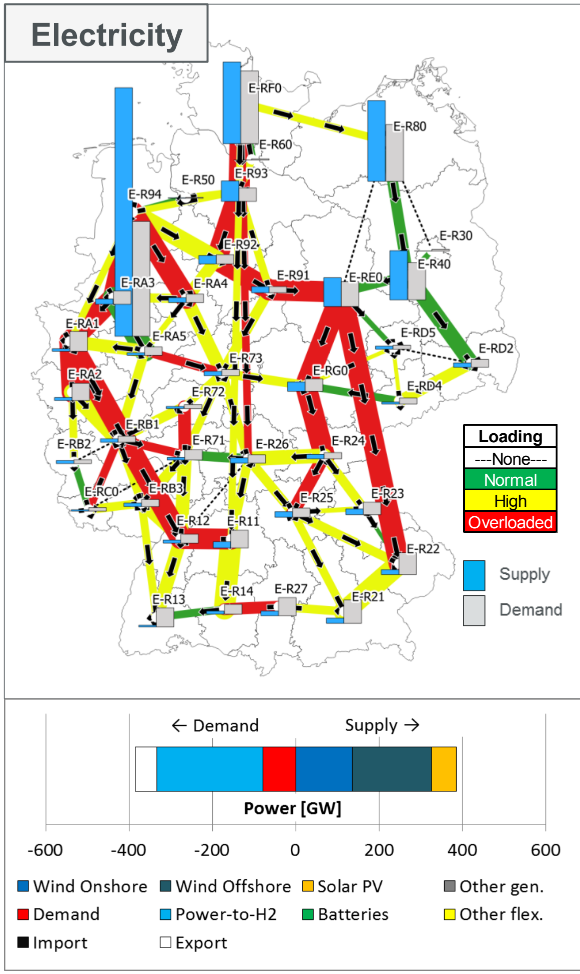
gasunie crossing borders in energy

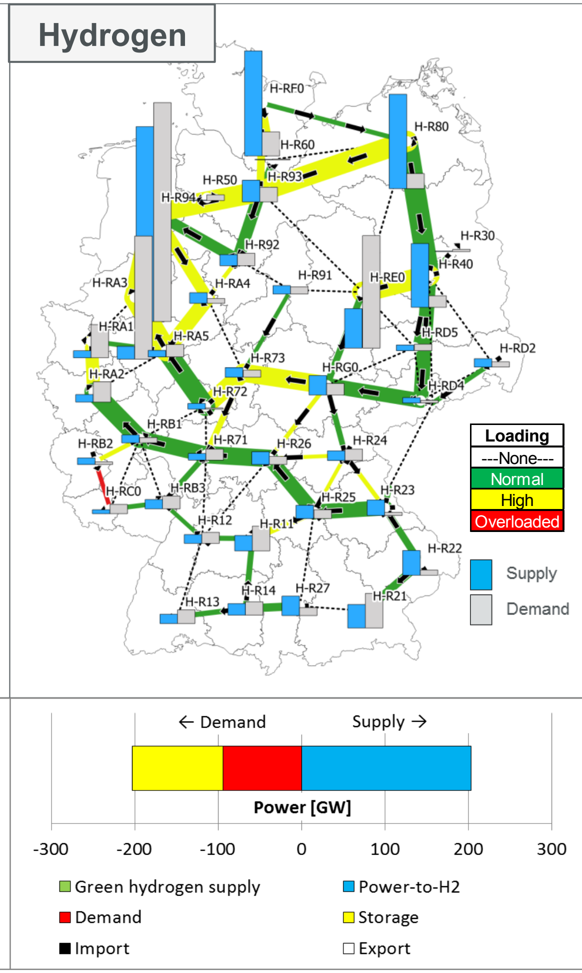
TenneT Taking power further

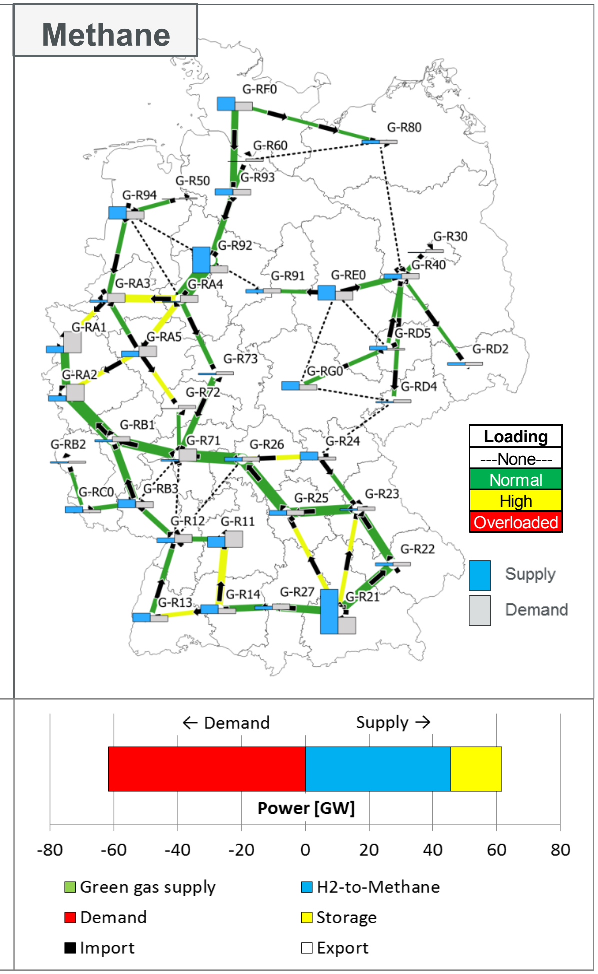
Infrastructure calculations (DE)

High RES + high electrical demand

Base cases (FNB_1450)





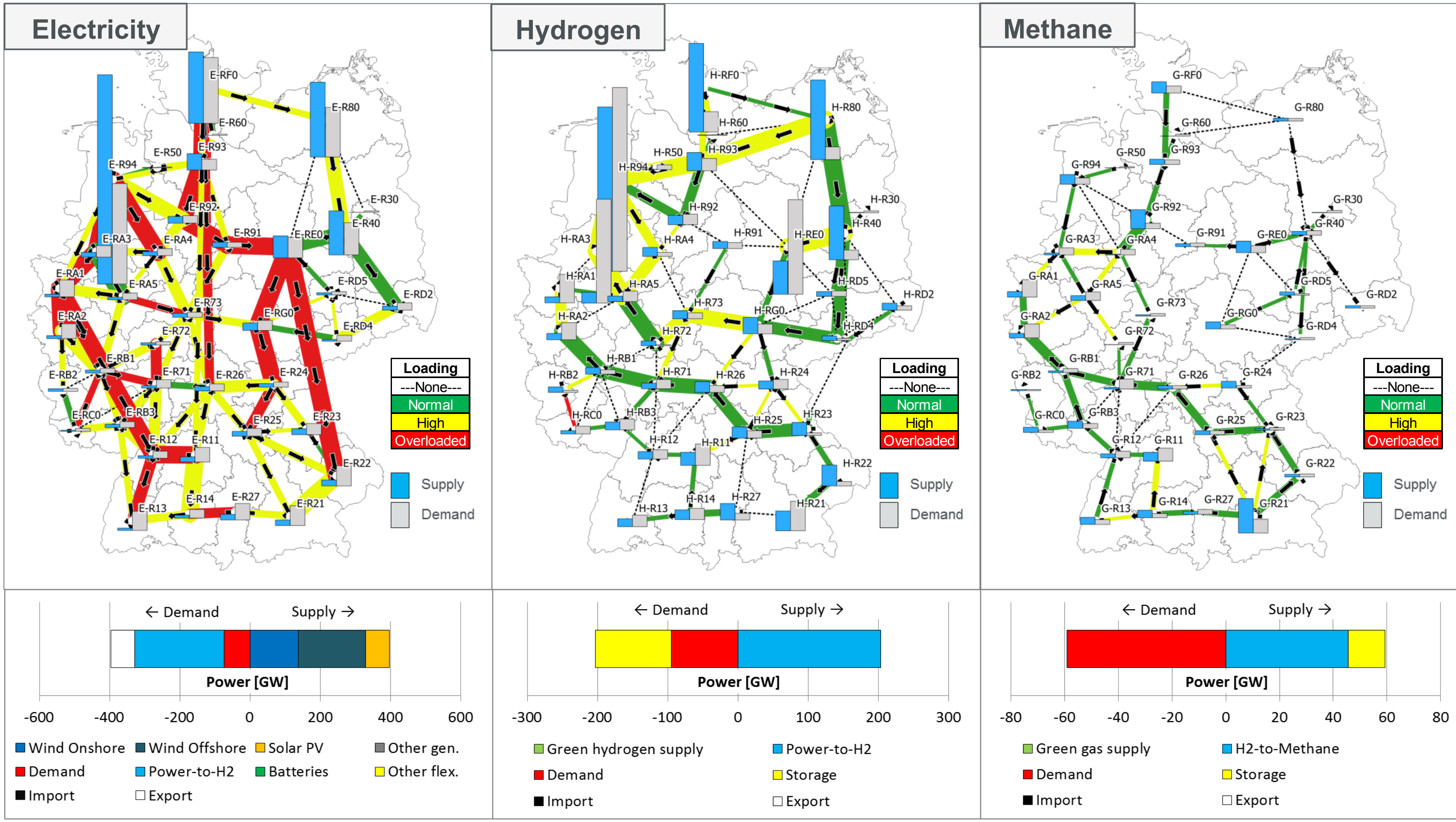


gasunie crossing borders in energy | TenneT Taking power further

Infrastructure calculations (DE)

High RES + high electrical demand

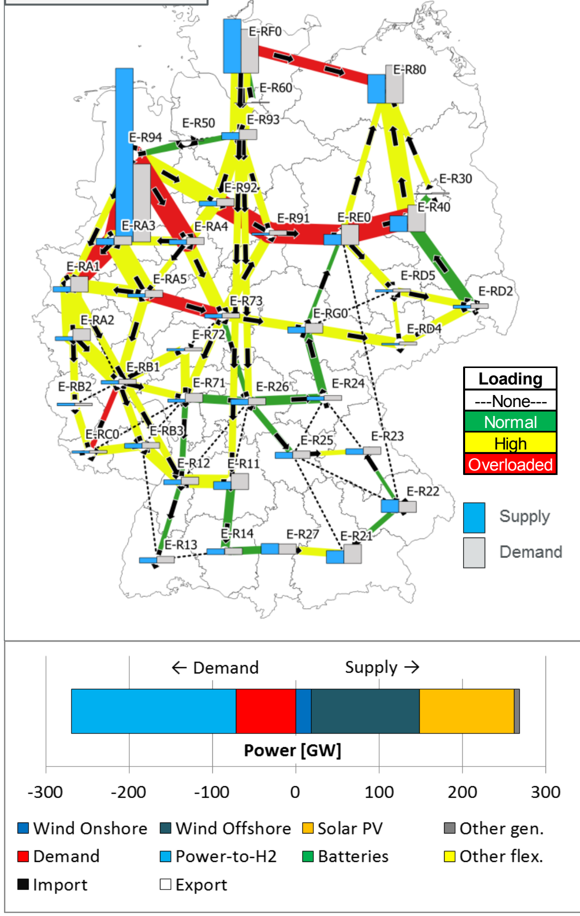
Base cases (FNB_41451)



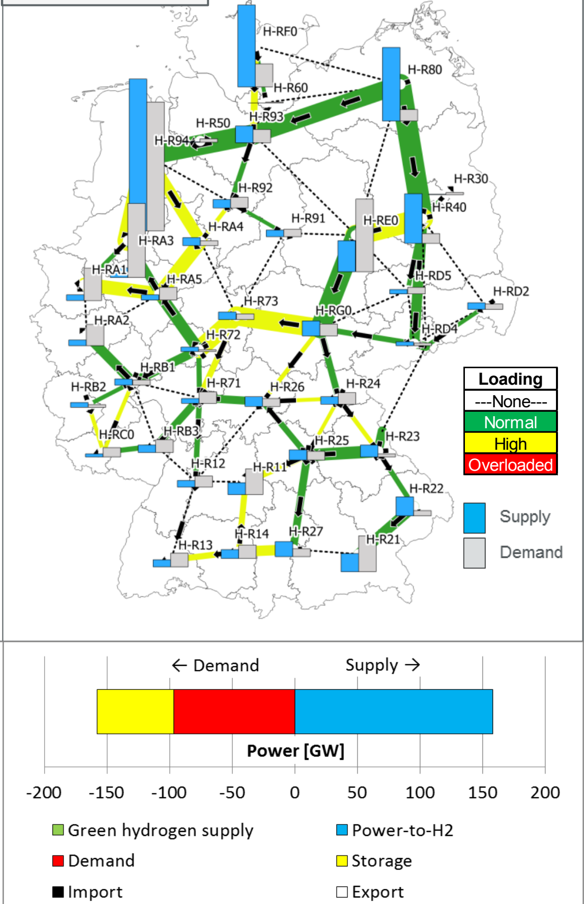
Infrastructure calculations (DE)

Base cases (FNB_4358)

