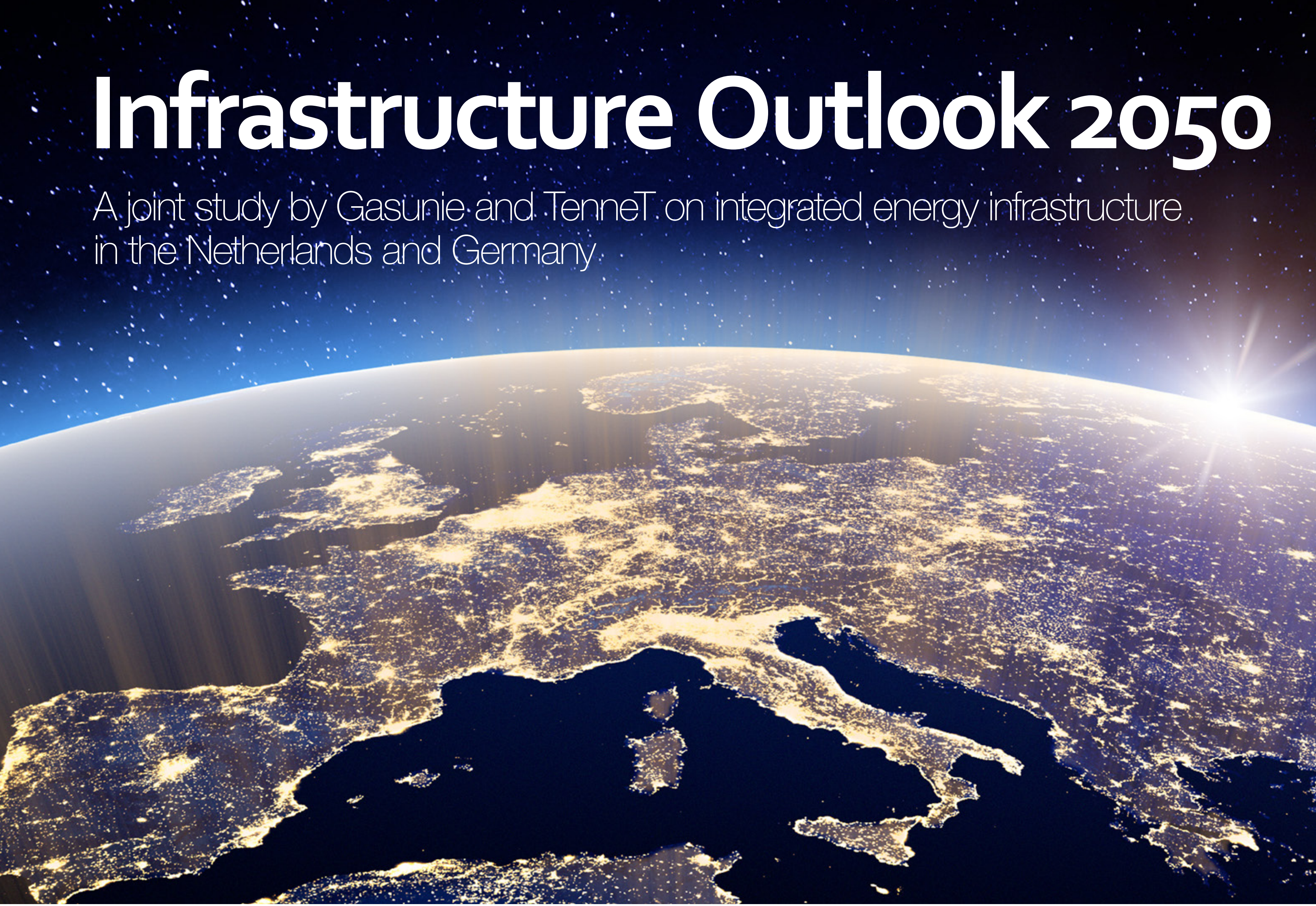
Infrastructure Outlook 2050

A joint study by Gasunie and TenneT on integrated energy infrastructure in the Netherlands and Germany



gasunie crossing borders in energy

TenneT Taking power further

Infrastructure Outlook 2050

A joint study by Gasunie and TenneT on an integrated energy infrastructure in the Netherlands and Germany

gasunie
crossing borders in energy

Han Fennema, CEO of Gasunie:

"The study shows the requirements and limitations of a future energy system based on solar and wind energy. With these highly fluctuating sources of energy, we need strong gas and electricity infrastructures that are seamlessly coordinated.
If something is clear from our Outlook 2050, it is that interweaving TenneT's grid with that of Gasunie will give the flexibility the energy system needs."

TenneT
Taking power further

Manon van Beek, CEO of TenneT:

"The cost of solar PV and offshore wind energy has rapidly declined over a very short period of time. If governments continue to set higher targets for limiting CO_2 emissions, the energy transition will accelerate. This Infrastructure Outlook 2050 by TenneT and Gasunie is a joint review, which provides valuable insights that had not been shown before. To reach the 2050 climate goals in an efficient and affordable way, cooperation with other partners, such as politics and industry, is crucial as energy systems are not transformed from one day to the next, but require a long-term commitment."

Foreword

Gasunie and TenneT hereby present their first Infrastructure Outlook 2050, which is the result of a joint study on the development of an integrated energy infrastructure in the Netherlands and Germany. It takes the target of the Paris Agreement (COP21), to achieve a 95% CO_2-emission reduction by 2050, as its starting point.

The European transition towards a renewable energy system is entering a new phase with plans by EU Member States that specify how the targets of the 2030 Climate and Energy Framework should be met. Although these plans do not specify all the details of the precise transition pathways towards 2050, the general direction is starting to become clear: a strong growth of solar and wind power in combination with the development of power-to-gas (P2G) (hydrogen) conversion, the production of chemicals and liquid fuels and the development of energy storage. For different scenarios, this Infrastructure Outlook describes the consequences of possible transition pathways for the existing gas and electricity infrastructures.

One of its key messages is that, in the energy system of the future, electricity, heat and gas will be increasingly integrated in order to absorb the large fluctuations in solar and wind power production. With respect to this matter, TenneT and Gasunie also welcome the repeated emphasis on the importance of system integration in the Dutch Draft Climate Agreement. The study furthermore shows that the long-term need for infrastructure expansion can be greatly reduced if guidance can be given to the locations of power-to-gas installations. The electricity grid in both Germany and the Netherlands will, however, still require considerable reinforcement due to the growth of peak demand under all scenarios.

With respect to the overall energy system, the study clearly reveals the important role that hydrogen can play in providing flexibility and system security.
As mentioned in the Dutch Draft Climate Agreement, Gasunie and TenneT will begin an explorative infrastructure study for the period 2030-2050 in cooperation with regional grid companies later this year. This study will be used as a basis for agreements on investments in infrastructure between network operators and governments and will be published in 2021.
To further analyse the infrastructural needs for the period 2030-2050 in Germany, TenneT has invited the IAEW energy research institute of the University of Aachen to make an in-depth analysis of the future national energy system. Gasunie Deutschland is involved as an important stakeholder, providing the gas expertise. Results of the already ongoing study are expected for mid-2019.

We expect that this Outlook 2050 will contribute to a better understanding of the current and future possibilities for the development of a sustainable, reliable and affordable future energy system.

Han Fennema
CEO, Gasunie

Manon van Beek
CEO, TenneT

Executive summary

To meet the 2050 emission targets set in the Paris Climate Agreement, the energy transition will require a complete overhaul of the current fossil fuel-dominated energy system. Although electricity produced from sun and wind is seen as the main source of energy by 2050, a major part of it has to be converted to molecules (such as hydrogen) to meet the demand of the chemical and fertilizer industries, and other forms of final consumption, all of which are difficult to electrify. The gas system also allows to accommodate green and CO_2 neutral gases from biomass and imports.

As a consequence, the energy system of the future is expected to not only require a strong electricity infrastructure, but also a strong gas infrastructure. For the Netherlands, this gas infrastructure is expected to transport hydrogen, bio-methane and imported natural gas, and for Germany it is expected to transport hydrogen, bio-methane and domestic or imported synthetic CO_2 neutral methane.

As such, TenneT and Gasunie, the electricity and gas transmission system operators (TSOs) in Germany and the Netherlands, have joined forces to answer questions regarding the future energy system. These questions address such matters as how both infrastructures interact, which energy will flow through which part of the infrastructure, and how to obtain a match between supply and demand, both in terms of space and time.

We decided for both Germany and the Netherlands to base the analysis on a common set of scenarios, outlining a plausible future energy system with power-to-gas (P2G) as a cornerstone to fulfil a major proportion of energy demand and reflecting different governance approaches regarding the energy transition. In both cases, we took the scenarios from state-of-the art studies[1] available for the respective countries.

As an infrastructure outlook, this study provides initial insights on infra-structure implications and should not be considered as an investment proposal. The model we have used considers electricity and gas trans-port infrastructure in an integrated way from a high-level perspective.

All the scenarios show that not only the electricity, but also the existing gas transport infrastructure in Germany and the Netherlands will play a crucial role in the future energy systems envisaged in this study

We observe that electricity and gas fulfil complementary roles. Wind and solar power are the major primary sources of renewable energy. The

[1] CE Delft (2017), Net voor de Toekomst; Enervis (2017), Erneuerbare Gase - ein Systemupdate der Energiewende; FNB Gas (2017), Der Wert der Gasinfrastruktur für die Energiewende in Deutschland; dena (2018), dena-Leitstudie - Integrierte Energiewende.

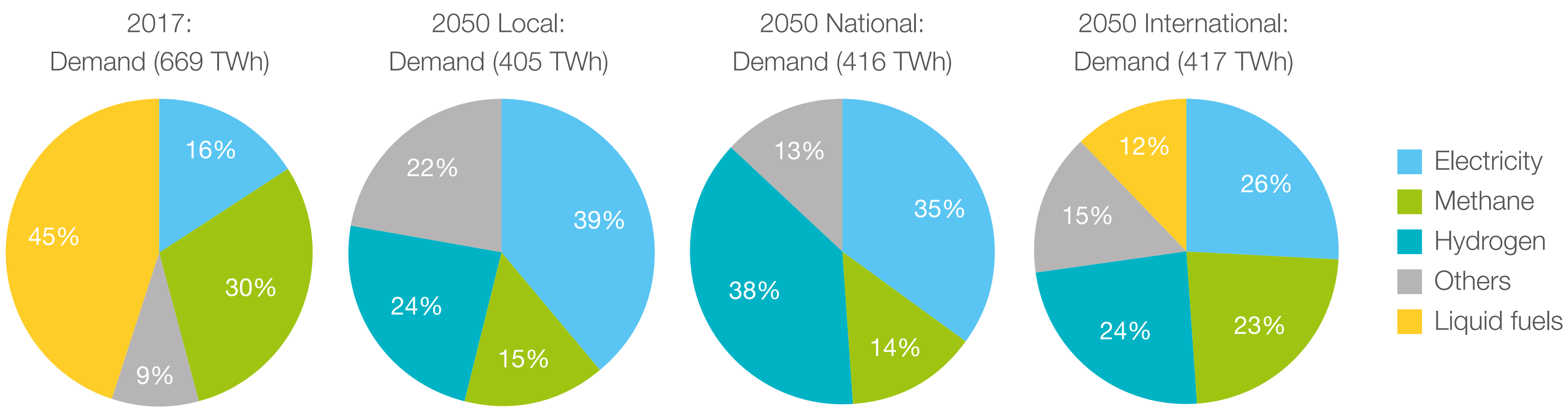
scenarios consider supplying this renewable energy as electricity or as green gases to the market. The advantage of transporting electricity directly to those sectors where electrification is technically and economically feasible has the advantage of avoiding energy conversion and the associated energy loss. Green gases, meanwhile, provide an option to decarbonise those sectors where electrification is harder to achieve. In the figures below it is shown that for all scenarios studied in the Infrastructure Outlook 2050 electricity and gas are the main energy carriers.

Electricity supply based on wind and solar power is very volatile by nature. Although generation sometimes exceeds demand by an order of magnitude, there are also times when wind and solar power generation is very low ('Dunkelflaute'), resulting in dramatic undersupply. The analysis we performed shows that coupling power and gas grids gives the energy system valuable flexibility and transport capacity, by using the existing infrastructure throughout the modelled year. The existing gas transmission grid has enough capacity to fulfil its fundamentally changed role in the future energy system, although some technical adaptations are needed due to the different characteristics of hydrogen.

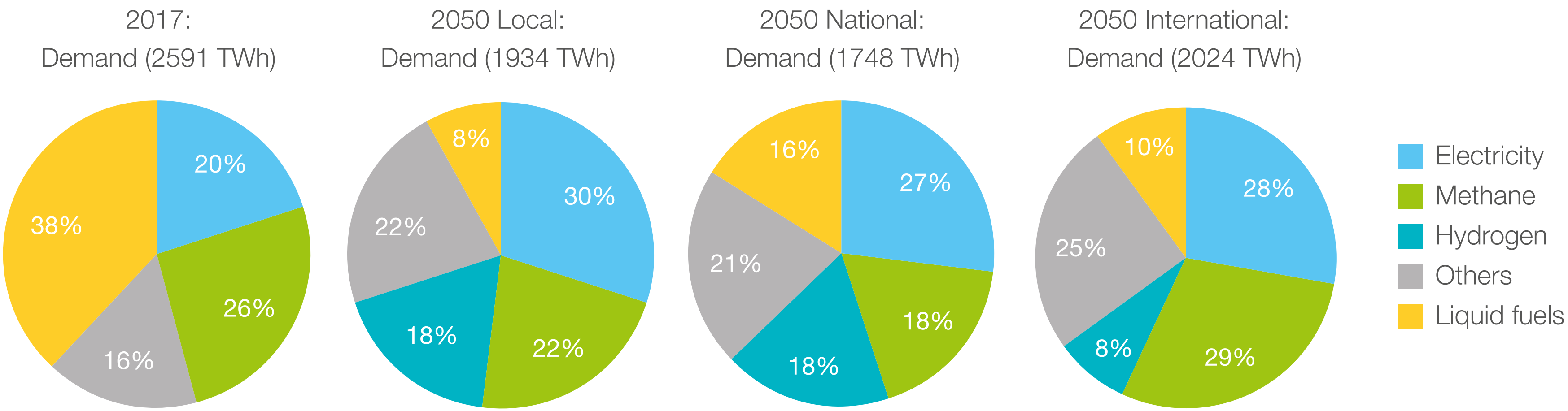
Provided that proper guidance can be given to power-to-gas (P2G) interfaces, coupling electricity and gas infrastructures may significantly alleviate the long-term expansion needs for electricity infrastructure. However, we foresee further expansion of the electricity grid after 2030 due to the expected growth in demand by end users.

We can conclude that the energy systems of the future will require both a strong gas and electricity backbone, including storage facilities, to secure supply to all forms of final consumption at any moment in time.

Final energy demand for the Netherlands (2017 and three 2050 scenarios)



Final energy demand for Germany (2017 and three 2050 scenarios)



Although electricity storage will be widely available by 2050, only gas storage will provide a solution for seasonal storage in a system based on solar and wind power

An energy system based on wind and solar power will require vast amounts of storage to cope with fluctuations in supply on timescales ranging between 'frequency restoration' to 'seasonal storage'. Furthermore, demand for energy varies considerably over the year (e.g. extra energy demand for heating in winter). Significant installed capacities of electricity storage (e.g. batteries, pump storage) have been considered in this study. However, the energy volume of such storage options, even until 2050, is limited. Existing underground gas storage facilities, on the other hand, can absorb large quantities of renewable energy for seasonal and long-term storage. Gas storage provides the main source of energy to the entire system during 'Dunkelflaute' situations. By coupling electricity and gas grids, renewable energy can gain access to existing underground gas storage facilities. As such, much like transmission infrastructure, electricity and gas storage are complementary.

The location, capacity and operation of P2G installations are decisive factors and must be aligned with both electricity and gas TSOs

Coupling the electricity and gas transport infrastructure with P2G installations gives the overall energy system additional flexibility. However, under scenarios with a high penetration of wind and solar power, the use of P2G causes a massive increase in electrical peak load, as a result of which it can potentially worsen infrastructural bottlenecks if the capacities and locations of these P2G installations are not properly aligned with the grids.

An analysis of the results indicates that locating P2G installations close to renewable production facilities can reduce the need for electricity grid expansion. This is especially the case when the overall P2G capacity is relatively high in comparison to renewables. It is not a given however that P2G installations always relieve grid constraints. Significant electricity and gas grid constraints may still arise if, from a grid perspective, the operation of these installations is suboptimal. Therefore, appropriate incentives for the operation of P2G units must be put in place to ensure efficient grid operation.

Socially accepted solutions for an integrated energy infrastructure require a new level of public and political support

In most scenarios, increasing peak demand in the electricity grid results in an increased utilization or even overloading of transmission lines. According to the methodology chosen for this study, this may indicate a need for additional electrical grid expansions in addition to the measures until 2030 that have already been confirmed, both technically and politically.

We have identified two crucial aspects for the realisation and success of the energy transition: political willingness to construct new electricity transmission lines, to accommodate the predicted demand growth by end users and a fundamentally changed energy supply structure based on renewable energy sources, and the creation of a clear supportive regulatory framework for the integration of P2G plants into the energy system in order to minimise the total number of grid expansions.

Recommendations and further work

- Future discussions within the overall debate on the energy transition should aim for a detailed P2G implementation strategy, with special consideration of the corresponding implications it will have on electricity and gas grids.
- This strategy should also include work on the technical and economic feasibility of large-scale P2G facilities.
- In order to ensure efficient network investments, the electricity and gas TSOs should be involved in drawing up a detailed P2G integration strategy.
- To facilitate an efficient transition, we recommend that various pathways to 2050 described in this study are worked out in further detail.
- The findings of this study can provide guidance to the investment plan processes (NEP in Germany and IP/NOP in the Netherlands).
- The scenarios used in this study were based on national CO_2 accounting rules and therefore did not consider the future energy demand for international aviation and sea shipping. Since these forms of transport are expected to require substantial amounts of energy in the future for both Germany and the Netherlands, we recommend including them in a follow-up analysis.

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1. Introduction

The European transition towards a renewable energy system is entering a new phase with plans from EU member states that specify how the targets of the 2030 Climate and Energy Framework should be met. Although these plans leave some room to manoeuvre for the transition pathways towards 2050, a certain clarity is starting to appear regarding the direction of the overall route to be taken.

As can now be seen, the overall transition route for Europe will be based on an interplay between the production of renewable electricity and the conversion of 'green electrons' into 'green molecules', which are needed in bulk quantities outside the electricity system, e.g. for base chemical and plastics production.

The electrolysis of water is currently the most promising technology to convert renewable electricity into a physical product (i.e. hydrogen), since the technology will be able to provide the required flexibility to deal with large fluctuations in electricity production by wind and solar power. Another advantage of the electrolysis process is that the hydrogen produced and its derivative, methane, can be stored and transported in the current natural gas infrastructure. Also, both products can readily be used as fuel and as a building block for a large range of chemicals.

The conversion of power into gas also offers the possibility for large-scale energy imports from elsewhere in the world. Some studies, such as by the International Energy Agency[2] already point out that the vast potential for offshore wind in the North Sea will not be enough to meet final demand[3] of surrounding countries and that by 2050 these countries will have to import considerable amounts (up to 50%) of renewable energy from outside Europe.

It has been predicted that the large-scale application of P2G conversion (and the continued use of methane and hydrogen in power plants for gas-to-power conversion) will lead to an increased interweaving of the gas and electricity transport infrastructures. Although the conceptual idea of coupling gas and electricity infrastructures has been observed in a number of studies, plotting the consequences for the transmission of energy on a national scale has not been addressed so far. Early 2018, TenneT and Gasunie decided to initiate a study into this matter.

The *Infrastructure Outlook 2050* outlines an integrated energy infrastructure design based on supply and demand requirements that fulfil greenhouse gas emission reductions as stated in the Paris Agreement. The goal of the study is to gain insight in the potential and limitations of the combined gas and electricity infrastructures of the Netherlands and Germany in 2050. For this, we used an integrated infrastructure model for gas and electricity that enabled us to study the possible infrastructure consequences of available supply and demand scenarios for 2050. This outlook presents a direction in which the infrastructure could develop to 2050. It serves to support the shorter-term decision-making processes. After all, although the Outlook concerns the year 2050, the relevant decisions must be made today.

[2] International Energy Agency, World Energy Outlook 2017
[3] Final demand includes energy demand (e.g., for heating, as feedstock, etc.) supplied by all energy carriers (e.g., electricity, hydrogen) together.

2. Methodology

This section describes the methodological approach of the Infrastructure Outlook 2050. Key elements of the approach are a comprehensive modelling approach of the national energy systems of Germany and the Netherlands, and the use of an integrated infrastructure model that can assess the gas and electricity transport systems simultaneously.

Figure 1: Overall study set-up

2.1 Corporate approach

The overall set-up for the study includes five consecutive steps, as presented in Figure 1.

Step 1: Scenario framework

We worked out in detail three different scenarios for each country. The scenarios differ in how the transition process will be steered. For this study, we assumed that steering can be done at a local level by local councils, at a national level by national governments and at a global level based on international trading agreements. All the scenarios fulfil the long-term climate target, i.e. reduction of CO_2 emissions by 95% in 2050 compared to the reference year 1990. For more information on the scenario framework and the contents of the scenarios, please refer to Appendix I.

Step 2: Energy system calculations

Each scenario considers four energy carriers: liquid fuel (synthetic and fossil oil), electricity, hydrogen and methane (natural gas, synthetic methane and biogas). For the latter three, hourly values for supply and demand (including interrelated conversions) were generated.

Historic hourly weather data from 2015[4] was used to quantify the weather-dependent behaviour of demand and of solar and wind power for the reference year 2050. We assessed the data focusing on the analysed country alone, i.e. not integrated in the European energy infrastructure system.
P2G (electrolysis) and gas-to-power (gas-fired power plant) installations were modelled as base options for balancing the electricity system. Batteries and pump storage (the second only in Germany) were modelled as to provide peak balancing (i.e. daily flexibility) due to their

[4] Temperature and wind data series from 2015 were used, as these were readily available in the tooling. This weather year represents an 'normal' year.

limited storage capability. We used the remaining flexibility possibilities, e.g. import/export and power to heat, in the model as the last option for balancing the electricity system. The annual pattern of the gas demand of different sectors of the economy was taken from the consulted studies. For each sector, the hourly gas demand was calculated in line with the weather data from 2015.

The main supply source of gas in scenarios with marginal gas imports is hydrogen produced by electrolysis (P2G). As such, the calculated gas supply is strongly influenced by the hourly production of solar and wind power. The same applies to gas demand, which is strongly affected by the consumption of the gas-fired power plants serving electrical demand during times with low production by solar and wind power.
In terms of flexibility, the main element on the gas side to cover the resulting supply/demand imbalances are the underground storage facilities for hydrogen and methane.

The result of this procedure is a set of hourly time series (8,760 hours) for supply, demand and flexibility for each scenario.

Step 3: Regionalisation and selection of critical hours (snapshots)
For the analysis of what infrastructure is needed, national supply and demand had to be split up into smaller regions. We based this regional split on category-dependent regionalization keys derived from a number of statistical sources. We determined the locations of P2G installations by testing different options for the Dutch and German energy systems.

Demand and supply values for the different energy carriers were available for all 8,760 hours of every scenario. For the selection of critical hours, we considered three infrastructure stressing situations:

- High renewable energy supply and high electrical demand (main stress test for the electricity grid)
- High renewable energy supply and low demand (stress test for both the gas and the electricity grid)
- Low renewable energy supply and high demand (main stress test for the gas network).

For these situations, we selected several representative hours from the time series. More information on snapshot selection is provided in Appendix I.

Step 4: Infrastructure analysis
One of the key elements of the chosen methodological approach is the integrated infrastructure model, developed by Gasunie Transport Services and TenneT TSO B.V.. This model enables simultaneous modelling of gas (methane and hydrogen) and electricity transport systems.

The model is based on a linear programming algorithm. For any balanced entry/exit combination, it calculates an optimised network flow pattern. The model assumes a (pipe)line transport load function T(Q) that is linear in transported power (Q) and (pipe)line length (L): $T(Q) = Q \cdot L$.
The minimum of the sum of (pipe)line load functions then determines the flow pattern. In this way, electricity and gas flows can be treated on the same basis.

Each (pipe)line in the model is assumed to have a (bidirectional) transport capacity, expressed as a maximum possible energy flow (MW) over this (pipe)line. The model is set up in a way that available (pipe)line capacity will always be fully used before a bottleneck occurs. The model assesses whether the total energy throughput is possible in the modelled combined grid. The calculated flow pattern may not always

represent the actual, physical flow, but it does provide a good indication whether bottlenecks will occur in the grid or not. The capacity of gas pipelines is based on available data of the present networks of Gasunie Transport Services, those of the electricity lines on similar data from TenneT. We assumed[5] that the transport capacity of a hydrogen pipeline is 80% of the capacity of a high-calorific methane pipeline and 95% of a low-calorific pipeline.
Due to the high reliability requirements imposed on electricity networks, we decided to decrease the nominal capacities of AC lines by a factor of 0.7 to mimic the N-1 requirement[6] of electricity transmission networks. Further details of the model can be found in Appendix II.

Step 5: Visualisation and analysis of results

The output of the grid model calculations for each snapshot is presented in the form of a grid map with coloured network flows: green for light to moderate (pipe)line loads, yellow for heavily loaded lines and red for overloaded lines. The width of the (pipe)lines indicates the (relative) magnitude of the flow.

2.2 Dutch specifics

1) Scenario framework

We developed Dutch scenarios using the data from the 'Net voor de Toekomst' (NvdT) study[7]. According to the chosen storyline framework of our outlook, we selected the scenarios 'local steering', 'national steering' and 'international steering'.

2) Energy system calculations

We calculated national hourly supply and demand values for the total Dutch energy system with the Energy Transition Model (ETM) developed by Quintel[8]. The total national energy demand was allocated to the three energy carriers considered. Where necessary, we considered additional data. With regard to the production of electricity from solar and wind power and the effect of temperature on energy demand (cooling and heating), we modelled the Netherlands as a single weather zone.

3) Regionalisation and selection of critical hours (snapshots)

We mapped the hourly data to municipalities, which means we considered 380 areas in total. The municipal values are linked to the nearest entry/exit[9] of the corresponding electricity or gas transport network in order to create the required input data for the integrated infrastructure model. We have assumed that the location of the conventional power plants in 2050 will not change. Power production was scaled with respect to current installed capacity.

4) Infrastructure analysis

We modelled the Dutch integrated transport infrastructure using TenneT's current 380/220kV high-voltage network, including expansions up to 2030, and the current high-pressure (80 and 67 bar) networks of Gasunie Transport Services (see Figure 2). The current Dutch high-calorific natural

[5] Based on a report by DNV-GL (DNV-GL, 2017, 'Verkenning waterstofinfrastructuur'.)
[6] This is the rule according to which the elements remaining in operation within a (TSO's) control area after a contingency occurs must be capable of accommodating the new operational situation without violating operational security limits.
[7] CE Delft (2017). 'Net voor de Toekomst' (Achtergrondrapport), november 2017.
[8] See: https://pro.energytransitionmodel.com/ ; the 'Net voor de Toekomst' scenarios are available on the Energy Transition Model (ETM) website and can be freely used for further analysis and evaluation purposes.
[9] The closest neighbour analysis considering the underlying infrastructure.

Electricity grid   Hydrogen grid   Methane grid

Figure 2: Geographic overview of assumed topologies for the Dutch gas and electricity infrastructures. (Line thickness represents maximum available transport capacity. Visual representation of gas and electricity capacities is not proportional.)

gas network is, in the model, largely assigned to future hydrogen transports and the low-calorific network to the transports of natural gas and bio-methane.

2.3 German specifics

For Germany, the modelling and analysis steps were generally similar to those applied for the Netherlands. The specific deviations from this approach are described in the following subsections.

1) Scenario framework

Since the ‘Net voor de Toekomst’ study did not include neighbouring countries, we selected specific energy studies for Germany in line with the general storyline definition of this outlook. As such, the German scenarios are not identical to the Dutch ones. The three selected studies are:

- Local: ‘Optimiertes System’ from the study ‘Erneuerbare Gase – ein Systemupdate der Energiewende’ published by INES and Enervis[10].
- National: ‘Strom und Grünes Gas’ from the study ‘Der Wert der Gasinfrastruktur für die Energiewende in Deutschland’ published by FNB Gas and Frontier Economics[11].
- International: ‘Technologiemix 95%’ from the study ‘dena Leistudie – Integrierte Energiewende’ published by dena and EWI[12].

2) Energy system calculations

We used the ETM to model the hourly structure of supply and demand for the considered scenarios. For Germany, we took regional weather conditions into account in the model, leading to regional profiles for supply and demand.

The supply of methane in two scenarios was based on methanation of carbon monoxide and carbon dioxide with hydrogen. The assumed ‘operation strategy’ (see Appendix II) for this process has a major effect on the use of storage for both hydrogen and methane.

[10] https://erdgasspeicher.de/files/20171212_studie_erneuerbare_gase.pdf
[11] https://www.fnb-gas.de/files/fnb_gas_wert_von_gasinfrastruktur-endbericht.pdf
[12] https://shop.dena.de/fileadmin/denashop/media/Downloads_Dateien/esd/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf

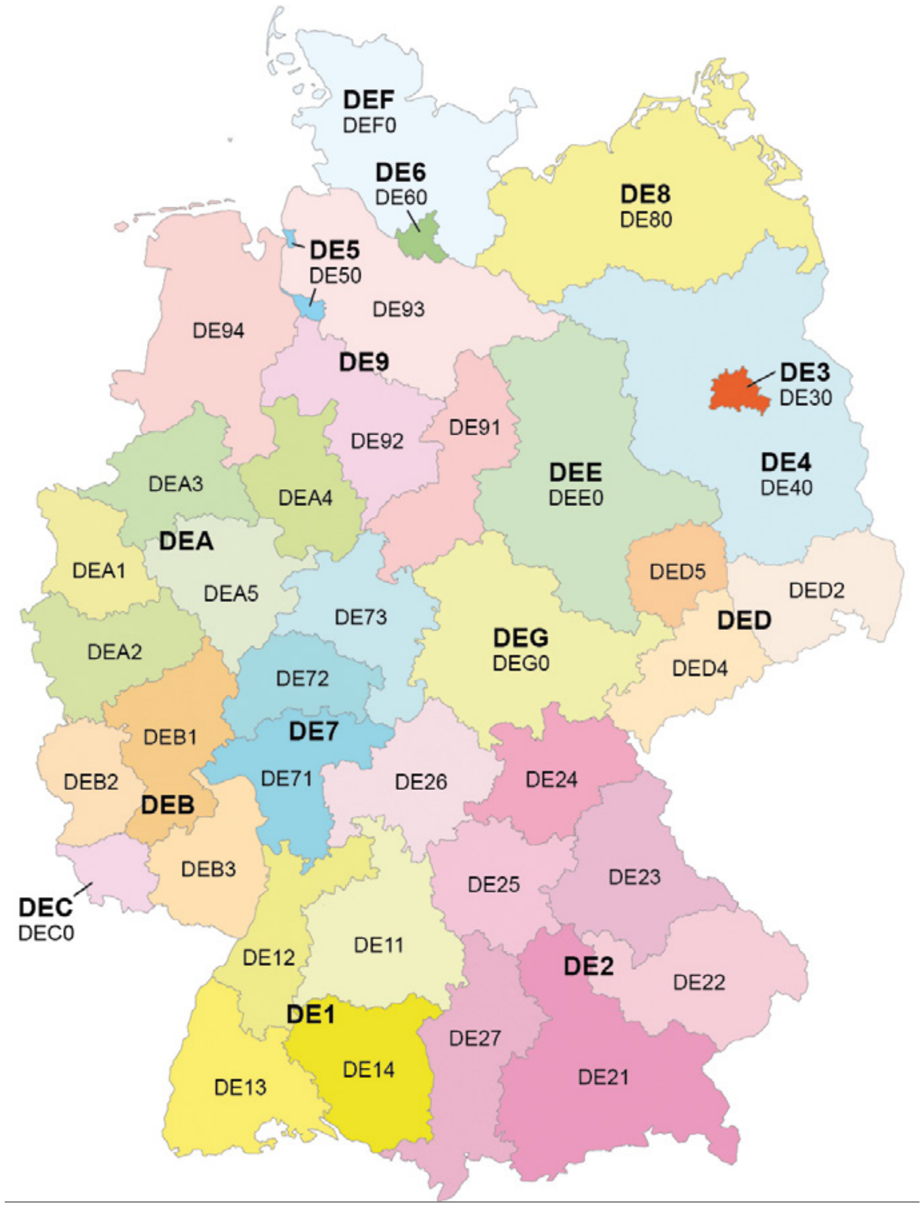

Figure 3: NUTS 2 regions of Germany (Source: de.wikipedia.org).

3) Regionalisation and selection of critical hours (snapshots)

We mapped the demand and supply data of Germany to the NUTS 2 regions and as such Germany was divided into 38 regions (see Figure 3).

4) Infrastructure analysis

As for the Dutch modelling, we modelled separate energy transport infrastructures for electricity, hydrogen and methane. The mapping of supply and demand data to NUTS 2 level meant we had to define a grid and an aggregated grid topology. To match the structure of the input data from regionalisation to the grid model and to also limit overall model complexity, we had to simplify the German grid topology as well.
The transport capacities between the nodes enable an exchange of energy between the regions. We modelled the connection links using a capacity and a length according to the asset properties. If there were more links between two corresponding regions, then we aggregated the capacity. Figure 4 shows the topology of the electricity grid including today's 380/220 kV transport grid and all the reinforcement and expansion measures until 2030 that are officially approved by the German regulator (Bundesnetzagentur)[13].

As the German gas grid is owned and operated by several TSOs, detailed grid data and a calculation tool for the whole grid are not available. To develop a calculation model in alignment with the NUTS 2 regions, we used public information like maps or data from the German NDP (Netzentwicklungsplan – NEP). This data was collected and combined to generate a simplified grid model that takes into account the capacity of each pipeline as a function of diameter, nominal pressure and gas quality. We only considered pipelines with a pressure higher

[13] Confirmed measures according to German grid development plan 2030 (v2017), not covering all measures proposed by the German transmission system operators (TSOs)

than 40 bar and a diameter larger than 400 mm. We assumed that the transport capacity of a pipeline used for hydrogen transport is 80% of the capacity of the same pipeline used for methane.

As the low calorific gas grid only covers part of North West Germany, we had to take a different approach for the split of the gas infrastructure than the one we used for the Dutch grid models. This approach was based on the fact that the future hydrogen system will have to provide the main flexibility to the integrated energy system to absorb the large fluctuations in the electricity generation in the scenarios with large amounts of solar and wind power. In order to create a strong hydrogen grid, we selected most of the 'backbone' pipelines in the German gas infrastructure, such as the main transit or import pipelines, for hydrogen transport. For the methane grid, we used smaller pipelines and loop pipelines to the transit infrastructure.

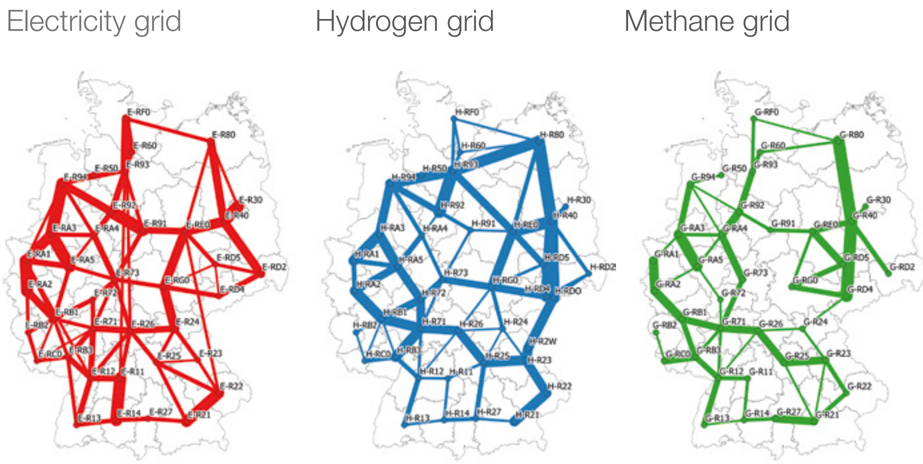

Figure 4: Geographic overview of assumed topologies for the German gas and electricity infrastructures. (Line thickness represents maximum available transport capacity. Visual representation of gas and electricity capacities is not proportional.)

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3. Scenario 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

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)

Table 1: Overview of the main CO_2 reduction measures per end user sector for each scenario

3.1 Overall storylines

As can be seen from Table 1, the use of the scenario driver, governance structure, has resulted in scenarios with significantly different energy systems though all achieve the 95% emission reduction target by 2050. graphic representation of the scenarios, which clearly indicates their differences, is provided on pages 23 through 28.

1) Local – focus on decentralised renewables

In this scenario (page 23-24), we assumed that municipalities and city councils are in the driver’s seat, thereby placing a strong emphasis on energy independency at a national level. Power and heat are generated decentrally where possible using local renewable sources, such as solar power, but also wind, biomass and geothermal energy play a rol. Overall electrification is the highest in this scenario. Due to the strong dependence on solar PV, we assumed a high amount of battery storage to cover intraday variations. The local scenario also contains the highest amount of installed power-to-hydrogen capacity to span seasonality in supply and demand. The hydrogen produced is mainly used as a transport fuel and as feedstock or heating fuel for the process industry. Hydrogen, and to some extent renewable methane, is also used as a fuel for back-up power plants.

2) National – focus on centralised renewable production

This storyline (page 25-26) assumes that national governments take the lead in the energy transition and, like the local scenario, aims for a high degree of energy self-sufficiency. There is an emphasis on centralised wind power and electrification of final energy demand. Besides electricity, there is a substantial demand for hydrogen and methane (bio-methane or methane from methanation of hydrogen) from renewable sources.

Hydrogen is used in the industry as a feedstock, process fuel for spatial heating and a transport fuel. Hydrogen and methane are also used as fuel for back-up power plants during periods with a low infeed of wind power. Due to the strong dependence on variable wind power, there is a need for a considerable amount of flexibility from power-to-hydrogen and battery storage.

3) International – focus on energy import

This storyline (page 27-28) assumes that renewable energy will be produced in bulk at locations around the world with the most favourable conditions for solar and wind power. This would lead to the majority of the required renewable energy being imported in the form of gas (methane or hydrogen) or as green liquid fuels hence, imported as 'molecules'. As such, domestic installed renewable capacities will be lower compared to the other two scenarios.

3.2 Dutch specifics

As presented in chapter two the Dutch scenarios were based on three of the four scenarios from the 2017 'Net voor de Toekomst' study. The main assumptions of these three scenarios are presented in Table 2.

3.3 German specifics

From the system studies described in the previous chapter, we used the scenario 'Optimiertes System' from the INES and Enervis study[14] for the local scenario, as this scenario considers Germany as mainly self-sufficient with high shares of solar PV in electricity generation. For the national scenario, we chose the scenario 'Strom und Grünes Gas' from the FNB Gas study[15], as this also takes a national approach with a focus on centralised offshore wind. For the international scenario, we chose the 95% technology mix scenario from the dena-Leitstudie[16] because of its high P2X imports from EU and non-EU countries. In order to make the data basis of these scenario comparable to the "International" Dutch Scenario from NvdT, the final energy demand for international aviation and sea shipping was not taken into account by performing this study. There is no pure electrification strategy in any of the considered scenarios. Instead, green gas (hydrogen or methane) accounts for a high share of demand in all sectors. Methane is mainly used to cover domestic heat demand, whereas hydrogen is used for for industrial processes and mobility. P2G plays a key role in decarbonising Germany's energy system. Green transport fuels from power-to-liquid process are nationally produced in the local scenario and otherwise imported. According to the scenario framework, imports are highest in the international scenario. Table 3 provides an overview of the scenarios' main parameters.

[14] https://erdgasspeicher.de/files/20171212_studie_erneuerbare_gase.pdf
[15] https://www.fnb-gas.de/files/fnb_gas_wert_von_gasinfrastruktur-endbericht.pdf
[16] https://shop.dena.de/fileadmin/denashop/media/Downloads_Dateien/esd/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf

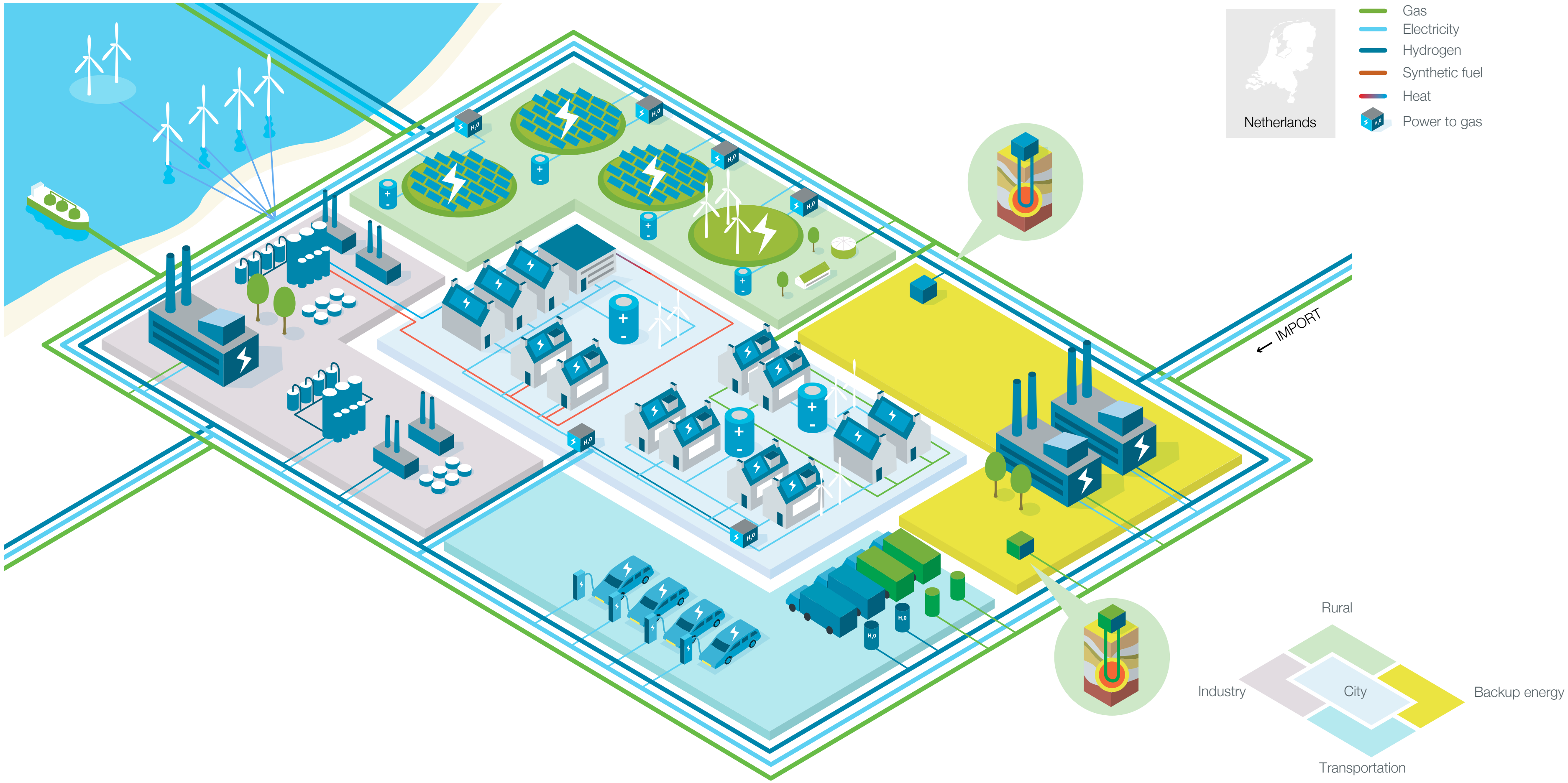
	Local	National	International
Power & Light	25% base-load savings through more efficient appliances. Substantial electrification of industry	25% base-load savings through more efficient appliances. Substantial electrification of industry	25% savings through more efficient appliances
Low-temperature heat	High penetration of heat grids and all-electric (restrictions on green gas, no H_2 distribution) Savings: 23%	High penetration of hybrid heat pumps burning H_2 (and green gas) (restrictions on green gas) Savings: 23%	High penetration of hybrid heat pumps burning H_2 and green gas (mild restrictions on green gas). Savings: 12%
High-temperature & feedstock industry	Circular industry and ambitious process innovation: 60% savings 55% electrification 97% lower CO_2 emissions	Circular industry and ambitious process innovation: 60% savings 55% electrification 97% lower CO_2 emissions	Biomass-based industry: 55% savings 35% biomass 14% electrification 95% lower CO_2 emissions
Passenger transport	100% electric	75% electric 25% hydrogen	50% electric 25% green gas 25% hydrogen
Freight transport	50% green gas 50% hydrogen	50% green gas 50% hydrogen	25% synthetic fuels 25% green gas 50% hydrogen
Renewables generation	84 GW solar 16 GW onshore wind 26 GW offshore wind	34 GW solar 14 GW onshore wind 53 GW offshore wind	16 GW solar 5 GW onshore wind 6 GW offshore wind
Conversion and storage	75 GW electrolysis 60 GW battery storage	60 GW electrolysis 50 GW battery storage	2 GW electrolysis 5 GW battery storage
Hydrogen	100 TWh domestic generation	158 TWh domestic generation	73 TWh import 4 TWh domestic generation
Methane	23 TWh domestic biomethane 35 TWh imported natural gas	46 TWh domestic biomethane 55 TWh imported natural gas	24 TWh domestic biomethane 72 TWh imported natural gas
Biomass			28 TWh import

Table 2: Main characteristics of the Dutch scenarios

	Local	National	International
Power & Light	25% base-load savings through more efficient appliances	10% savings	25% savings through more efficient appliances
Low-temperature heat	High penetration of efficient electric heat pumps. Savings: 41%	High penetration of heat pumps and gas fired heaters burning methane. Savings: 33%	35% Electric heat pumps. Savings: 41%
High-temperature & feedstock industry	Mix of many energy sources: 15% savings 16% biomass 29% electrification 100% lower CO_2 emissions	Mix of many energy sources: 25% savings 24% biomass 29% electrification 100% lower CO_2 emissions	Growing importance of green gas in industry: 18% savings 4% biomass 36% electrification 86% lower CO_2 emissions
Passenger transport	100% electric	25% electric 25% hydrogen 50% synthetic fuels	25% electric 25% hydrogen 25% methane 25% synthetic fuels
Freight transport	50% hydrogen 50% synthetic fuels	35% hydrogen 65% synthetic fuels	25% electric 25% hydrogen 50% synthetic fuels
Renewables generation	600 GW solar 210 GW onshore wind 64 GW offshore wind	218 GW solar 193 GW onshore wind 191 GW offshore wind	114 GW solar 171 GW onshore wind 26 GW offshore wind
Conversion and storage	281 GW electrolysis 110 GW battery storage	254 GW electrolysis minor effect of battery storage on transmission level	63 GW electrolysis 15 GW battery storage
Hydrogen	365 TWh by domestic P2G *No imports* Demand from industry/transport Fuel for power-plants	323 TWh by domestic P2G *No imports* Demand from industry/transport Fuel for power-plants	164 TWh by domestic P2G *5 TWh imports* Relatively small demand from industry/transport
Methane	365 TWh by domestic methanation 200 TWh by domestic biomethane *No imports* High demand in all sectors	323 TWh by domestic methanation *No imports* Demand from residential	No domestic methanation *108 TWh imports* High demand in all sectors
Power-fuels	151 TWh by domestic generation *No imports* Demand from transport	No domestic generation *286 TWh imports of green power-fuels* Demand from transport	87 TWh by domestic generation *108 TWh imports of green power-fuels* Demand mainly from transport, but also from industry and residential

Table 3: Main characteristics of the German scenarios

Local scenario (the Netherlands)



Supply: Large volume solar PV and limited wind power. Some biogas production and import of natural gas

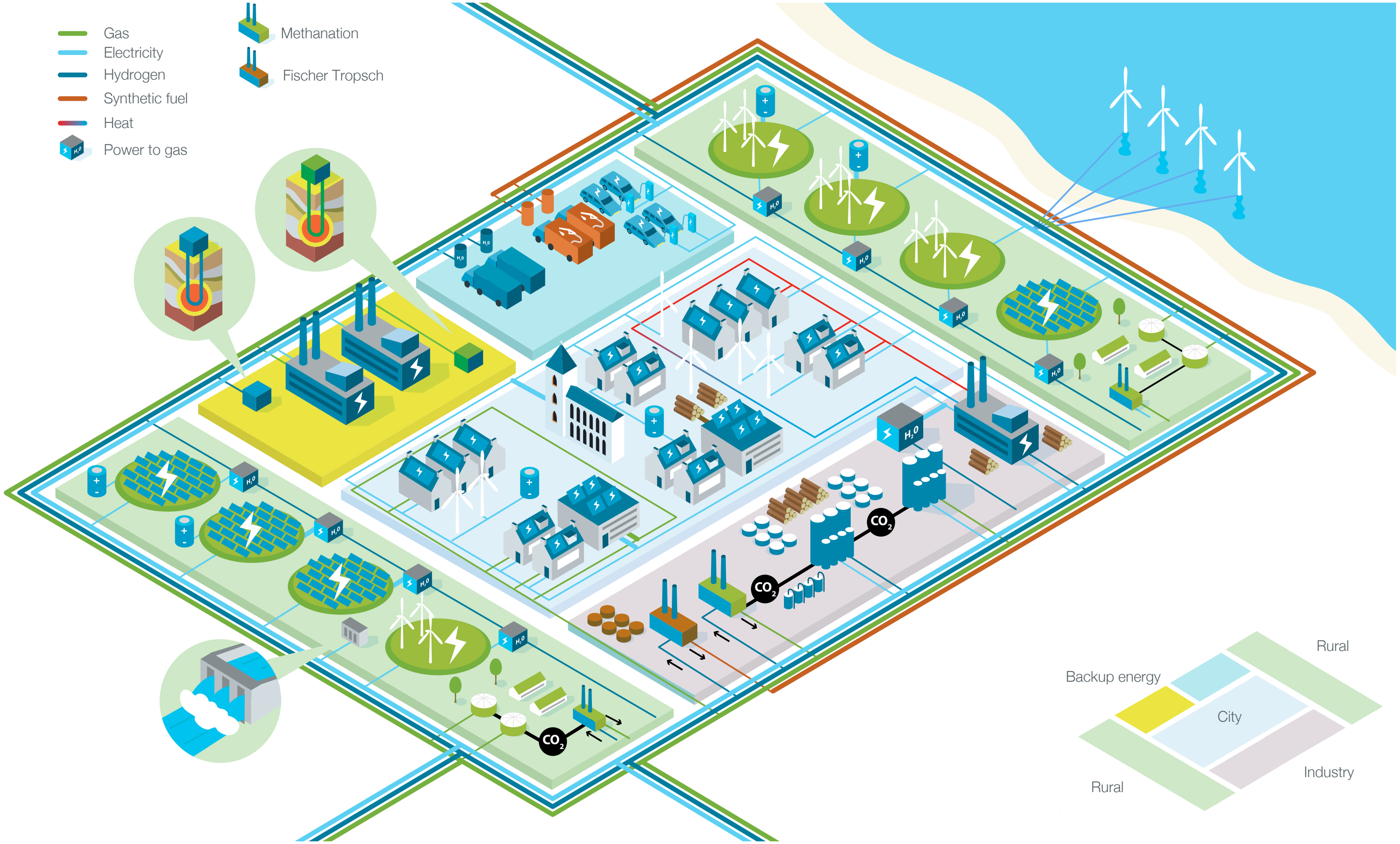
Demand: Spatial heating: district heating (geothermal, residual heat), electric heat pumps and hybrid green gas boilers.

Industry: feedstock: plastic waste and hydrogen, heat: hydrogen and electricity

Transport: passenger cars: 100 % electric, trucks: 50% hydrogen and 50% green gas

Flexibility: Power to gas and batteries

Local scenario (Germany)

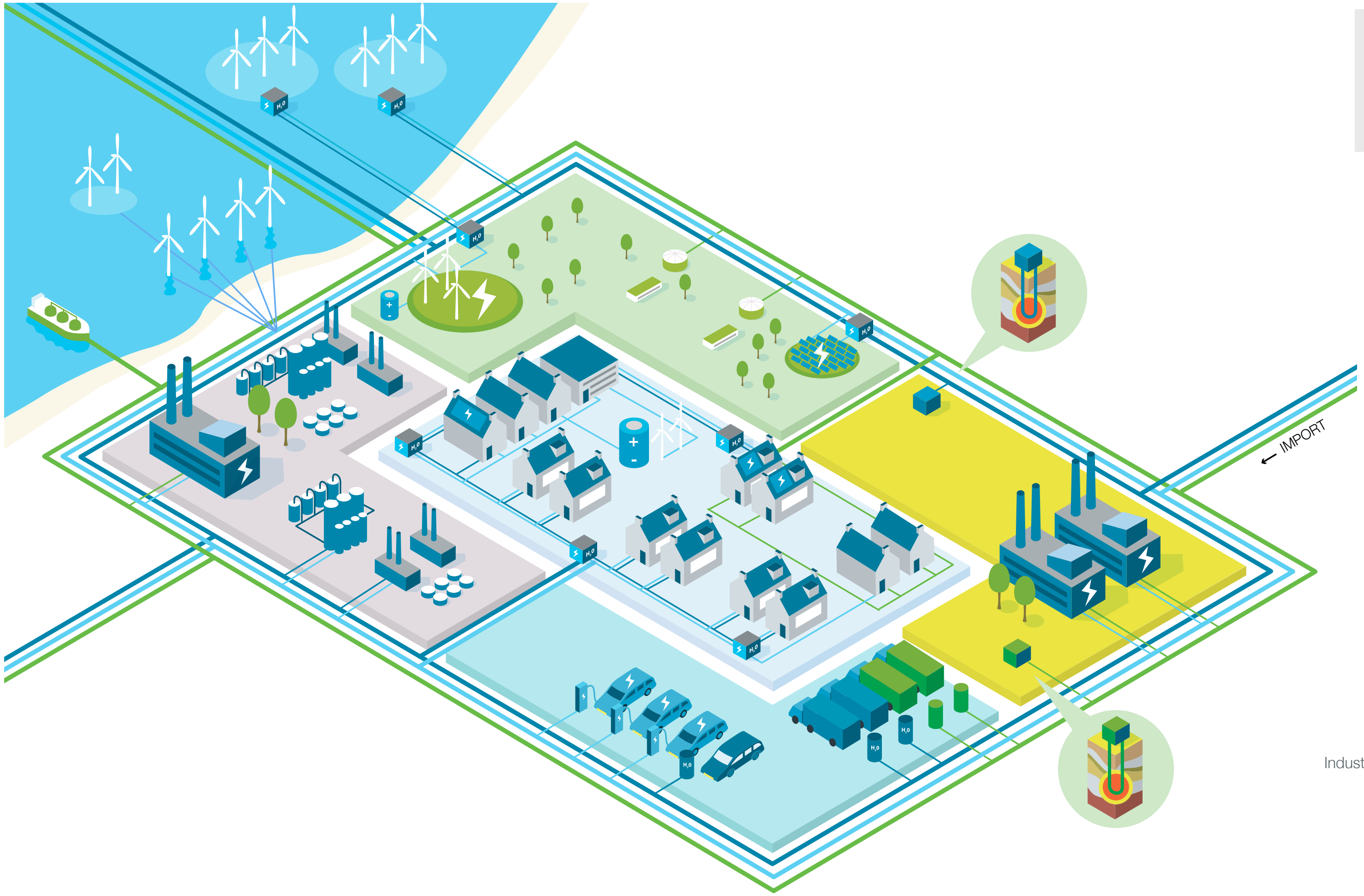


Supply: Large volume of installed solar PV and considerable amount of wind power. Biogas production

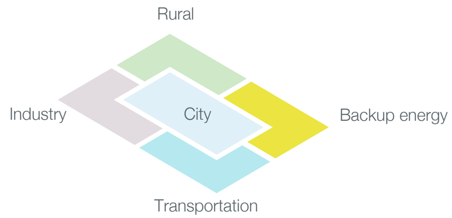
Demand: Spatial heating: district heating, electric heat pumps and green gas boilers.
Industry: feedstock: methane, heat: biomass, electricity, hydrogen and methane
Transport: passenger cars: 100 % electric, trucks: 45% hydrogen, 50% synthetic fuel, 5% electric

Flexibility: Power to gas and batteries

National scenario (the Netherlands)

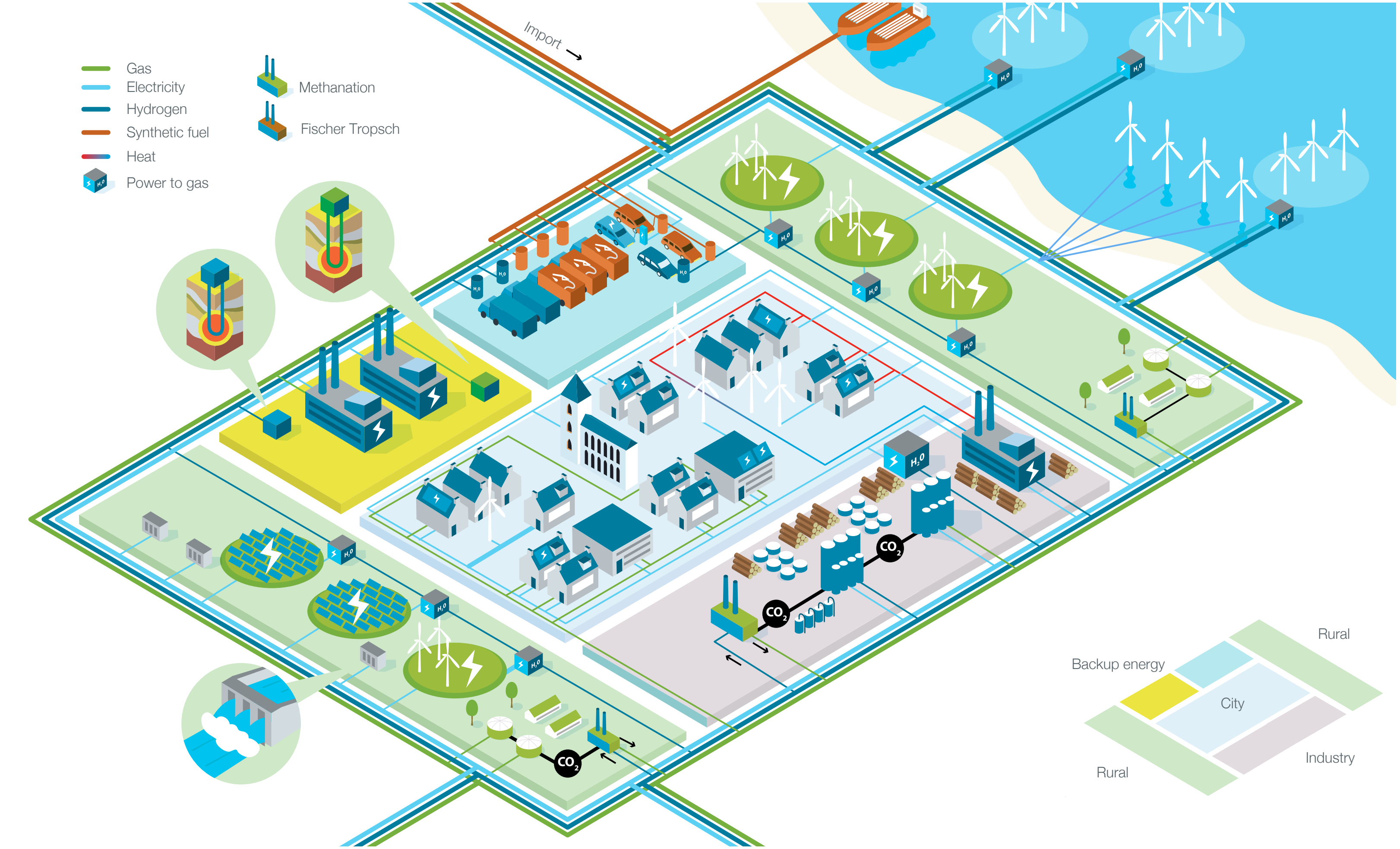


- Gas
- Electricity
- Hydrogen
- Synthetic fuel
- Heat
- Power to gas



Supply:	Large volume offshore wind and limited solar PV. Some biogas production and import of natural gas.
Demand:	Spatial heating: hybrid and conventional hydrogen and methane gas boilers.
	Industry: feedstock: plastic waste and hydrogen, heat: hydrogen and electricity
	Transport: passenger cars: 75 % electric, 25% hydrogen, trucks: 50% hydrogen and 50% green gas
Flexibility:	Power to gas and batteries

National scenario (Germany)



Supply: Large volume of off- and onshore wind and considerable amount of solar PV. Biogas production and import synthetic fuel

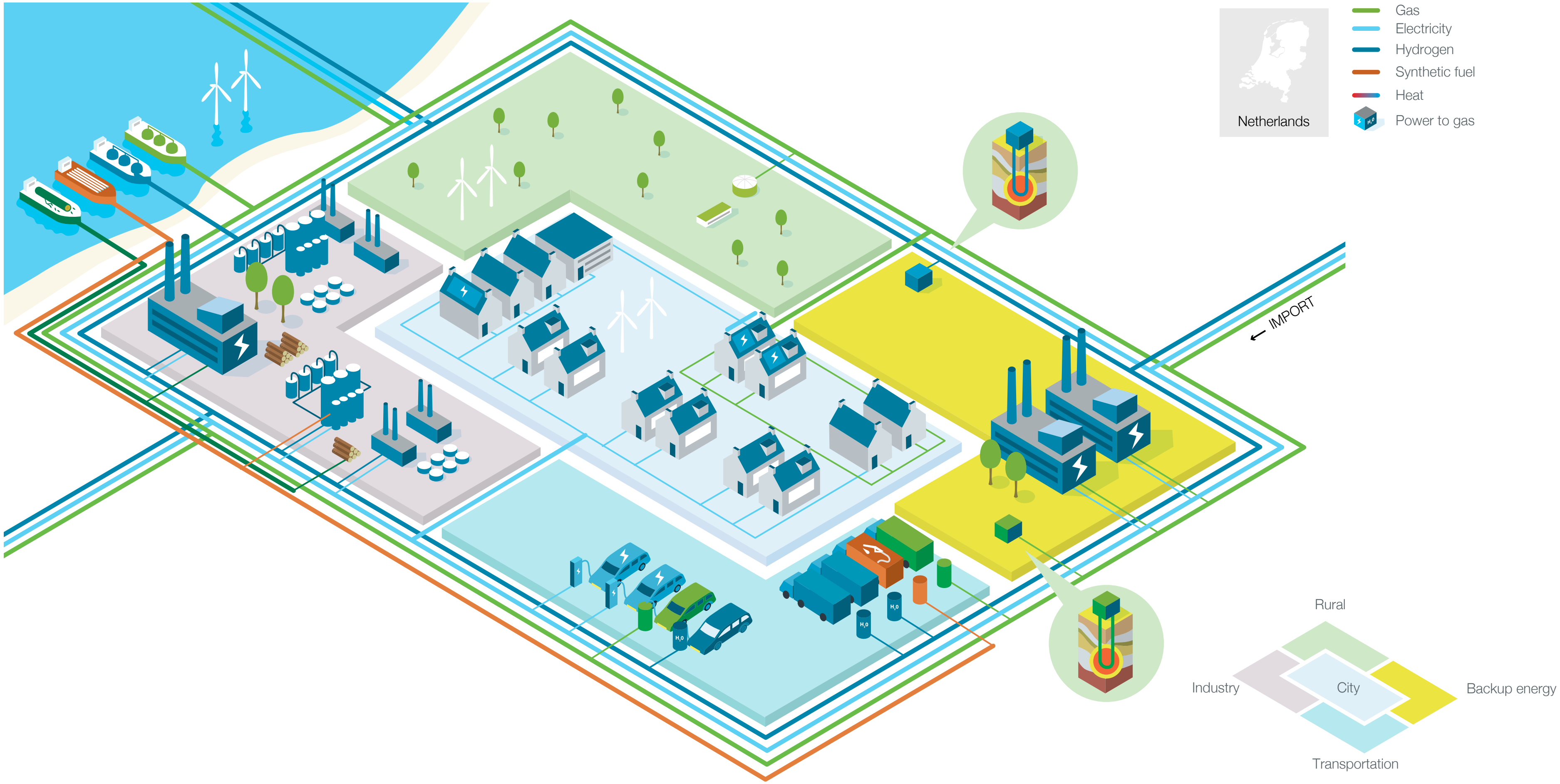
Demand: Spatial heating: mainly green gas boilers and electric and district heating.

Industry: total: biomass, hydrogen, methane and electricity.

Transport: passenger cars: 25 % electric, 50% hydrogen, 25% synthetic fuel, trucks: 40% hydrogen and 60% synthetic fuels

Flexibility: Power to gas

International scenario (the Netherlands)



Supply: Import of biomass, synthetic liquid fuels, hydrogen and methane. Some biogas production

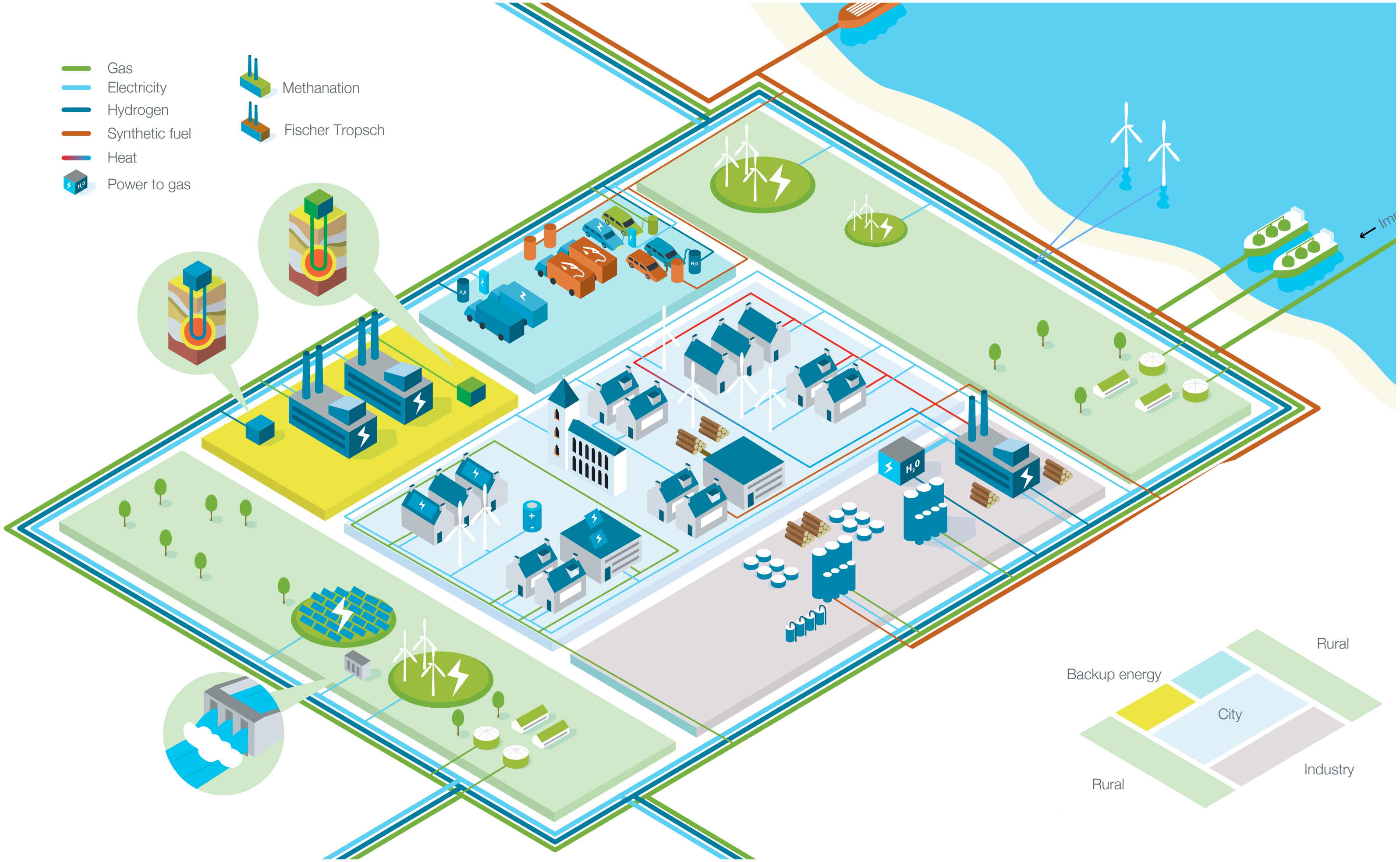
Demand: Spatial heating: Hybrid and conventional hydrogen boilers and hybrid biogas boilers

Industry: feedstock: biomass and hydrogen, heat: hydrogen, biomass, green gas and synthetic fuel

Transport: passenger cars: 50 % electric, 25% hydrogen and 25% biogas; trucks: 50% hydrogen, 25% green gas and 25% synthetic fuels

Flexibility: (no specific measures)

International scenario (Germany)



Supply: Considerable volumes of wind and solar PV. Biogas production and import of synthetic methane and fuels

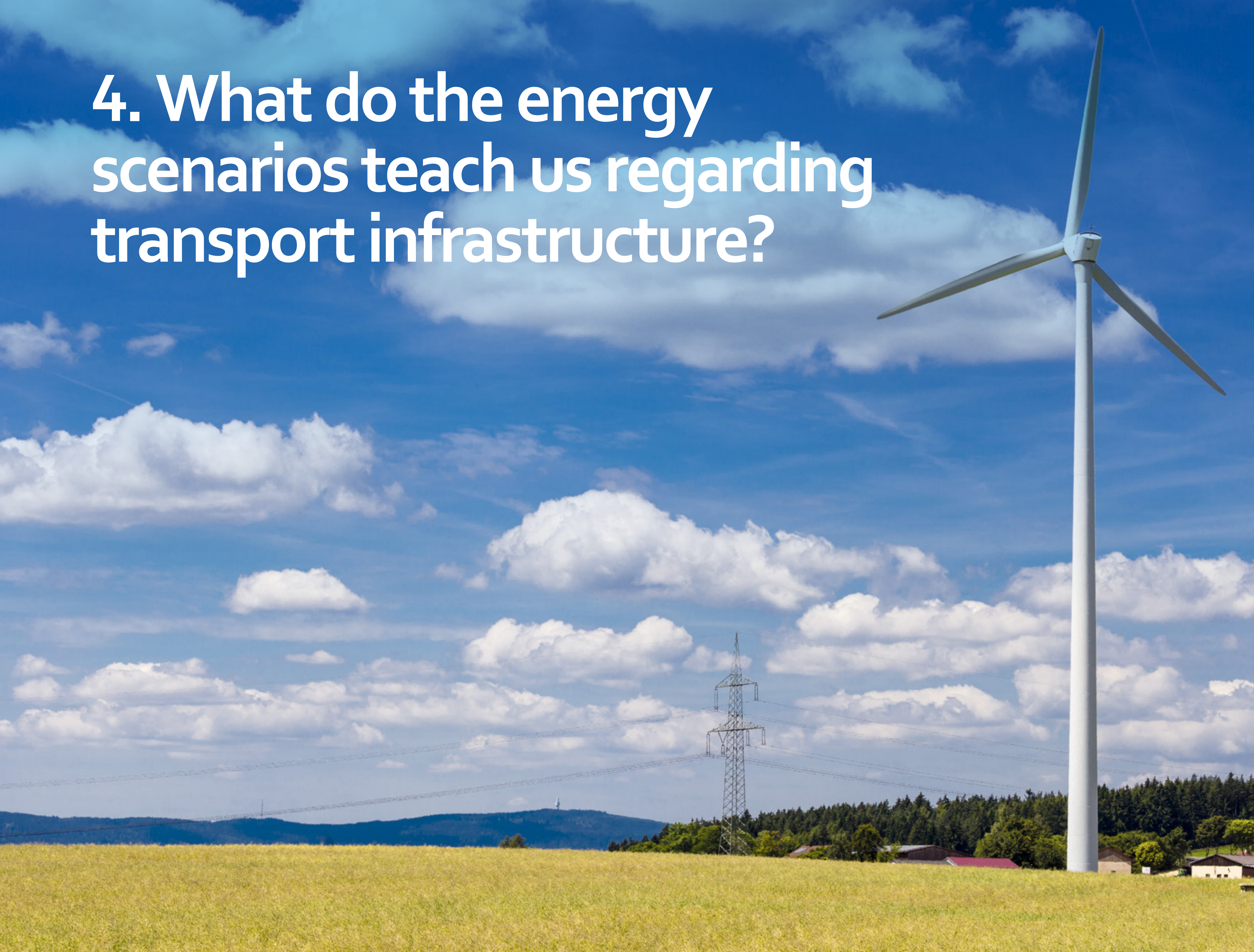
Demand: Spatial heating: Electric heat pumps, synthetic gas and fuel boilers

Industry: feedstock: methane and synthetic fuel, heat: hydrogen, methane and electricity

Transport: passenger cars: electricity, methane, hydrogen and synthetic fuel (all 25%); trucks: 25% hydrogen, 25% electricity and 50% synthetic fuel

Flexibility: Power to gas and some batteries

4. What do the energy scenarios teach us regarding transport infrastructure?



4.1 Final annual electricity and gas demand

For the Netherlands, the scenarios with a high share of domestic renewable electricity production ('Local' and 'National') show an increase of 30% in the total amount of electricity that will need to be transported. For the international scenario, the total amount of electricity that will need to be transported is comparable to today's transport volumes. The total amount of electricity that will be transported through the German electricity system in 2050, will remain within a range of ± 10% of the present levels.

For all German and Dutch scenarios, we found that the total annual volume of gas that will need to be transported (synthetic methane and hydrogen) will be either comparable to, or even higher than today's volume.

In addition to the above mentioned findings, Figures 3 and 4 also show that the final total energy demand will decrease in both countries. This is mainly because of a decline in liquid fuel consumption. It should be noted that both figures present the values for ***final*** demand. The primary production of electricity will be much higher in both countries due to the intermediate conversion of power into gas.

For most German scenarios, the demand for hydrogen will also be higher, due to the subsequent conversion of hydrogen into methane and liquid fuels.

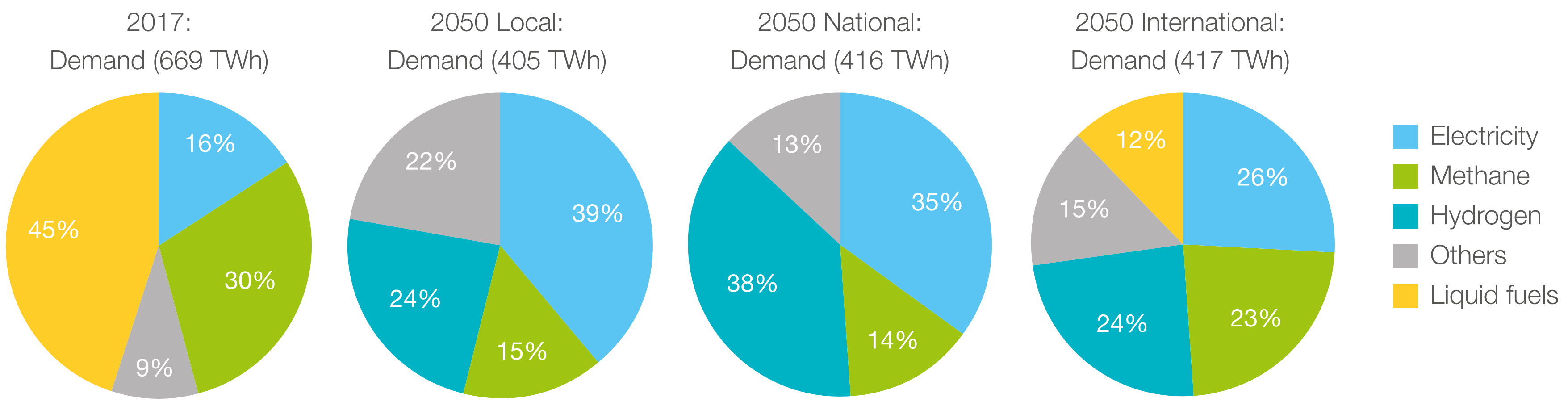


Figure 3: Final annual demand in the Netherlads in 2017 and in 2050 for the three Dutch scenarios.

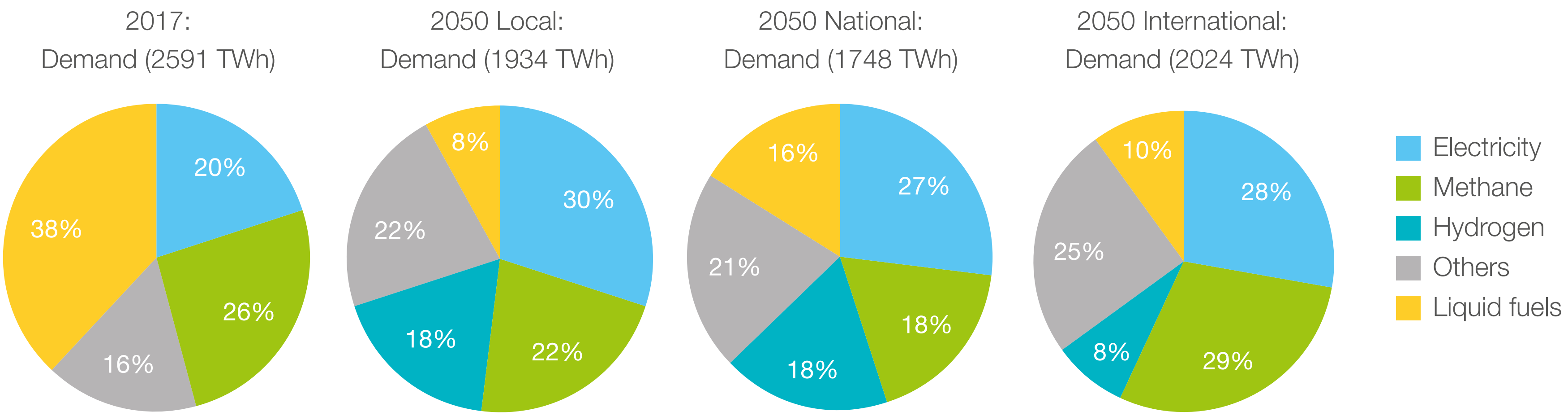


Figure 4: Final annual demand in Germany in 2017 and in 2050 for the three German scenarios.

4.2 Annual gas storage demand

The findings regarding gas storage are based on the assumption that the available pore and aquifer storages will be used to store methane in 2050. For hydrogen, we assume storage in salt caverns to be the preferred option, based on a recent report by TNO[17].

The results show that there are currently enough pore and aquifer storages (depleted gas fields) available for both countries to store methane in all of the considered scenarios. The available storage volumes of salt caverns in the Netherlands need to be expanded for all scenarios considered. For Germany the results show that the available cavern storage capacity is sufficient to meet the demand for the international scenario. For the other two scenarios a certain expansion is foreseen.

Due to the lower calorific value of hydrogen, converting caverns from methane to hydrogen storage will reduce the energy content of the facility by a factor three. In the Netherlands, around 3 TWh of cavern storage is available for natural gas. Converting all caverns from methane to hydrogen would therefore reduce the energy content to 1 TWh. The modelling results for the Netherlands show that, depending on the scenario, a cavern storage volume up to 20 times higher than current capacity will be needed to secure future hydrogen supply.

The currently available pore and aquifer storages in the Netherlands have a total storage capacity of 150 TWh for natural gas, which is more than enough for the future storage of methane.