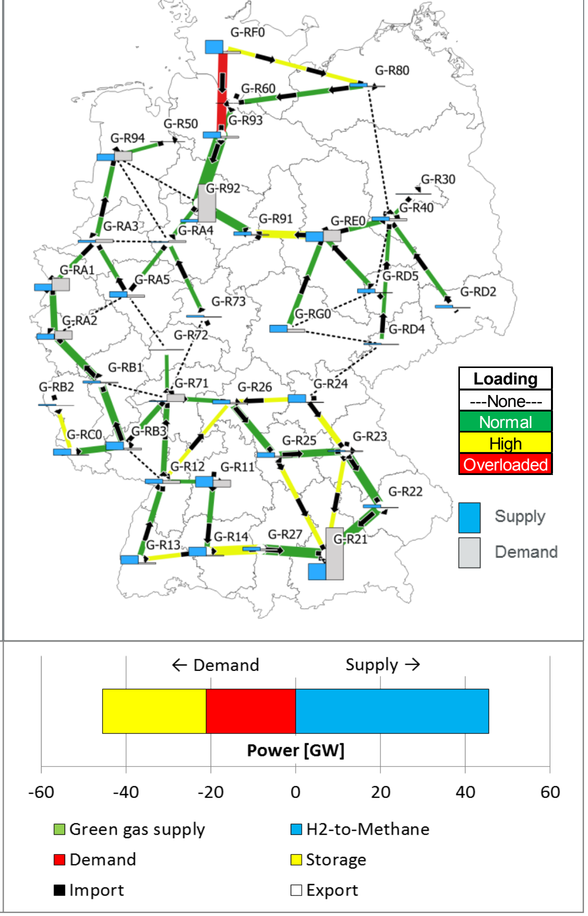
Electricity



Hydrogen



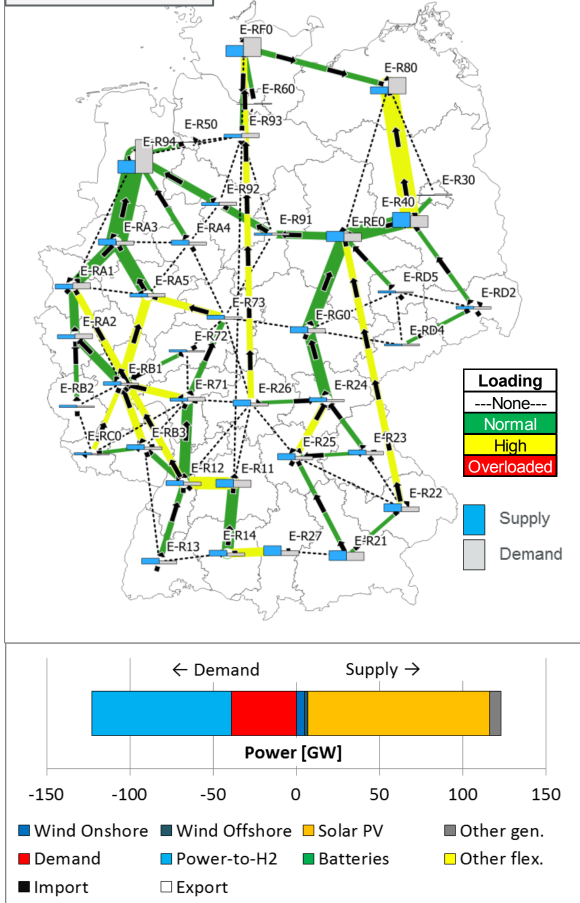
Methane



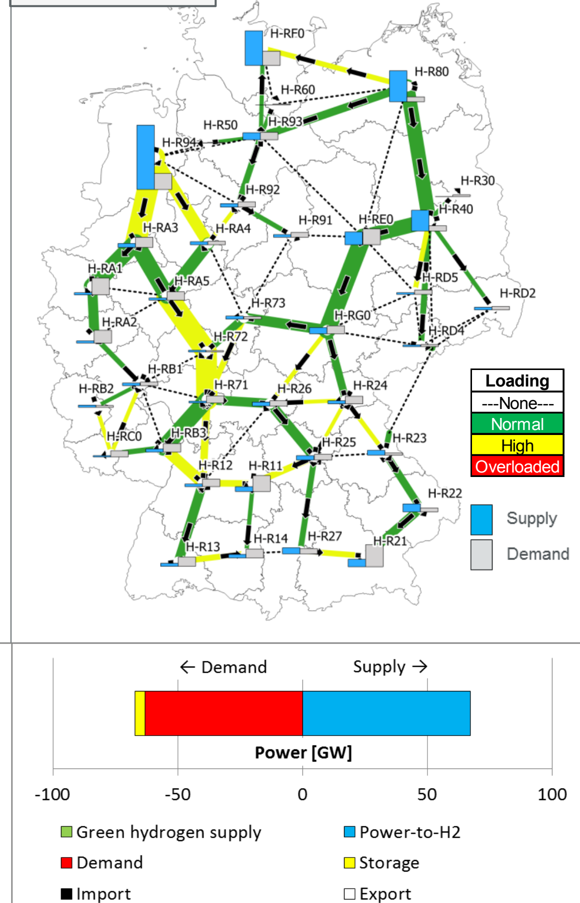
Infrastructure calculations (DE)

Base cases (FNB_5126)

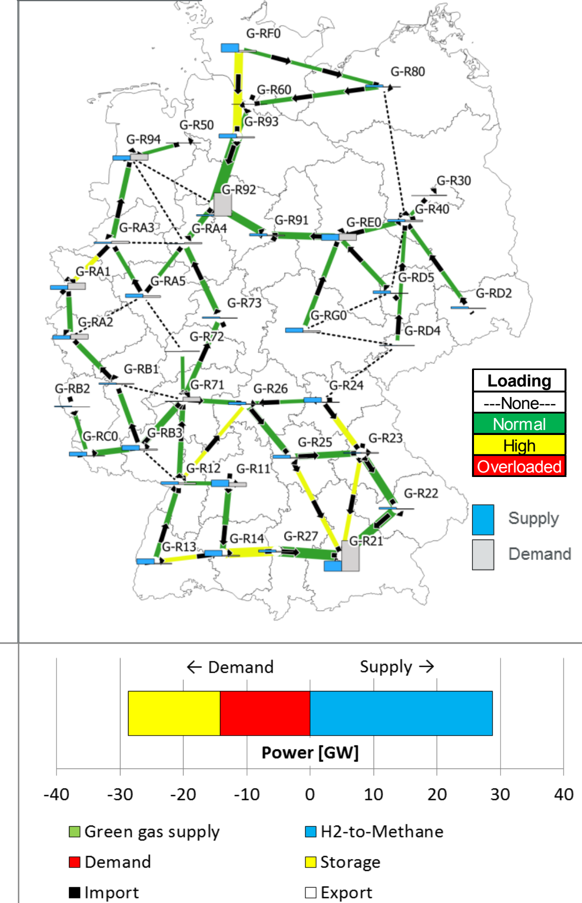
Electricity



Hydrogen



Methane



Infrastructure Calculations

- International Szenario (dena)

Infrastructure calculations (DE)

Overview snapshot base cases

Scenario	Snapshot hour	Description
Dena	1450	High Wind - High Conventional
Dena	915	High Wind - Low Conventional
Dena	1884	High Solar - High Conventional
Dena	5126	High Solar - Low Conventional
Dena	474	Low RES - High Conventional
Dena	1477	Maximum hydrogen supply + hydrogen/gas demand + maximum gas storage decharging

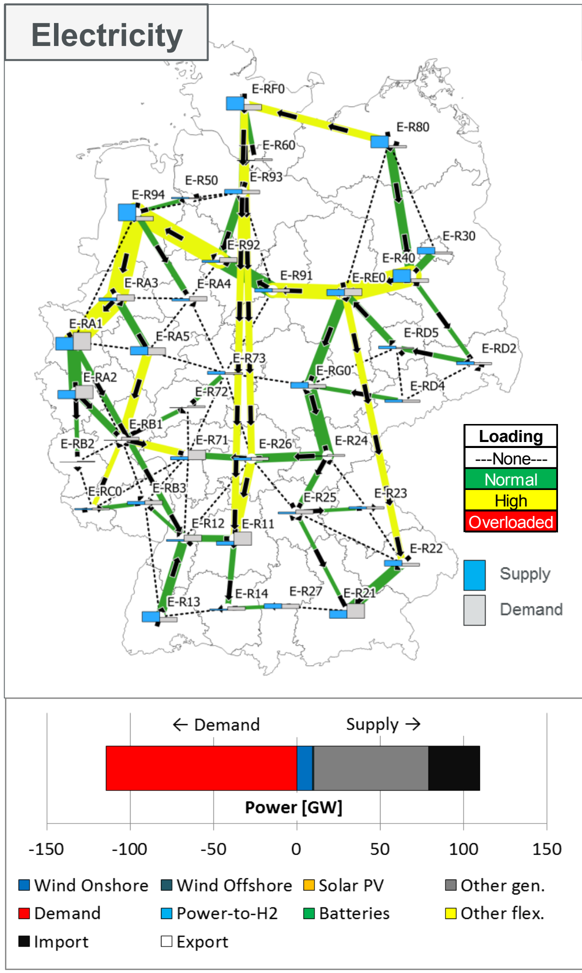
gasunie
crossing borders in energy

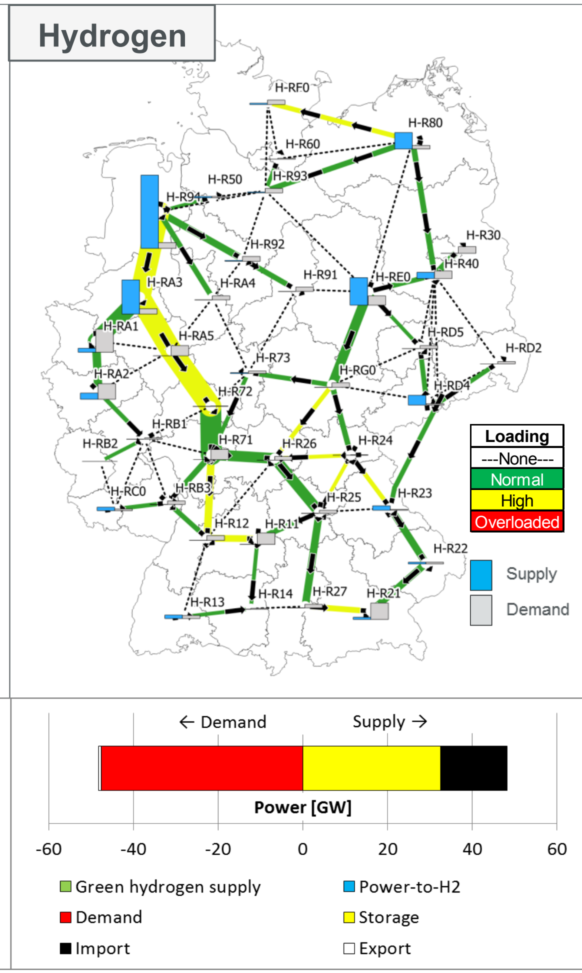
TenneT
Taking power further

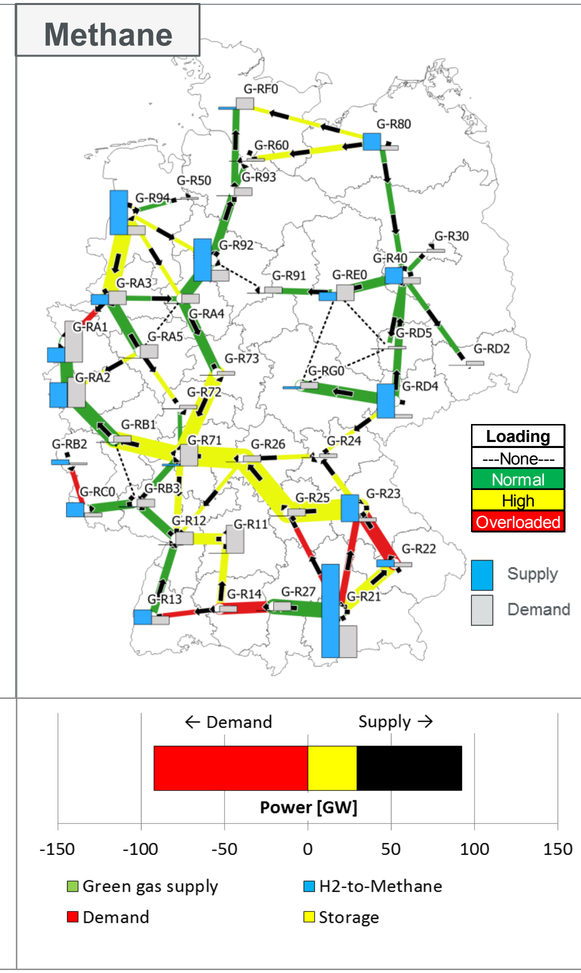
Infrastructure calculations (DE)

High RES + high electrical demand

Base cases (dena_474)





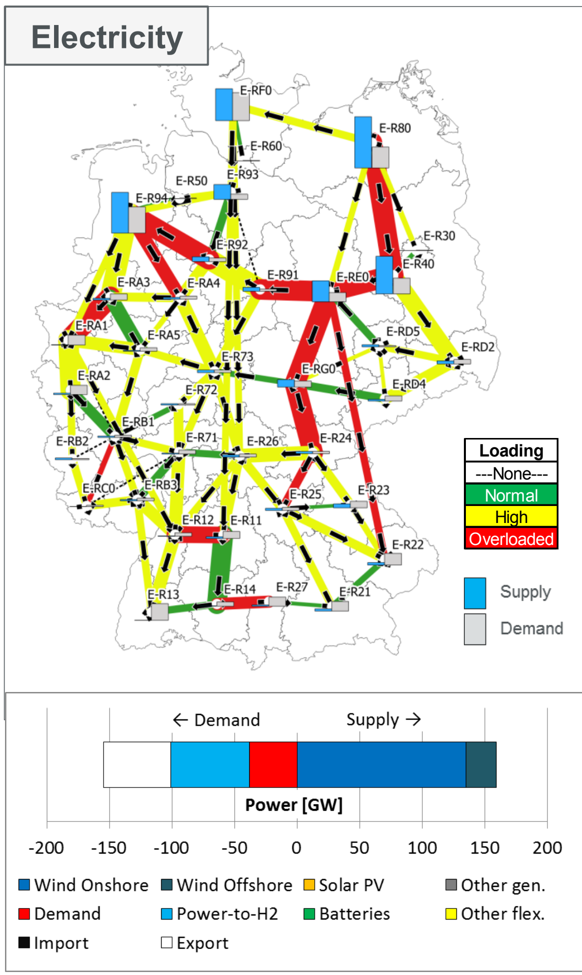


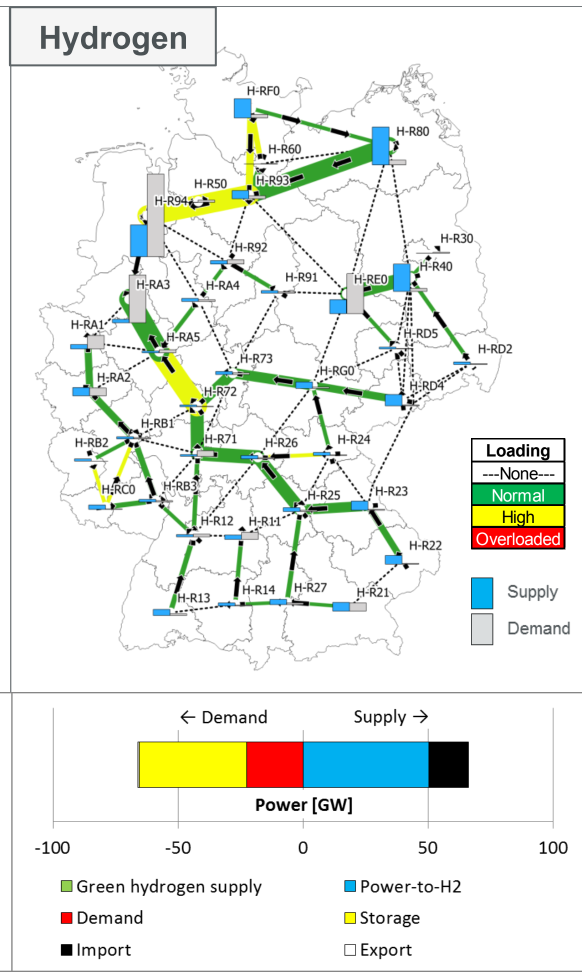
gasunie crossing borders in energy

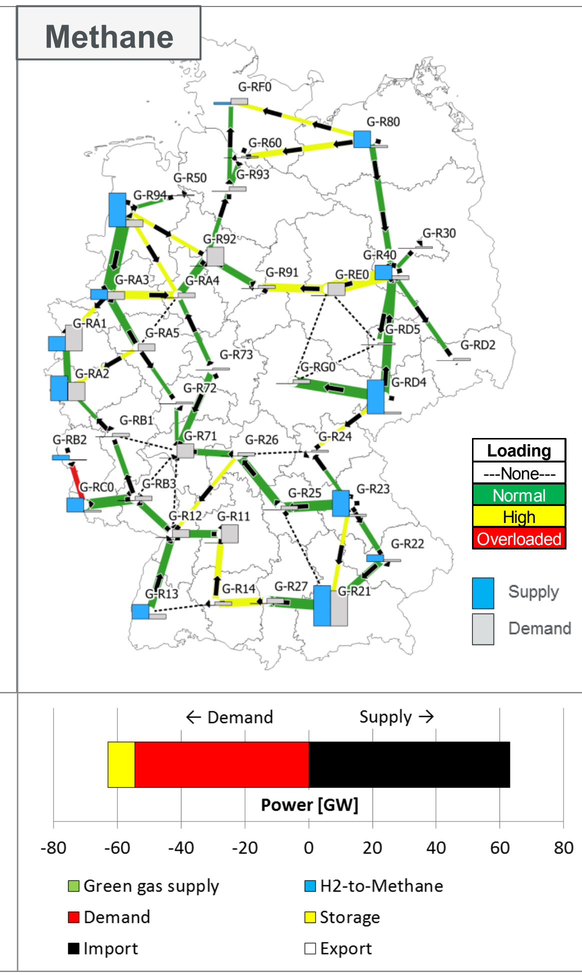
TenneT Taking power further

Infrastructure calculations (DE)

Base cases (dena_915)

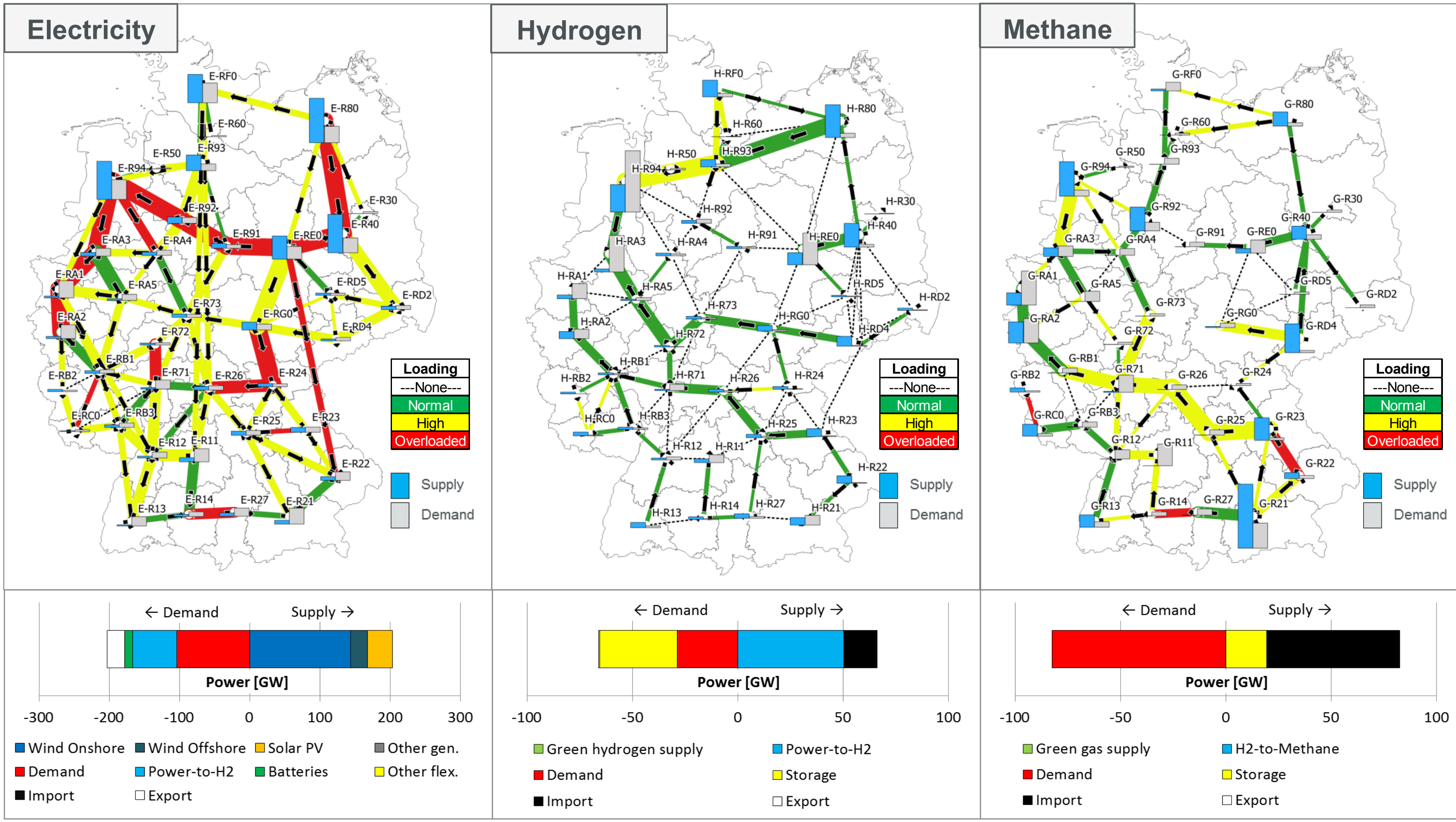






Infrastructure calculations (DE)

Base cases (dena_1450)

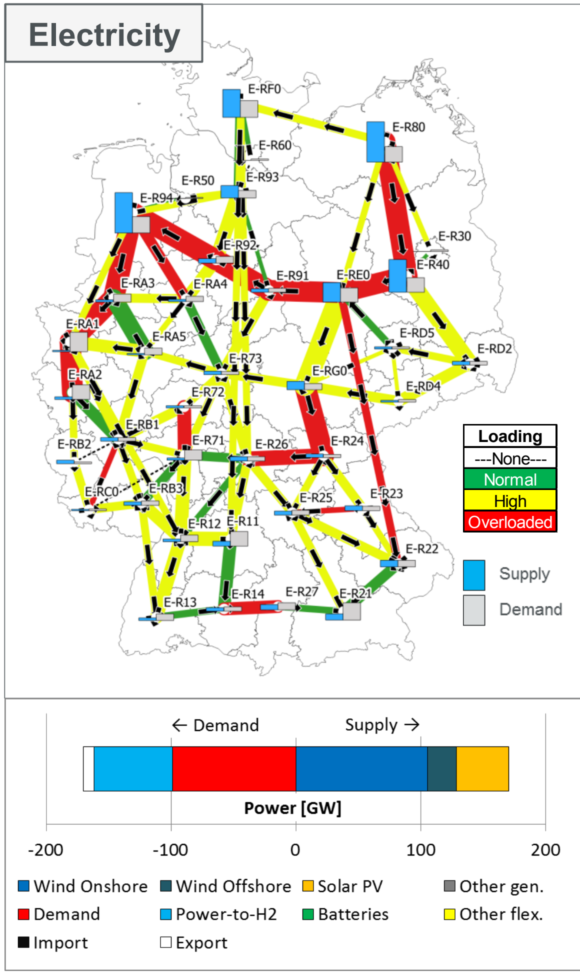


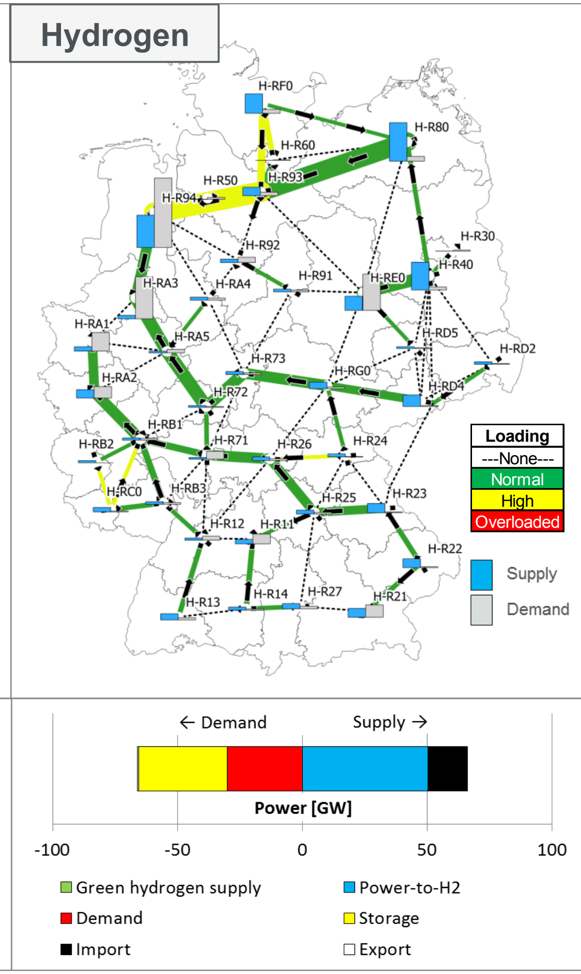
gasunie crossing borders in energy

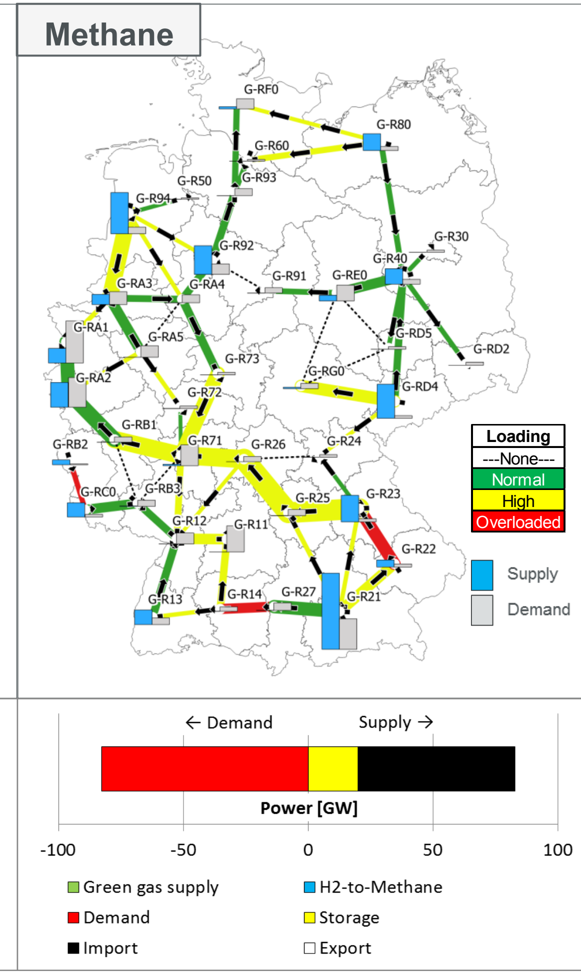
TenneT Taking power further

Infrastructure calculations (DE)