[17] https://www.nlog.nl/sites/default/files/2018-11/Ondergrondse+Opslag+in+Nederland+-+Technische+Verkenning.pdf

Required gas storage volumes in the Netherlands (TWh)

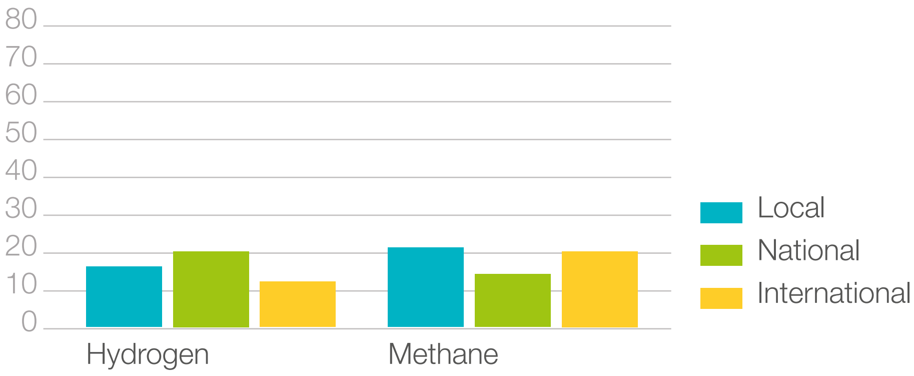


Figure 5: Required hydrogen and methane gas storage volumes in 2050 for the three Dutch scenarios

Required gas storage volumes in Germany (TWh)

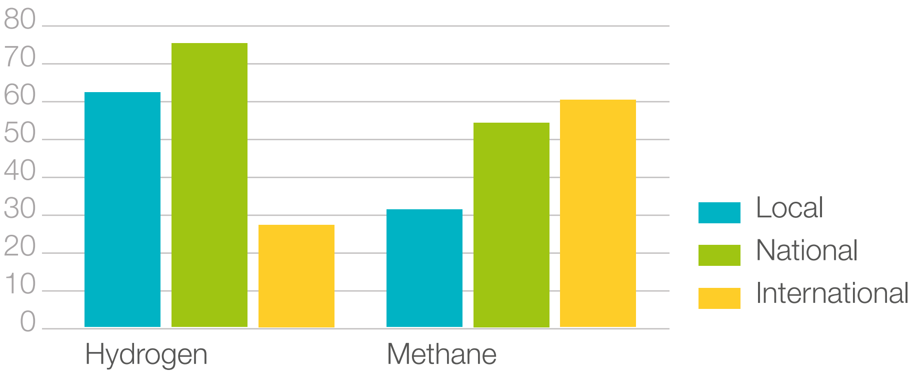


Figure 6: Required hydrogen and methane gas storage volumes in 2050 for the three German scenarios

In Germany, some 140 TWh of cavern storage is available for methane. Converting all caverns from methane to hydrogen storage would reduce the energy content of cavern storage to 45 TWh. This is enough for the international scenario, but not enough for the other scenarios, based on the current assumptions.

Cavern storages for hydrogen will play an important role for all three German scenarios due to the large amounts of installed P2G capacities that are foreseen. In all scenarios the storages are also heavily used with respect to capacity and storage volume. As mentioned above it may be necessary to expand not only storage volumes, but also their capacity in the future hydrogen system. However, this issue will require further study because the need for hydrogen and methane storage very much depends on the way the methanation installations are handled.

The currently available pore and aquifer storages in Germany have a total storage volume of 120 TWh for methane, which, based on the current assumptions, is more than enough for future methane storage.

4.3 National peak supply and demand for electricity and gas

In order to cover annual energy demand with solar and wind power, the electricity system must absorb supply surpluses of up to five times the current peak electricity demand. This is the case in both Germany and the Netherlands.

The total gas system has sufficient capacity for hydrogen and methane transport to handle the volatilities in electricity supply, if enough storage for hydrogen, both in terms of capacity and volume, is made available. Peak electricity demand for power and light applications will increase up to a factor two for both Germany and the Netherlands.

Above findings are illustrated in Figures 7 and 8, which present the values for peak demand and supply of electricity, hydrogen and methane for both the Dutch and the German scenarios.

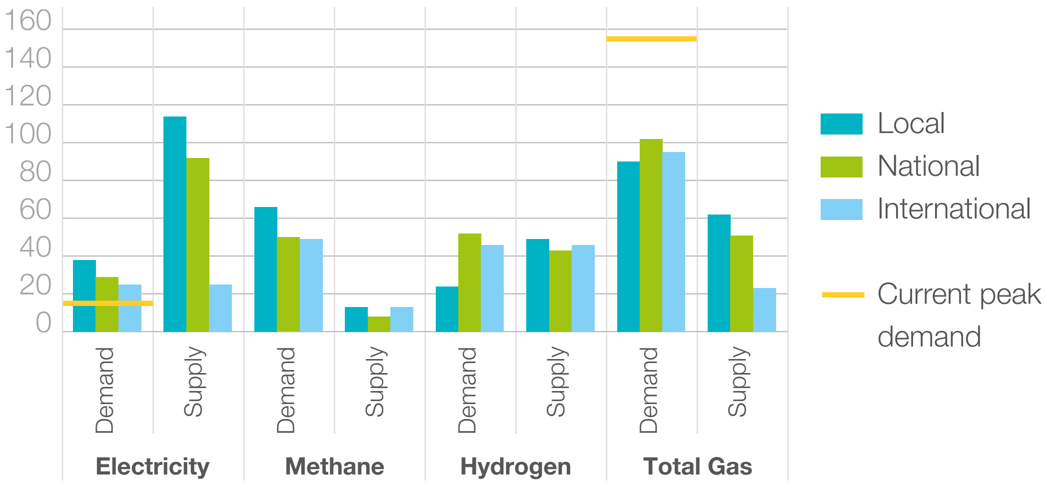


Figure 7: Dutch national peak demand and supply (GW) for the three scenarios[18].

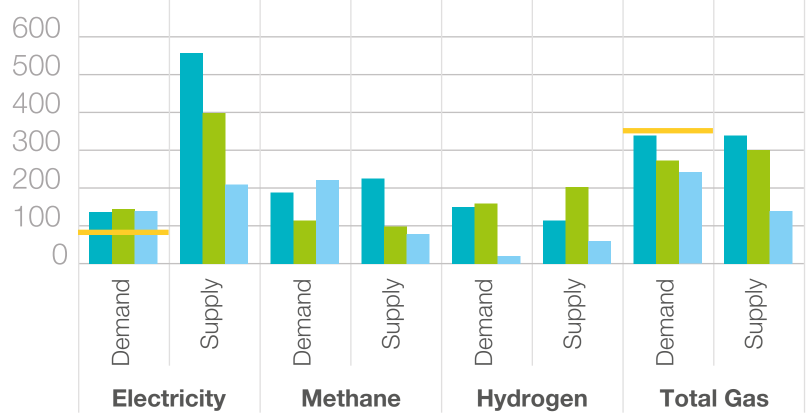


Figure 8: German national peak demand and supply (GW) for the three scenarios[19].

The considerable increase in electricity peak demand already indicates that reinforcement of the transmission grid will become necessary. t is also clear, that measures must be taken to prevent an overload of the electricity system, which may occur by inappropriate choice of P2G locations or way of operation.

As the model results show that the transport needs in 2050 for both total gas demand and total gas supply will be lower than the currently observed levels, no severe problems are foreseen if the locations for P2G and methanation (Germany) are properly selected. Under the local scenario for Germany this location selection can become a critical factor, because the total gas demand corresponds exactly with the current peak transport capacity.

[18] Demand and supply do not include any flexibility instruments, e.g. storage capacities.
[19] Demand and supply do not include any flexibility instruments, e.g. storage capacities.

5. What does the infrastructure model teach us?

5.1 Regarding the coupling of gas and electricity infrastructure?

Converting renewable energy to hydrogen at locations close to the renewable production facilities will relieve bottlenecks in the electricity infrastructure, without causing problems for the gas infrastructure. This means that the location of P2G installations is crucial for the energy flows in the system and the amount of renewable energy that can be collected using hydrogen as a carrier.

We tested the abovementioned findings by analysing the grid consequences for a situation where P2G installations are located near solar and wind energy production (proportional to installed generation capacity) and for a situation where the P2G installations are sited near industrial areas with hydrogen demand. As illustrated by Figure 9, where a critical situation of high demand and high infeed of renewables in the Netherlands is used as an example, siting P2G installations near renewable supply will decrease the total transport demand for electricity and will reduce the number of bottlenecks.

Model results, which are provided in Appendix III, also revealed that siting of P2G installations near renewable supply at quantities proportional to the total installed capacity of solar and wind power does not always prevent congestion in the electricity grid. This is because the favourable locations for solar and wind power installations in both countries are in different areas of the country, e.g. for Germany, wind power in the north and solar power in the south. This finding is best illustrated on the basis of two snapshots for Germany as presented in Figure 10. The left side of the figure shows the results of a snapshot for the local scenario for an hour at the end of February with a simultaneous high infeed of wind and solar power. As the figure shows, the German electricity system is able to accommodate this situation in the given set-up of the P2G installations.

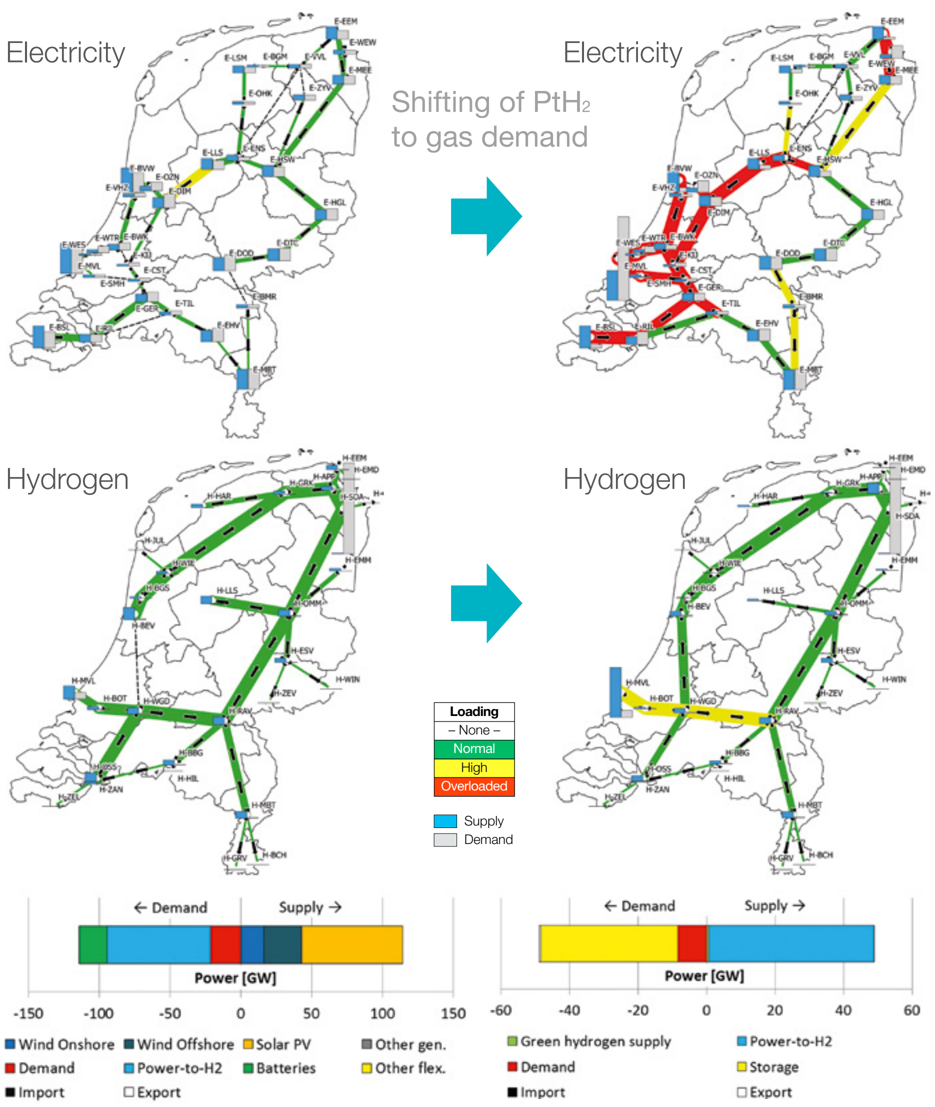


Figure 9: Impact of electrolyser location on electricity flows in the Netherlands. Snapshot 4044 (high demand and high infeed of renewable energy), with electrolysers located close to renewable electricity supply (left) and close to hydrogen demand (right).

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The right side of the picture shows an hour at the beginning of February, again for the local scenario, with only a high infeed of electricity from wind. In this case, we found that the German electricity transmission system will be considerably overloaded, even though the fact that total supply is lower than calculated for the left situation. This is because a large share of the surpluses of wind power produced in the north of the country has to be transported to the P2G installations in the south, near locations of solar generation.

Our analysis underlines the importance of the careful consideration of the locations and installed capacities of P2G facilities for the efficient use of existing infrastructures. For example, placing P2G installations predominantly at the same locations as wind generation may be advantageous because, over time, 1 GW of installed wind power generates more energy than 1 GW of installed solar power.

The way P2G facilities are operated could also have a major impact on the grids. For example, if not all P2G capacities are used at a certain point in time, the decision of which plant to have in operation will determine the flow on the electricity and gas grids.

5.2 Regarding the electricity infrastructure?

In addition to the findings in the previous section regarding the locations and capacities of P2G installations, our study also found that the Dutch electricity transmission network (as foreseen for 2030) will be able to accommodate a considerable part of the forecasted load increase for everyday power and light applications. However, for situations in which the Dutch electricity grid has to accommodate transit flows, there appears to be insufficient available transport capacity.

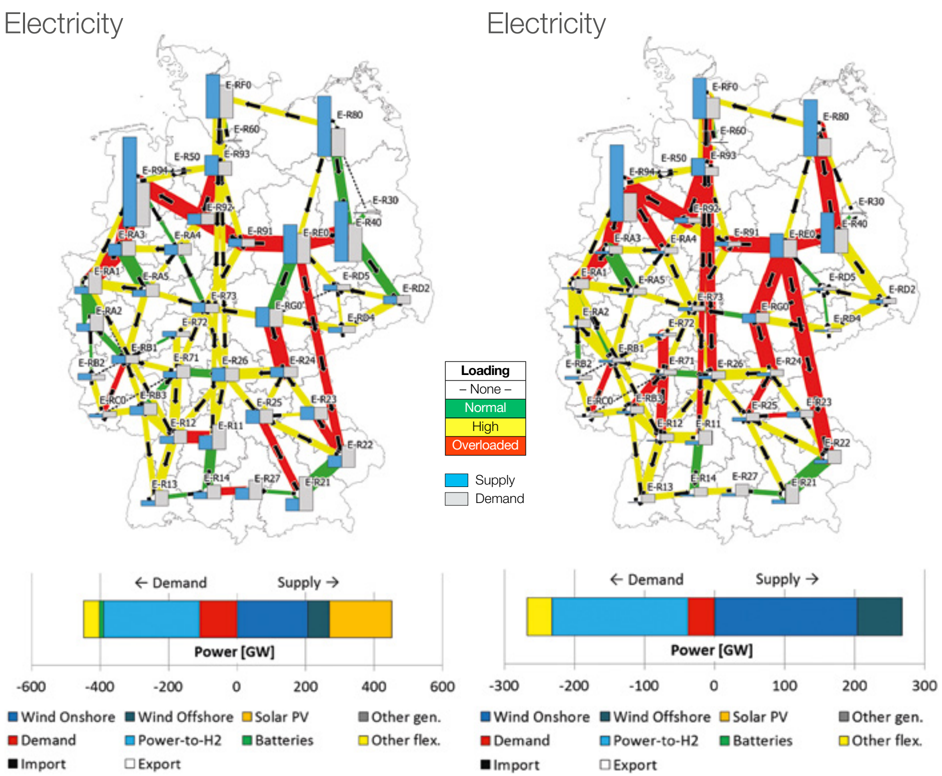


Figure 10: Left: snapshot with high infeed of wind and solar Germany ('Local' scenario, hour 1450, which is a daytime hour at the end of February). Right: snapshot high infeed of only wind ('Local' scenario, hour 916, which is a nighttime situation in the beginning of February).

For Germany, meanwhile, we have found that the electricity network as foreseen for 2030 will still not have sufficient capacity to cover the peak demands as forecast for 2050.

The specific findings for the Netherlands, as illustrated in Figure 11, show that the transmission network in 2030 can facilitate an increase in peak electricity demand to some extent, but that doubling the peak demand to 35 GW will result in network bottlenecks.
Model results for Germany show that an increase of 20% in current peak load for power and light applications will cause bottlenecks in the 2030 transmission network.

Electricity

Electricity

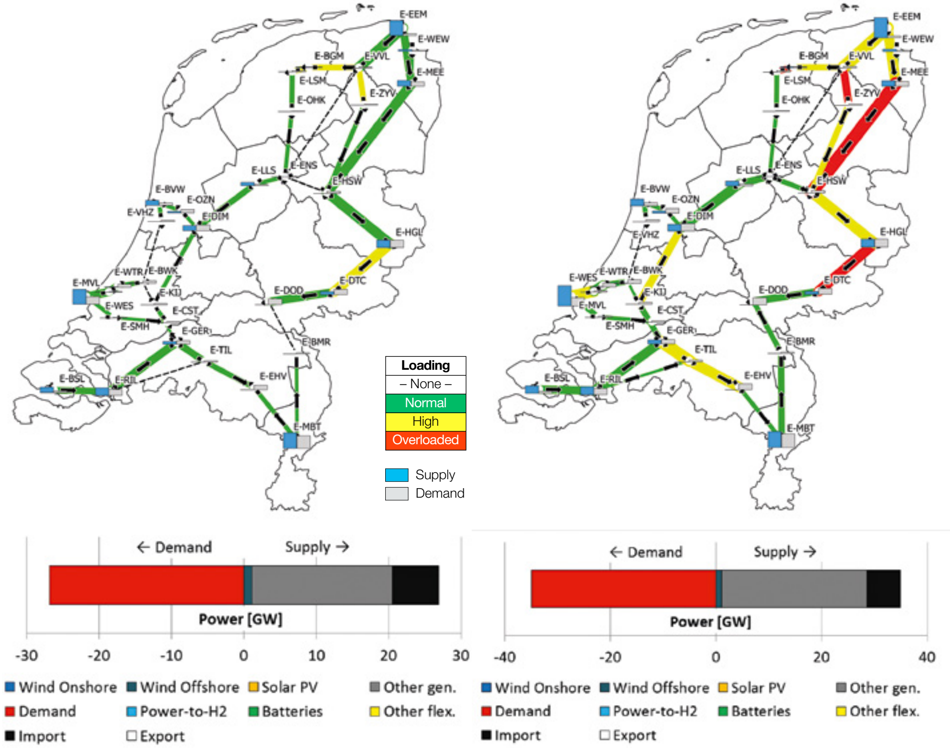


Figure 11: Model results for Dutch snapshots with high demand (Left: National, hour 7746 / Right: Local, hour 954).

Electricity

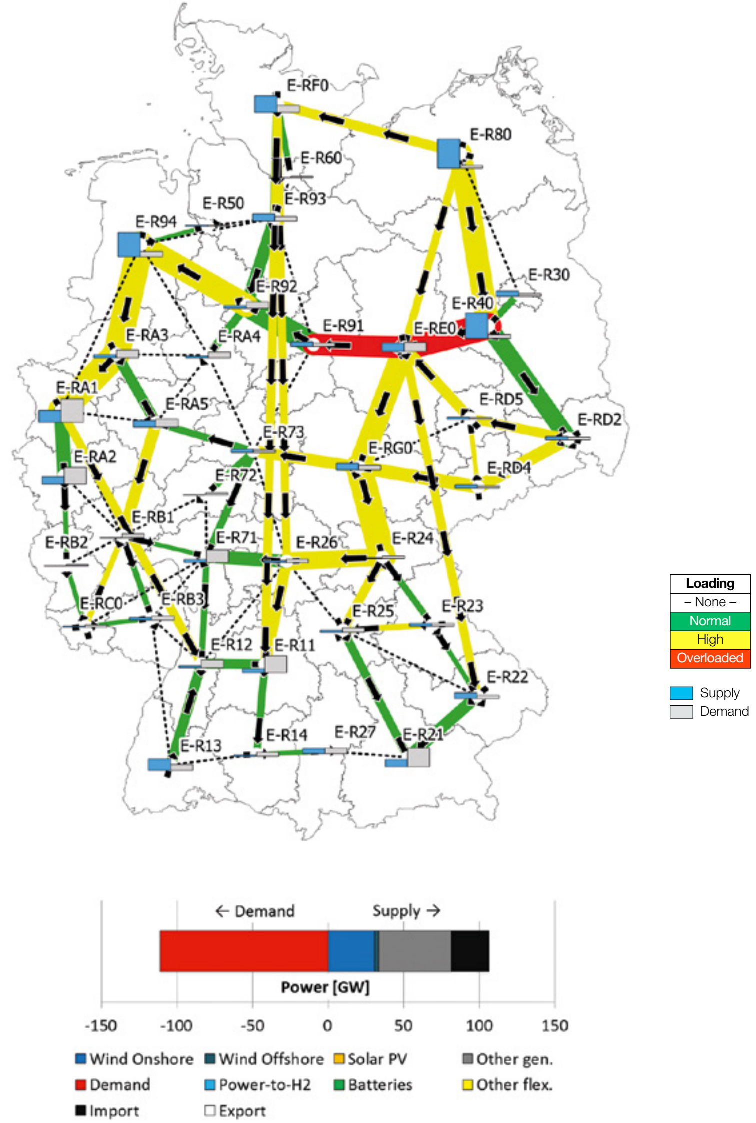


Figure 12: Model results for German snapshot with high demand (Local, hour 473).

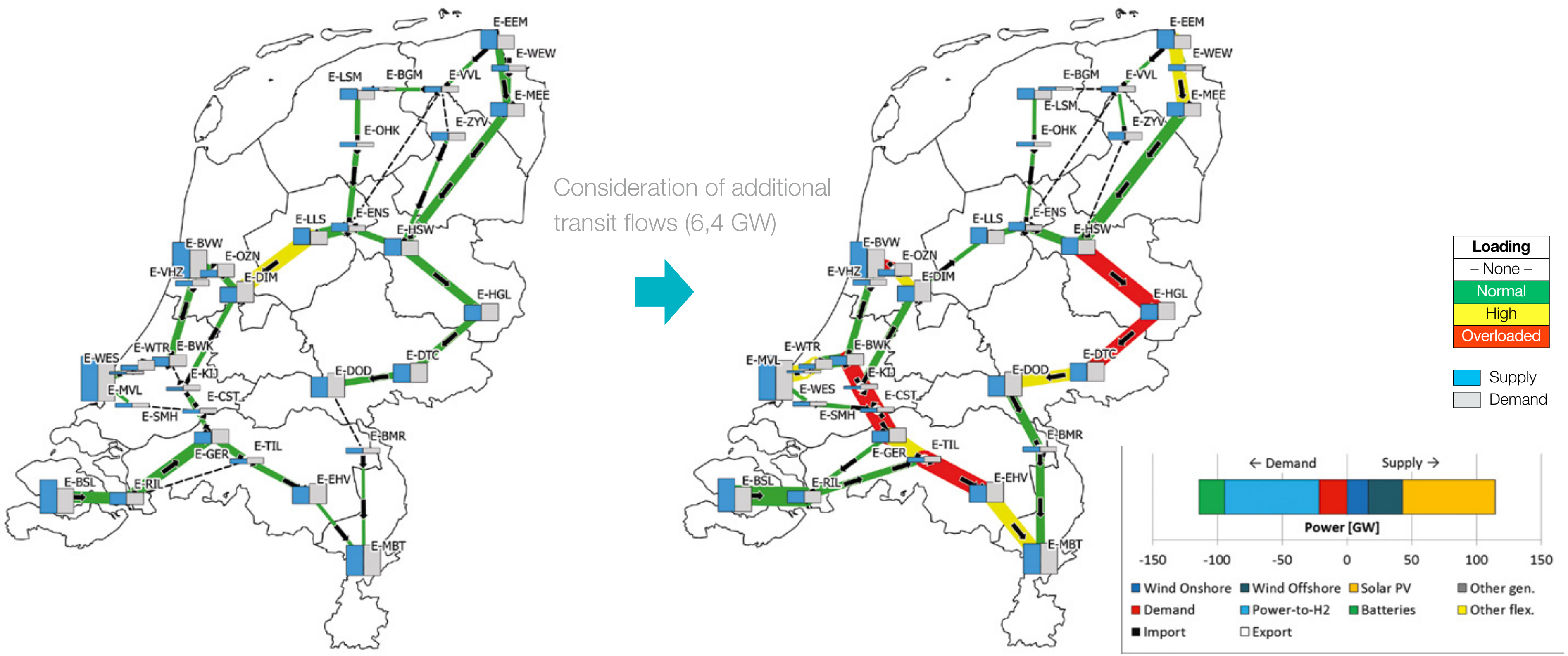


Figure 13: Example of the impact of transit flows on the Dutch electricity transmission grid (Local, hour 4044).

Figure 13 illustrates the impact of transit flows on the Dutch electricity system, assuming an international transit flow from the north of the country to the south. As can be seen, this transit leads to a higher load, leaving less capacity available for domestic energy transports.

5.3 Regarding the gas infrastructure?

Even without performing infrastructure calculations, it is clear that the future use of the gas infrastructure in the Netherlands and Germany will be different from its present use. TSOs currently transport natural gas (of different gas qualities), but in 2050 gas networks must transport hydrogen, (synthetic) methane and maybe even CO_2, if carbon capture has a role in the future energy system.

The infrastructure calculations for the Dutch gas network show that the gas system can accommodate all foreseen severe combinations of hydrogen and methane transport. This includes transport of hydrogen to and from cavern storage facilities in the north-east of the country and the transport of (bio)methane to and from empty gas fields, also mainly located in the north-east.

For Germany, the infrastructure model generally shows higher loads on the methane and hydrogen grids than in the Netherlands. Some snapshots show a high load of the methane or the hydrogen grid infrastructure. The limitations are local: for a small number of connections, the available capacity, assigned based on a relatively simple method, is exceeded.

In the Netherlands, the assumed conversion of the present gas network to a hydrogen transmission network and a methane transmission network is fairly straightforward. The present high-calorific gas network has excellent connections to all large industrial areas in the Netherlands, and to the import and export points. Because hydrogen will become very important as feedstock and as fuel for industrial heating, there are many advantages to assigning the high-calorific network to the transport of hydrogen. The low-calorific network is very well connected to the domestic market (via the intermediate pressure network of GTS and low pressure networks of a number of DSOs), making it the obvious choice for the transmission of methane. With this design, (existing) end-user applications can still be used in the future. As hydrogen and methane pipelines can be found in many areas in parallel stretches, the transport of hydrogen to DSO networks is also possible in these areas.

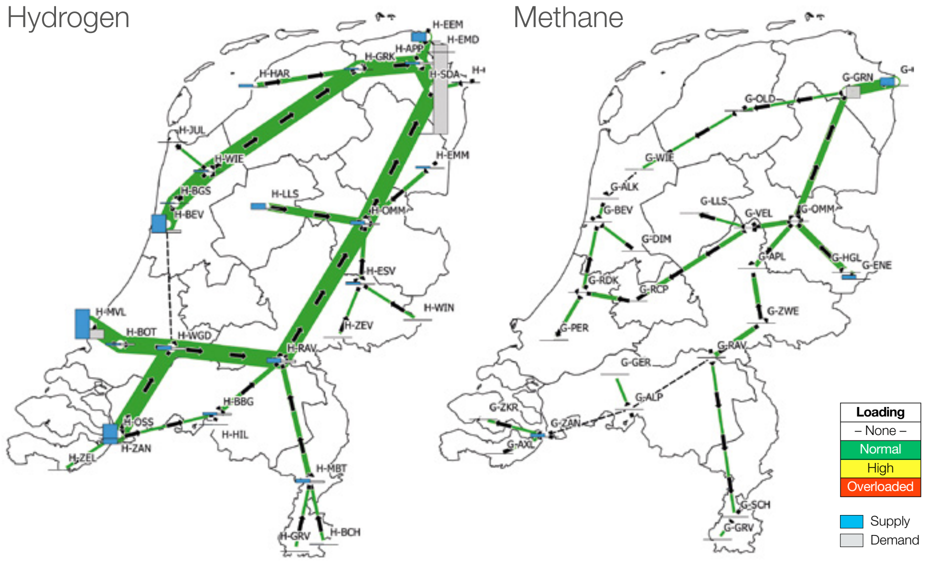
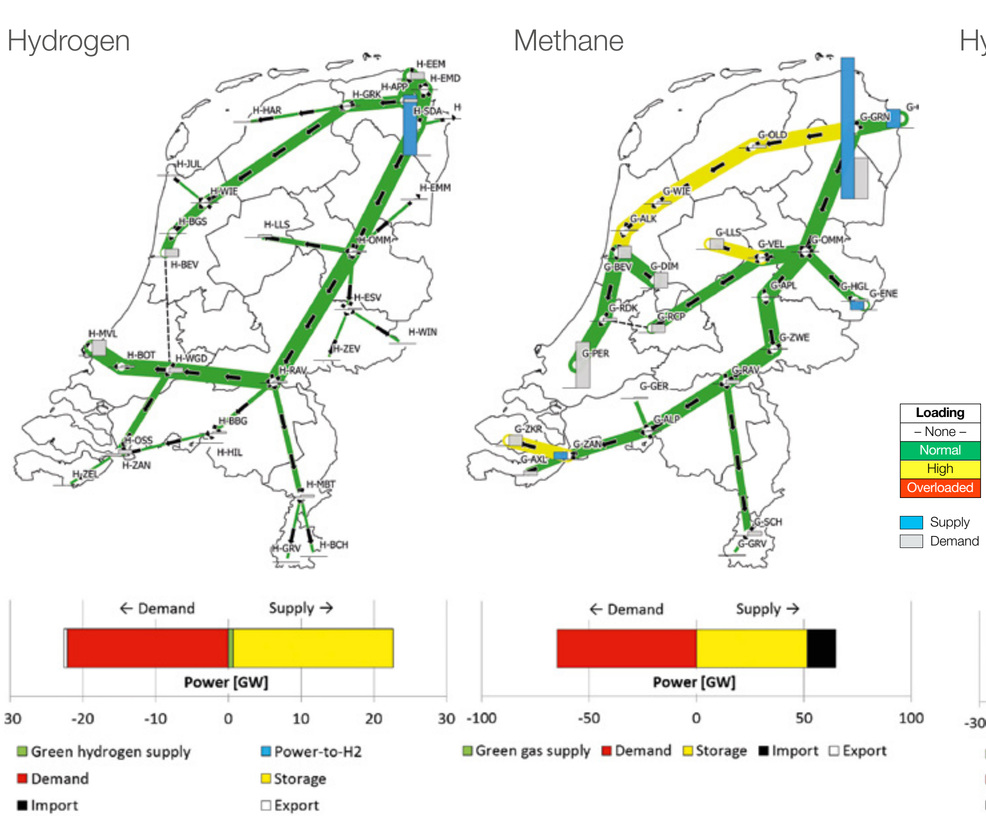


Figure 14: Results of model run for situation with low demand and extensive P2G conversion (National, hour 4044) in the Netherlands.

The above findings for the Netherlands' infrastructure are proven in the model runs, where extensive P2G conversion will be used to store excess energy during a high supply situation, while for a high-demand situation and no infeed from renewables, previously stored energy will be used. As can be seen in Figure 14, situations with low demand and high hydrogen production give rise to hydrogen flows in the direction of the storage locations in the north of the country, which can easily be accommodated by the current high-calorific system.

The model results for a situation with high gas demand due to extra demand for spatial heating and the operation of gas power plants supplied with methane from gas storages show a high load of the future methane infrastructure (see Figure 15).



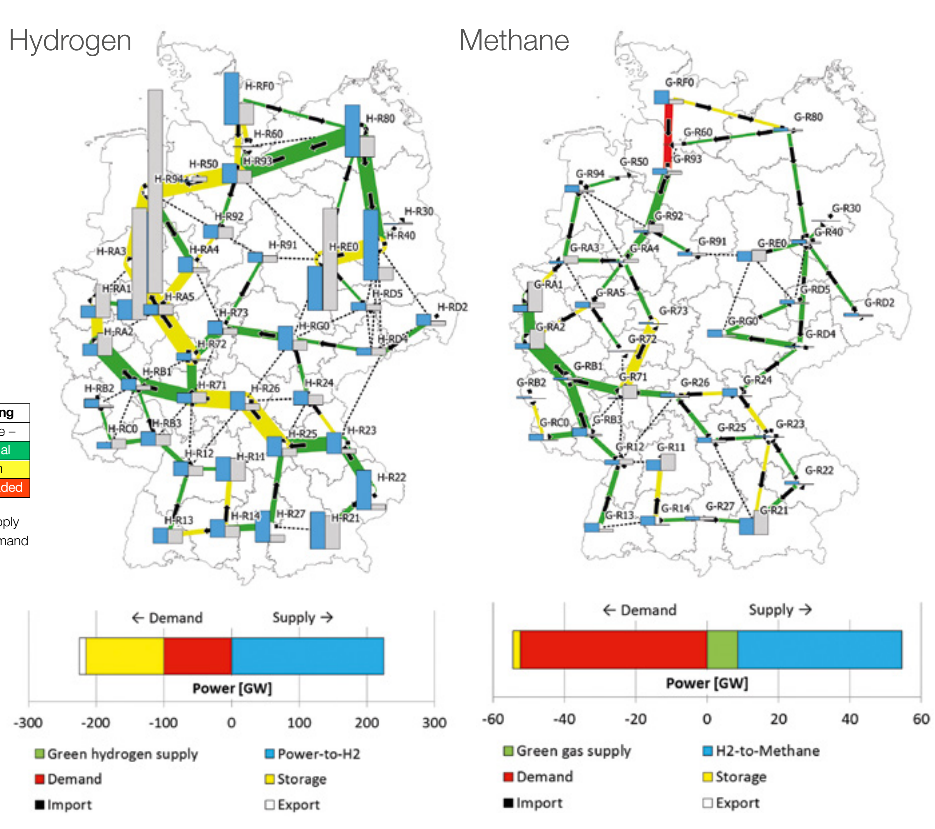


Figure 15: Results of model run for situation with high demand due to spatial heating and operation of back-up power plants (Local, hour 954) in the Netherlands.

Figure 16: Snapshot for a daytime hour at the end of June (Local, hour 4358), with maximum hydrogen production from a high infeed of solar and wind power in Germany.

For Germany, there are a few situations where the assigned capacities of the gas system are exceeded locally, e.g. when all P2G installations are operating at full capacity to convert a large surplus of electricity resulting from a high infeed of solar and wind power.

Figure 16 shows high flows occurring on the German hydrogen grid due to the transport of hydrogen from the P2G facilities to the storage locations, which are mainly located in northern Germany due to the presence of geological salt formations there.

The methane grid shows a moderate transport situation, since it only has to cope with a constant, relatively small supply of methane from methanation installations. The bottleneck in the methane grid in the very north of Germany (Schleswig-Holstein) results from the high amount of methanation installations in this area, optimising the integration of offshore renewable production.

Similar to the Netherlands, another stressful situation for the German gas infrastructure (mainly in the local and the national scenario) appears in hours with no hydrogen supply from P2G plants. Here, basically the total gas demand (including gas-for-power plants) will be covered by withdrawal from storages in different regions of Germany. As mentioned above, most hydrogen storages are located in the north of the country, while methane storages can be found in the central area and to a large extent in the south of Germany.

As can be seen in Figure 17, this so-called ‘Dunkelflaute’ situation results in a high load of the total gas infrastructure. Hydrogen from storages in north-west regions is transported to the south of the country, while at the same time methane is transported from storages in the south to the north-west of the country (an important industrial region with high demand is the Ruhr Area). A high load flow exceeding the maximum capacity can be seen for the methane grid in the south of the country.

We should emphasise that, in ‘splitting’ the German gas infrastructure, the hydrogen grid was modelled as a stronger system. The high load of the system we observed may also be a result of the simplifications made for the infrastructure model. As such, detailed modelling for the relevant grid regions is required to draw clear conclusions about any bottlenecks.

Furthermore, it should be kept in mind that the ‘split’ of the gas infrastructure into a hydrogen and a methane grid could be optimised with a broad range of options, which was not done in the context of this study.

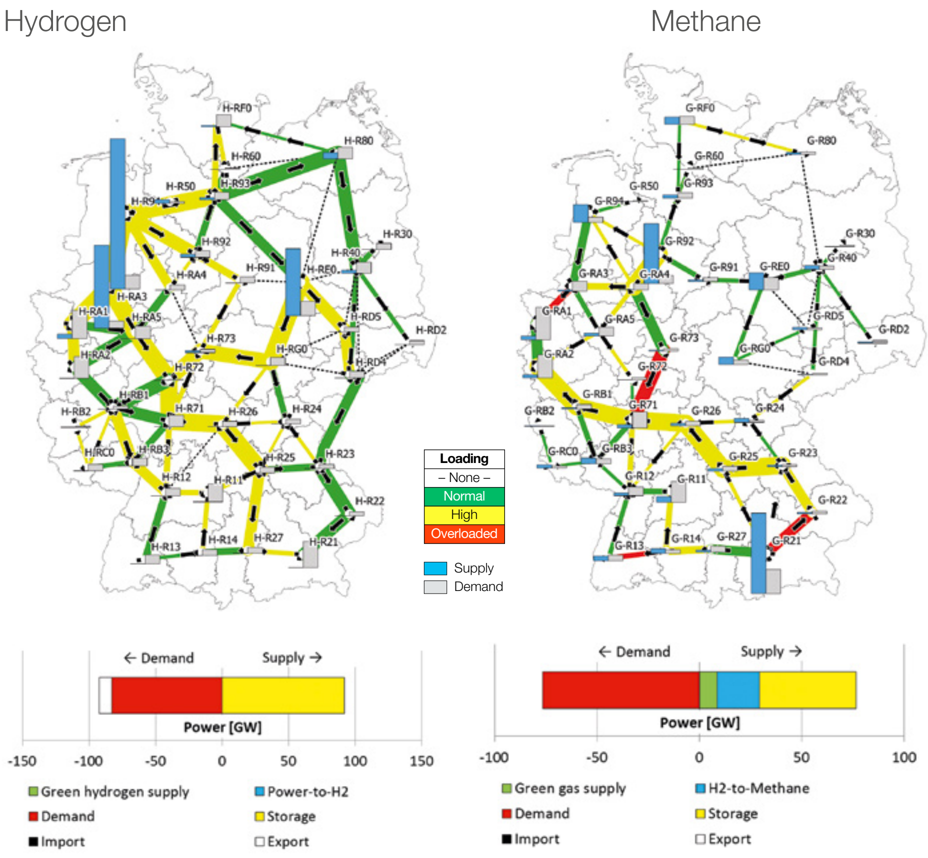


Figure 17: Snapshot of a ‘Dunkelflaute’ situation at the end of January at 6 p.m. (Local, hour 474) in Germany.

6. Conclusions and recommendations

This joint study by TenneT and Gasunie addresses the requirements and limitations of a future energy system largely based on solar and wind power. Meeting demand with these highly fluctuating energy sources will require both a strong electricity and gas infrastructure, in which gas storage plays a crucial factor in securing supply at every moment in time.

This study is intended to support the development of a clear infrastructure strategy that can be of value in the (political) discussions on sector coupling. It should be noted that there are still some ‘unknowns’ surrounding the energy transition and although technology is progressing rapidly, some major components of the future energy system are economically unfeasible under present conditions. However, as technology progresses, costs will continue to fall. Also, if governments continue to set higher targets for carbon emission reductions, energy producers and consumers will react. To achieve this, however, we must take action now. After all, energy systems are not transformed overnight, but require a long-term commitment.

This study applied an innovative modelling approach focused on coupling the gas and electricity infrastructure, which enabled it to consider the (future) infrastructures for electricity, methane and hydrogen as well as their mutual dependence for the Netherlands and Germany. A model simulation was used to examine three different energy system-wide supply and demand scenarios. These scenarios formed the starting point for an exploration of the interplay between electricity and gas, in order to determine the roles and requirements for both energy carriers and illustrate their future application.

The most salient findings from the study are:

Both the existing electricity and gas infrastructure will play a crucial role the energy system of the future

We have found that electricity and gas will play complementary roles in future energy systems, where wind and solar power are the major primary sources of energy for both Germany and the Netherlands. In the scenarios this renewable energy is mainly supplied to end users as electricity or as a green gas. The advantage of transporting electricity directly to those sectors where electrification is feasible is that it avoids energy conversion and the associated energy loss. Green gases, meanwhile, will provide an option for those sectors where electrification is harder to achieve.

Our analysis shows that coupling electricity and gas will give the energy system the flexibility it needs. The existing gas transmission grid has enough capacity to fulfil its fundamentally changed role in the future energy system, although some technical adaptations are needed due to the different characteristics of hydrogen.

Provided that proper guidance can be given to P2G locations, coupling electricity and gas infrastructures may significantly alleviate the long-term expansion needs of the electricity transmission networks. However, further expansion of the electricity grid after 2030 will be required due to the expected growth in demand from end users and the fundamentally changed energy supply structure based on renewable energy sources.