Base cases (dena_1477)





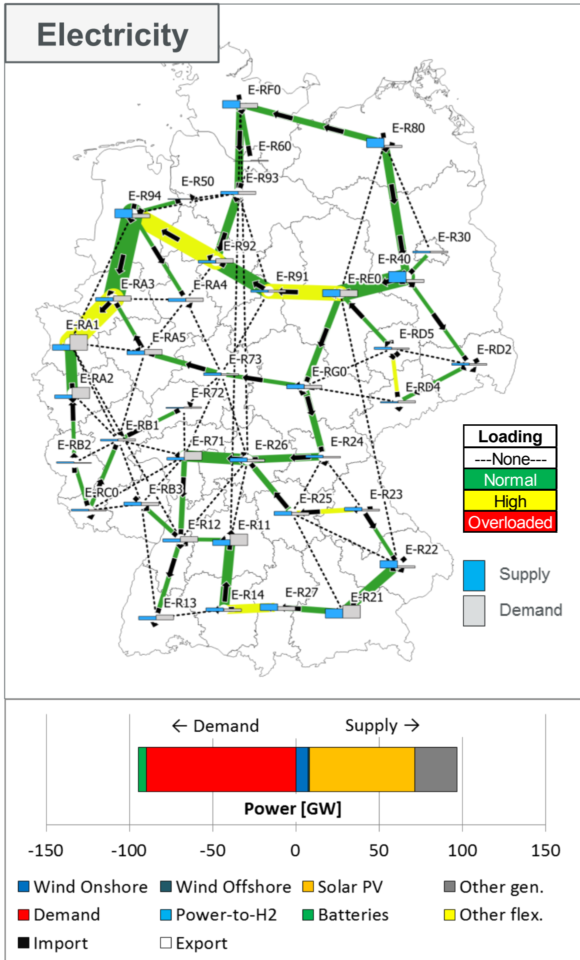


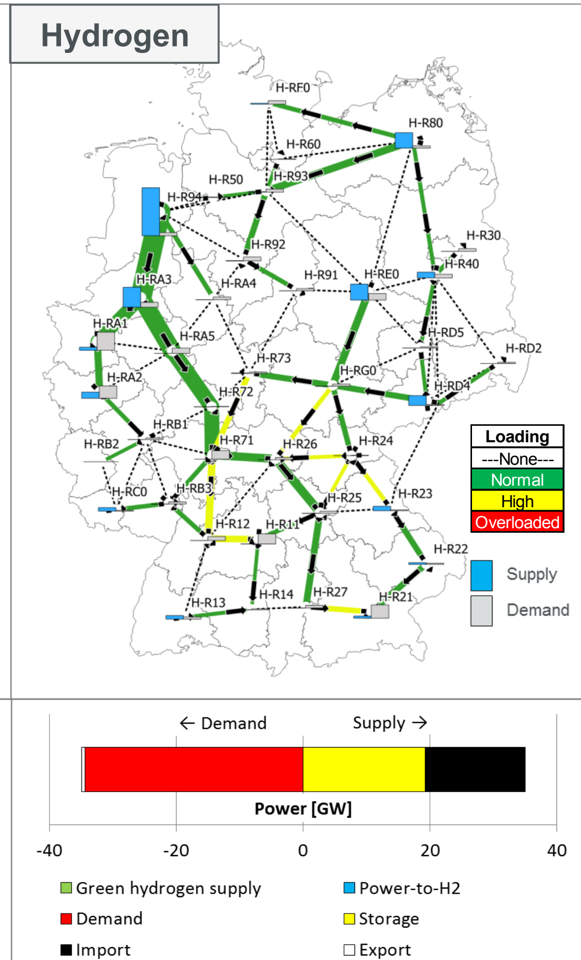
gasunie crossing borders in energy

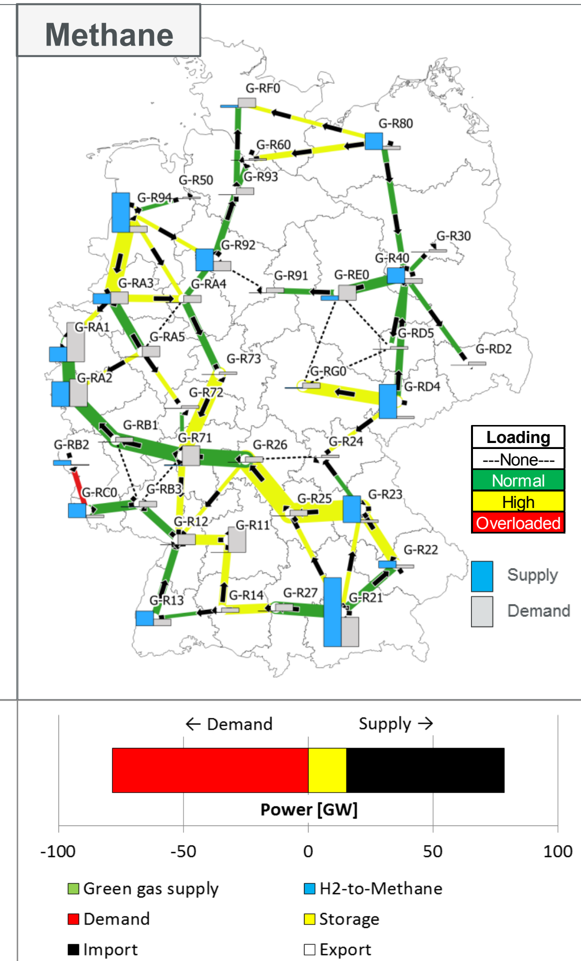
TenneT Taking power further

Infrastructure calculations (DE)

Base cases (dena_1884)





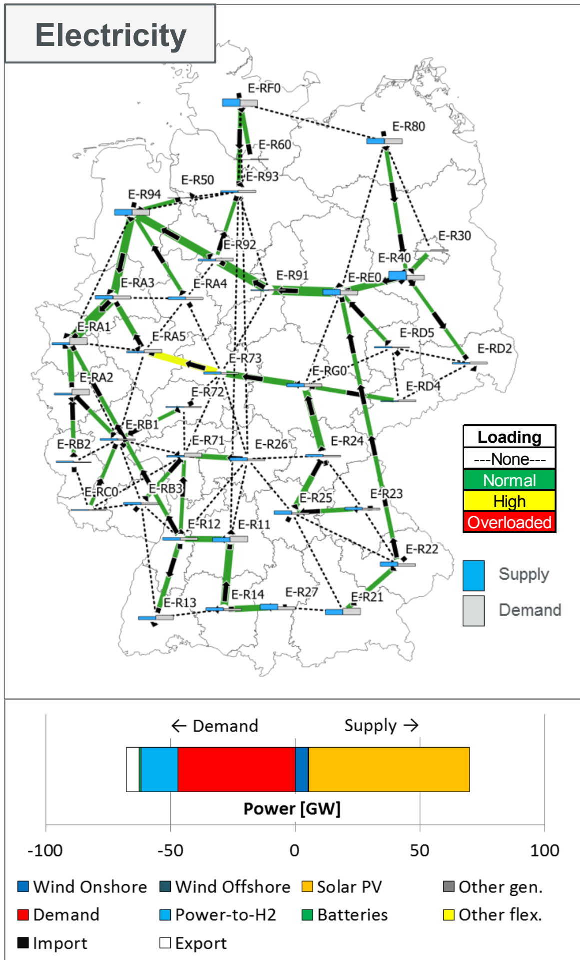


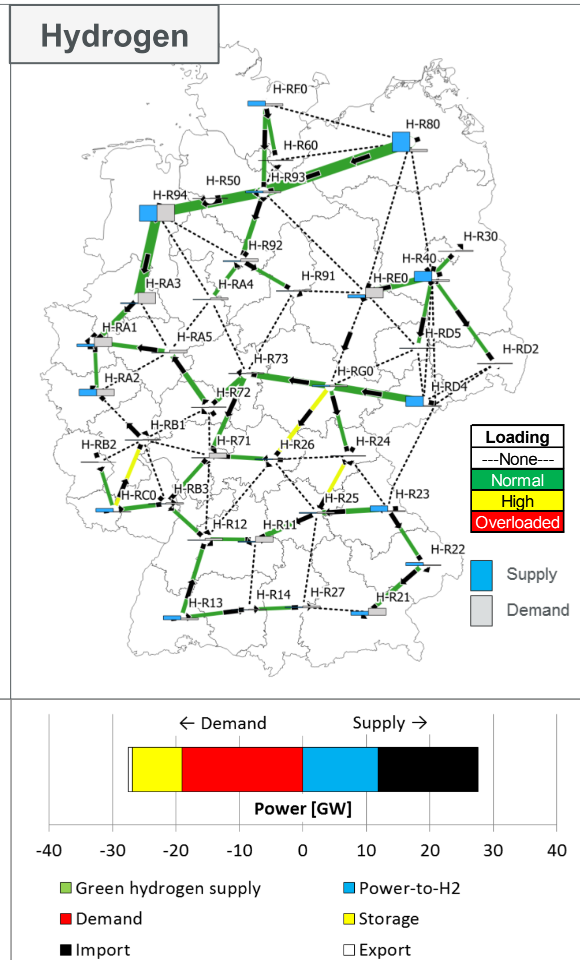
gasunie crossing borders in energy

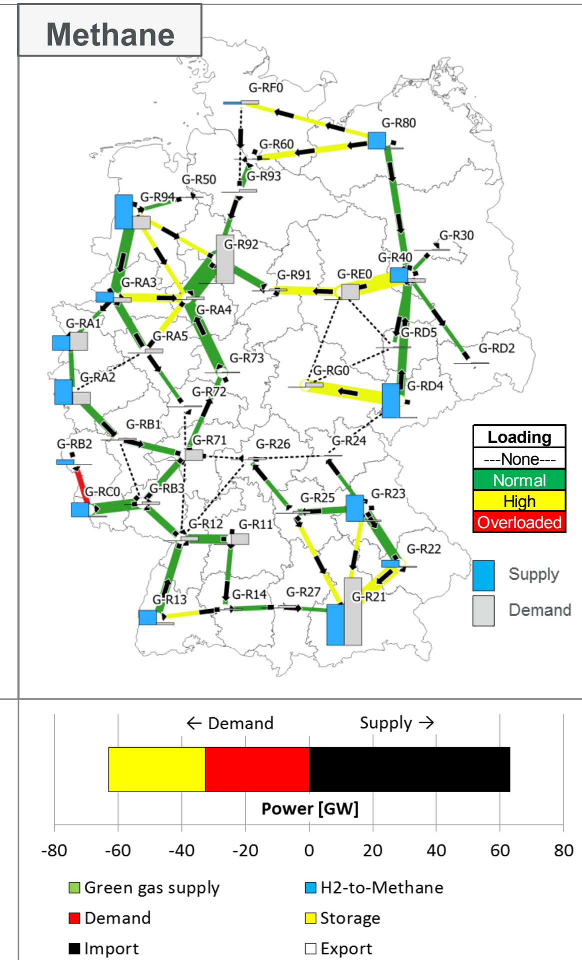
TenneT Taking power further

Infrastructure calculations (DE)

Base cases (dena_5126)







Infrastructure Calculations

Sensitivity electrolyser

gasunie crossing borders in energy

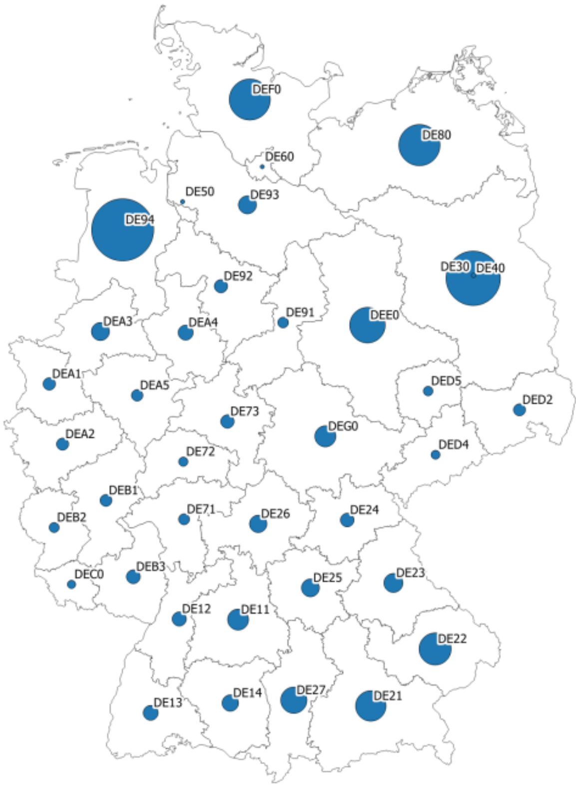
TenneT Taking power further

Infrastructure calculations (DE)

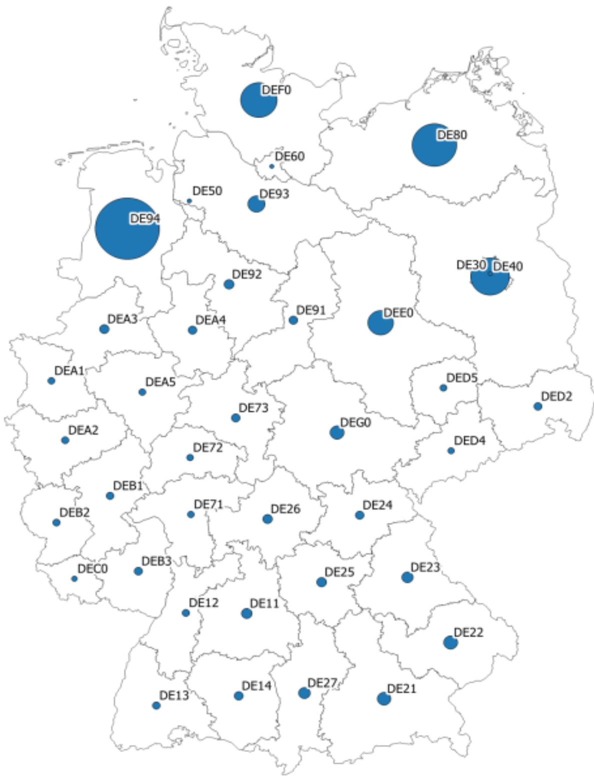
RES-capacity weighted regional distribution key

Variation of PtG locations

Distribution keys according to RES Capacity



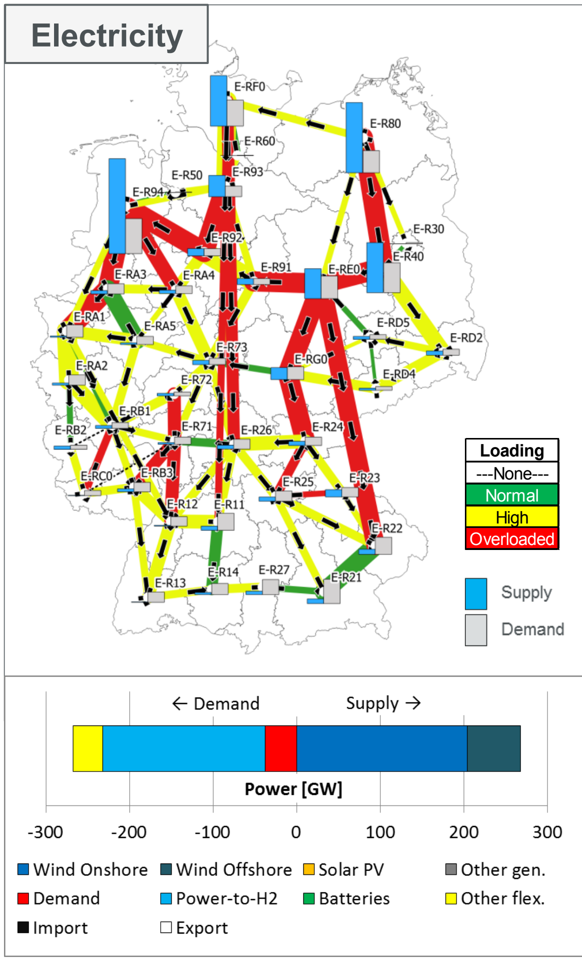
Distribution keys according to RES Energy

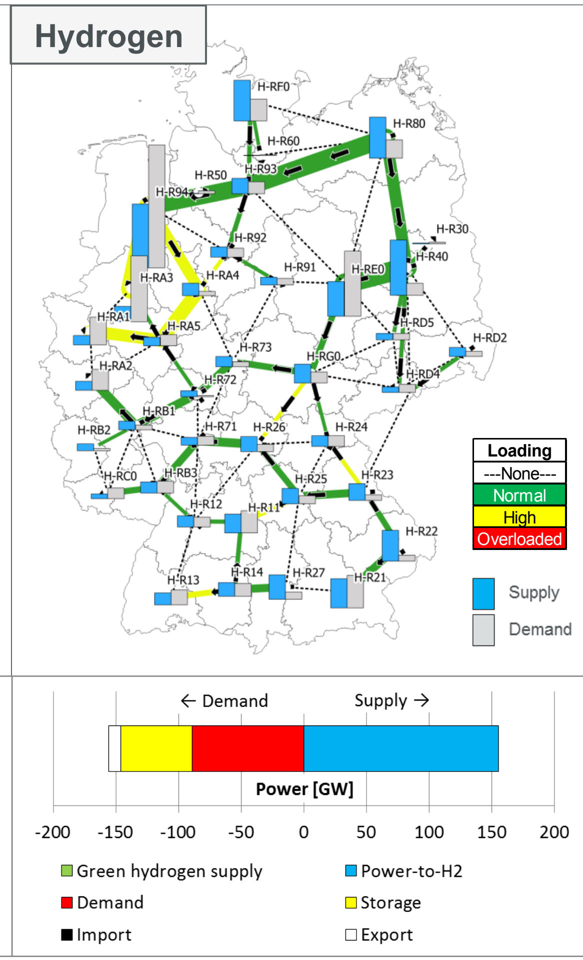


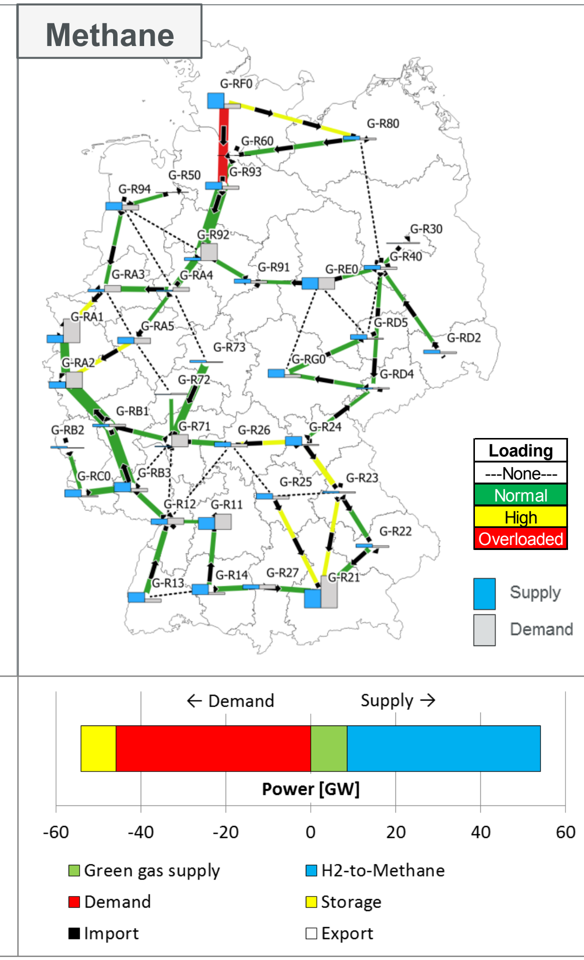
Infrastructure calculations (DE)

RES-capacity weighted regional distribution key

Base cases (Enervis_916)







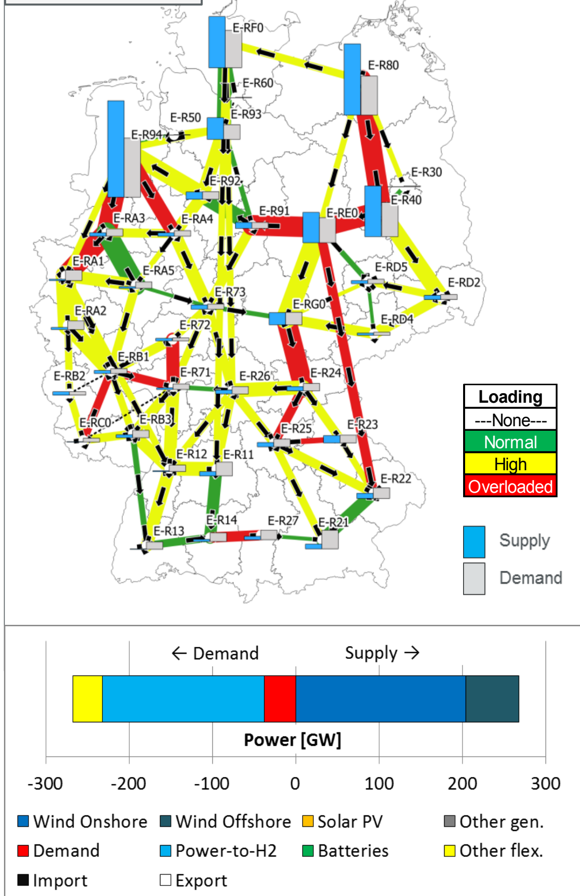
gasunie crossing borders in energy | TenneT Taking power further

Infrastructure calculations (DE)

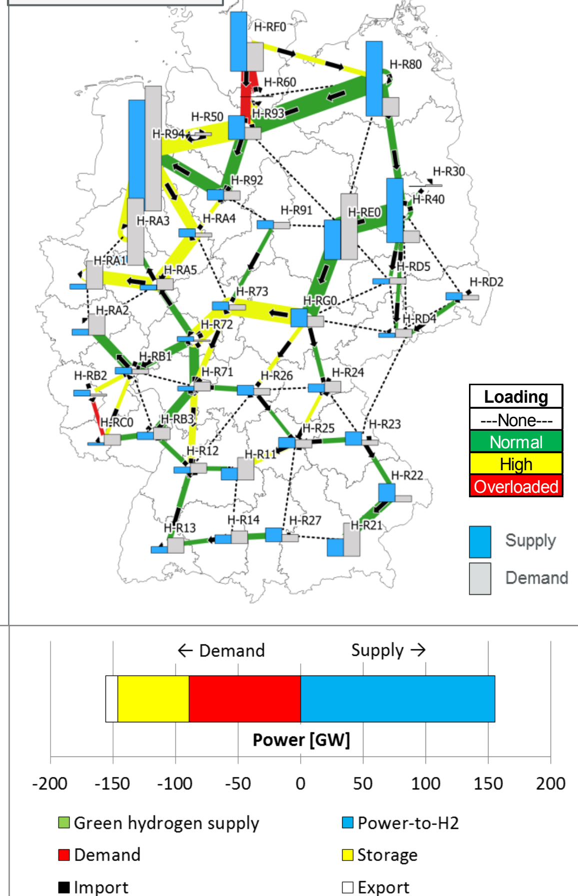
RES-energy weighted regional distribution key

Sensi cases (Enervis_916)