We can conclude that the energy system of the future will require a strong integrated gas and electricity backbone, including storage facilities to secure supply to all forms of final consumption at any moment in time.

Although additional electricity storage will be available by 2050, only gas storage provides a solution for seasonal storage

An energy system based on wind and solar power will require vast amounts of storage to cope with fluctuations in supply, ranging from 'frequency restoration' to 'seasonal storage'. Significant *installed capacities* of electricity storage (e.g. batteries, pump storage) have been considered in various scenarios. However, the energy volume of such storage options is still limited. Existing underground gas storage facilities, on the other hand, can absorb large quantities of renewable energy for seasonal and long-term storage via P2G conversion. Gas from storage provides the main source of energy to the entire system during 'Dunkelflautes'. As such, gas and electricity storage are also complementary.

Location, capacity and operation of P2G installations are decisive factors and must be aligned with both electricity and gas TSOs

Coupling the electricity and gas transport infrastructure with P2G installations gives the overall energy system additional flexibility. However, under scenarios with a high penetration of wind and solar power, the use of P2G causes a massive increase in electrical peak load, as a result of which it can worsen the infrastructural bottlenecks if the capacities and locations of these P2G installations are not properly aligned with the grids.

Our analysis of results indicates that locating P2G installations near renewable production facilities can reduce the need for electricity grid expansion. This is especially the case when the overall P2G capacity is relatively high in comparison to renewables. It is not a given however that P2G installations always relieve grid constraints. Significant electricity and gas grid constraints may still arise if, from a grid perspective, the operation of these installations is suboptimal. Therefore, appropriate incentives for the operation of P2G units must be put in place to ensure efficient grid operation.

Socially acceptable solutions for an integrated energy infrastructure require a new level of public and political support

Increasing peak demand in the electricity grid, as is the case under all scenarios that were researched in this study, will result in an increased use or even overloading of transmission lines. According to the methodology chosen for this study, this can lead to a need for additional electrical grid expansions in addition to the long-term measures until 2030 that have already been confirmed, both technically and politically.

We have identified two crucial aspects for the realisation and success of the energy transition: political willingness to construct new electricity transmission lines to accommodate the predicted demand growth by end users and the creation of a clear supportive regulatory framework for the integration of P2G plants in the system in order to minimise the total number of grid expansions.

Recommendations and further work

- Future discussions on energy transition should aim for a detailed P2G implementation strategy, with special consideration of the corresponding implications it will have on electricity and gas grids.
- This strategy should also include work on the technical and economic feasibility of large-scale P2G facilities.
- In order to ensure efficient network investments, the electricity and gas TSOs should be involved in drawing up a detailed P2G integration strategy.
- To facilitate an efficient transition, we recommend that various pathways to 2050 described in this study are worked out in further detail.
- The findings of this study can provide guidance to the investment plan processes (NEP in Germany and IP/NOP in the Netherlands).
- The scenarios used in this study were based on national CO_2 accounting rules and therefore did not consider the future energy demand for international aviation and sea shipping. Since these forms of transport are predicted to require substantial amounts of energy in the future for both Germany and the Netherlands, we recommend including them in a follow-up analysis.

gasunie
crossing borders in energy

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Gasunie is a European gas infrastructure company. Gasunie's network is one of the largest high-pressure pipeline networks in Europe, comprising over 15,000 kilometres of pipeline in the Netherlands and northern Germany. Gasunie wants to help accelerate the transition to a CO_2-neutral energy supply and believes that gas-related innovations, for instance in the form of renewable gases such as hydrogen and green gas, can make an important contribution. Both existing and new gas infrastructure play a key role here. Gasunie also plays an active part in the development of other energy infrastructure to support the energy transition, such as district heating grids. **Crossing borders in energy.**

TenneT
Taking power further

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TenneT is a leading European electricity transmission system operator (TSO) with its main activities in the Netherlands and Germany. With almost 23,000 kilometres of high-voltage connections we ensure a secure supply of electricity to 41 million end-users. We employ approximately 4,000 people, have a turnover of EUR 3.9 billion and an asset value totalling EUR 21 billion. TenneT is one of Europe's major investors in national and cross-border grid connections on land and at sea, bringing together the Northwest European energy markets and enabling the energy transition. We make every effort to meet the needs of society by being responsible, engaged and connected. **Taking power further.**

February 2019

Appendices

Table of contents

Appendix I

Methodology overview (NL)

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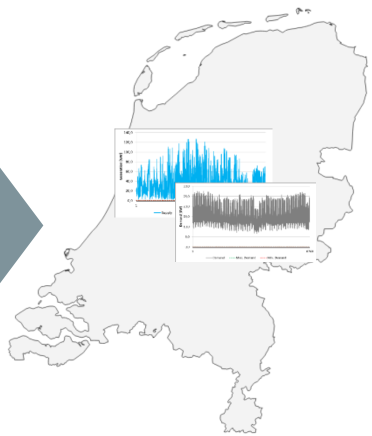
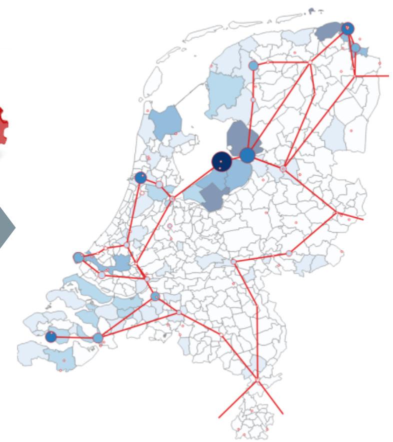
Methodology overview (NL)

Scenario A

Scenario B

...





Scenario framework

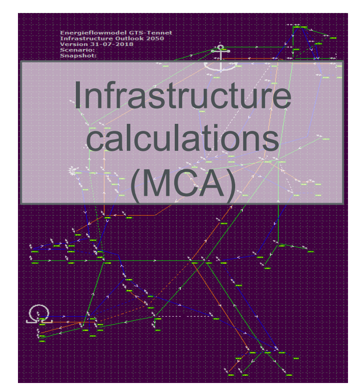
Energy system calculations

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

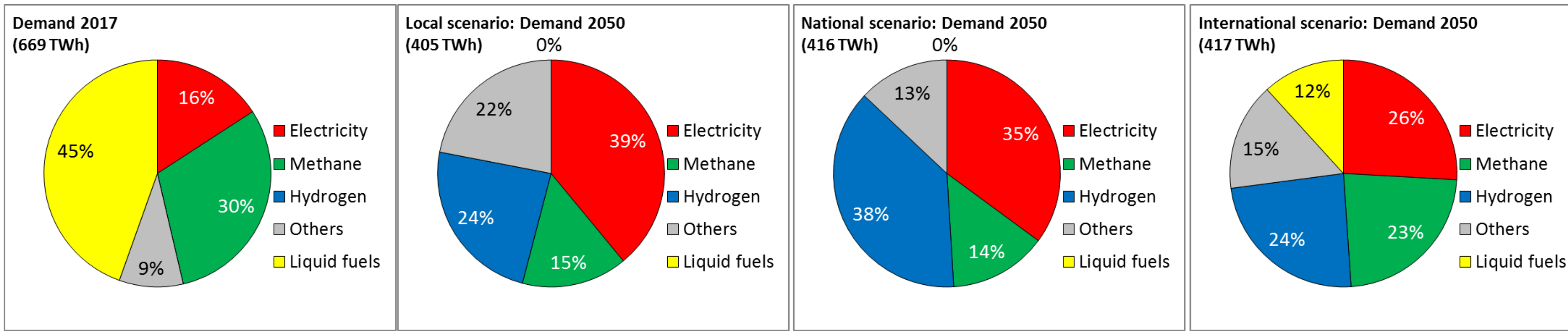
NvdT 'regional' (NL)
Enervis 'Optimiertes System' (DE)

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

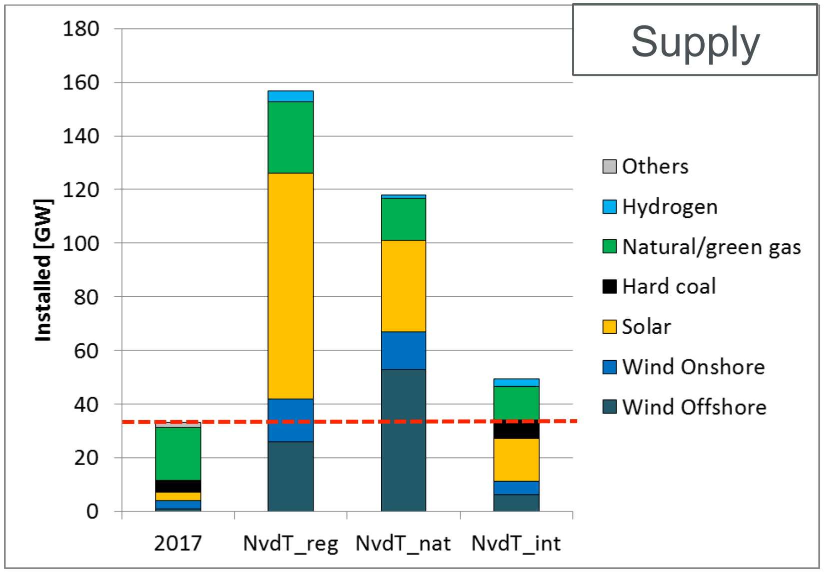
Scenarios: Study overview

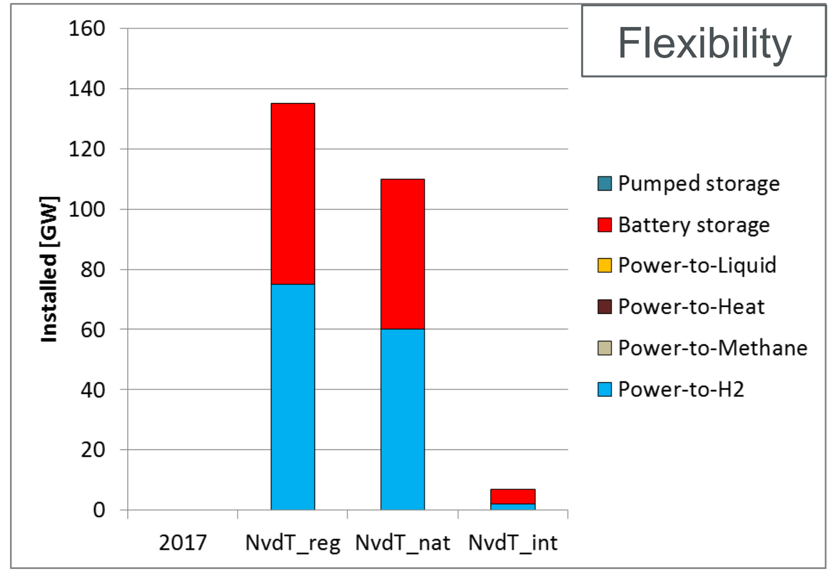
- “Net voor de toekomst” (CE Delft, 2017) → NvdT: local, national, international
- “Erneuerbare Gase - ein Systemupdate der Energiewende“ (Enervis, 2017) → Enervis
- „Leitstudie integrierte Energiewende“ (dena, 2018) → dena
- „Der Wert der Gasinfrastruktur für die Energiewende in Deutschland“ (Frontier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

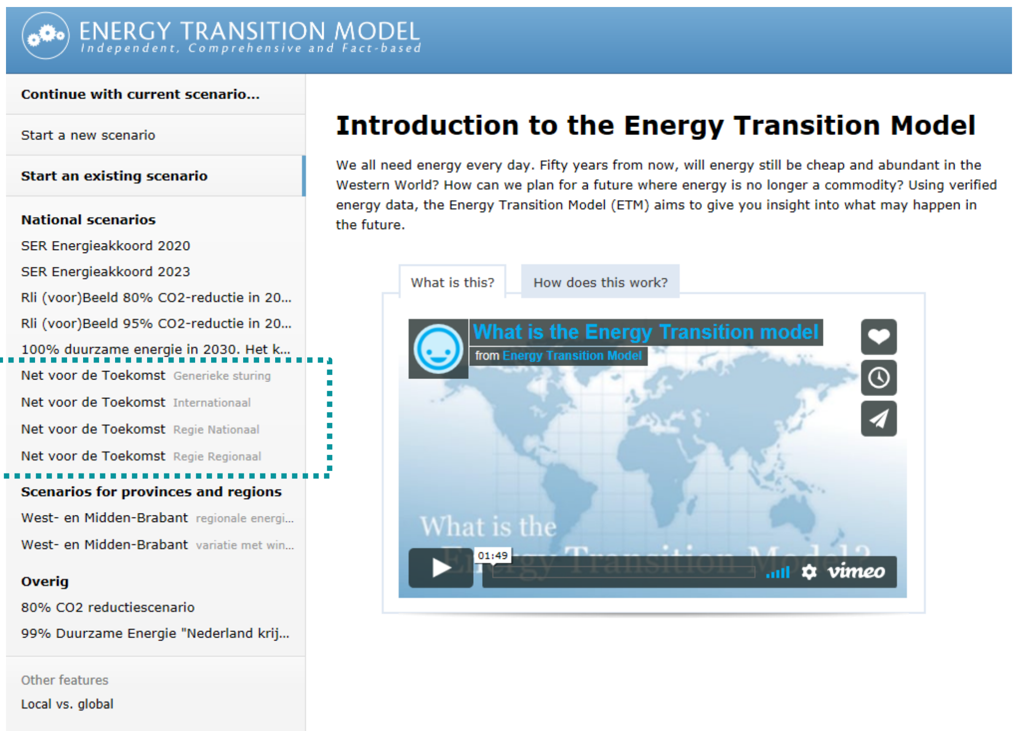
Scenarios: Concrete dataset for 2050 (NL)

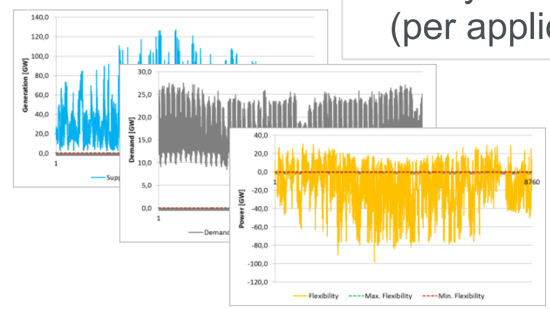
Category	Unit	2017*	NvdT_reg	NvdT_nat	NvdT_int
Supply					
Wind Offshore	GW	1	26	53	6
Wind Onshore		3	16	14	5
Solar		3	84	34	16
Hard coal		5	0	0	7
Natural/green gas		20	27	16	13
Hydrogen		0	4	1	3
Others		2	0	0	0
Sum of supply		**33**	**157**	**118**	**49**
Demand					
Households	TWh	**102**	**59**	**79**	**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)

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

Flexibility option	Description
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

Infrastructure Outlook 2050

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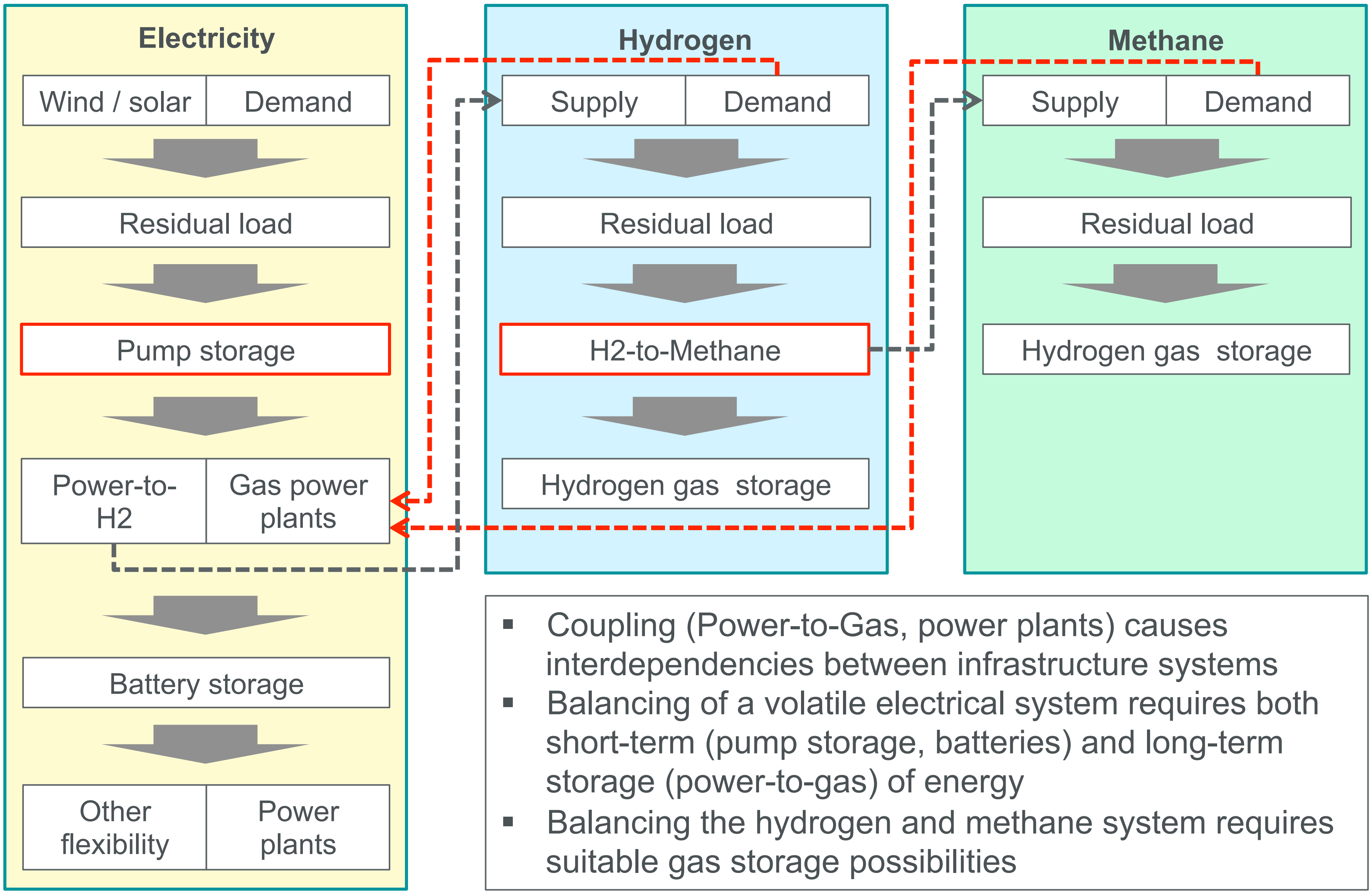
Energy system calculations: General scheme coupling

Only modeled for DE



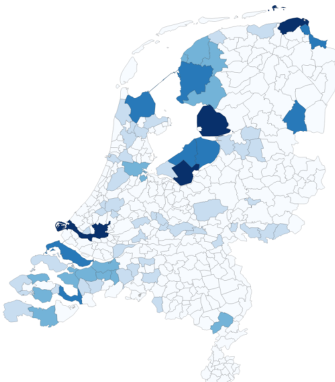
- Coupling (Power-to-Gas, power plants) causes interdependencies between infrastructure systems
- Balancing of a volatile electrical system requires both short-term (pump storage, batteries) and long-term storage (power-to-gas) of energy
- Balancing the hydrogen and methane system requires suitable gas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

Regionalization of scenario data (NL)

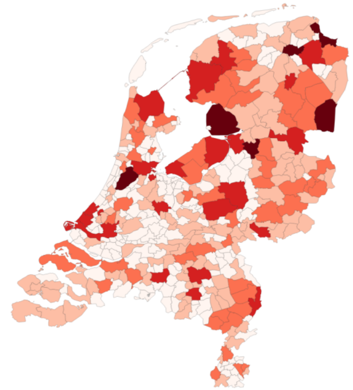
Regionalization (NL): Base assumptions for distribution keys

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

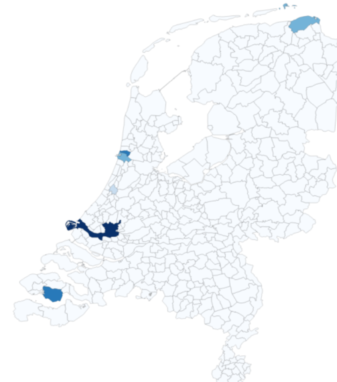
Regionalization (NL): Base assumptions for distribution keys



Wind onshore

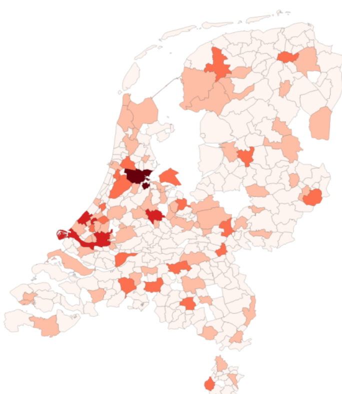


Solar PV

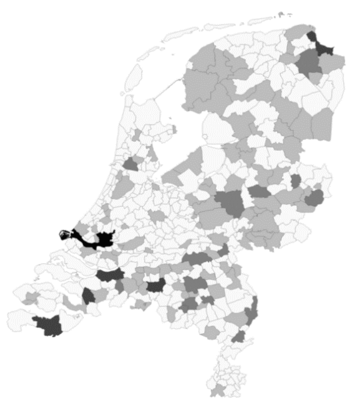


Wind offshore

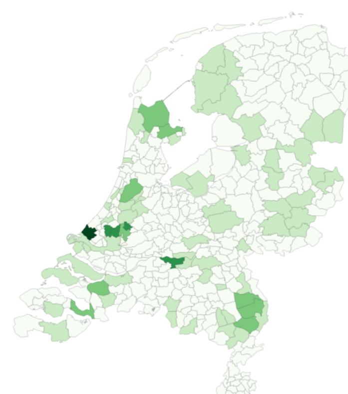
Gas power plants



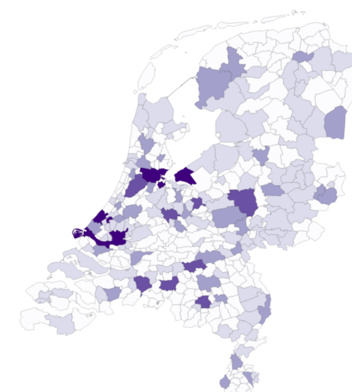
Household demand / batteries



Industry demand / PtHeat



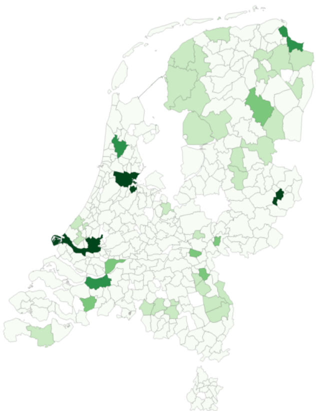
Agriculture demand



Transport demand / batteries

Regionalization (NL): Base assumptions for distribution keys

Import / Export (E)



Green gas / green hydrogen

Import / Export (G, H)

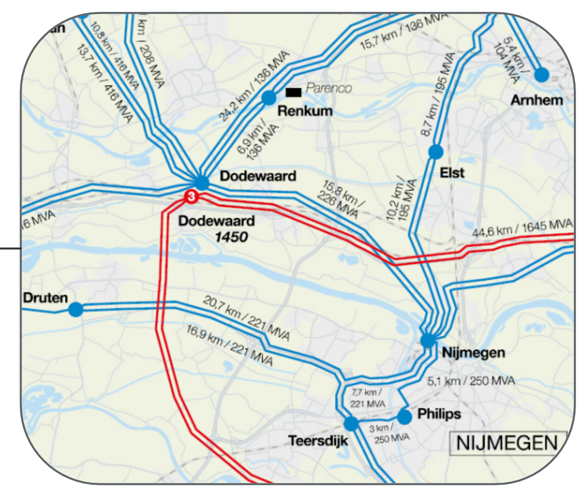
Storage (G, H)

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



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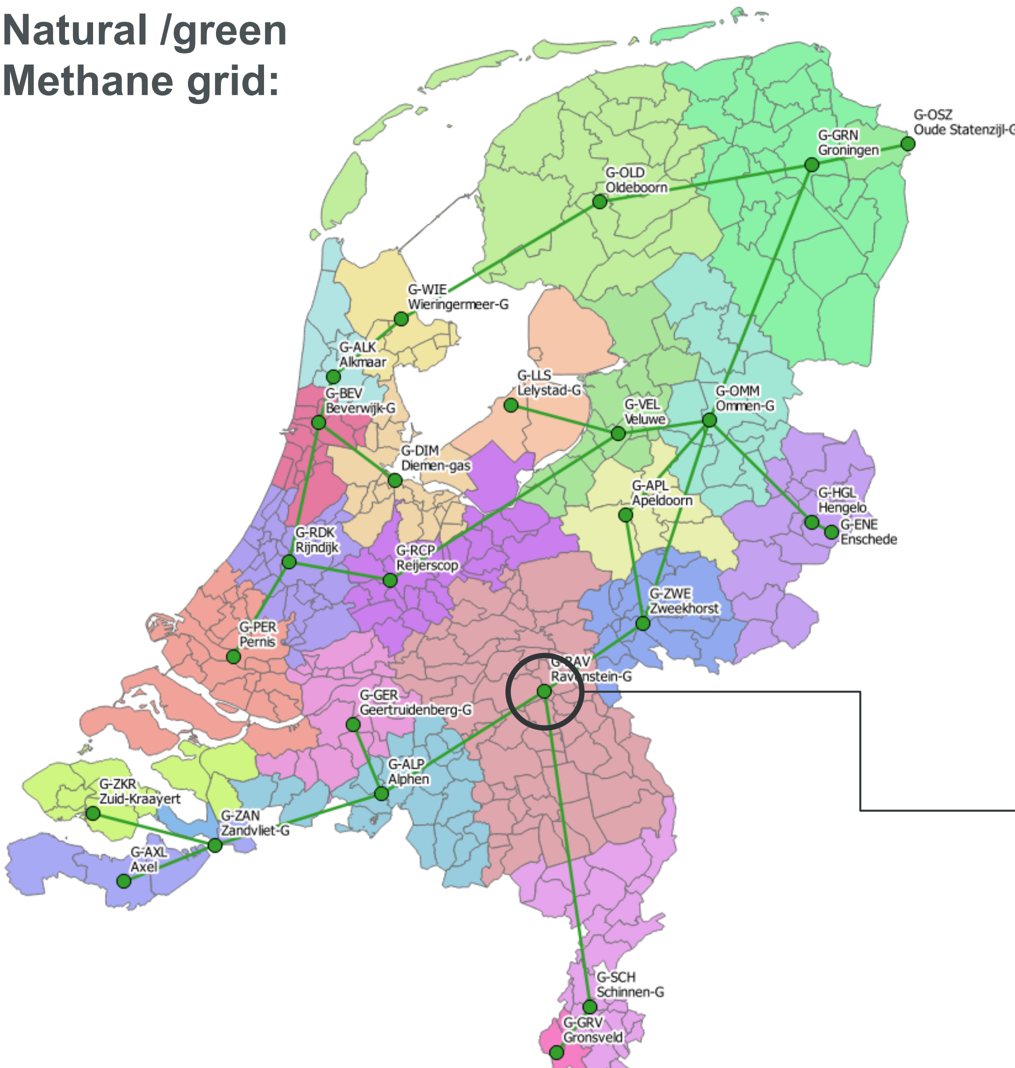
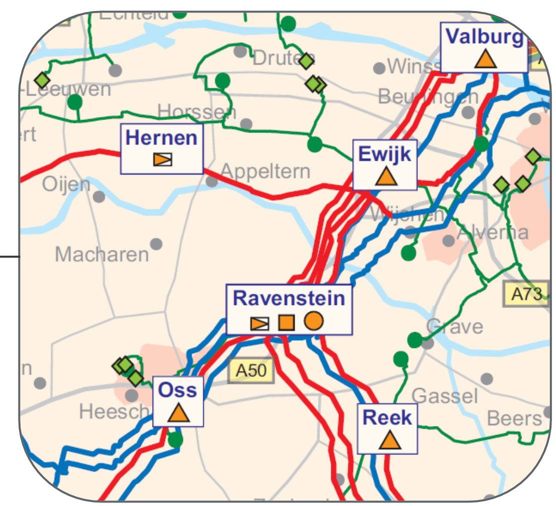
Regionalization (NL): Linking of municipalities to grid nodes

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



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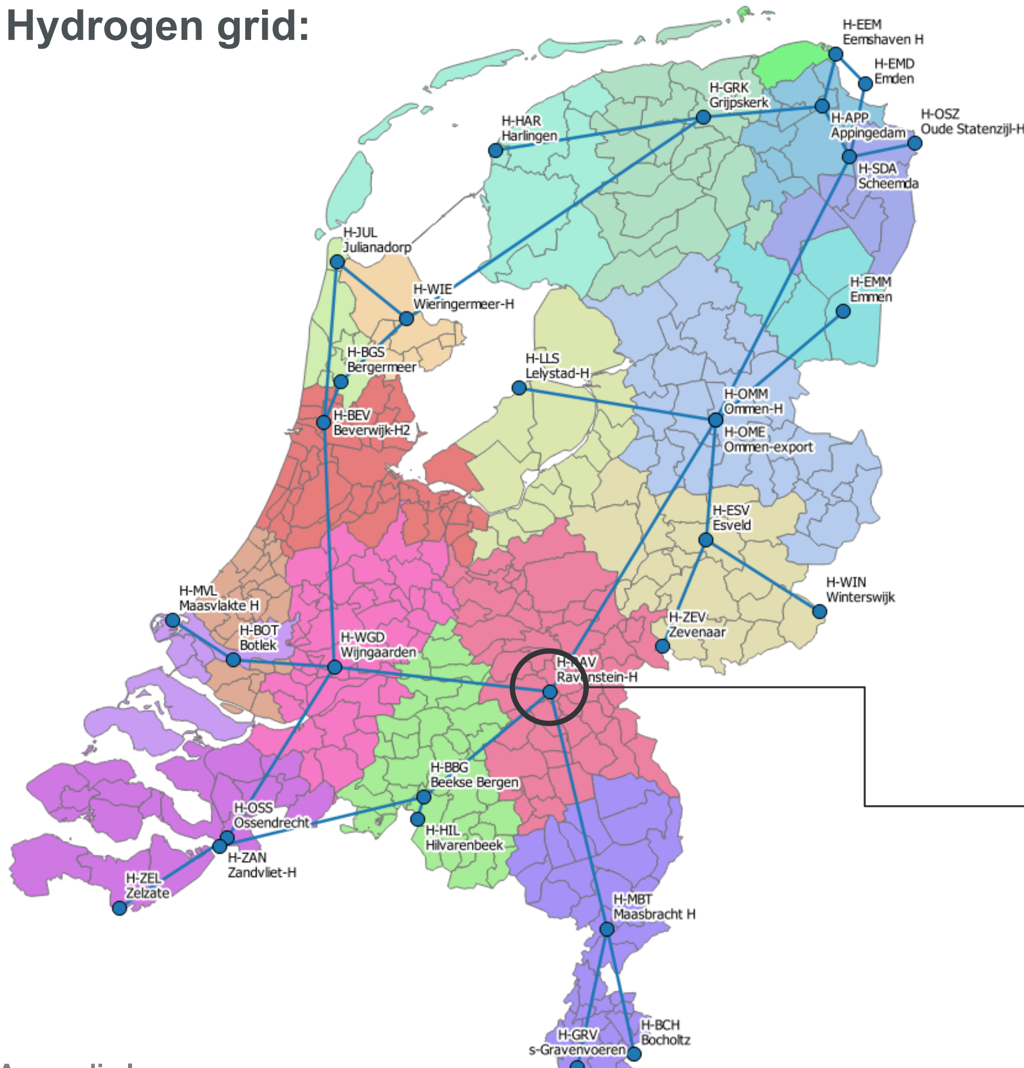
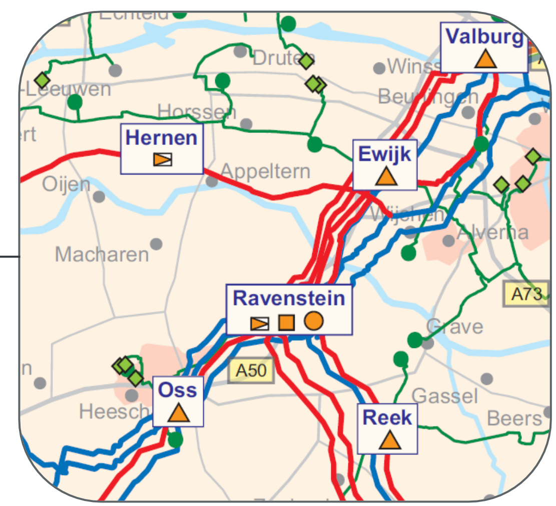
Regionalization (NL): Linking of municipalities to grid nodes

Hydrogen grid:

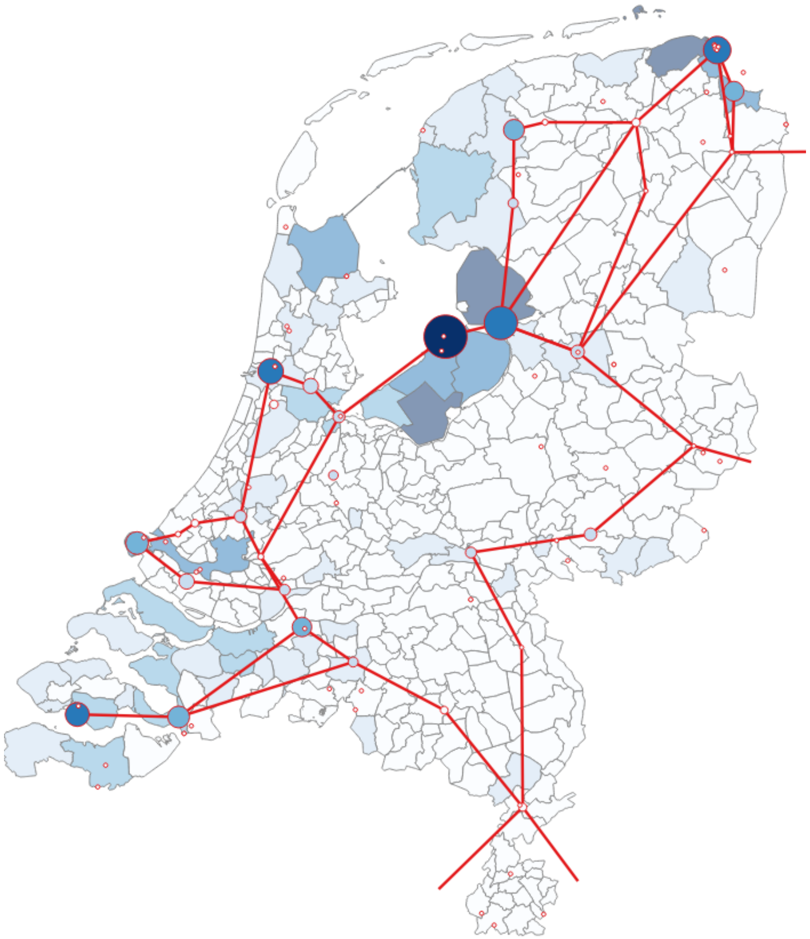


Linking of municipalities to Methane grid nodes:

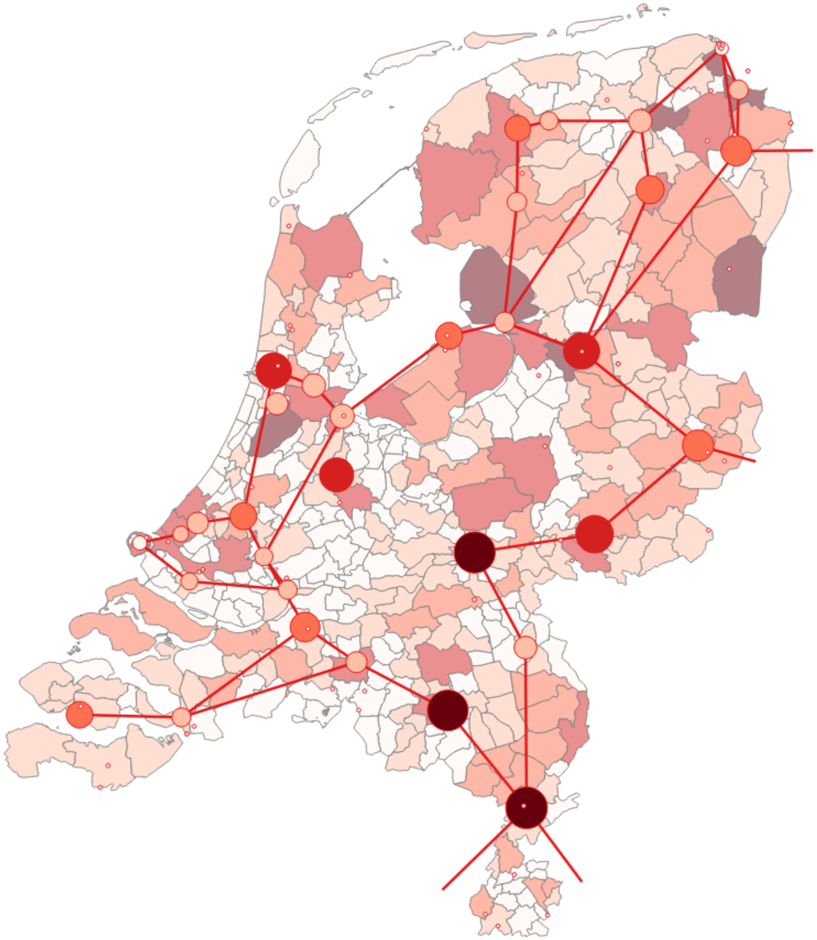
- Filtering of grid nodes
- „Nearest neighbour“ approach
- Manual validation / adjustment using real grid map



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

Example

GW

High demand
conventional

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

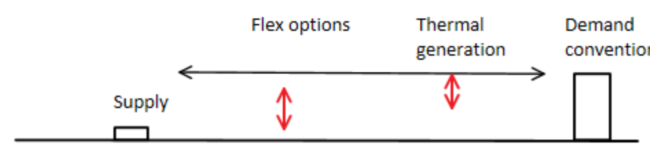
># GW

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

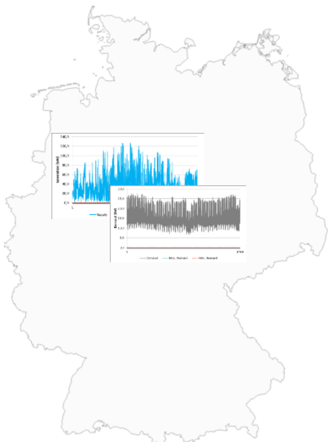
Methodology overview (DE)

Methodology overview (DE)

Scenario A

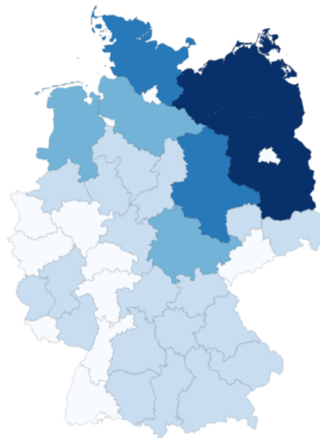
Scenario B

…



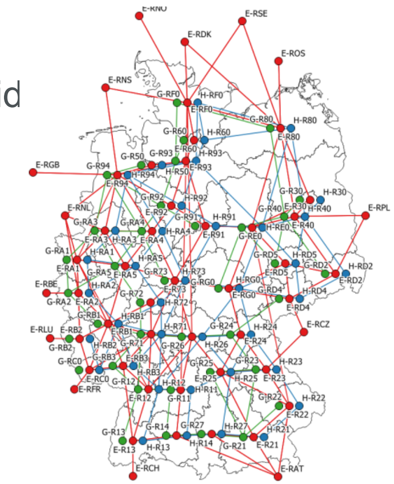
Energy system calculations (IAEW)