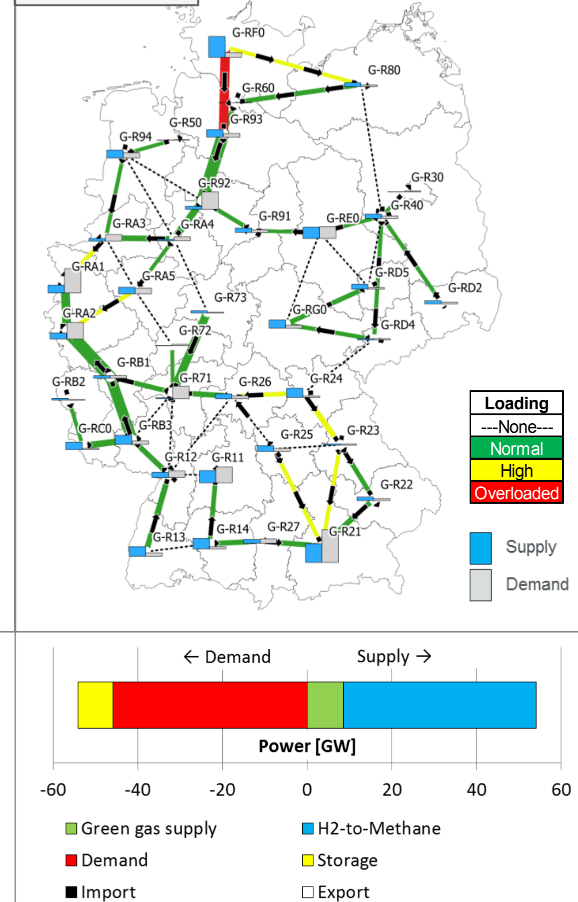
Electricity



Hydrogen



Methane



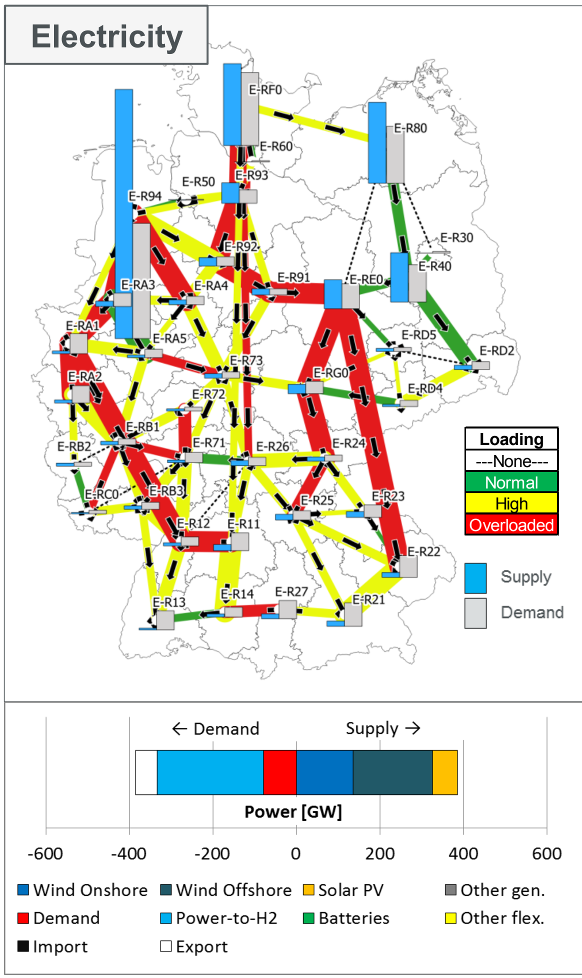
gasunie crossing borders in energy

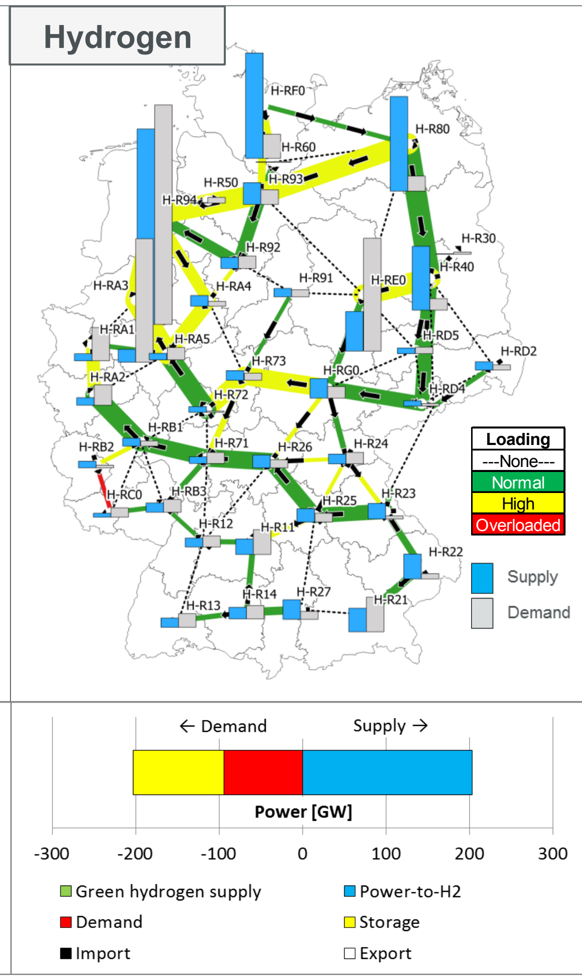
TenneT Taking power further

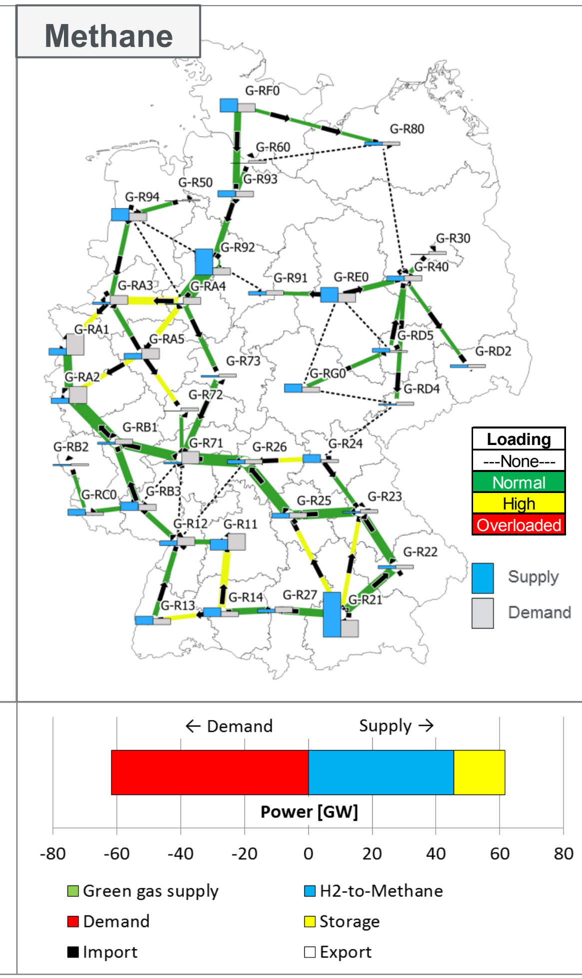
Infrastructure calculations (DE)

RES-capacity weighted regional distribution key

Base cases (FNB_1450)







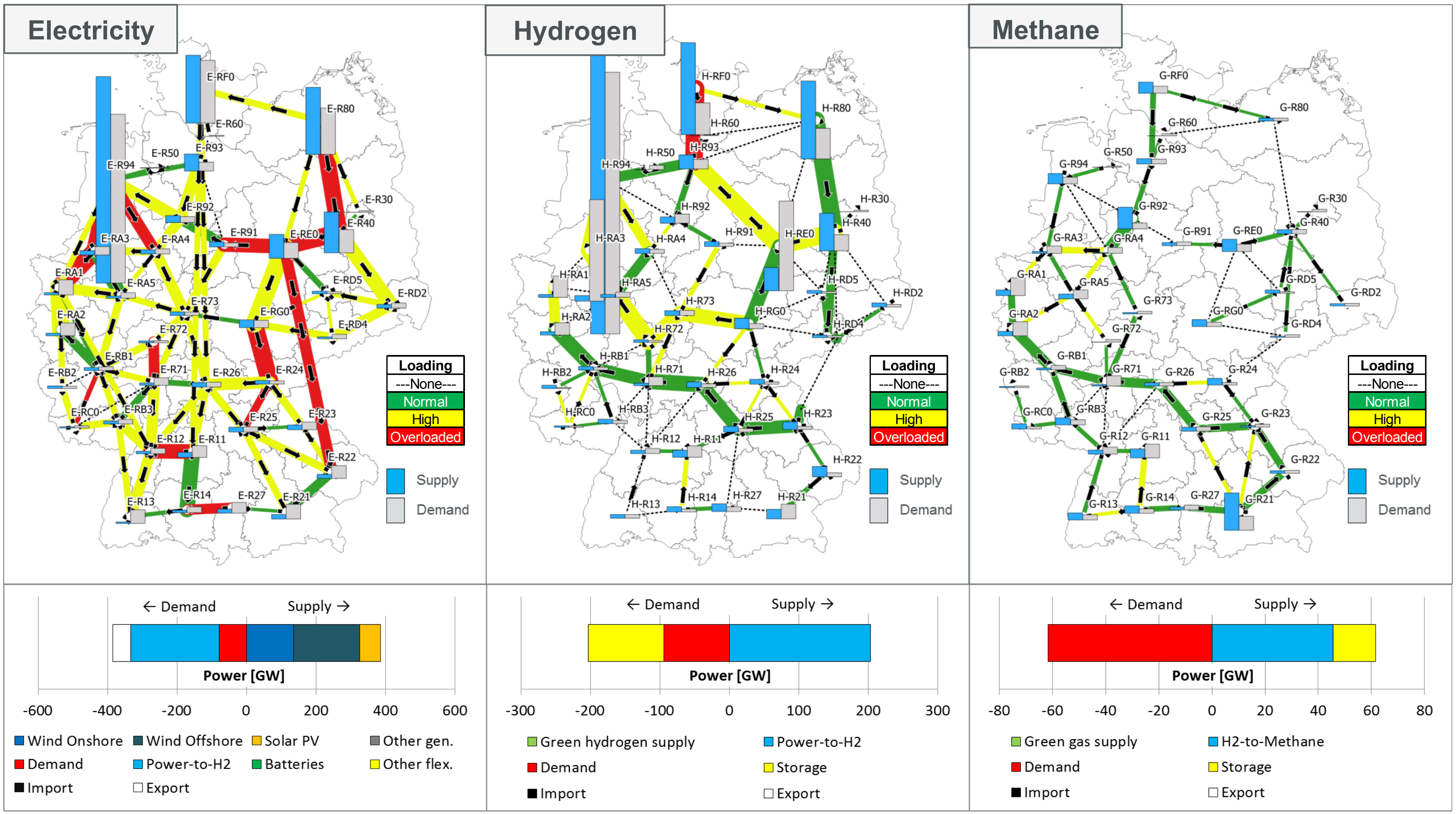
gasunie crossing borders in energy

TenneT Taking power further

Infrastructure calculations (DE)

RES-energy weighted regional distribution key

Sensi cases (FNB_1450)



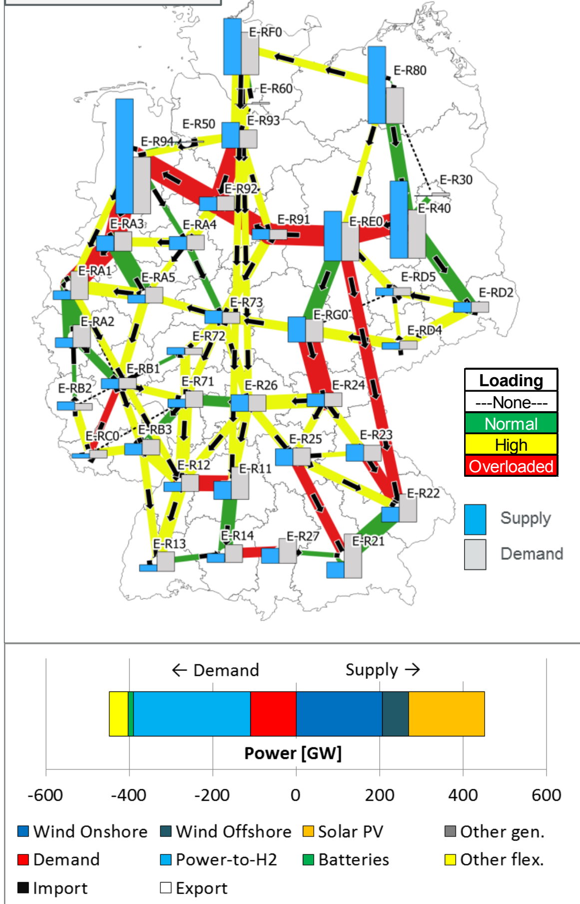
gasunie crossing borders in energy | TenneT Taking power further

Infrastructure calculations (DE)

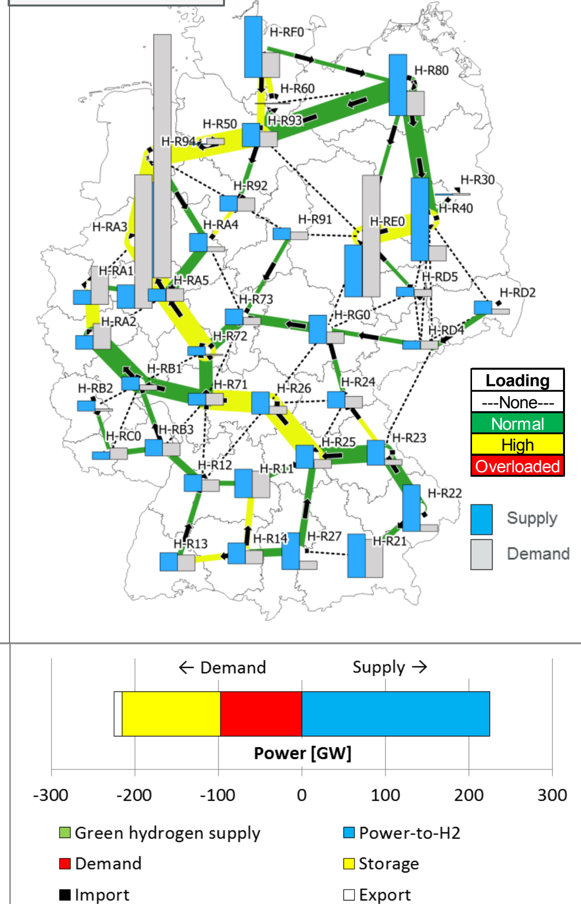
RES-capacity weighted regional distribution key

Base cases (Enervis_1450)