Snapshot selection

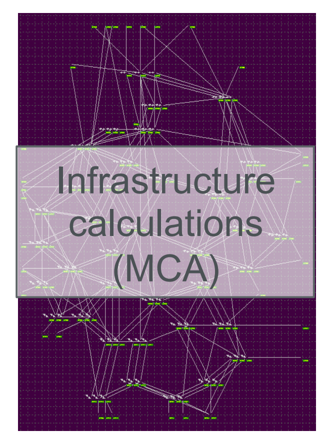


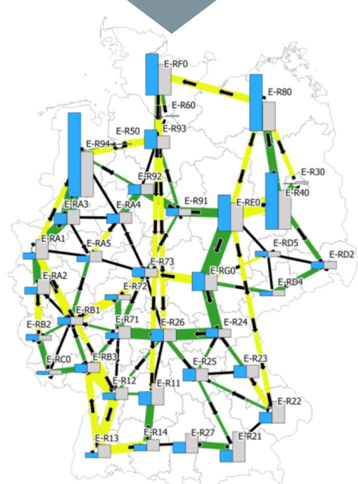
Regionalization of scenario data

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

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

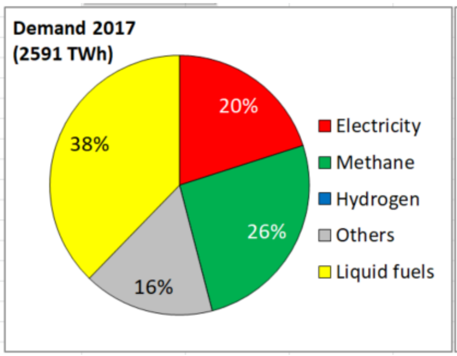
NvdT 'regional' (NL)
Enervis 'Optimiertes System' (DE)

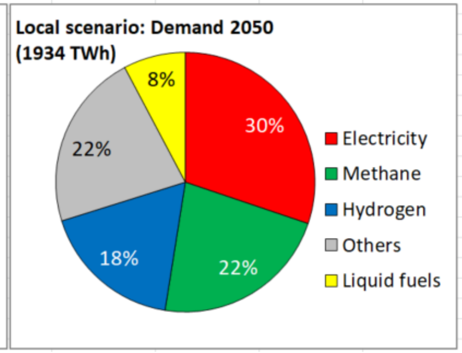
*(Based on agreed european reduction goal between reference year 1990 and 2050)

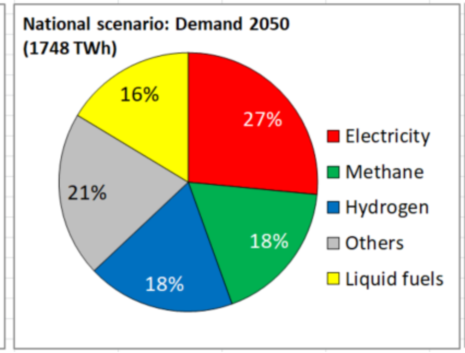
Scenarios: Study overview

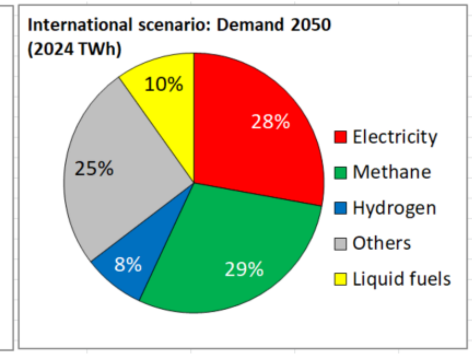
- “Net voor de toekomst” (CE Delft, 2017) → NvdT: local, national, international
- “Erneuerbare Gase - ein Systemupdate der Energiewende“ (Enervis, 2017) → Enervis
- „Leitstudie integrierte Energiewende“ (dena, 2018) → dena
- „Der Wert der Gasinfrastruktur für die Energiewende in Deutschland“ (Frontier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

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





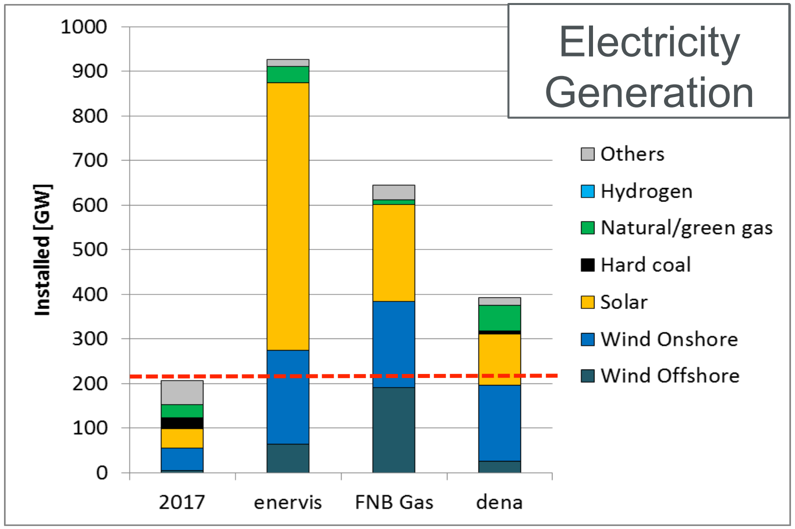


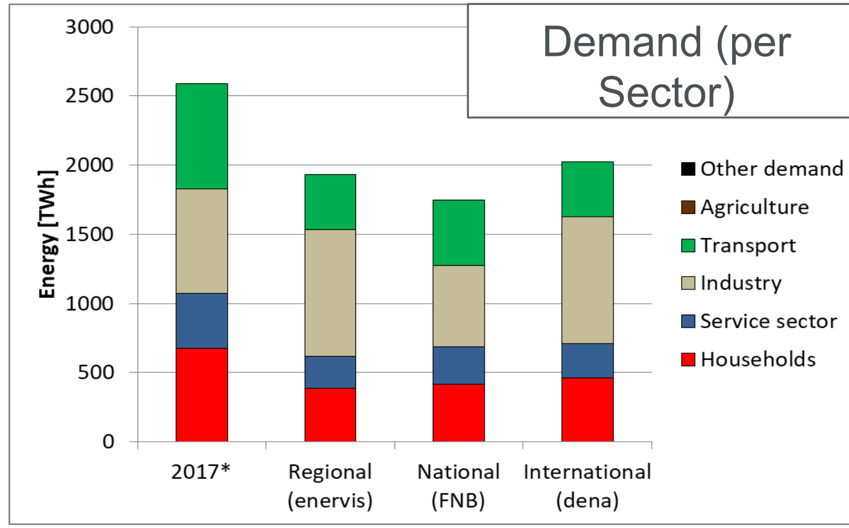


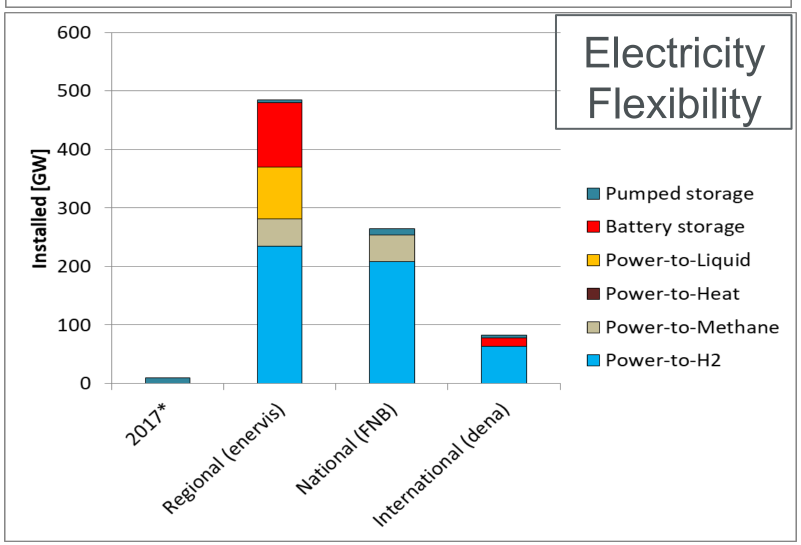
Category others: Includes coal, biomass and district heating
Category liquids: Includes oil and power-to-liquid

*(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

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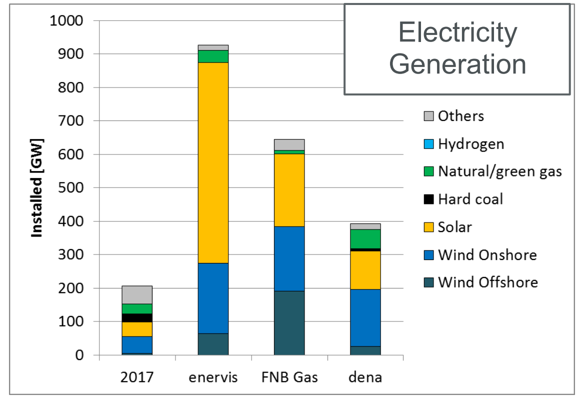
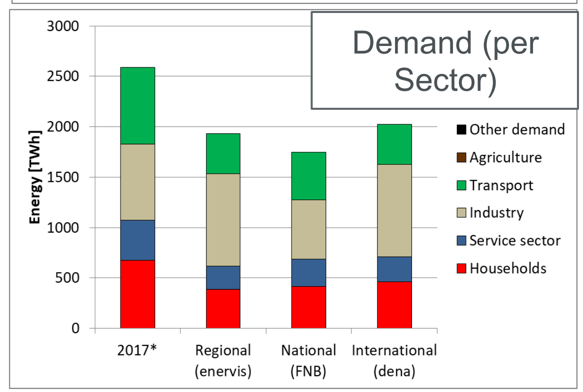
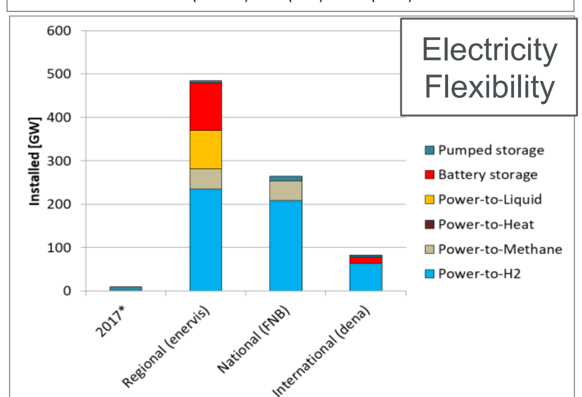
Scenarios: Concrete dataset for 2050 (DE)

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**





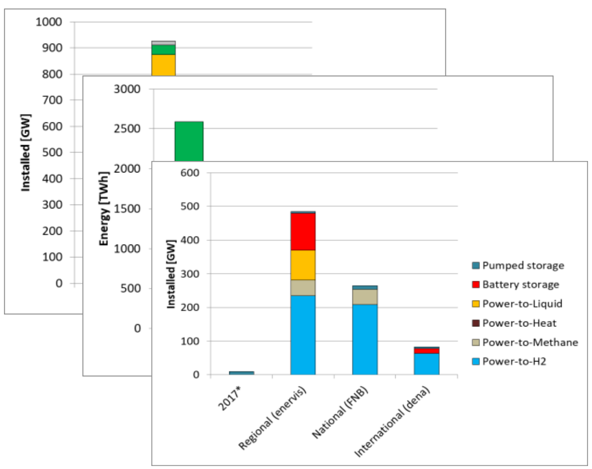


* Data source: BMWi, Zahlen und Fakten Energiedaten

Energy system calculations (DE)

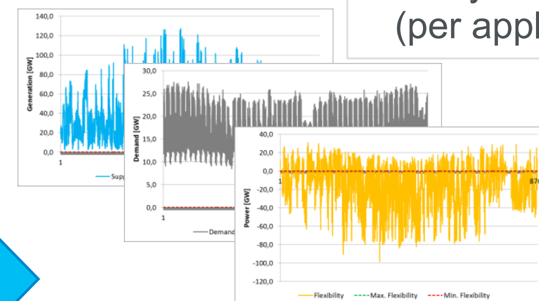
Energy system calculations (DE): ETM and Modelling IAEW

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

Infrastructure Outlook 2050

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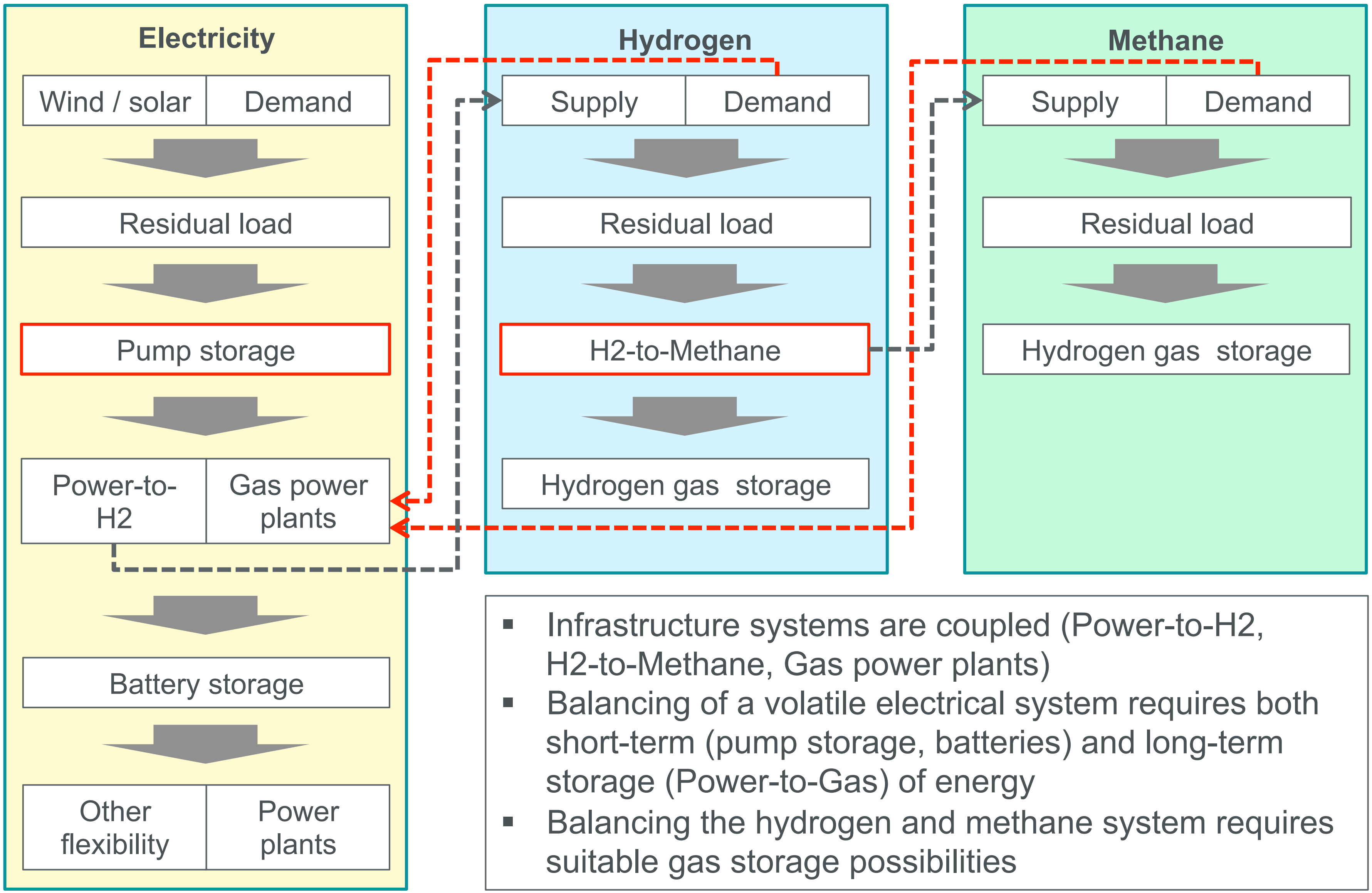
Energy system calculations: General scheme coupling

Only modeled for DE



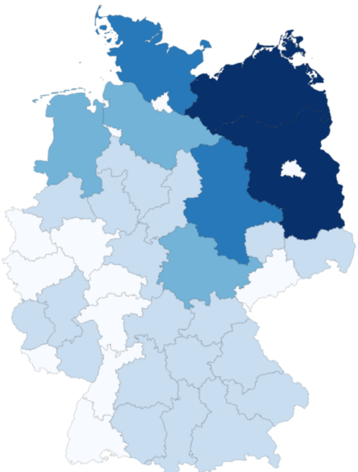
- Infrastructure systems are coupled (Power-to-H2, H2-to-Methane, Gas power plants)
- Balancing of a volatile electrical system requires both short-term (pump storage, batteries) and long-term storage (Power-to-Gas) of energy
- Balancing the hydrogen and methane system requires suitable gas storage possibilities

Regionalization of scenario data (DE)

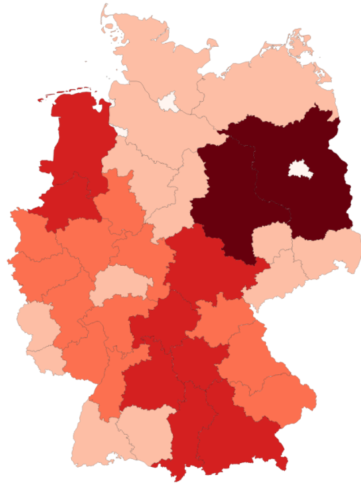
Regionalization (DE): Base assumptions for distribution keys

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

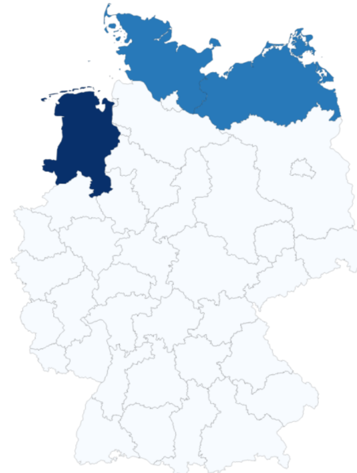
Regionalization (DE): Base assumptions for distribution keys



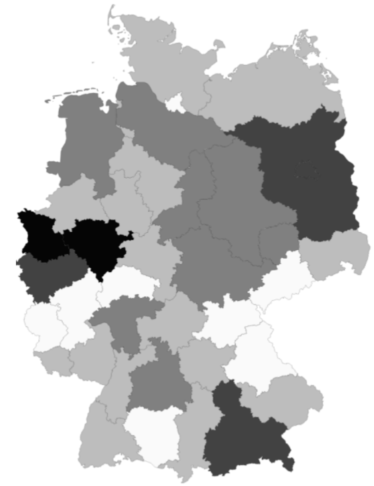
Wind onshore*



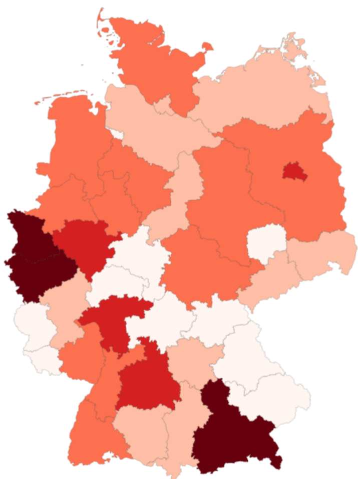
Solar PV*



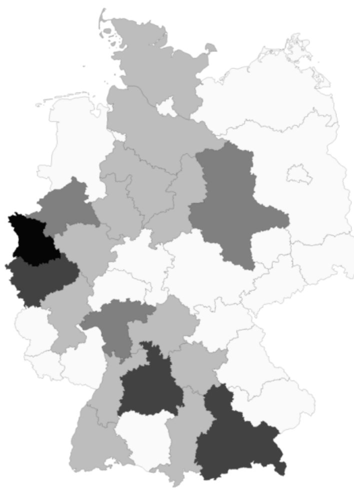
Wind offshore



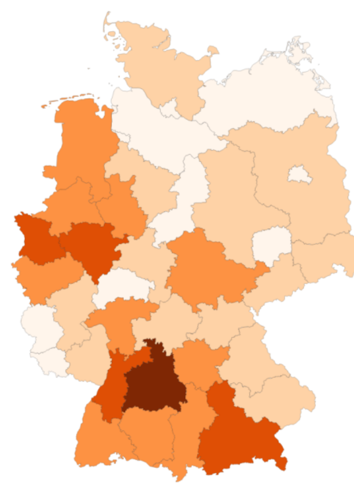
Gas power plants



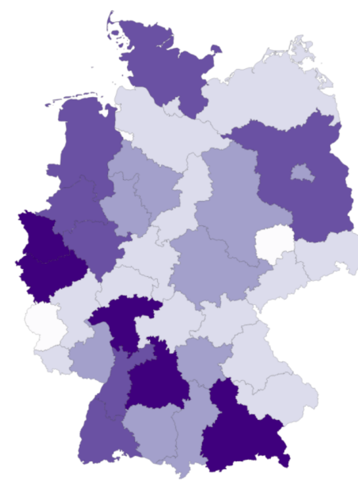
Household demand



Industry demand

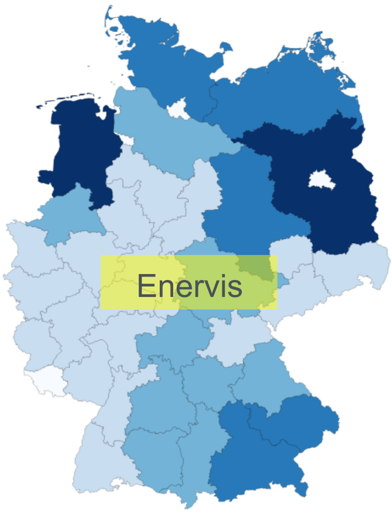


Buildings demand

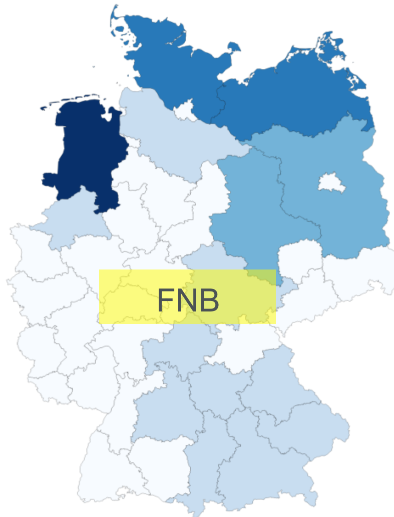


Transport demand

Regionalization (DE): Base assumptions for distribution keys

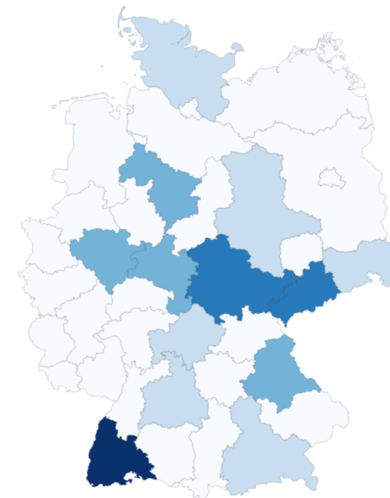


Power-to-H2 (E, H)

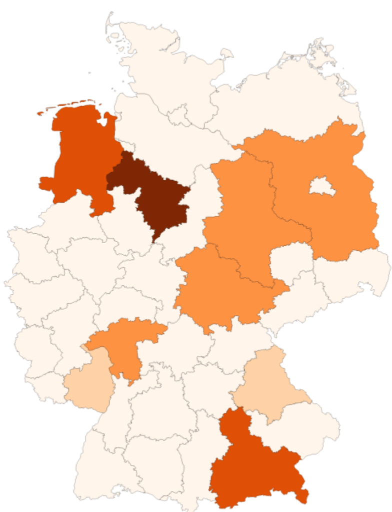


Power-to-H2 (E, H)

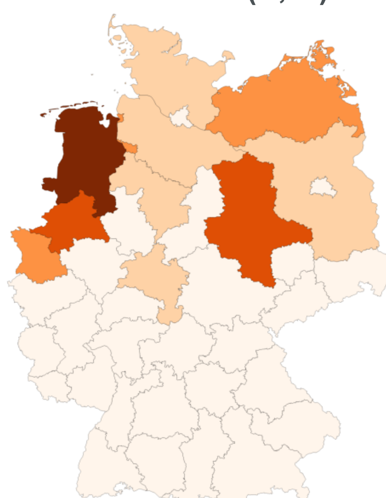
Power-to-H2 (E, H)



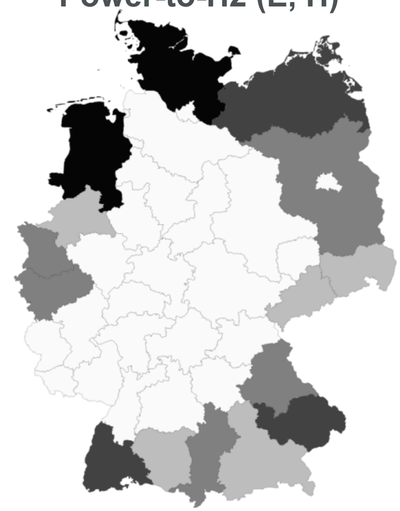
Pump storage (E)



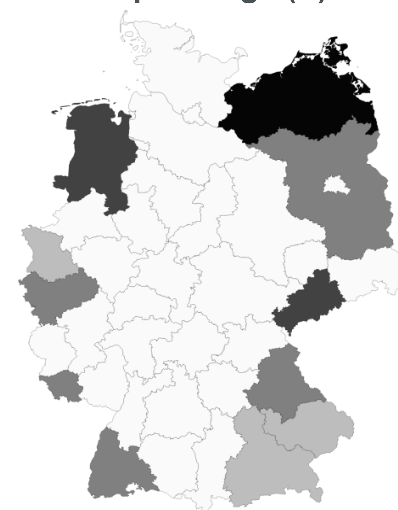
Gas storage (G)



Gas storage (H)

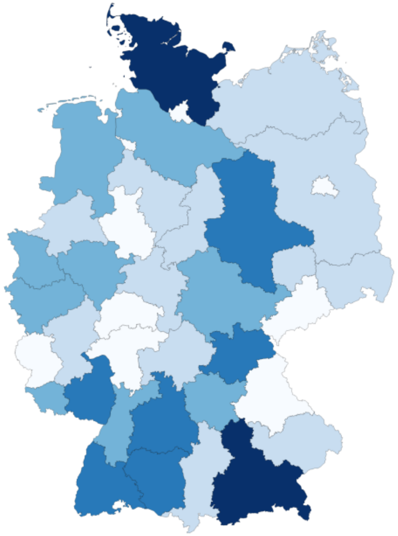


Import / Export (E)



Import / Export (G, H)

Regionalization (DE): Base assumptions for distribution keys



H2-to-CH4 (G)

Infrastructure modeling (DE)

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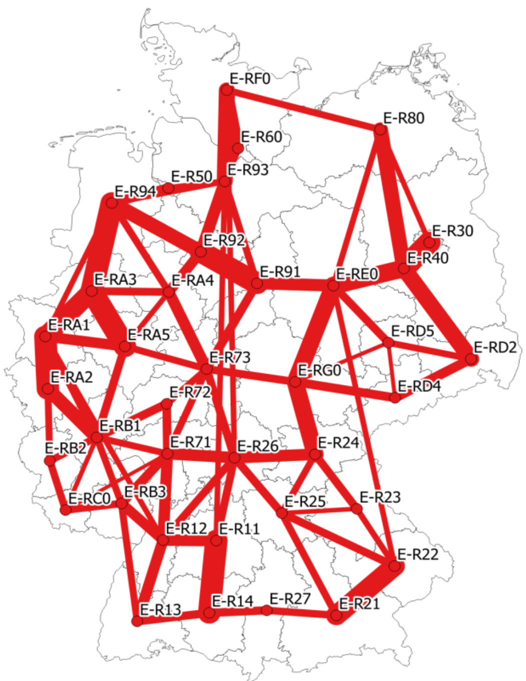
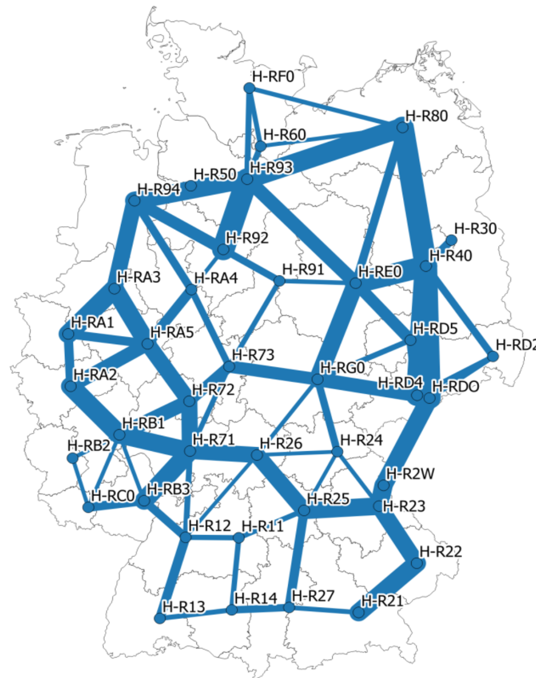
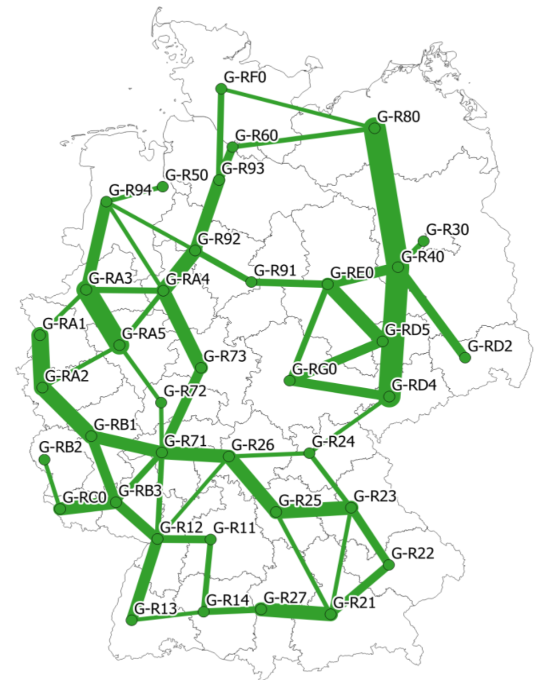
Infrastructure modeling (DE): Assumed topologies







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

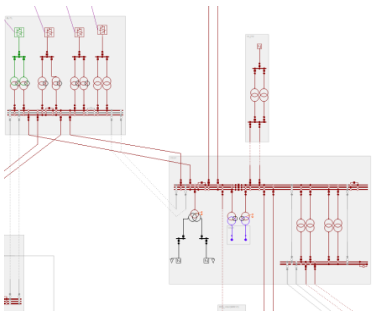
- Based on today's natural gas grid
- Including Expansions of NEP2018
- Gas grid split into hydrogen and methane grid
- Hydrogen grid 'designed' as a strong back-bone

Methane grid

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

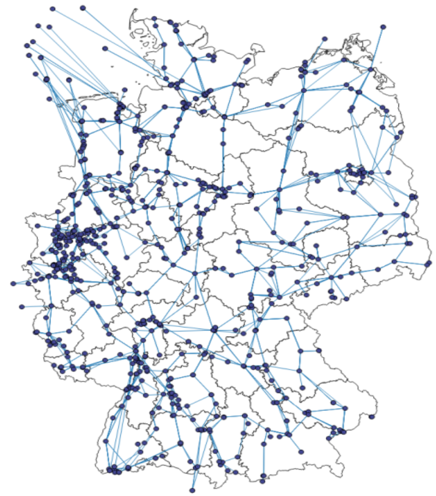
Remark: Line thickness indicates amount of maximum transport capacity

Infrastructure modeling (DE): Methodology (electricity)



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

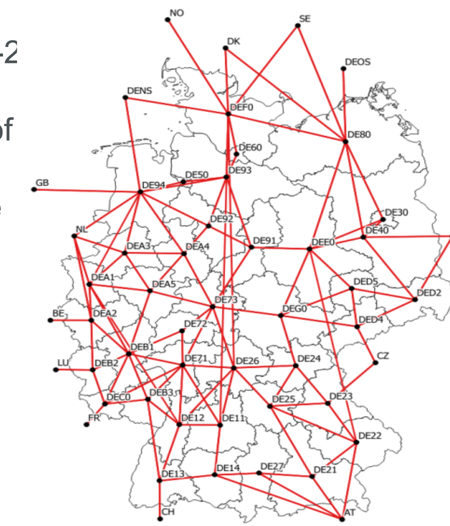
Filtering of relevant grid nodes



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

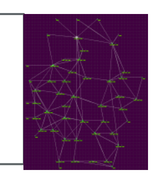
Geographical data on grid node locations

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)



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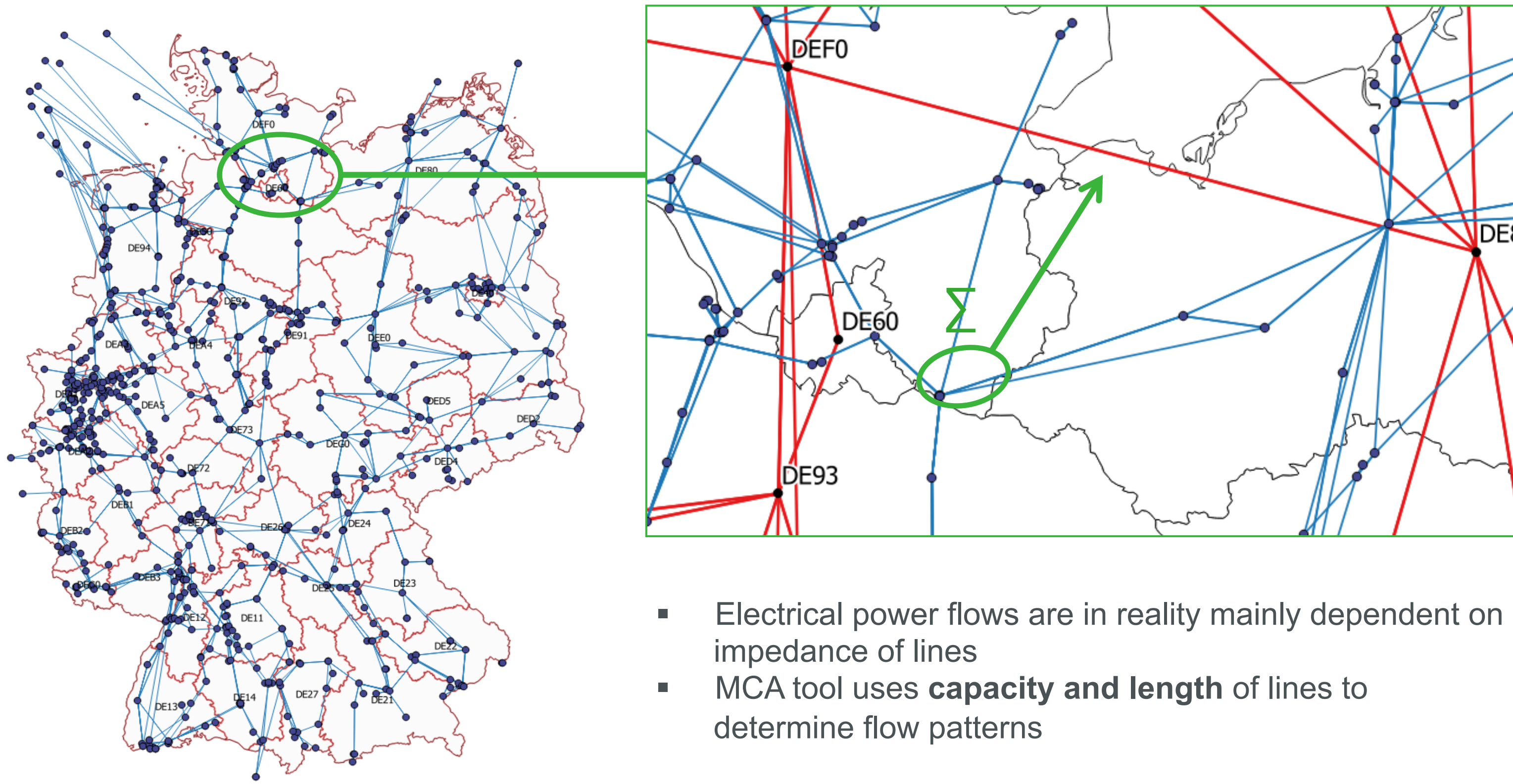
Infrastructure modeling (DE): Methodology (electricity)



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

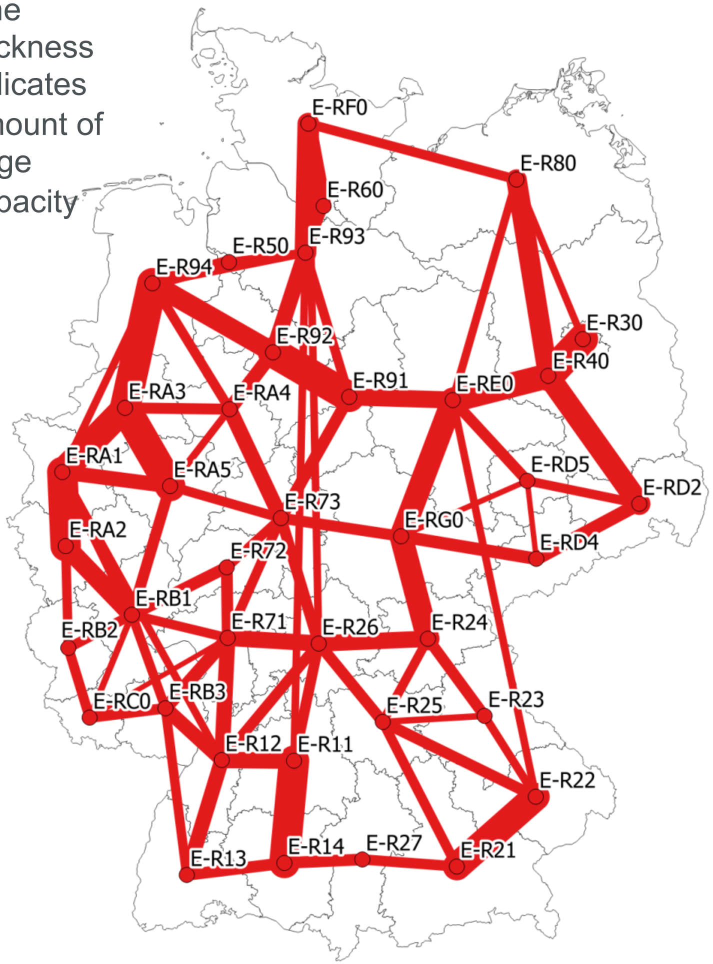
- **Capacities:** Summing up of line capacities to achieve equivalent transmission capacity of edge
  (e.g. 2 x 1 GW line cap. = 2 GW)
- **Edge length**: Average of corresponding line lengths and division through number of lines

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

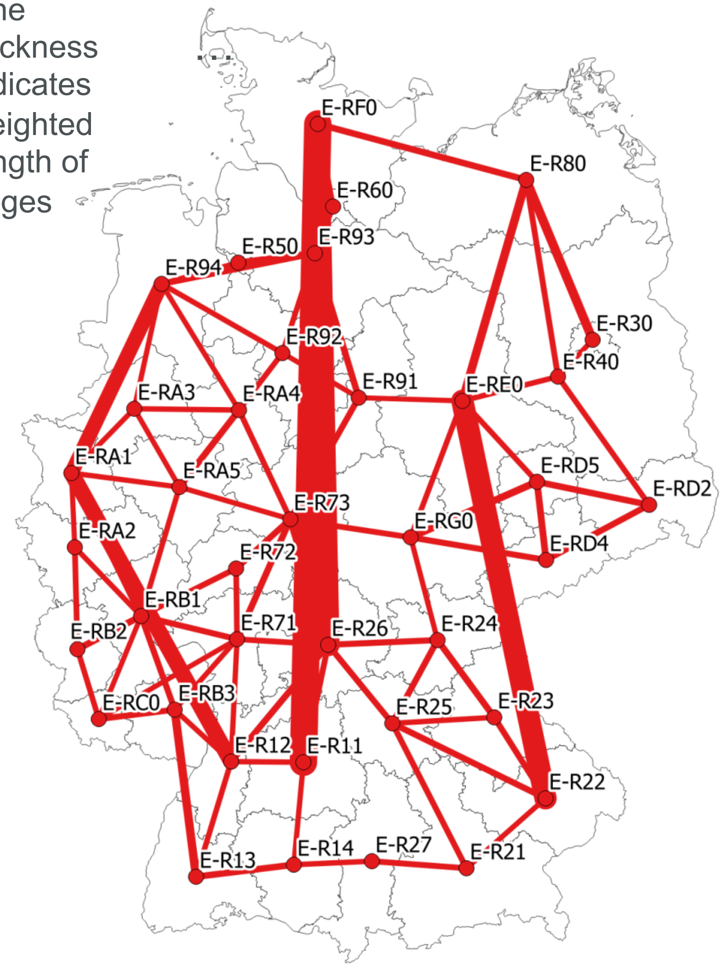
Infrastructure modeling (DE): Methodology (electricity)

Line thickness indicates amount of edge capacity



Line capacities (2030)

Line thickness indicates weighted length of edges



Weighted lengths (2030)

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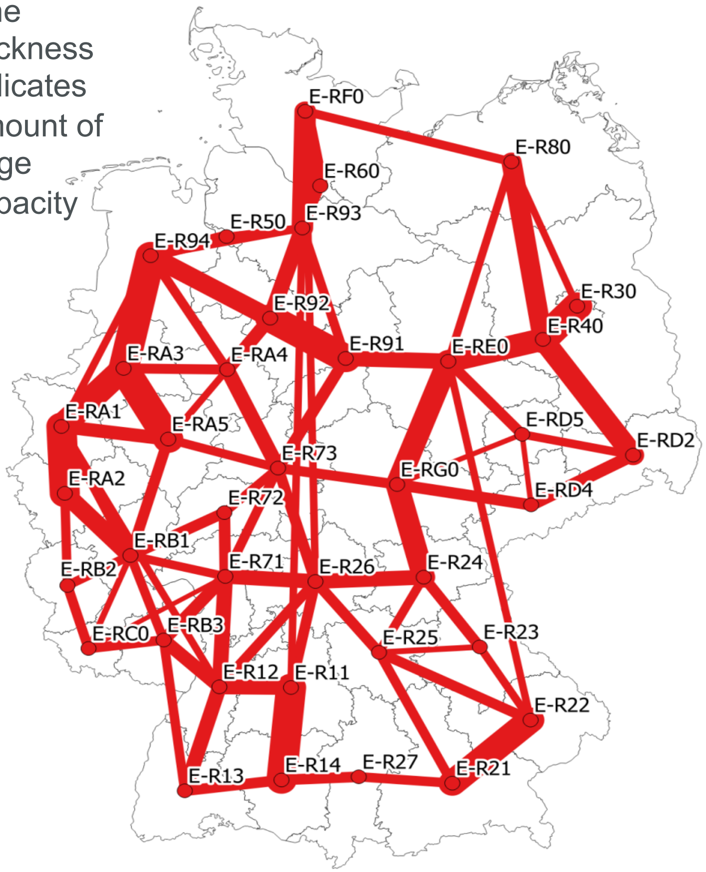
TenneT Taking power further

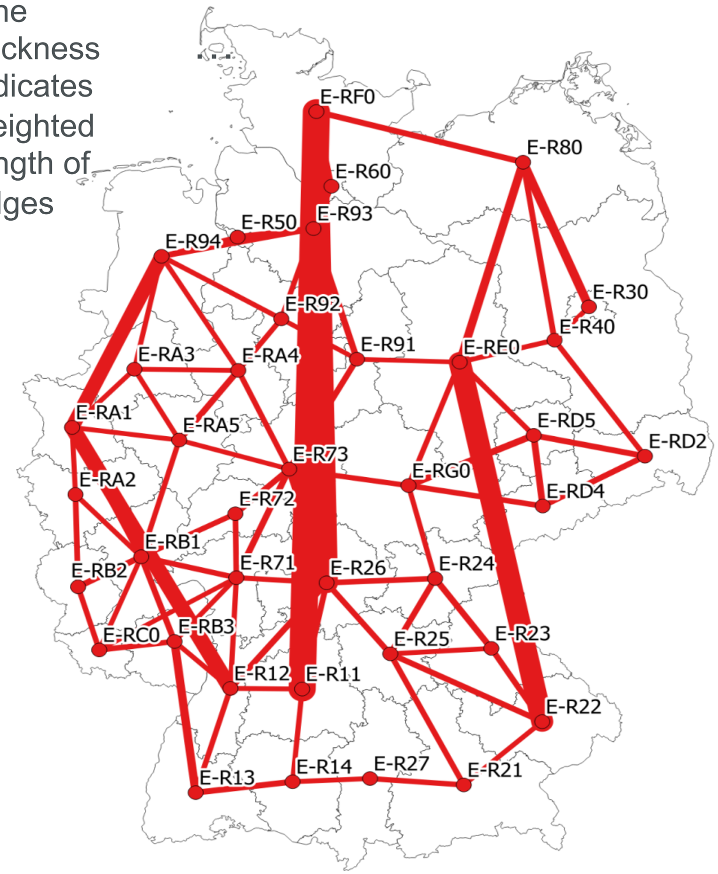
Infrastructure modeling (DE): Methodology (electricity)

Line thickness indicates amount of edge capacity



Line capacities (2030)

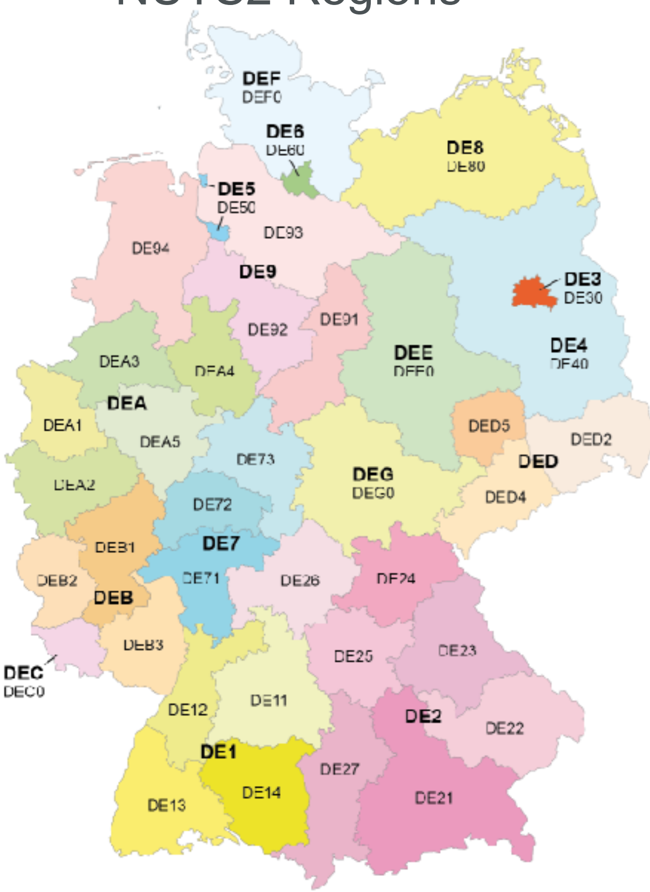
Line thickness indicates weighted length of edges



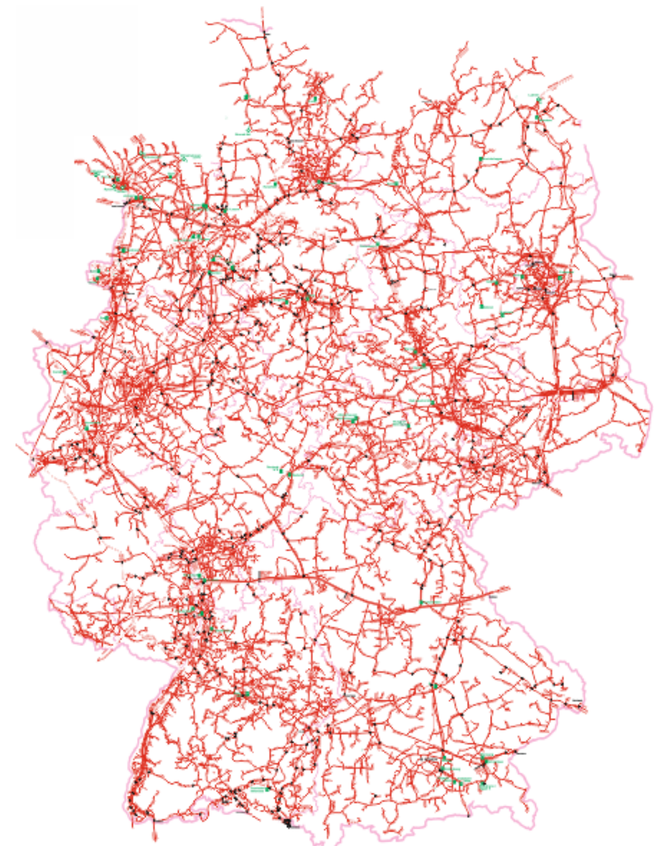
Weighted lengths (2030)

Infrastructure modeling (DE): Methodology (gas)

NUTS2 Regions



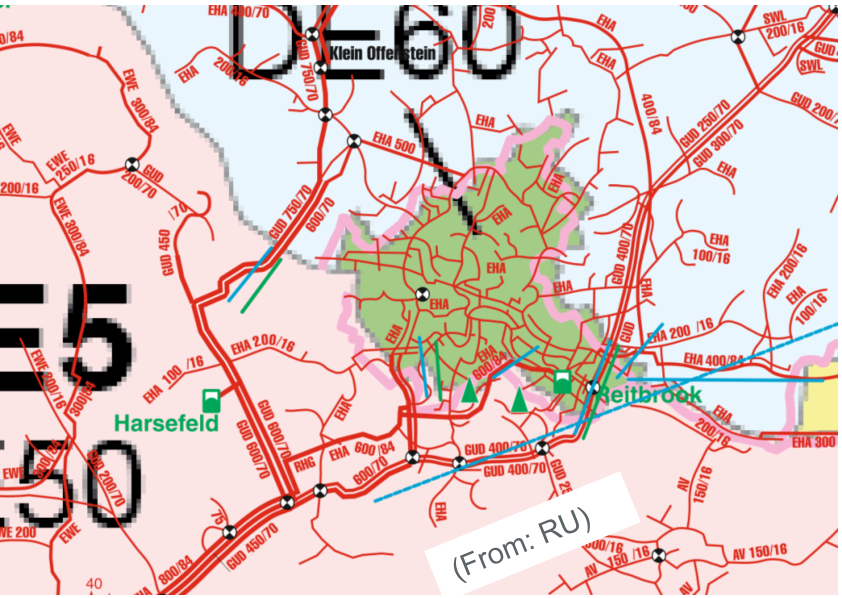
VGE MAP 2010 + Information NEP



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

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

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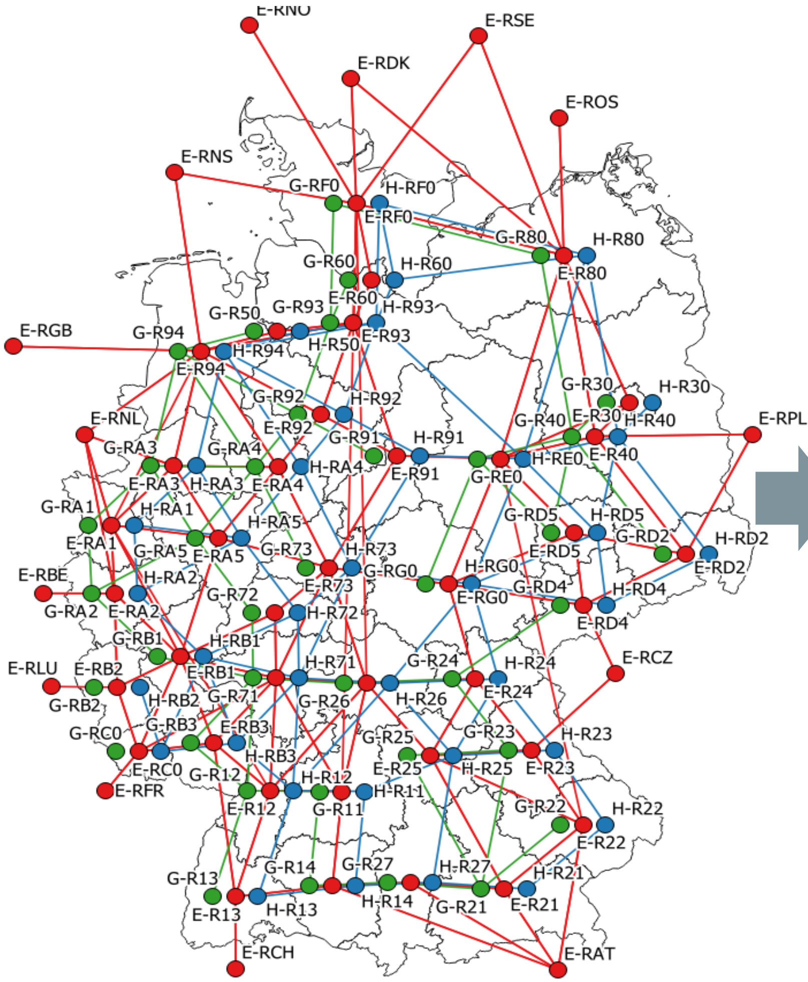
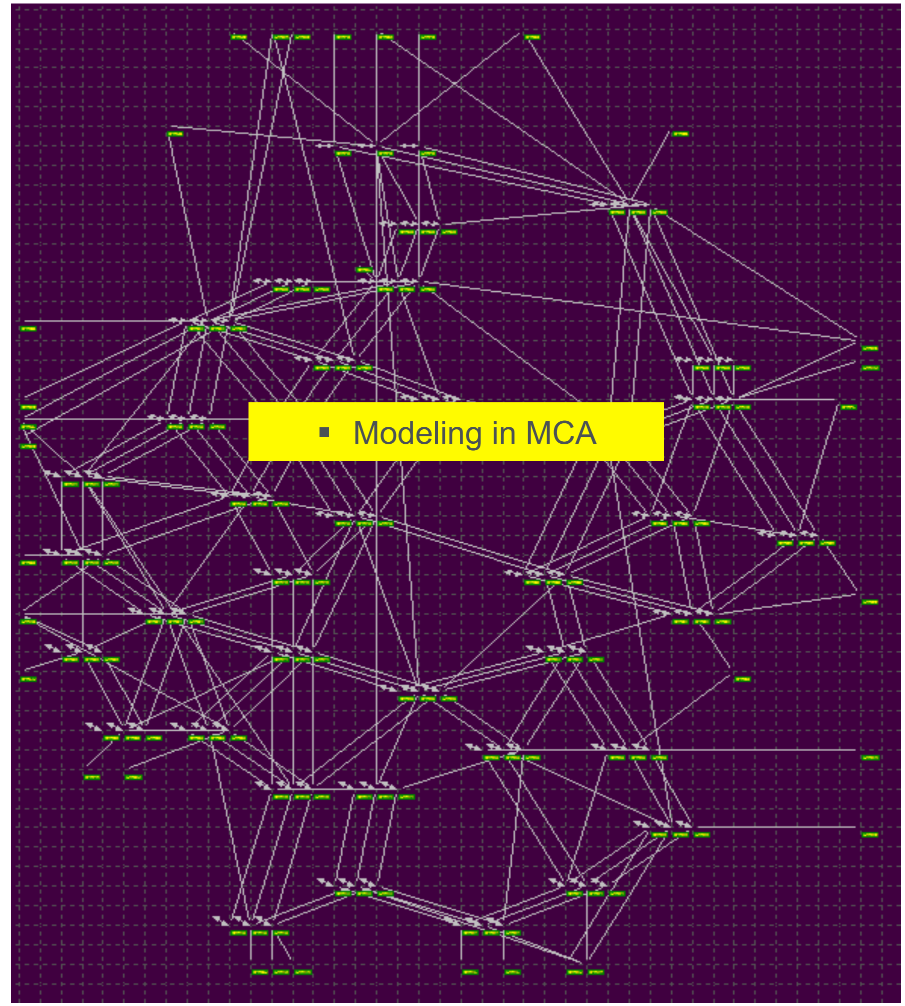
Infrastructure modeling (DE): Interface to MCA-tool





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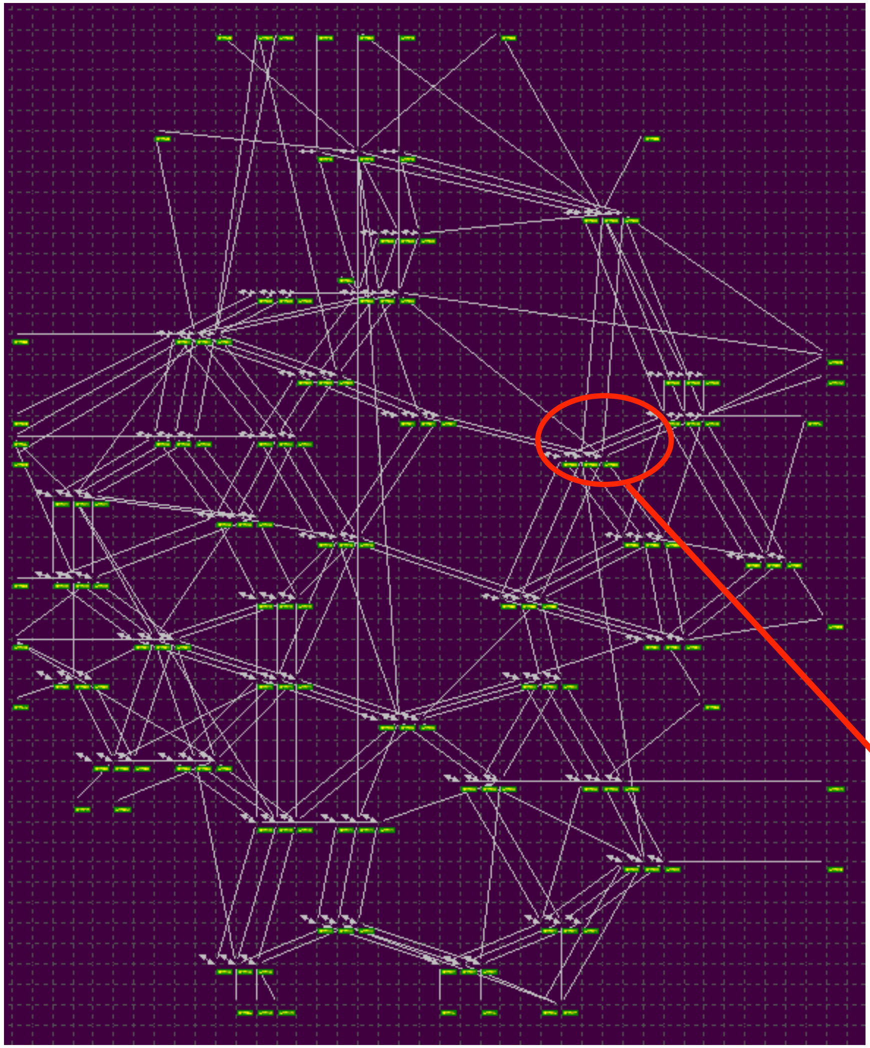
Infrastructure modeling (DE): Interface to MCA-tool



Standardized identifiers (IDs) for each grid node:

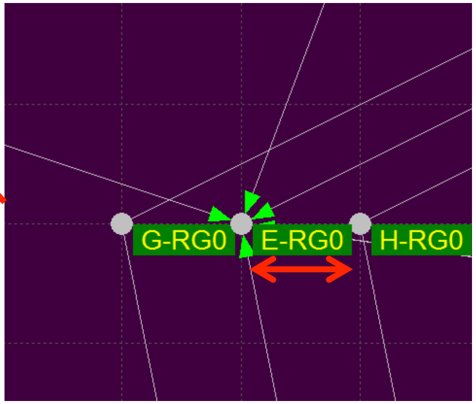
- E-RXX
- G-RXX
- H-RXX

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

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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

Example

GW

High demand
conventional

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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

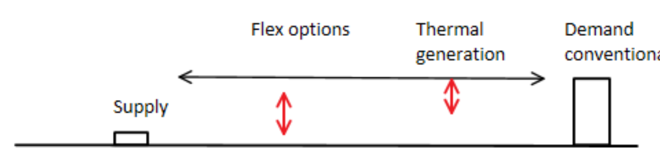
># GW

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 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).

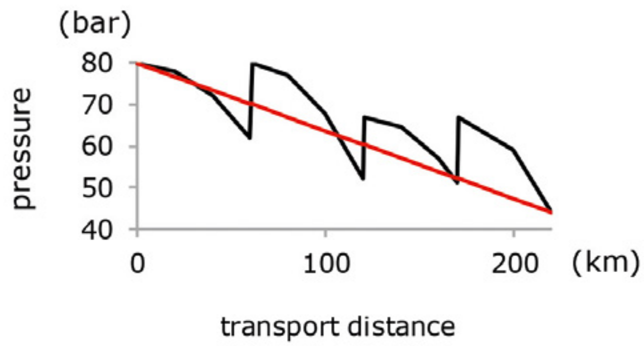


Figure 1: Pressure decrease for transport of gas in a network with intermediate compression (black line) and its linearization (red line)

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.

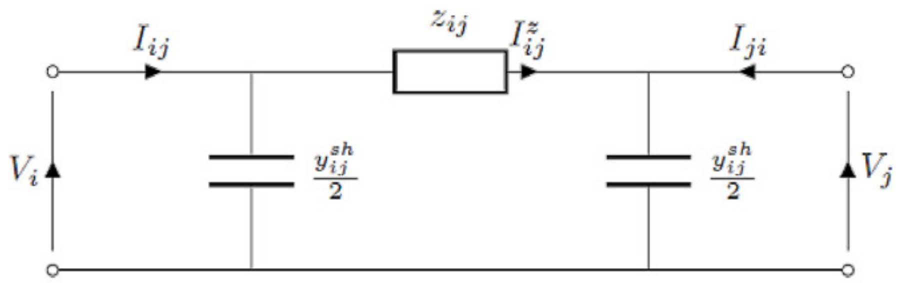


Figure 2: Equivalent circuit for medium-distance (80 – 240 km) power lines

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

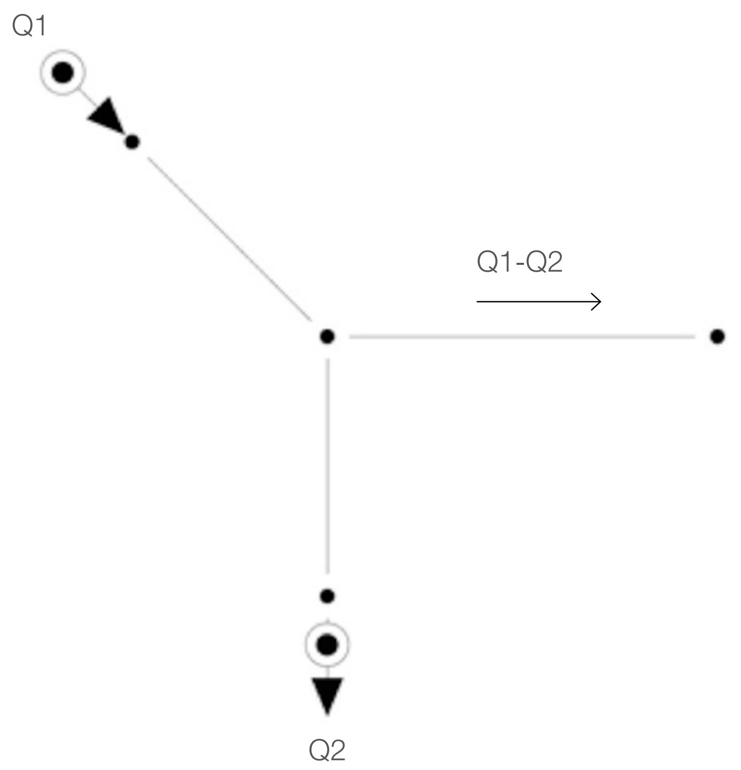


Figure 3: Kirchhoff's law representing energy conservation at node N

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

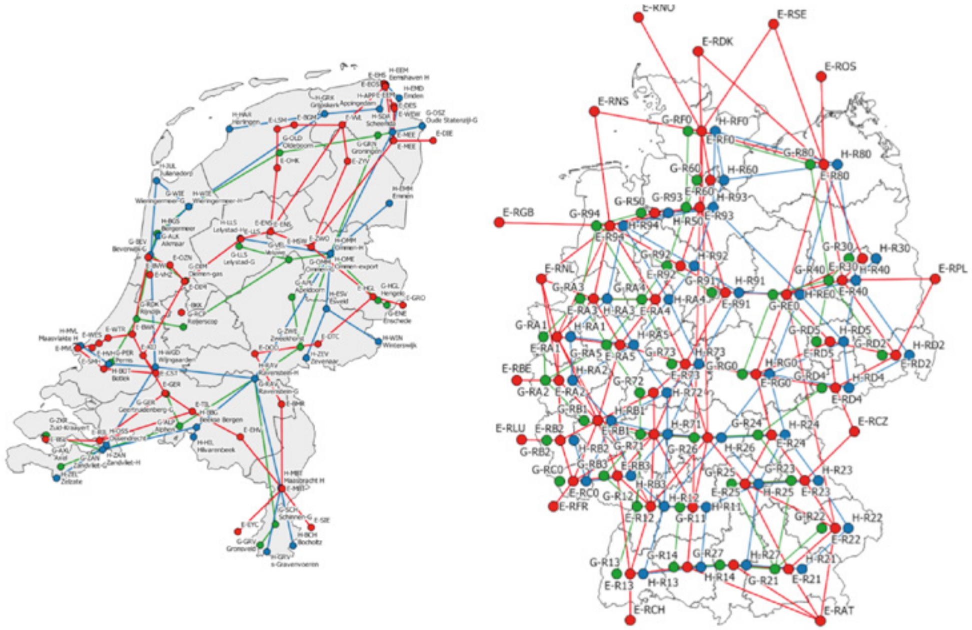


Figure 4: Coupled electricity, hydrogen and gas networks for the Netherlands (left) and Germany (right). The Dutch network is modelled according to the actual network topologies, while the German network is on a higher level of aggregation based on the 38 German NUTS-2 regions

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: $T(Q) \rightarrow f.T(Q)$ 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.

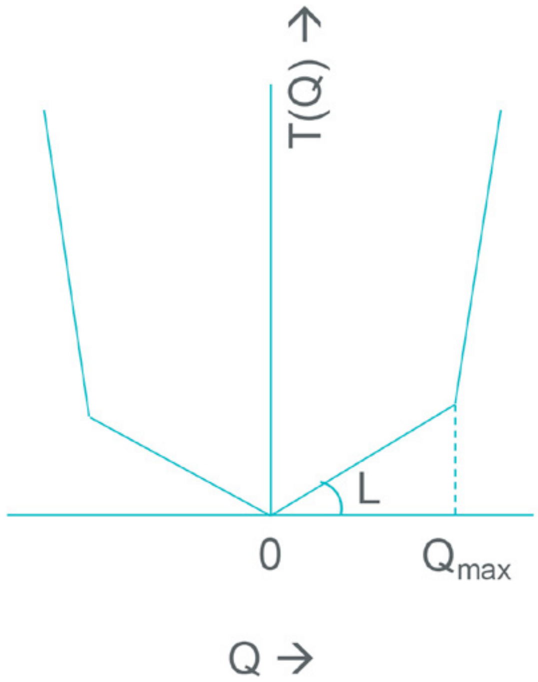


Figure 5: Piecewise linear load function of a line of length L. A longer line will have a steeper load function. The steepness ratio for Q > Qmax determines the penalty for overloading

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 represen-

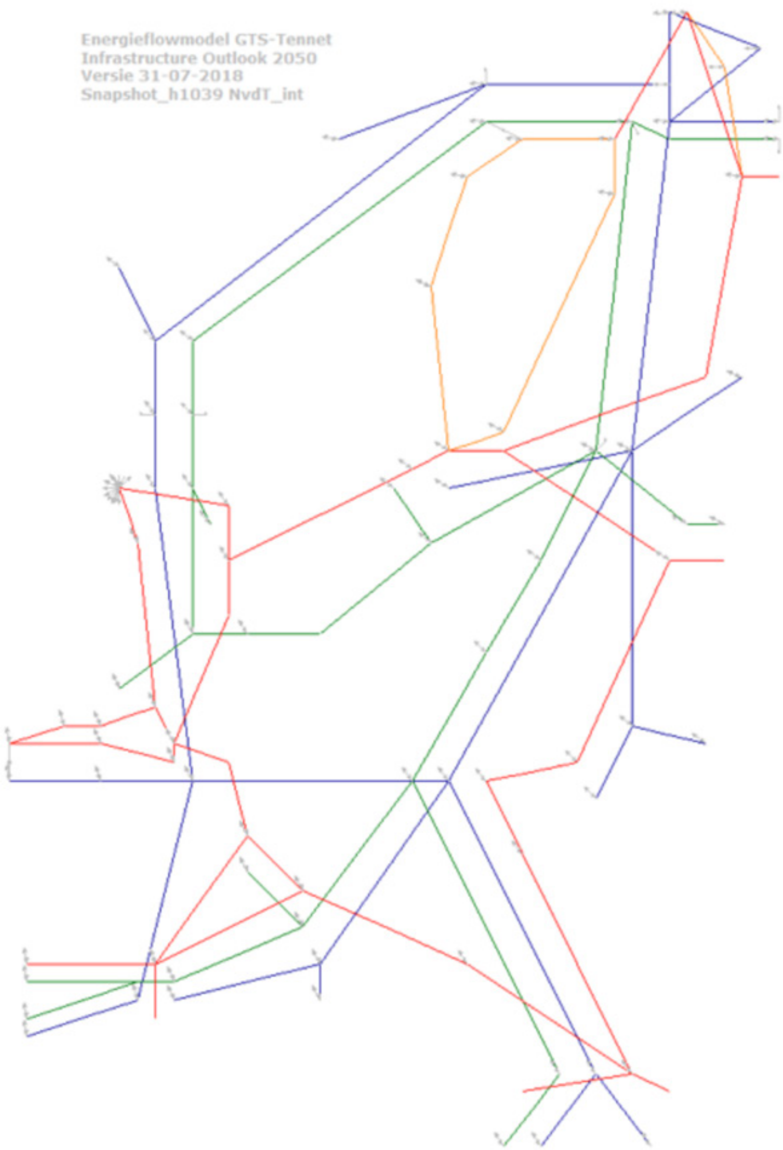


Figure 6: Combined network of the Netherlands in the graphical topological interface of MCA (red/orange = electricity; blue = hydrogen; green = methane)

tation 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}.

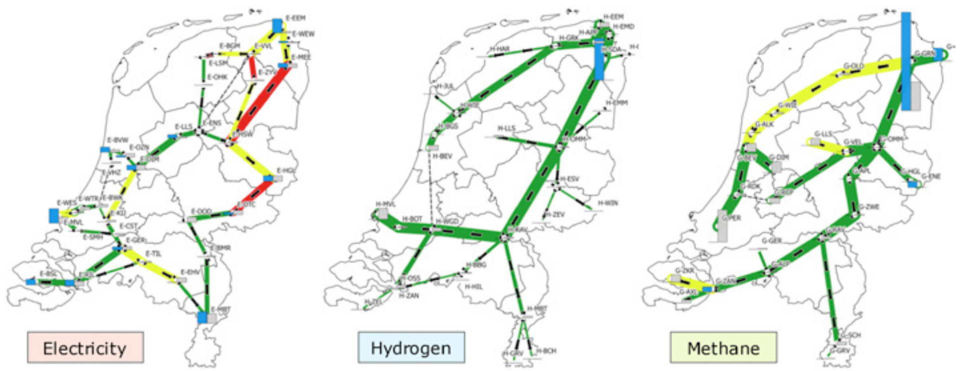


Figure 7: Intensity representation of a flow pattern for a typical snapshot (green = moderate loading; yellow = high loading; red = overloaded; line width proportional to flow)

Project documentation / appendix III

Dutch study part

Model Results Contents

Index:

Demand and supply curves

- 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)

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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

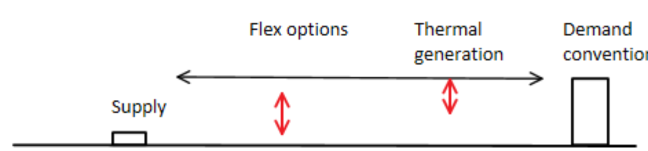
>># GW

Low demand conventional

Case: High RES WIND and low conventional demand

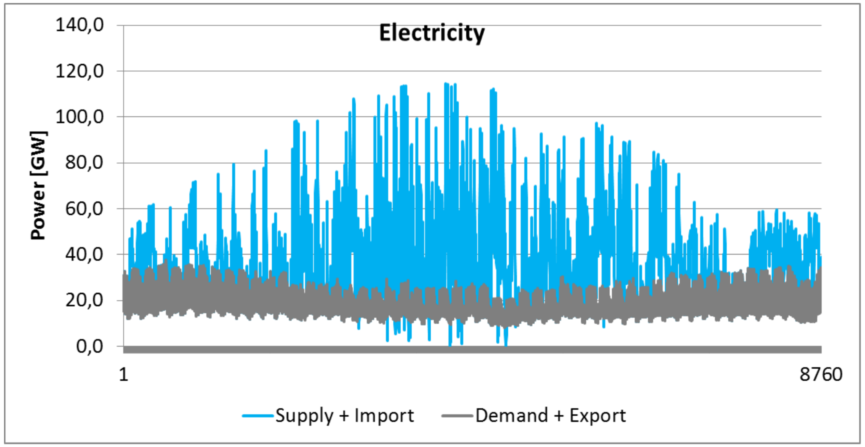
Situation C:

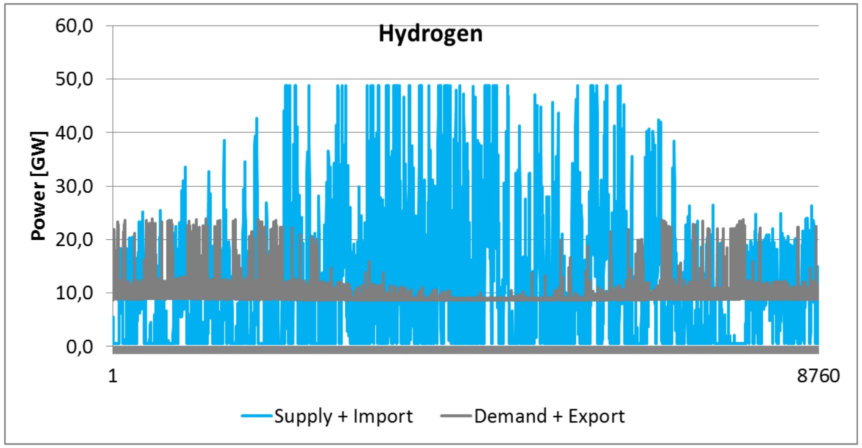
- Low wind and/or solar supply
- High final demand
- *NOTE: thus could result in a need for back-up power plants*

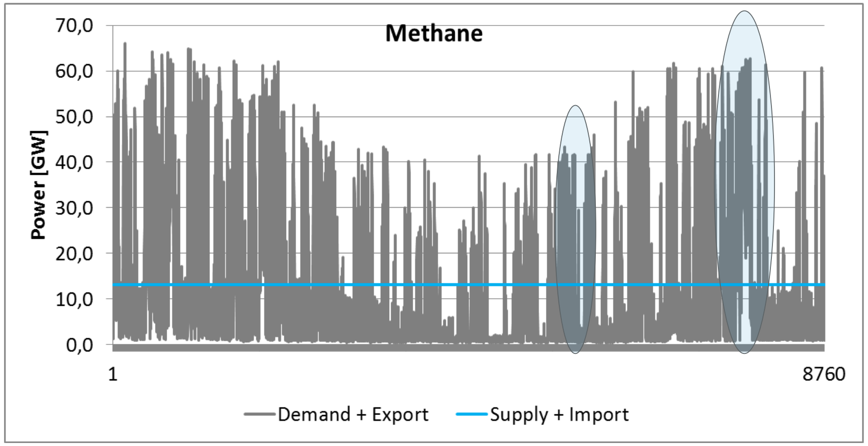


Regional scenario NL

Supply and Demand







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

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

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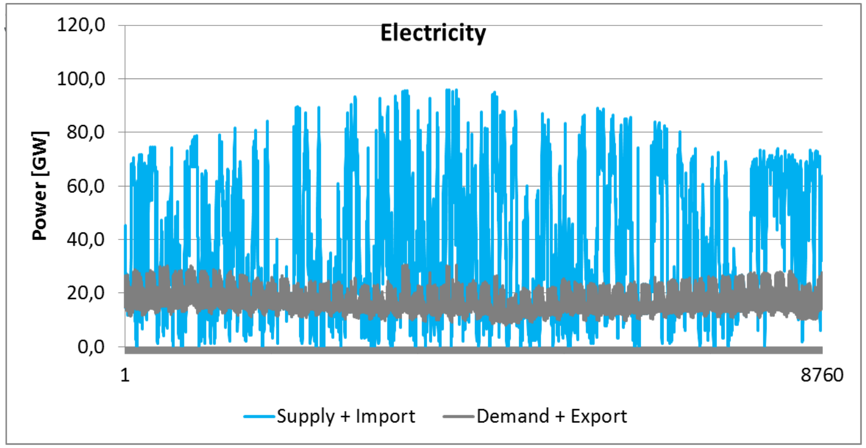
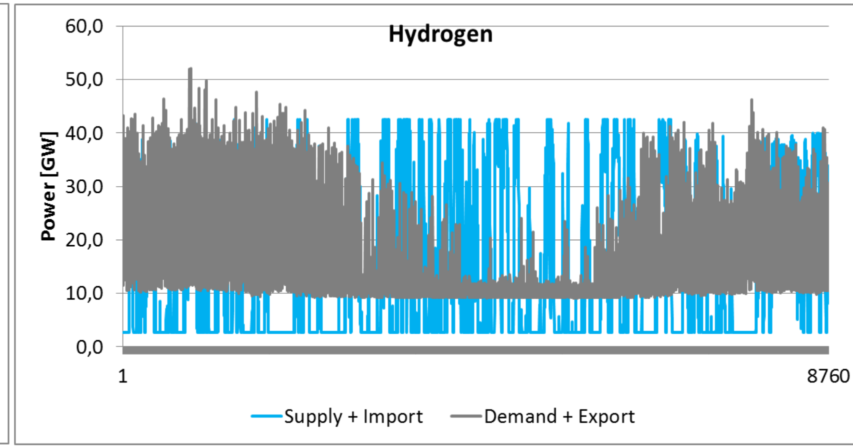
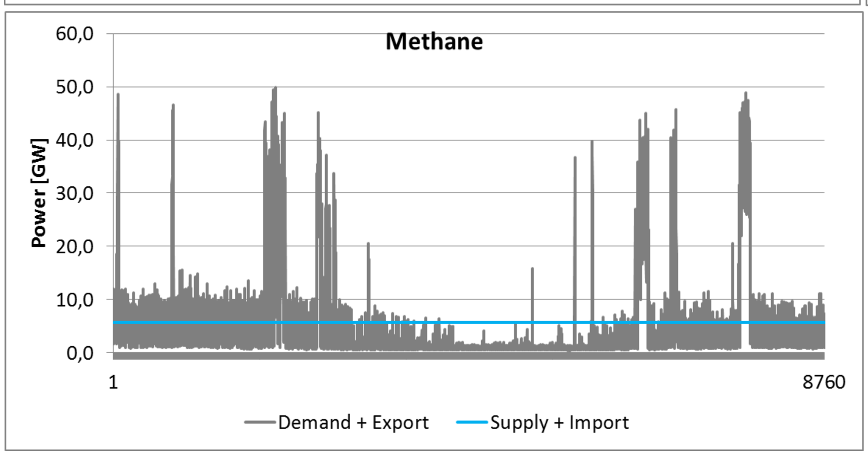
National scenario NL







- 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

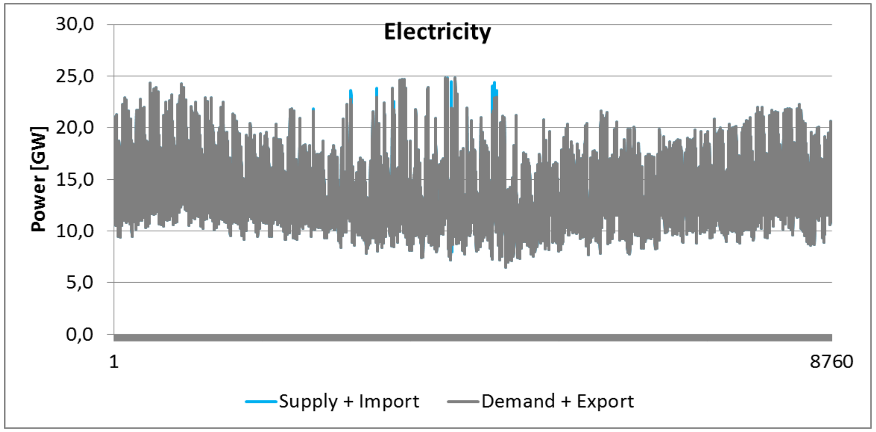
Supply = Total supply to the system including imports
Demand = Total demand from the system including exports