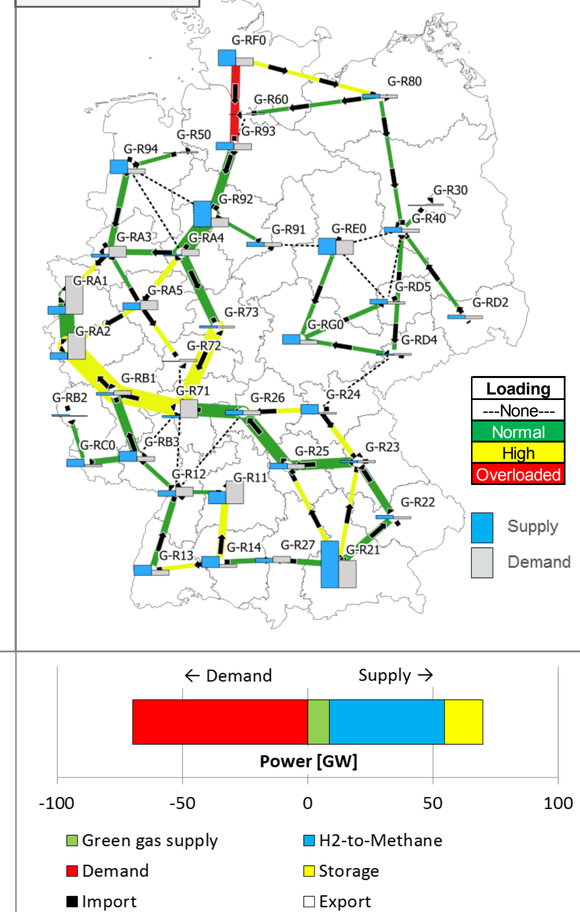
Electricity



Hydrogen



Methane



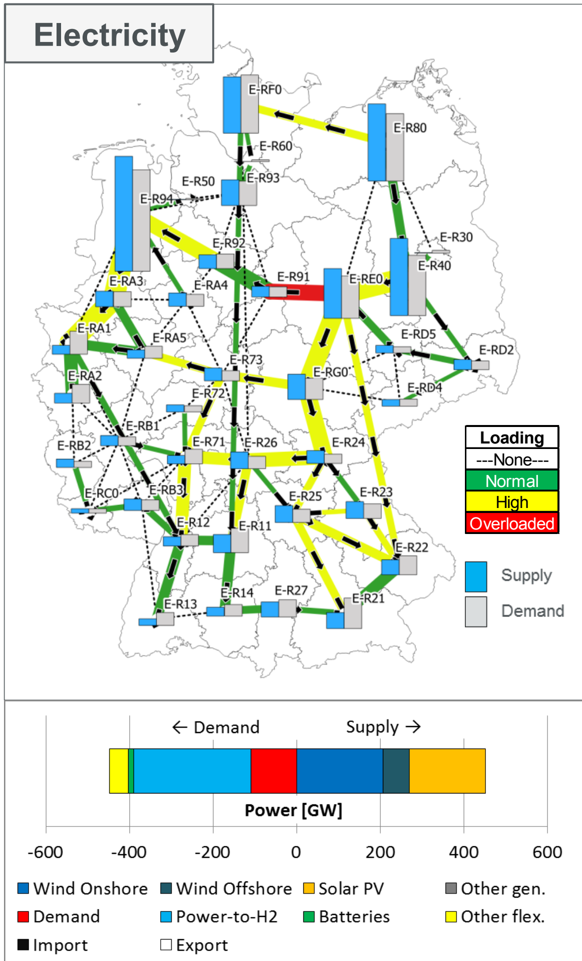
gasunie crossing borders in energy

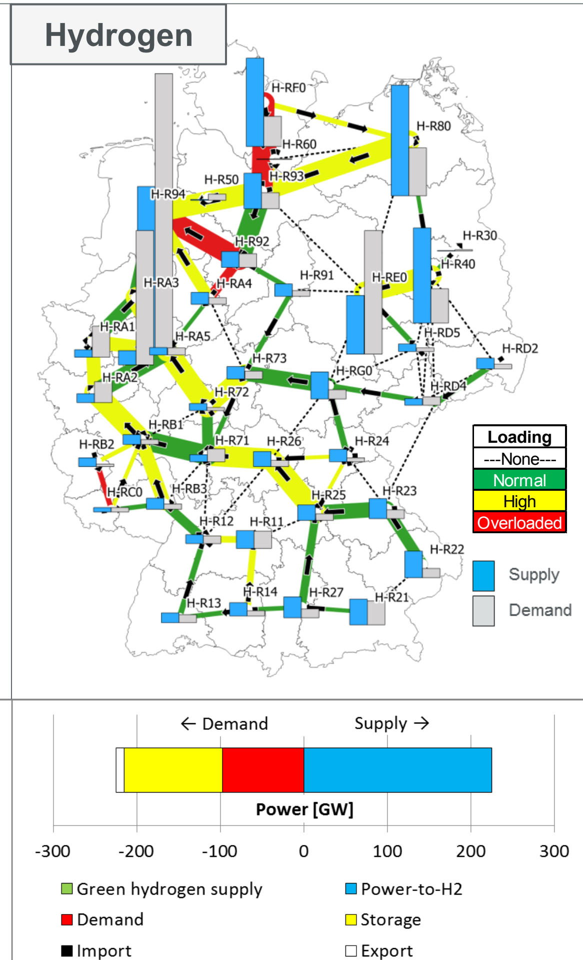
TenneT Taking power further

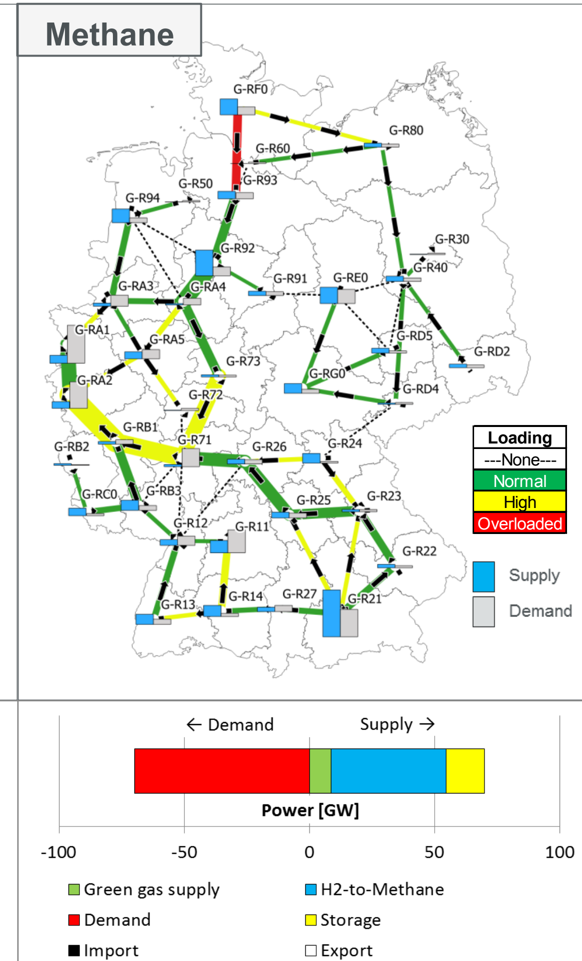
Infrastructure calculations (DE)

RES-energy weighted regional distribution key

Sensi cases (Enervis_1450)







gasunie crossing borders in energy

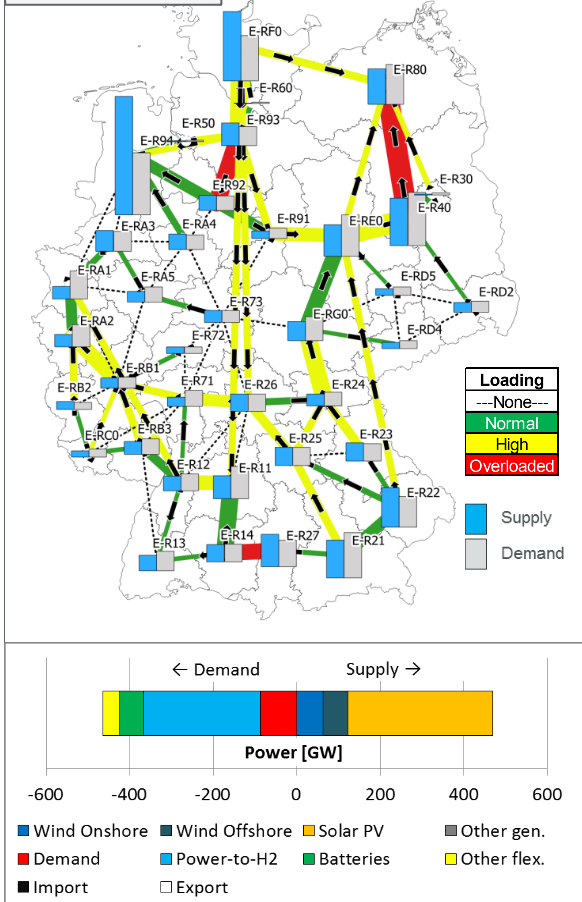
TenneT Taking power further

Infrastructure calculations (DE)

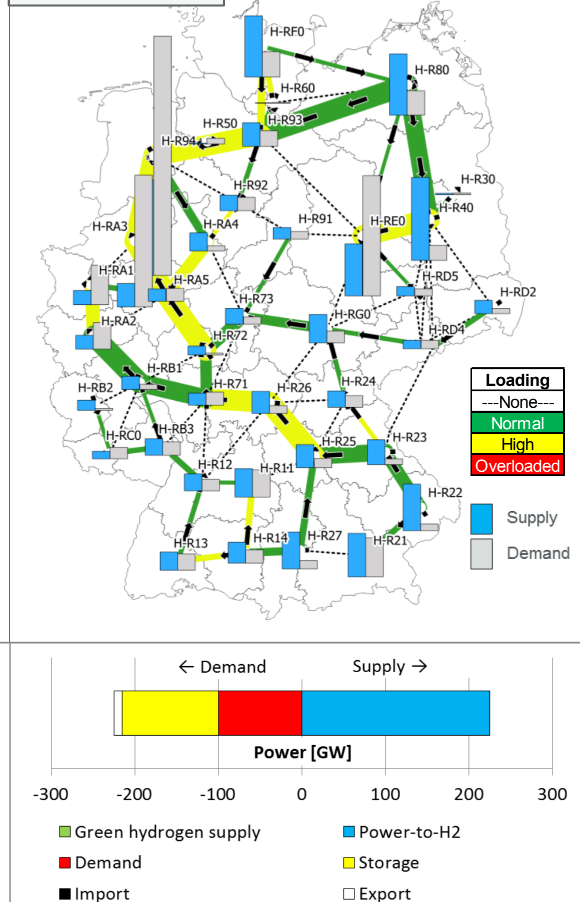
RES-capacity weighted regional distribution key

Base cases (Enervis_4358)