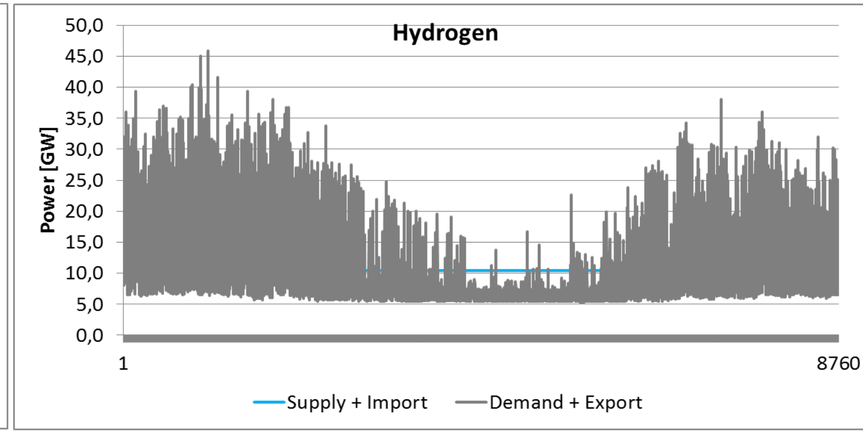
National Scenario NL

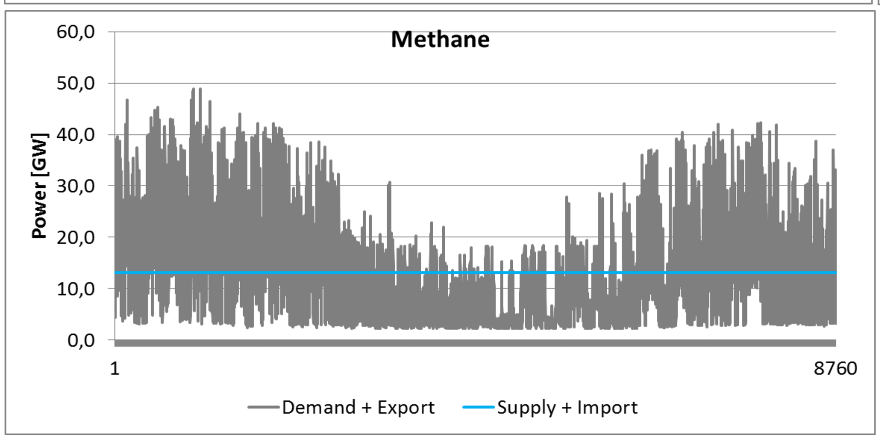
- **Significant mismatch between electrical supply and demand** due to high installed capacity and volatile infeed of wind and solar
- For a large part of the year the **supply to the electrical system exceeds the demand**
- To fill the gap and fully integrate the RES infeed, a combination of power-to-hydrogen („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

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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)

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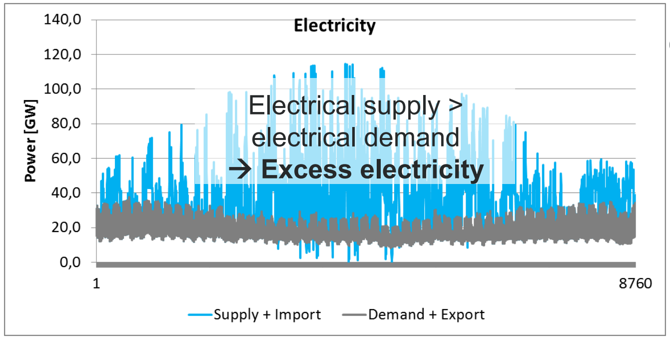
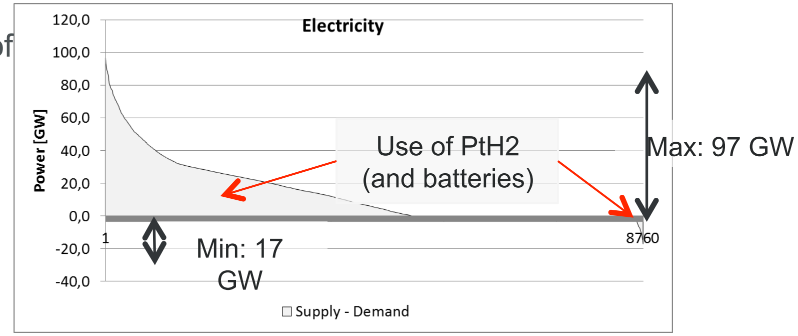
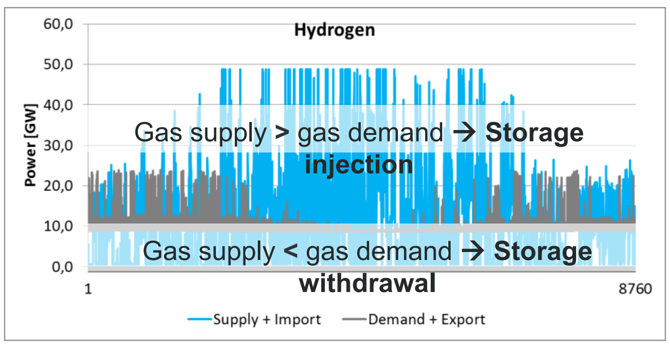
Regional Scenario NL

Charge and Discharge capacities (GW)

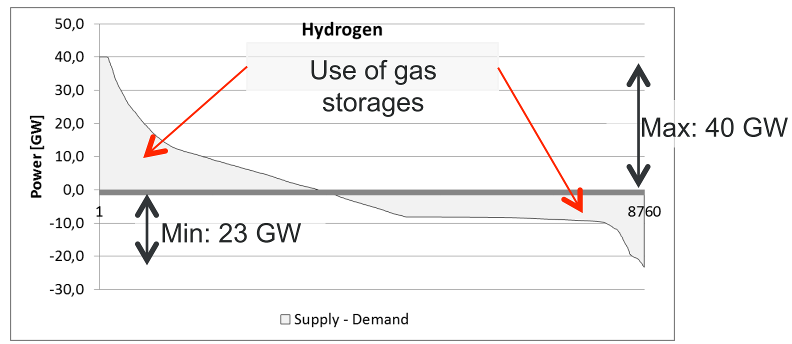


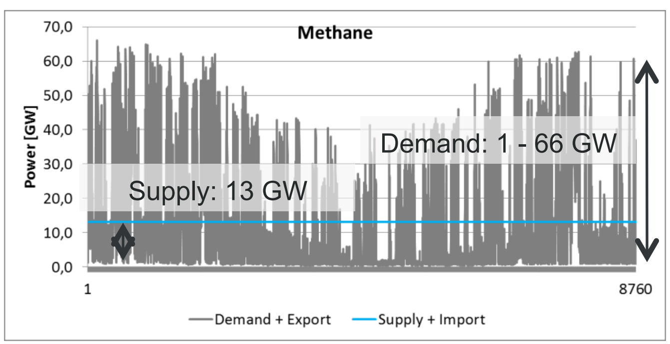
Conversion of excess electricity to hydrogen

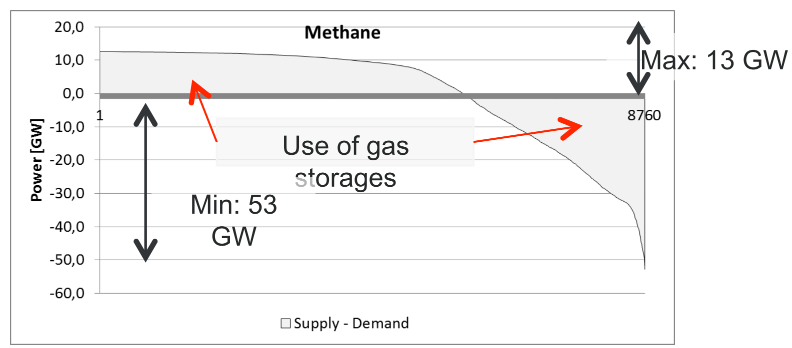




Balancing through gas storages

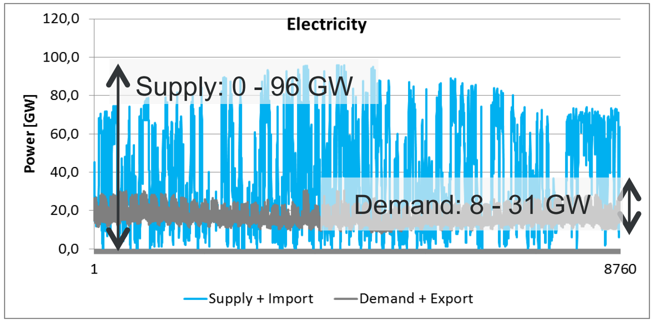


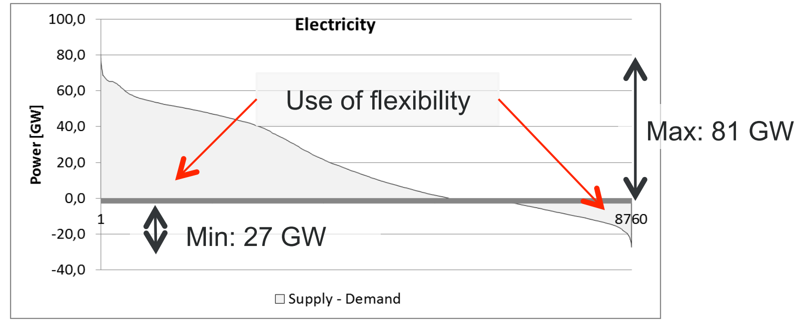


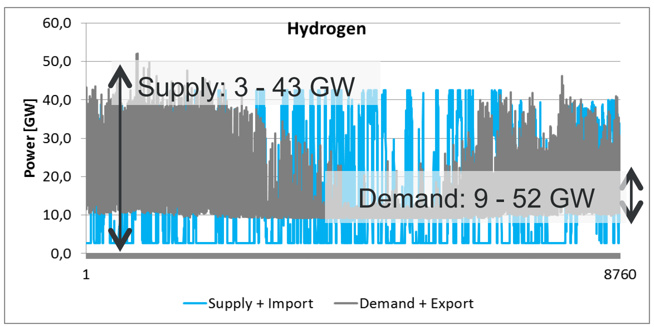


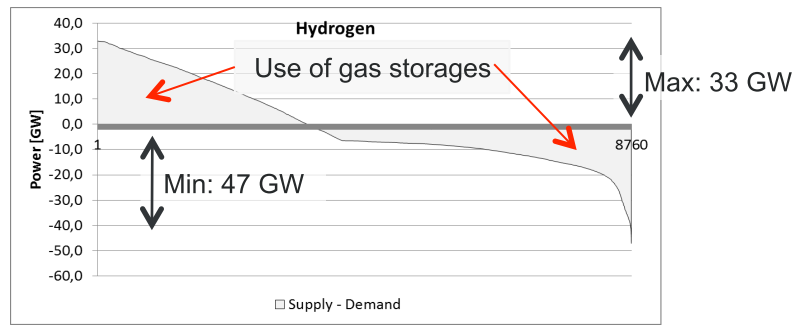
National Scenario NL

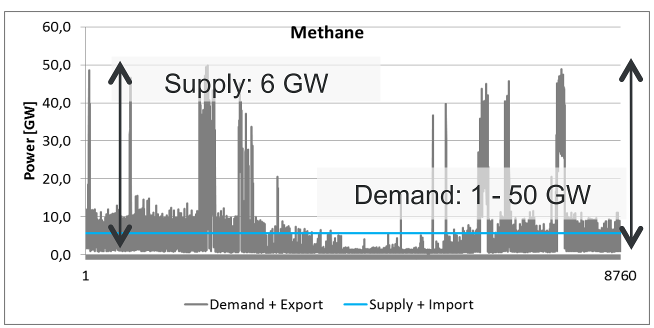
Charge and Discharge capacities (GW)

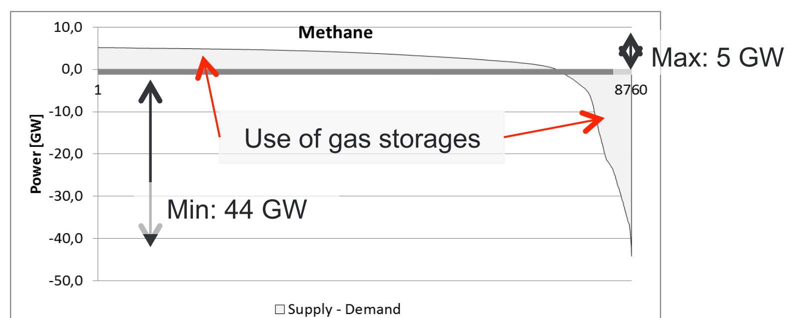






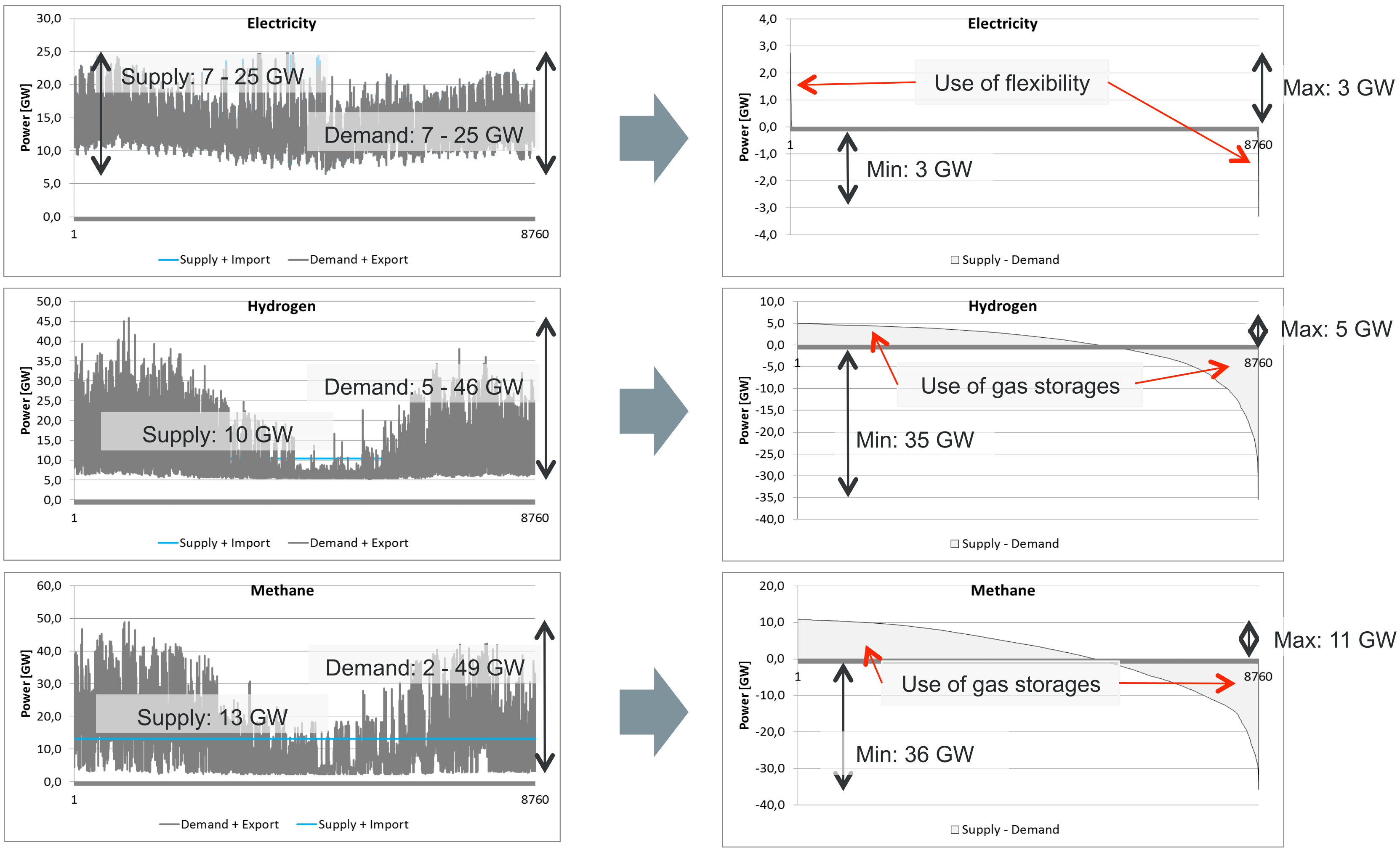






International Scenario NL

Charge and Discharge capacities (GW)



Storage requirements

- Derived from ETM model
- Storage volumes (TWh)

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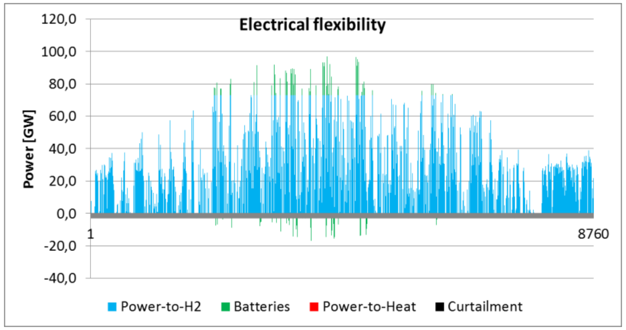
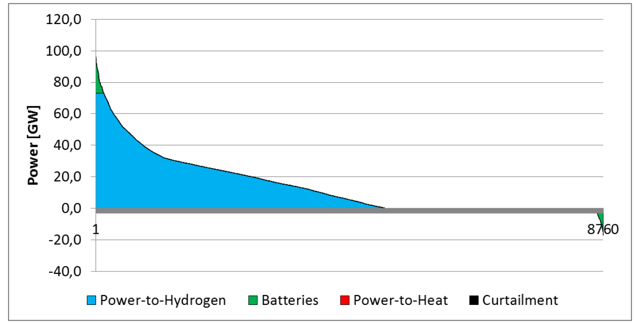
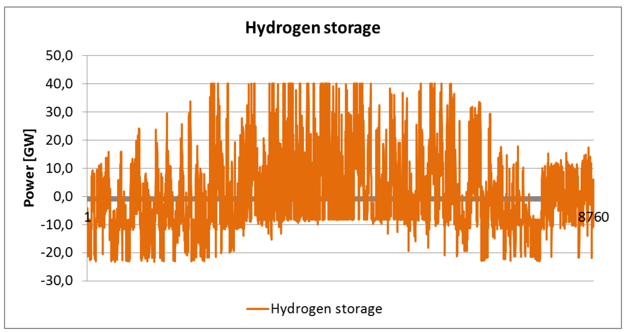
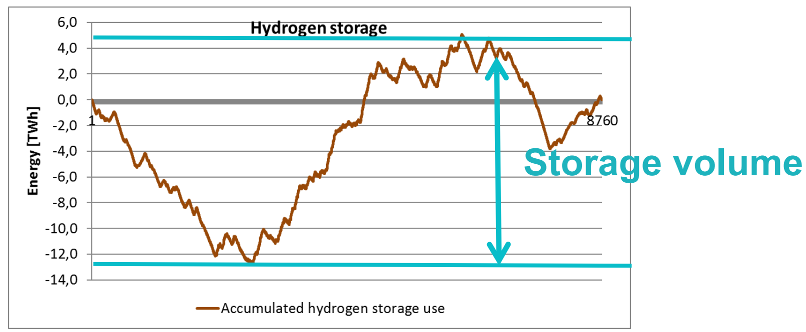
Decentral scenario NL

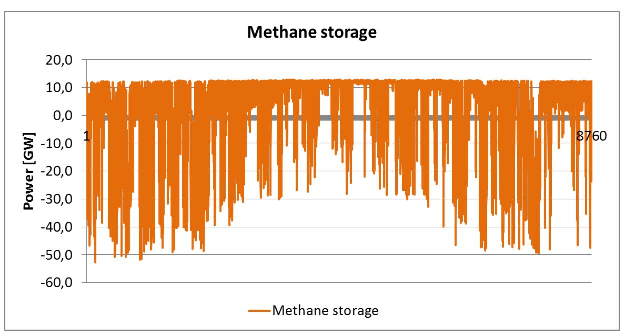
Storage volumes (TWh)

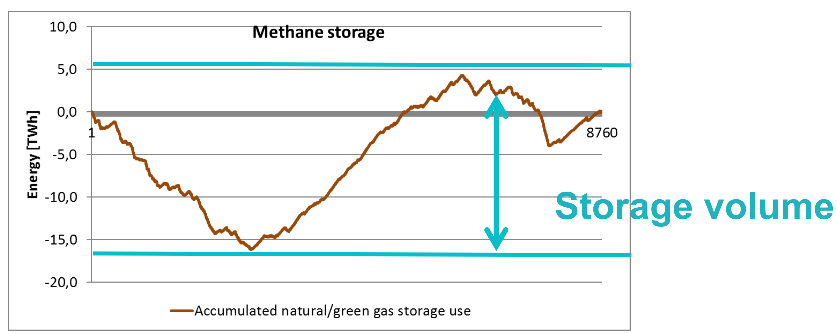






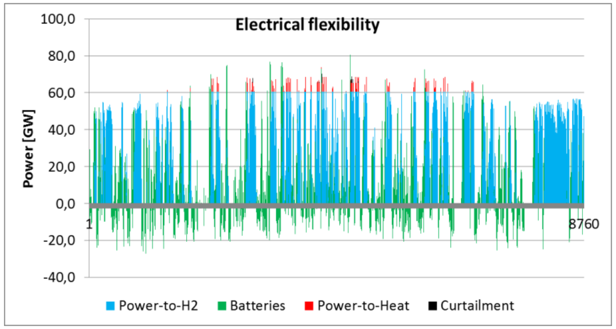


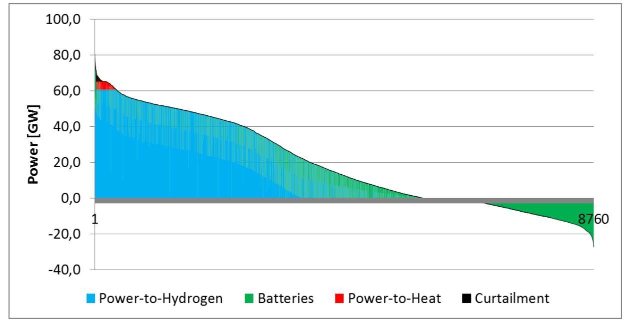


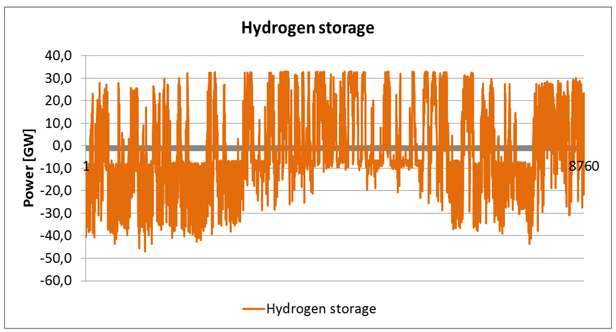


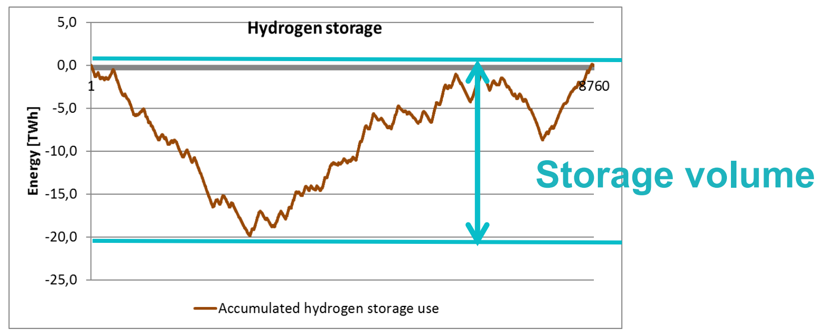
National Scenario NL

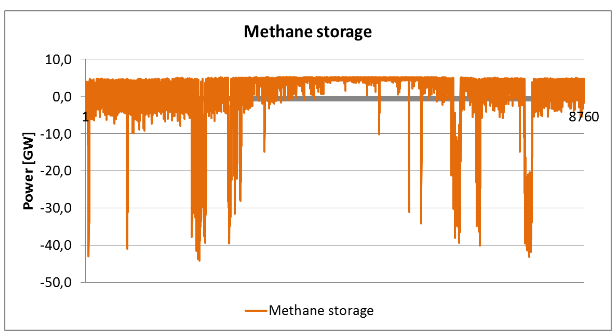
Storage volumes (TWh)

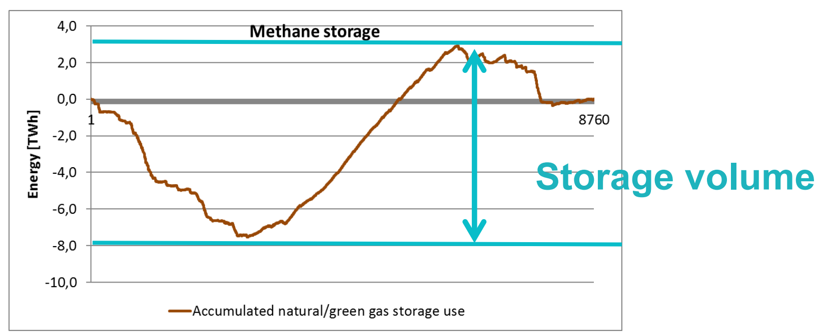






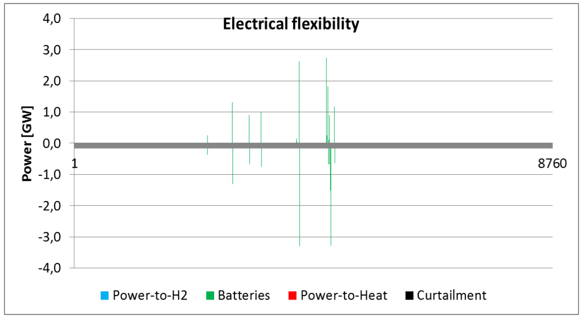


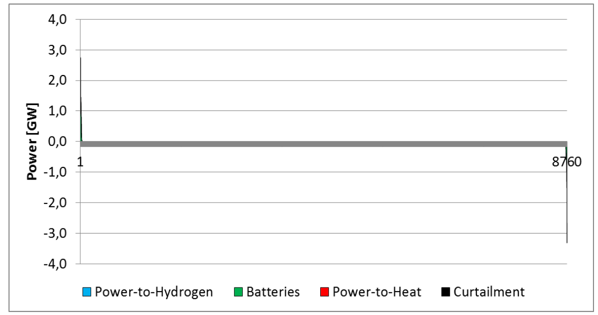


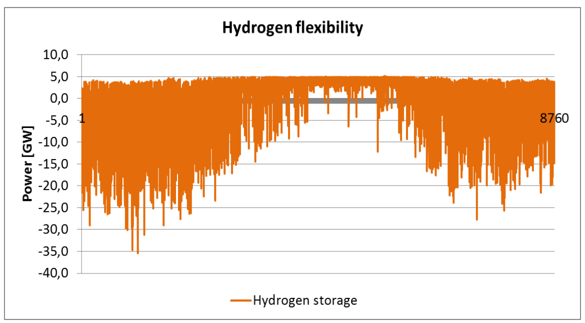


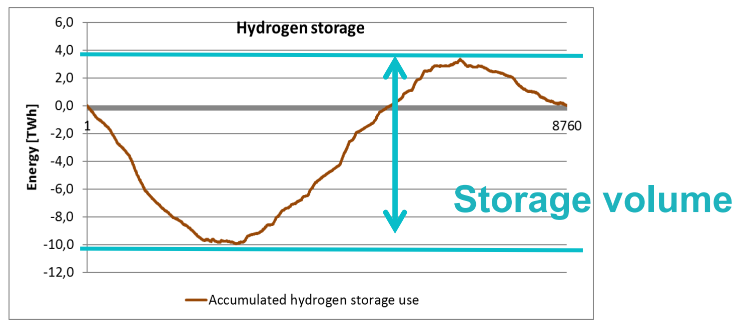
International Scenario NL

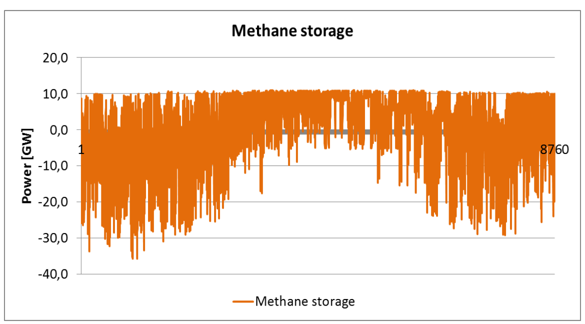
Storage volumes (TWh)

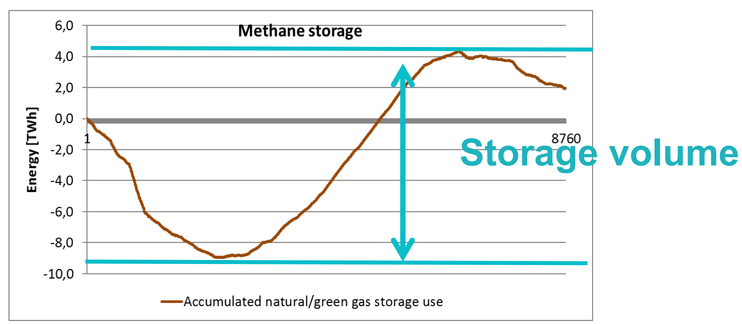












Infrastructure Calculations

- Selection of operating envelope snapshots

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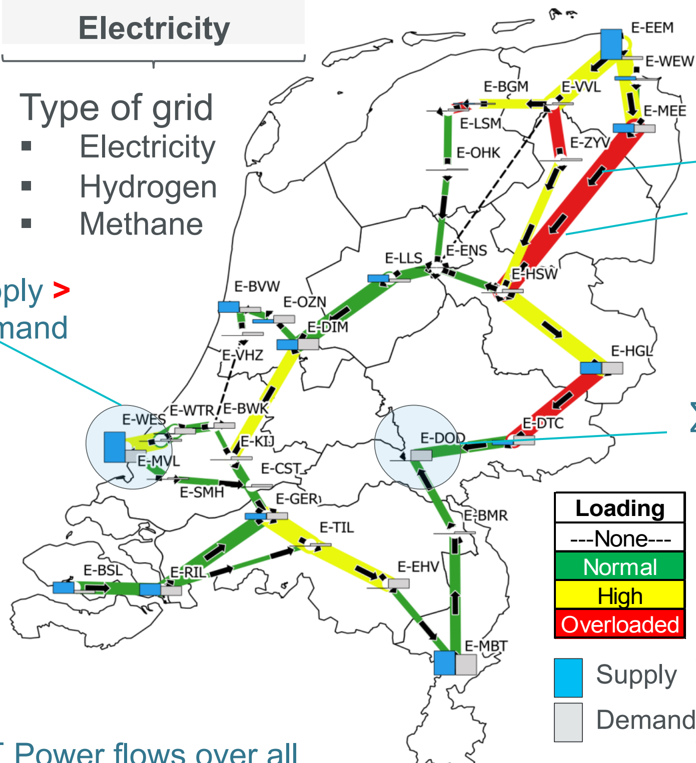
Infrastructure Calculations: Introduction

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

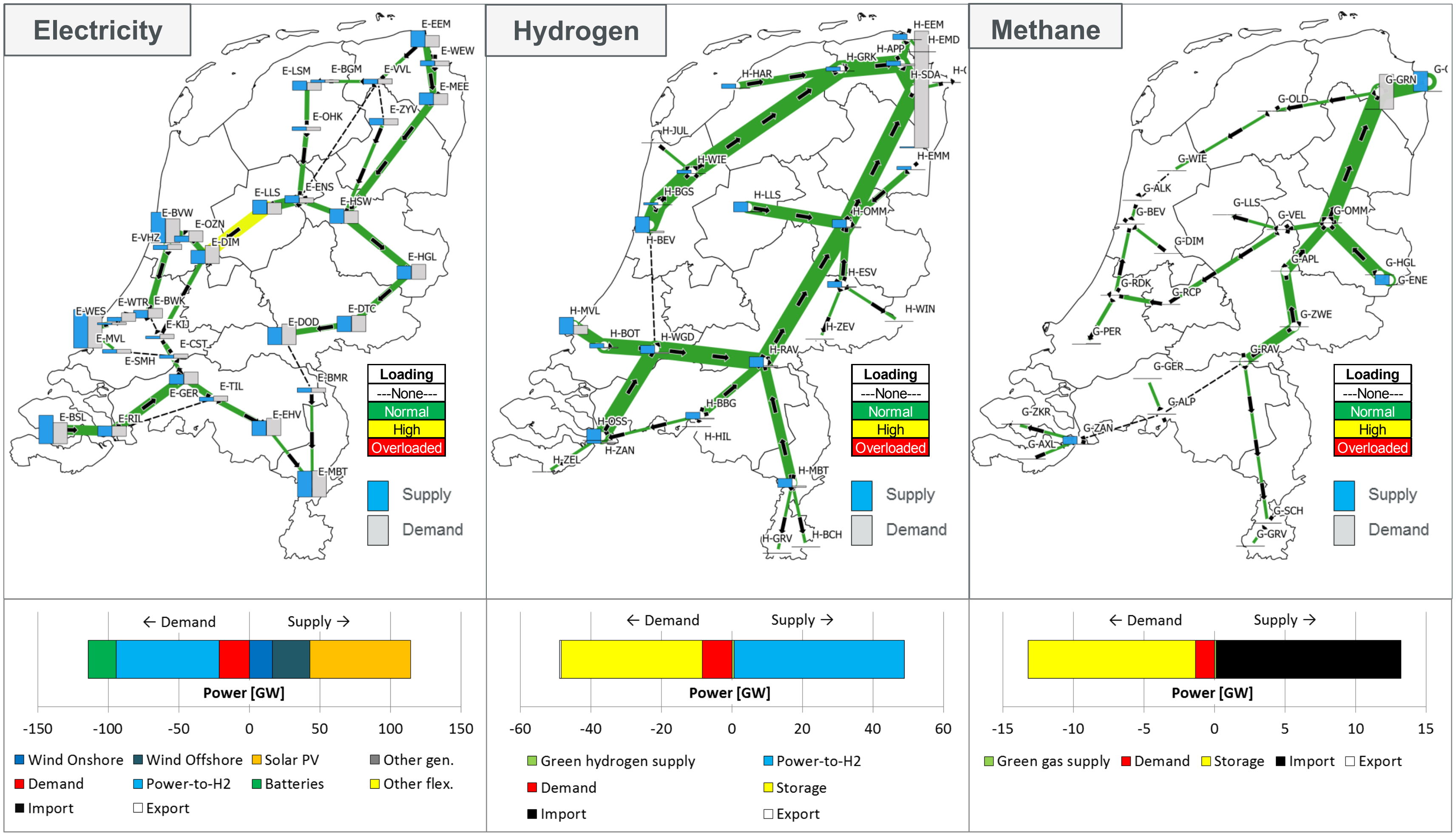
Power flow = 1,3 TWkm
Rel. usage = 0 TWkm

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

Regional Scenario NL

High RES + high electrical demand

Operating Envelope Snapshot Hour 4044



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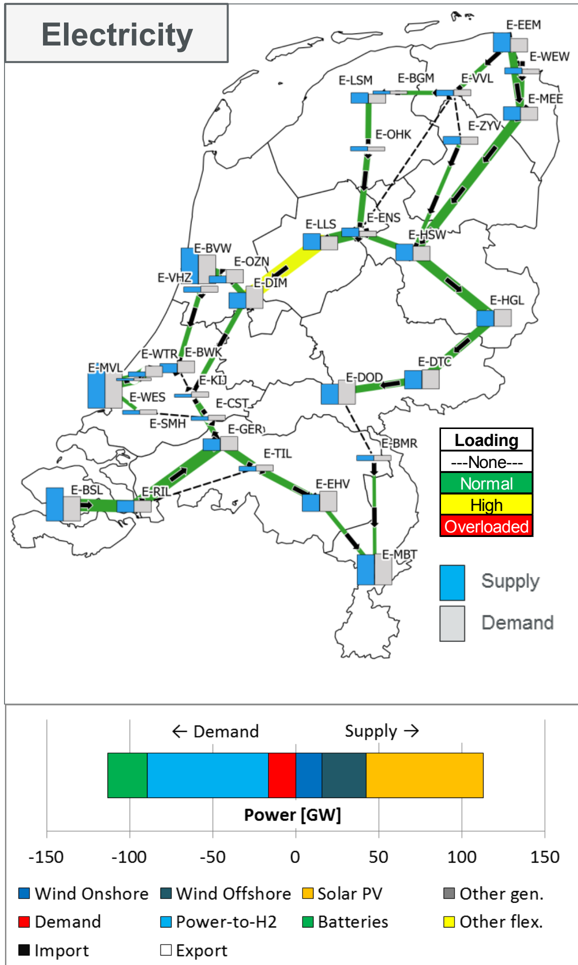
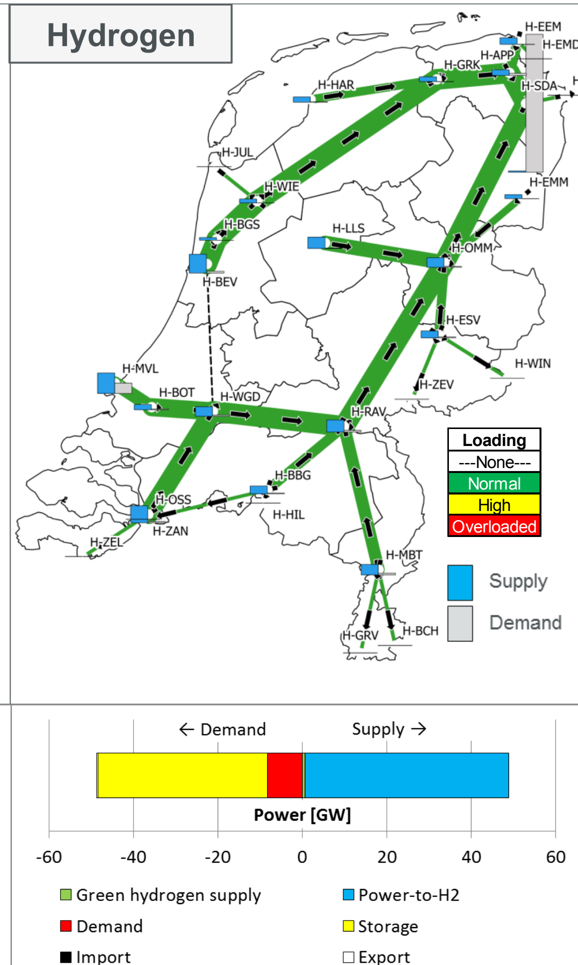
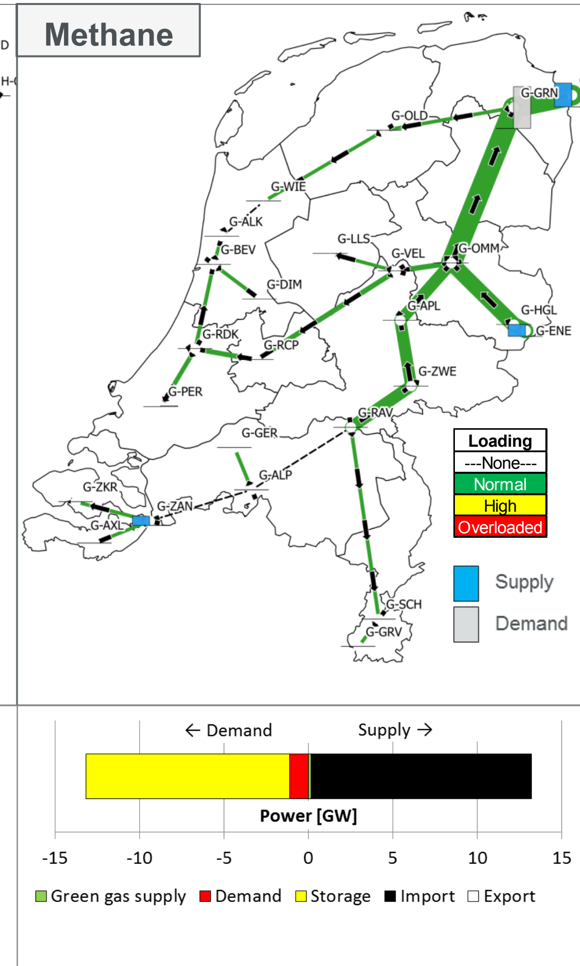
Regional Scenario NL