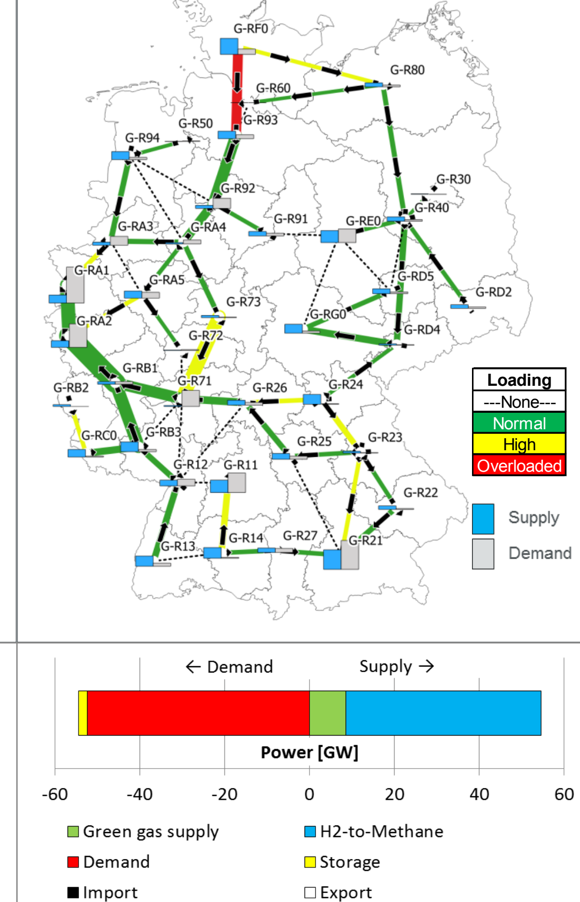
Electricity



Hydrogen



Methane



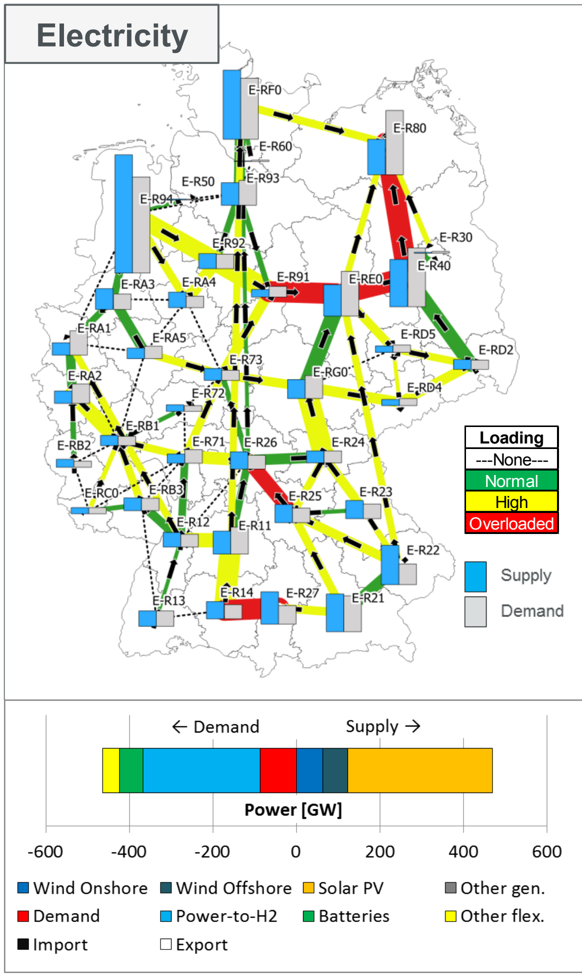
gasunie crossing borders in energy

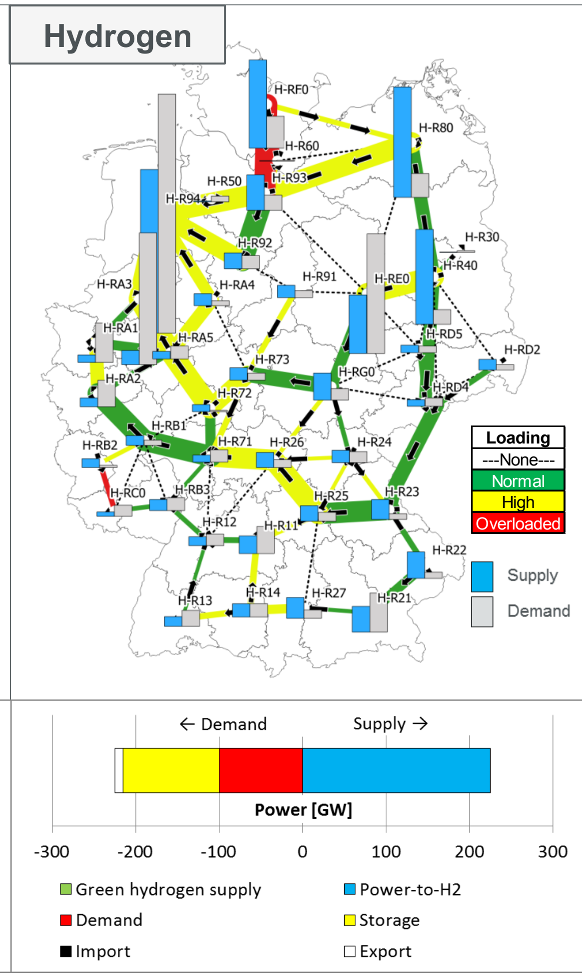
TenneT Taking power further

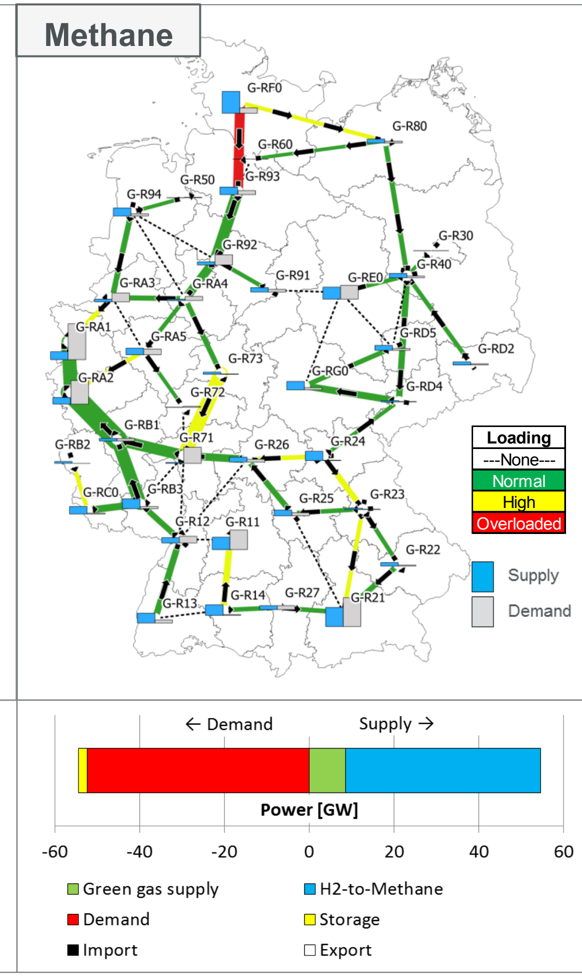
Infrastructure calculations (DE)

RES-energy weighted regional distribution key

Sensi cases (Enervis_4358)







gasunie crossing borders in energy

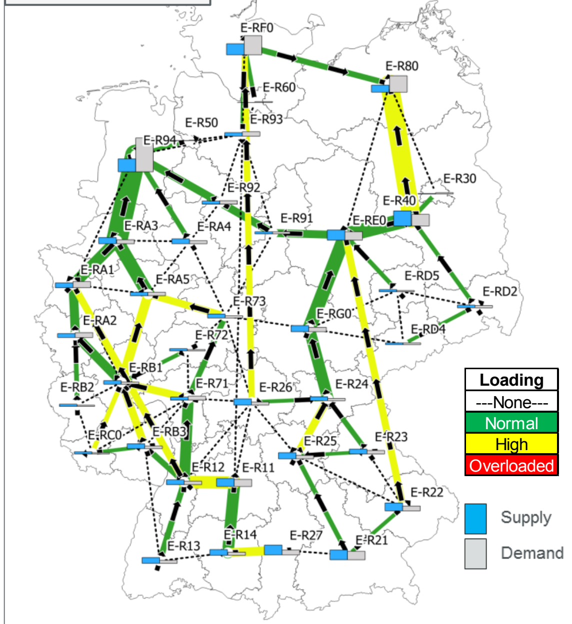
TenneT Taking power further

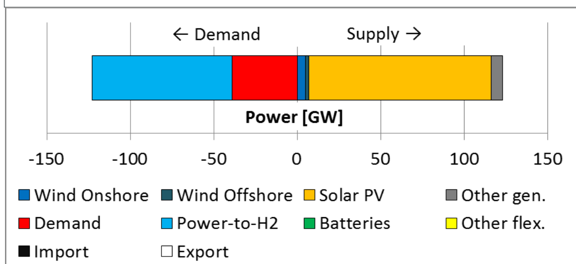
Infrastructure calculations (DE)

RES-capacity weighted regional distribution key

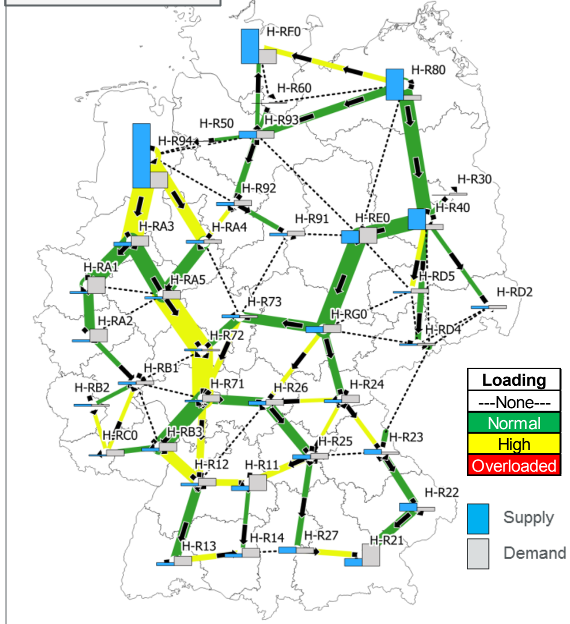
Base cases (EFNB_5126)

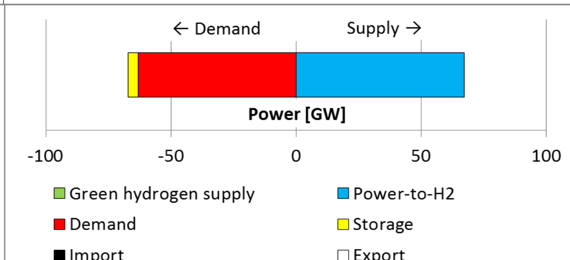
Electricity



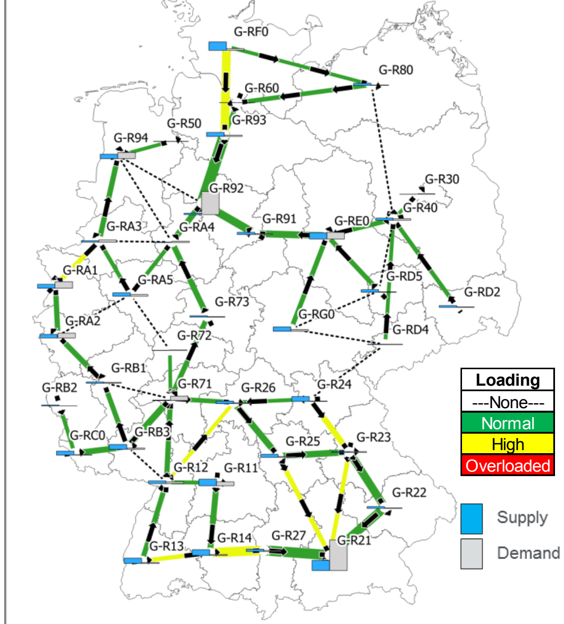


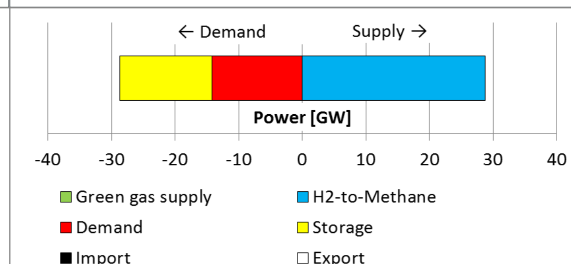
Hydrogen





Methane





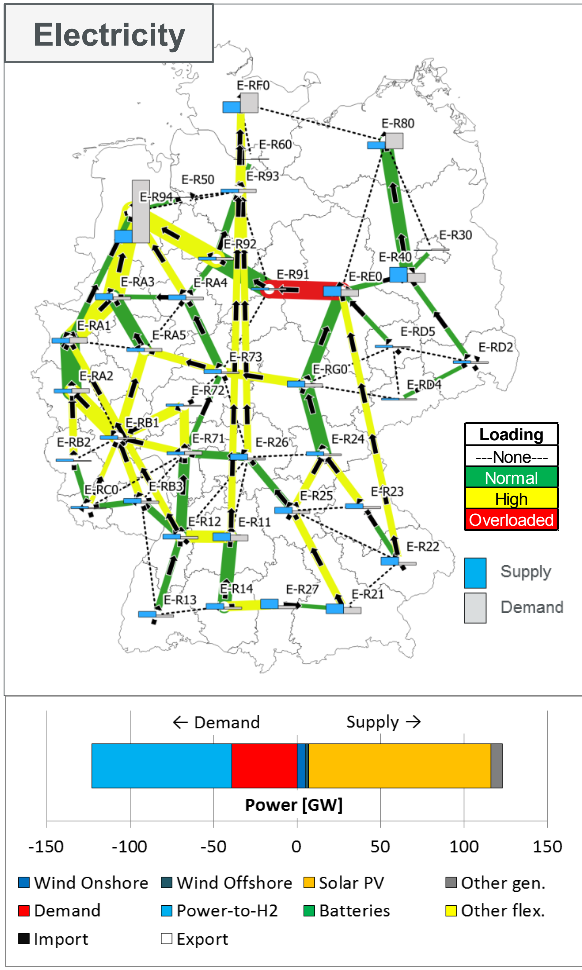
gasunie crossing borders in energy

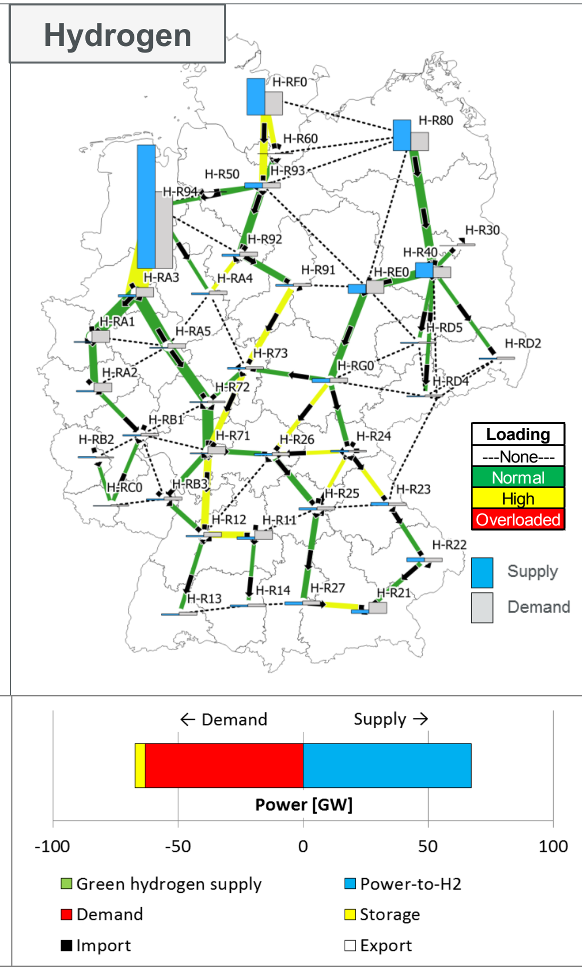
TenneT Taking power further

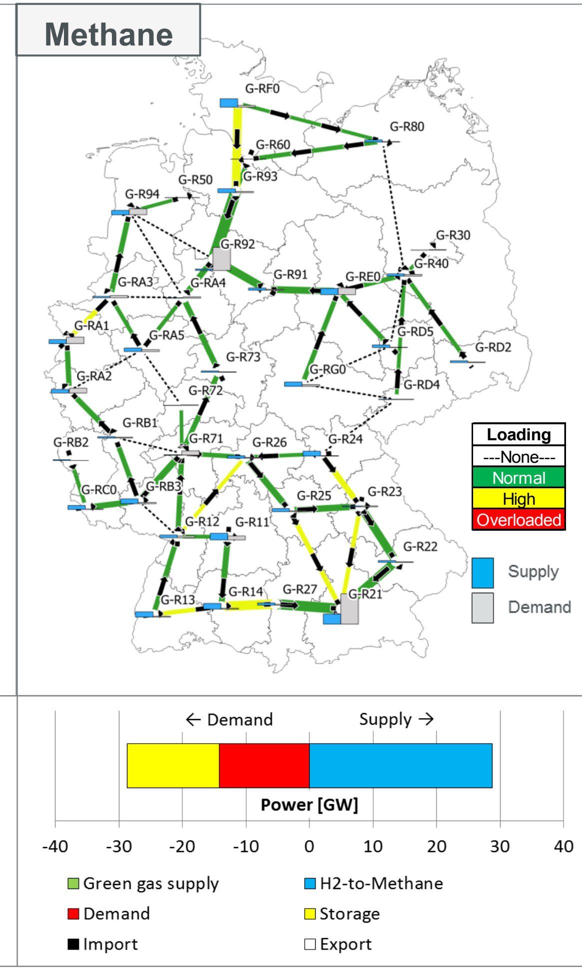
Infrastructure calculations (DE)

RES-energy weighted regional distribution key

Sensi cases (EFNB_5126)







Infrastructure calculations: Sensitivity

- The **locational choice of flexibility options** (PtG, batteries, PtHeat, H2-to-CH4, …) strongly determines the energy transport in the particular infrastructure(s)
- The placement of PtG installations strongly affects the load situation (especially) bottlenecks in the electricity grid – the gas grids seem to be able to handle the changed supply locations
- The focus for placing PtG installations can therefore be oriented on the usefulness for the electricity grid
- Systems with strong supply from Wind and Solar in different/opposite locations are more difficult to handle – a PtG installations can be placed only once