High RES + low electrical demand

Operating Envelope Snapshot Hour 4116



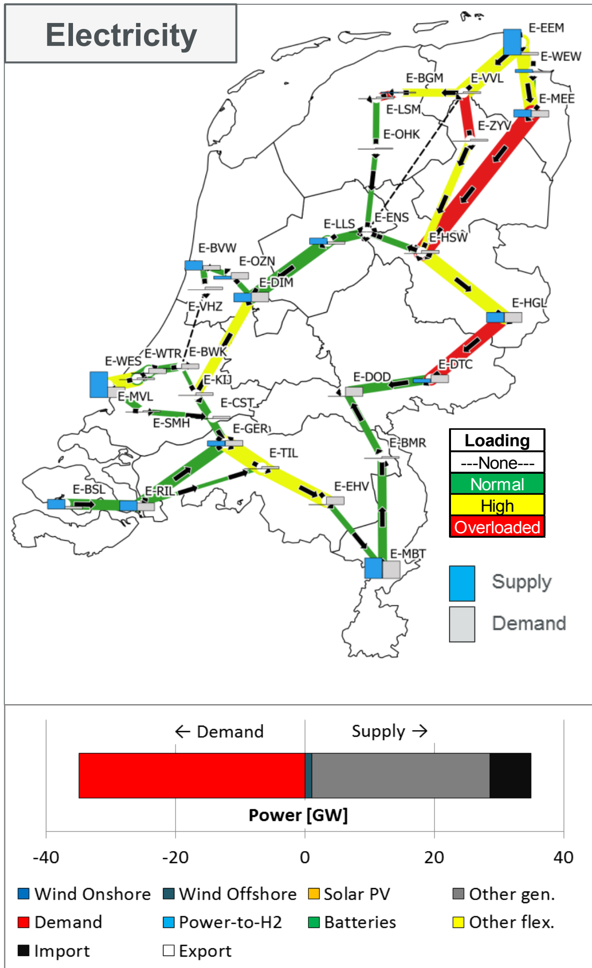


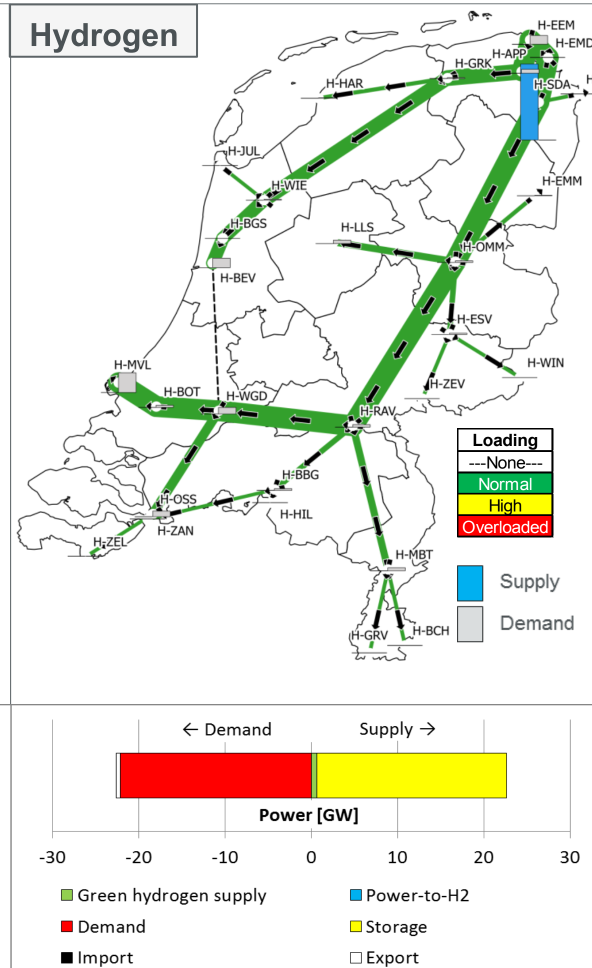


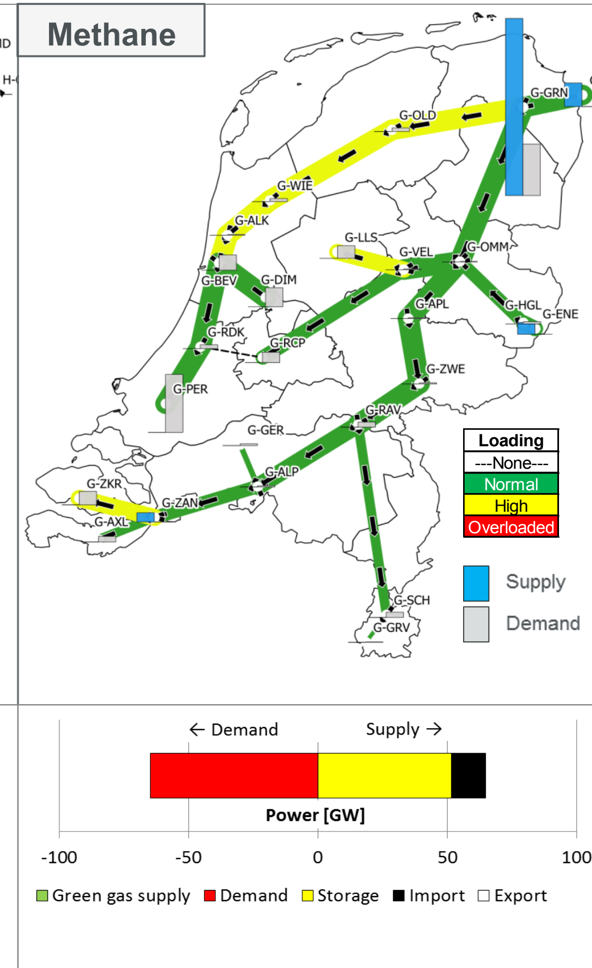
Regional Scenario NL

Low RES + high electrical demand + high conv. supply

Operating Envelope Snapshot Hour 954



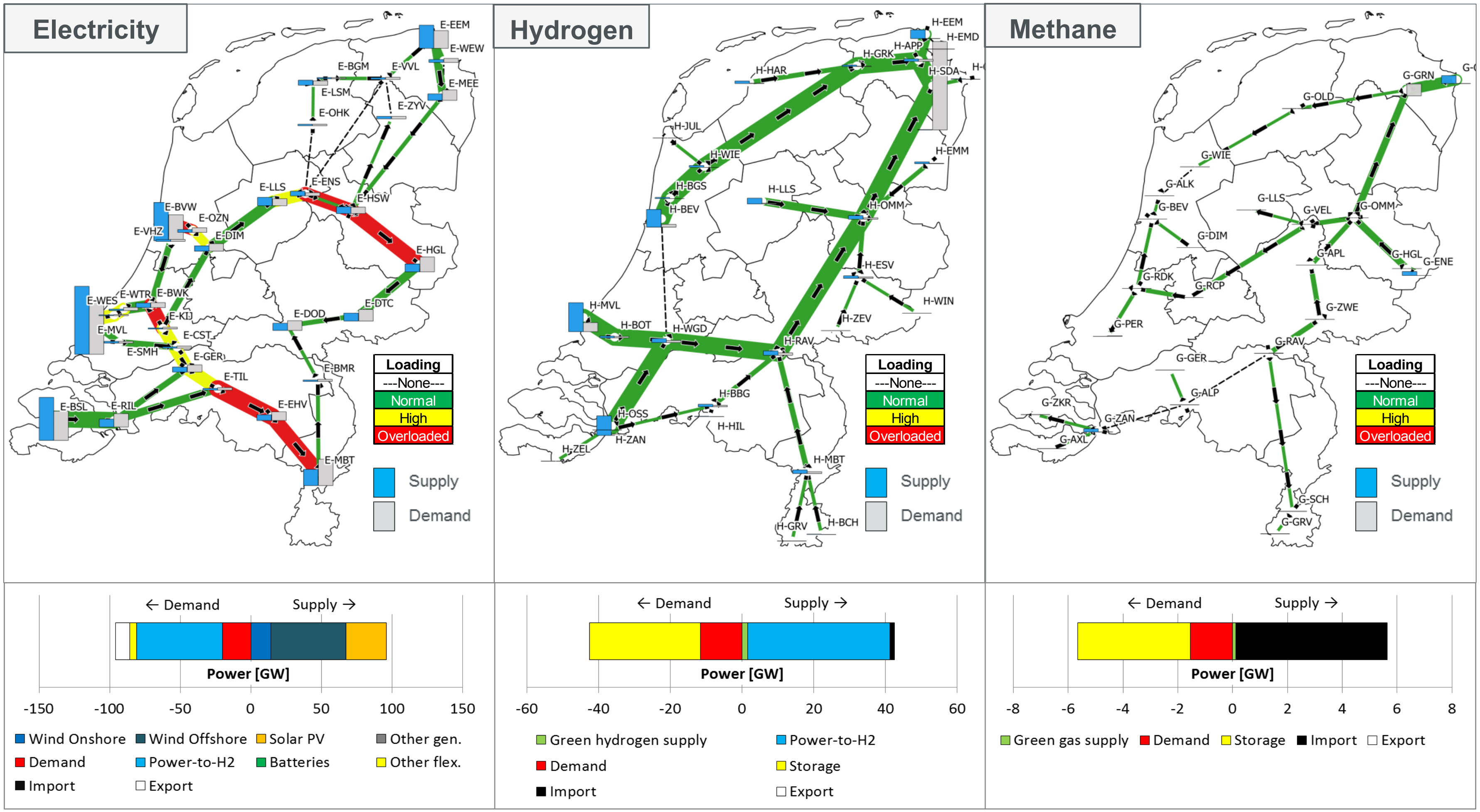




National Scenario NL

Operating Envelope Snapshot Hour 4044

High RES + high total electrical demand



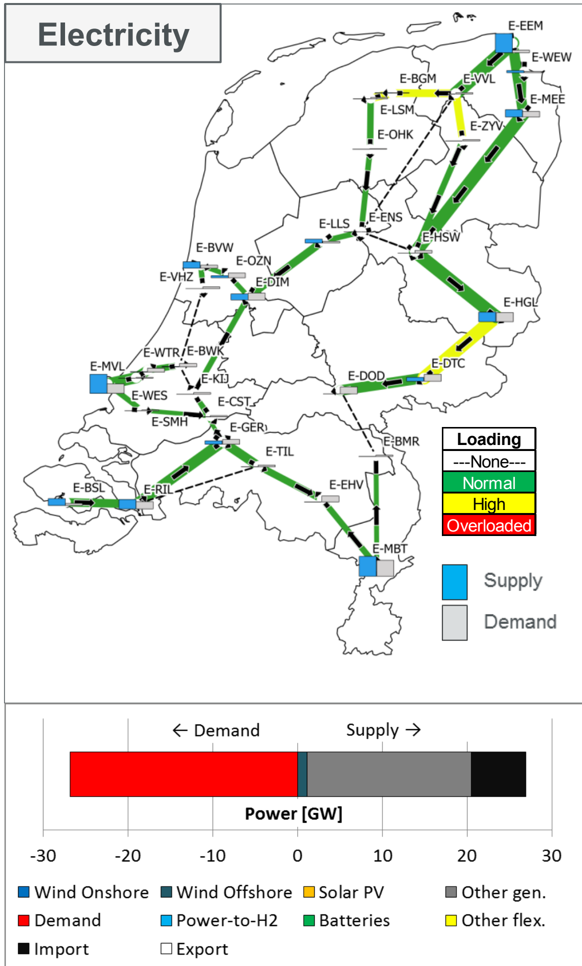
crossing borders in energy

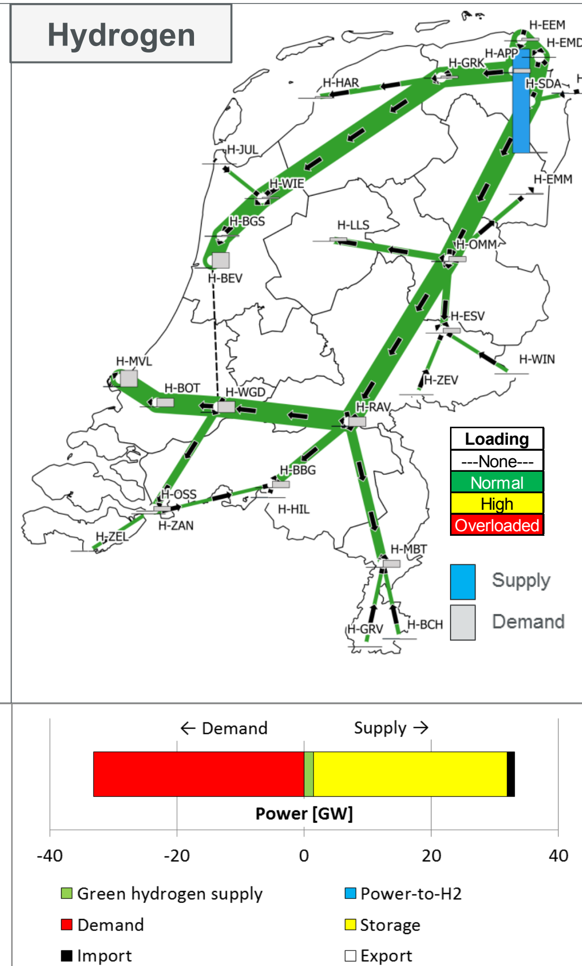
Taking power further

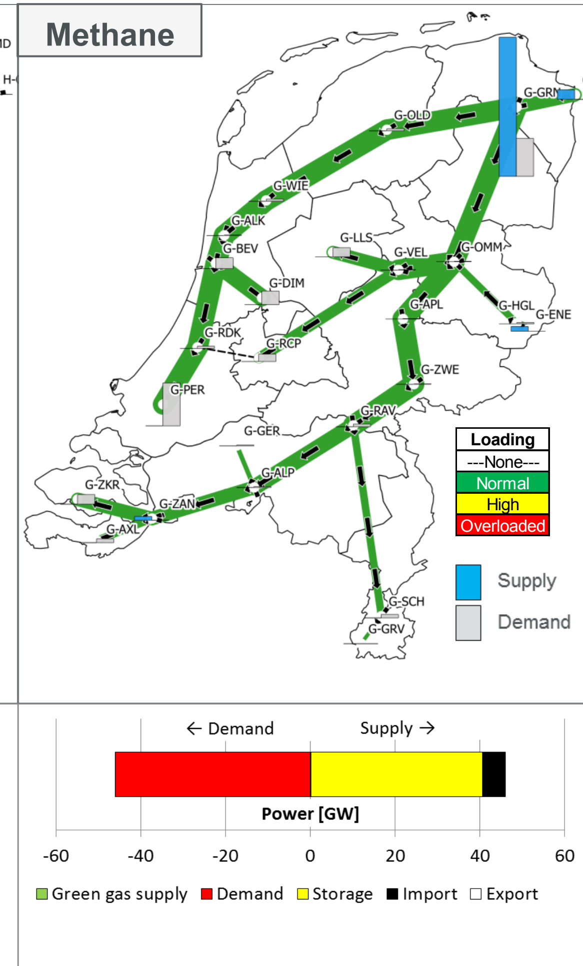
National Scenario NL

Low RES + high electrical demand + conv. generation

Operating Envelope Snapshot Hour 7746







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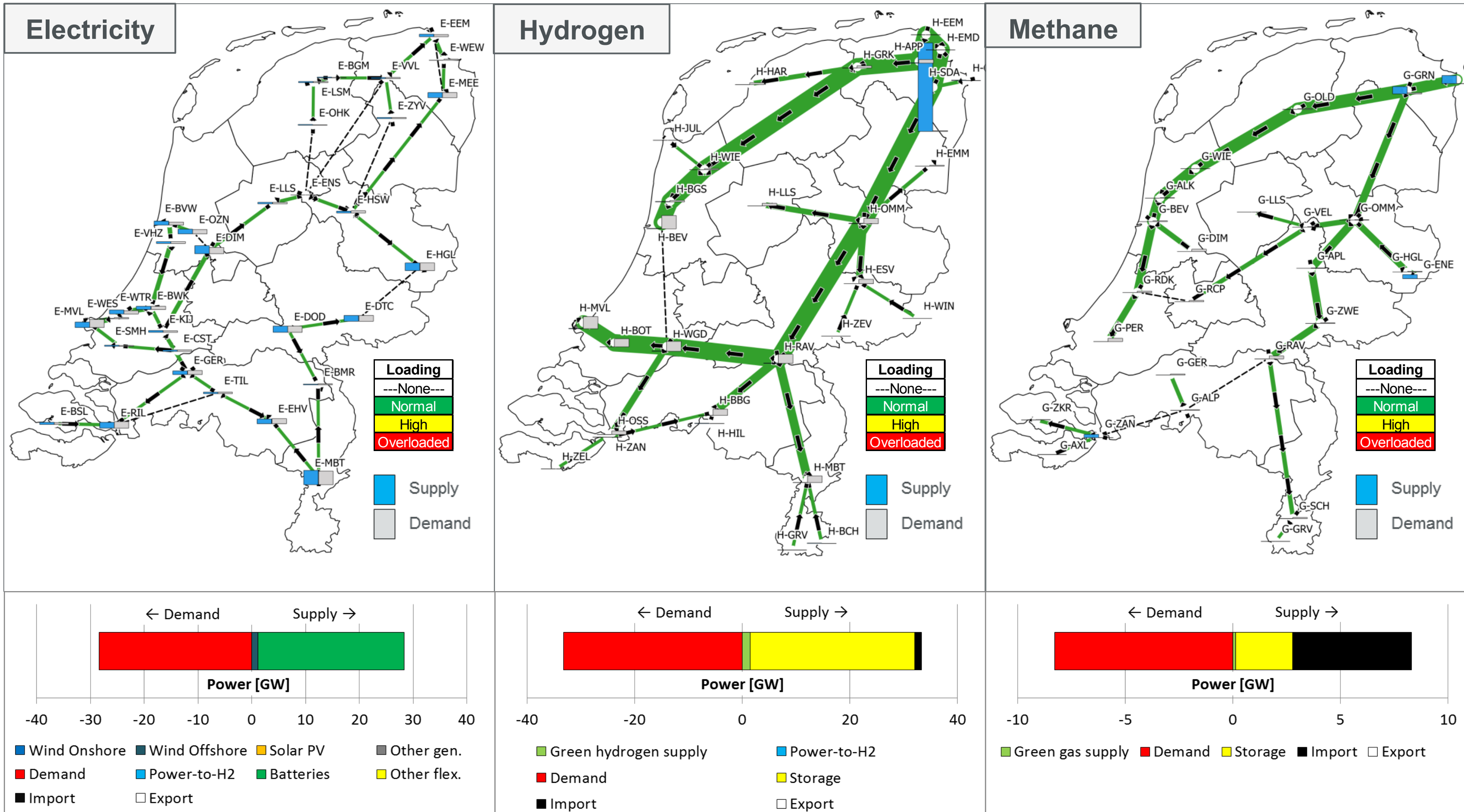
National Scenario NL

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

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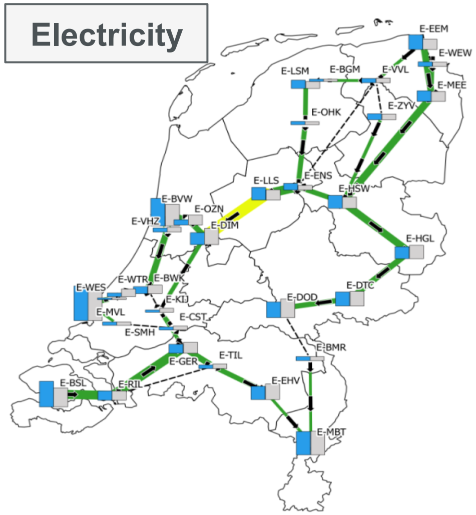
Regional Scenario NL

High RES + high electrical demand

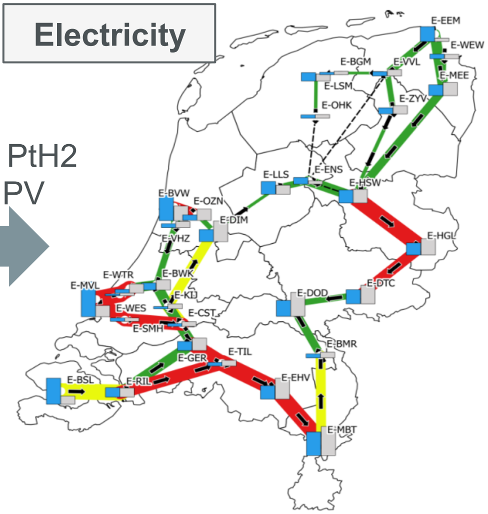
Hour 4044 concentrating electrolysers near solar

Electricity

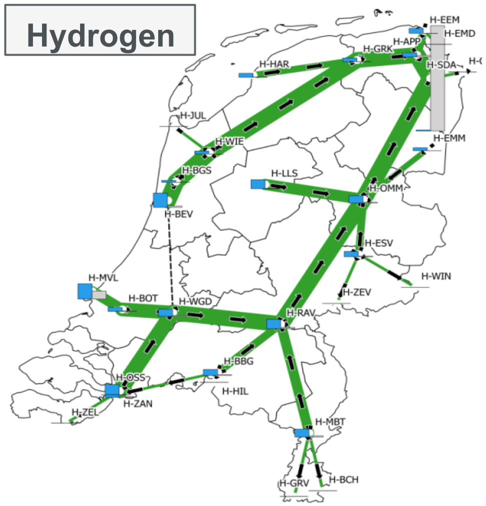


Shifting of PtH2 to solar PV

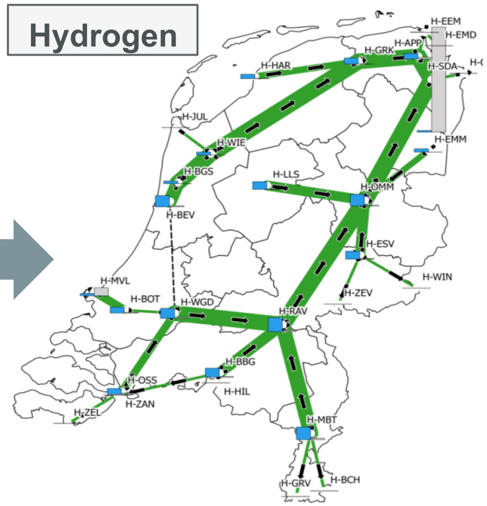
Electricity



Hydrogen



Hydrogen



- 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

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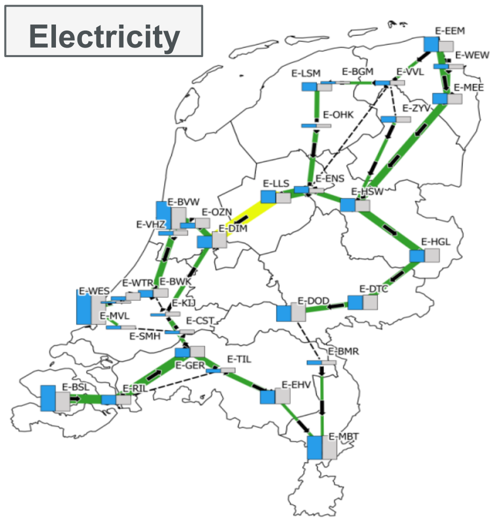
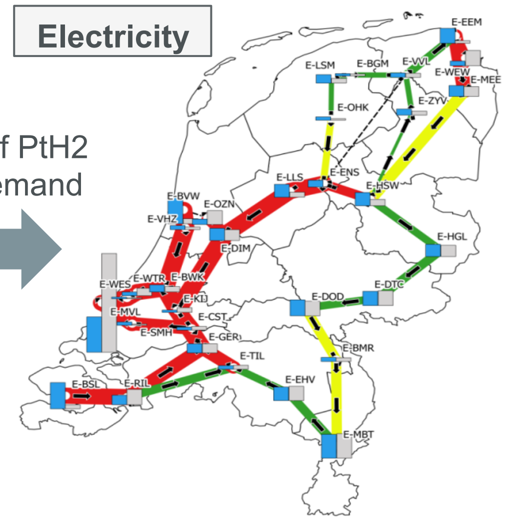
Regional Scenario NL

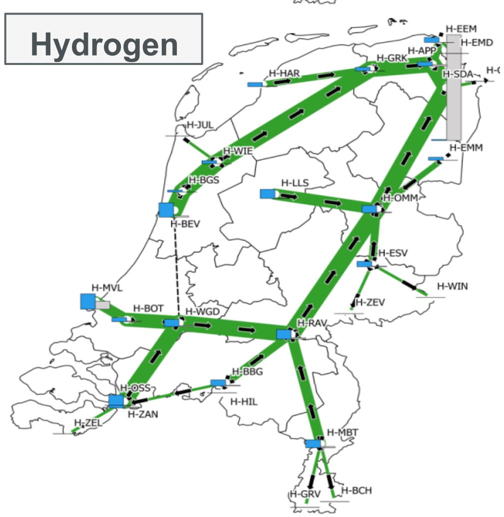
High RES + high electrical demand

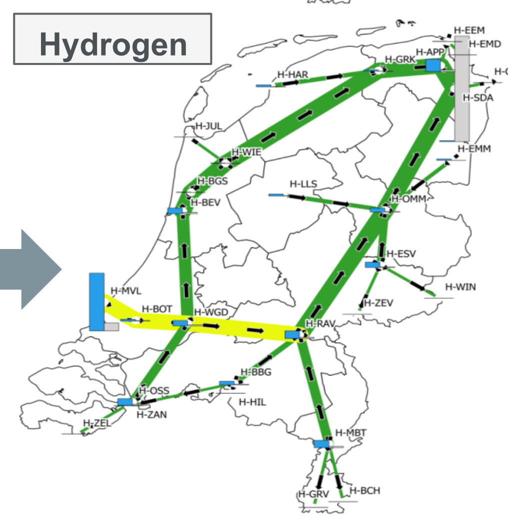
Hour 4044 concentrating electrolysers near solar



Shifting of PtH2 to gas demand







- Localizing PtH2 at <u>gas demand locations</u> 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

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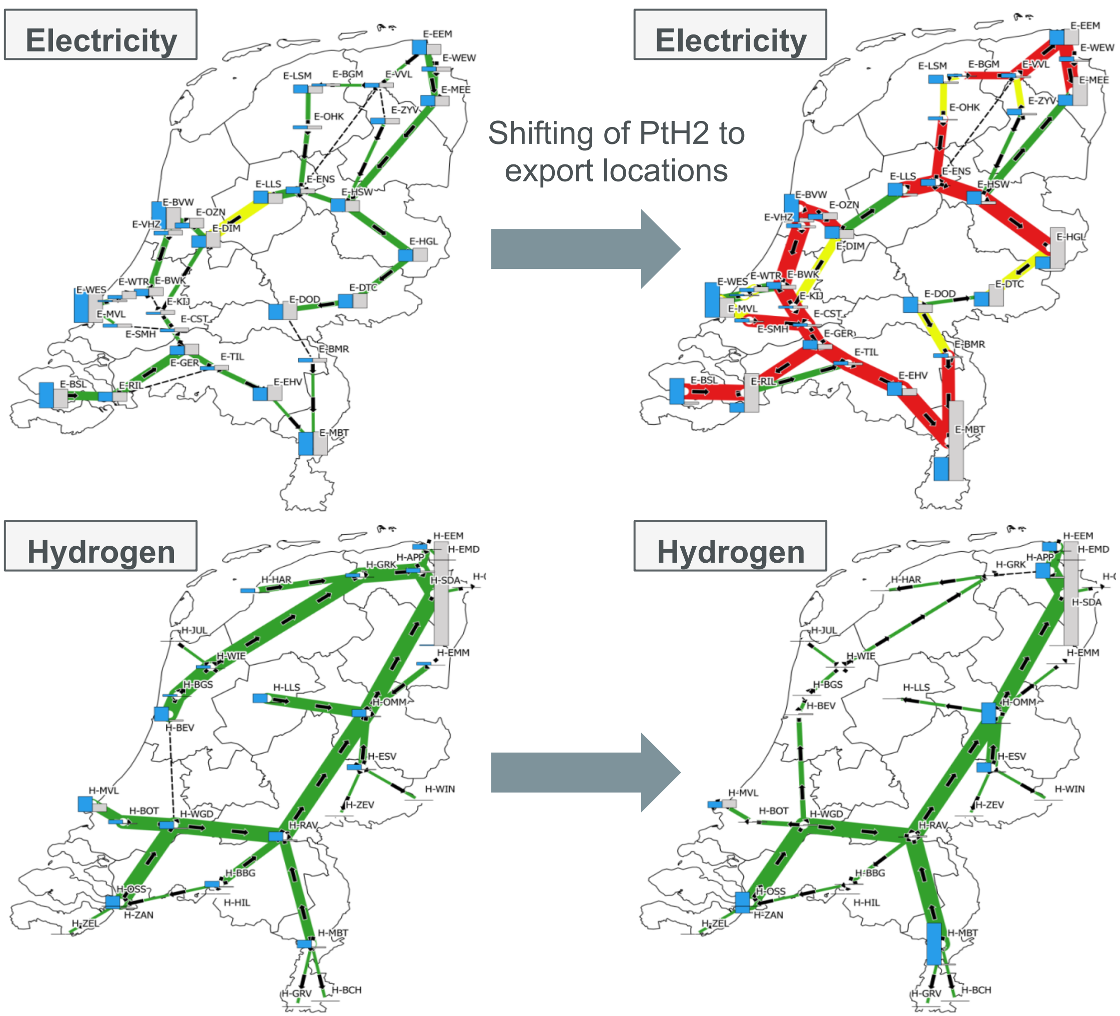
TenneT Taking power further

Regional Scenario NL

High RES + high electrical demand

Hour 4044 concentrating electrolysers near system borders

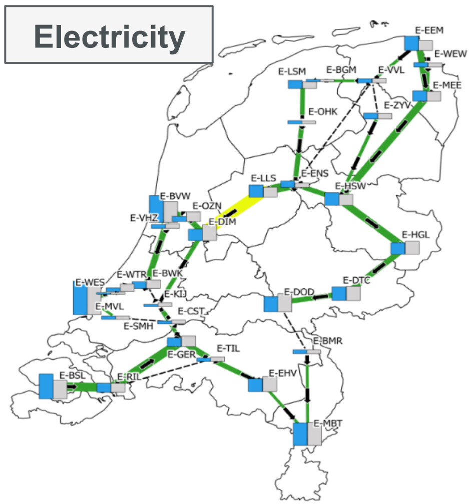


- Localizing PtH2 at the <u>borders of the system</u> leads to a high transport distance between RES supply and electrical demand and a very high transport in the electrical grid
- Direction of power flows mainly towards export nodes
- Still no bottlenecks in hydrogen grid as result of high assumed north-south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

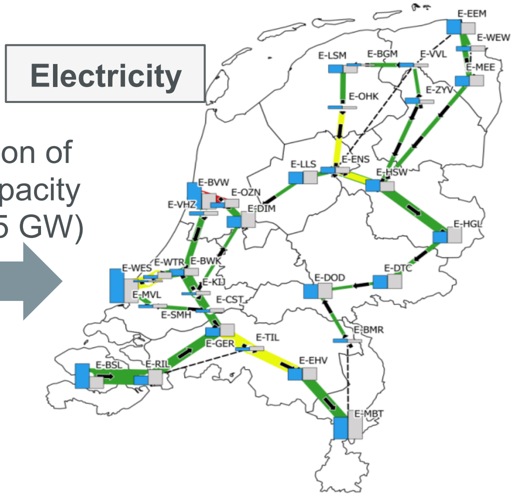
Regional Scenario NL

High RES + high electrical demand

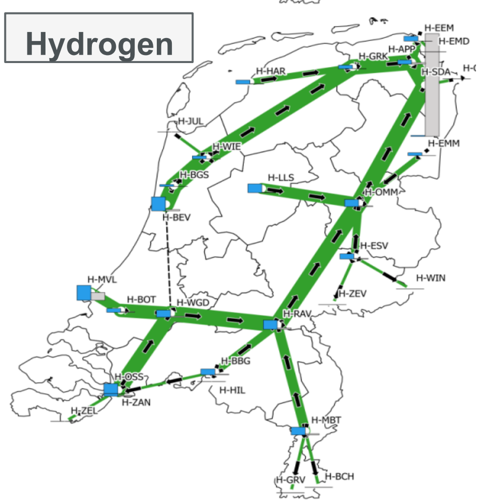
Hour 4044 Reduction of electrolyzer capacity (75GW -> 25GW)

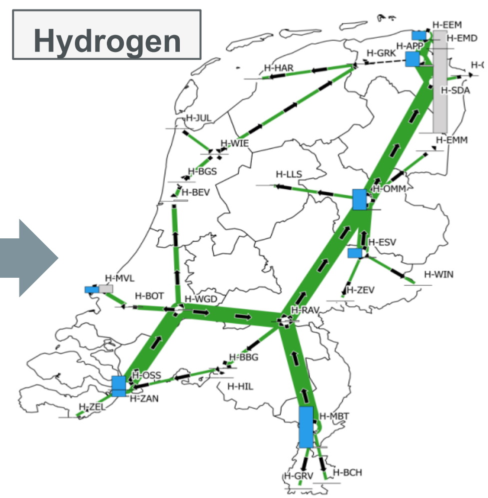


Reduction of PtH2 capacity (75 -> 25 GW)



- <u>Reducing the PtH2 capacity from 75 GW to 25 GW</u> 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

Infrastructure Calculations

- Transit excursions

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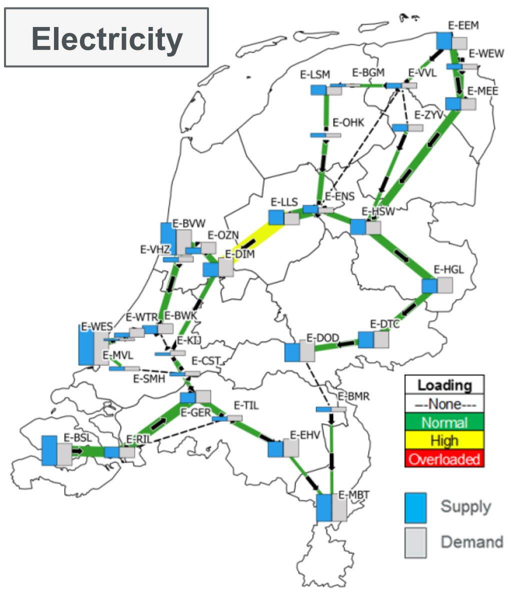
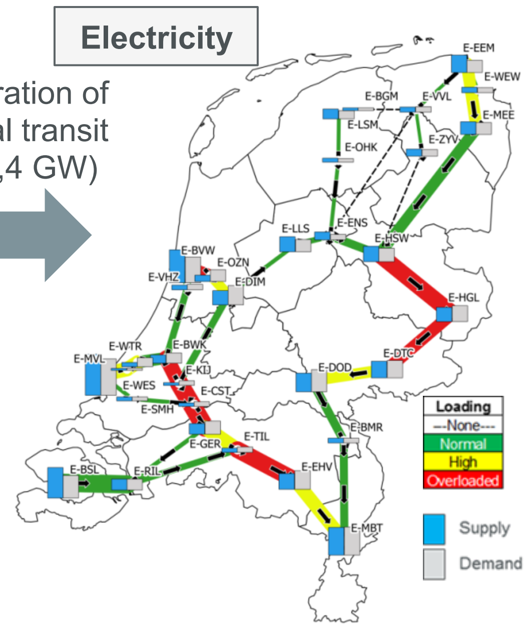
Regional Scenario

High RES + high electrical demand

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



Consideration of additional transit flows (6,4 GW)



<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

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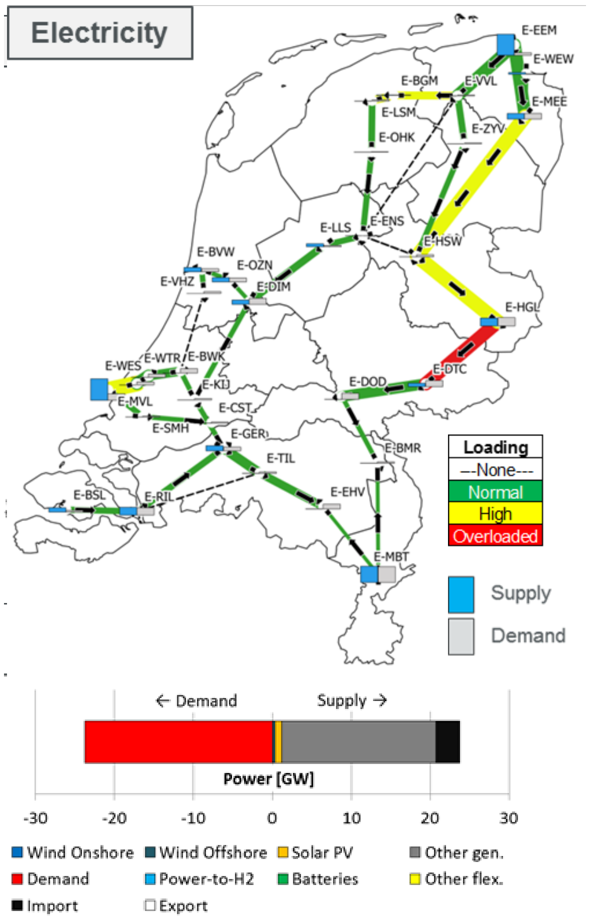
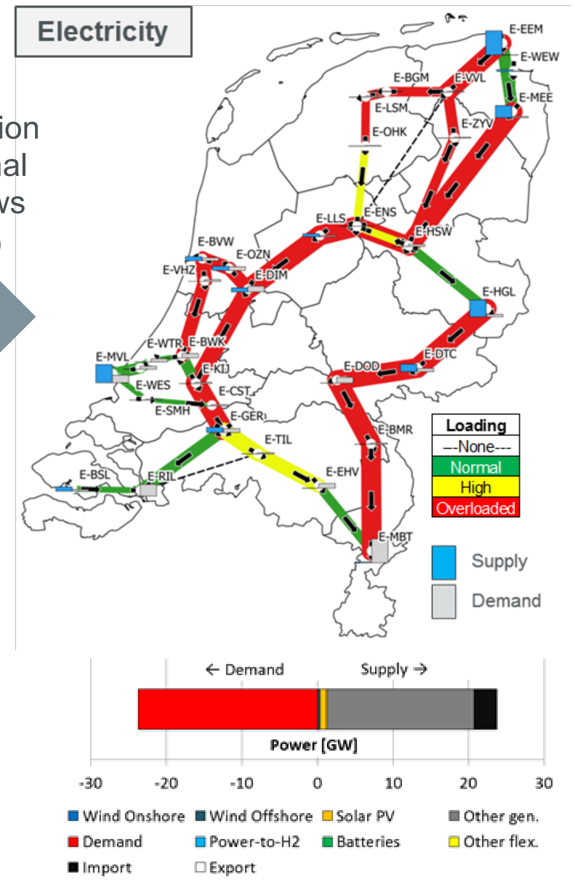
International scenario

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:

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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

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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

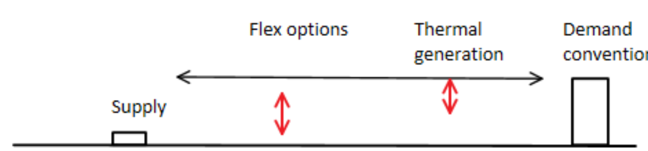
Flex options:
Demand management
Battery
Conversion p-2-h2
Export
Curtailment

># 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*



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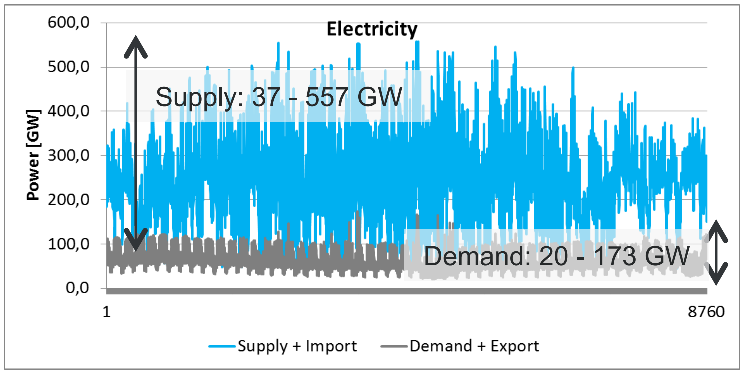
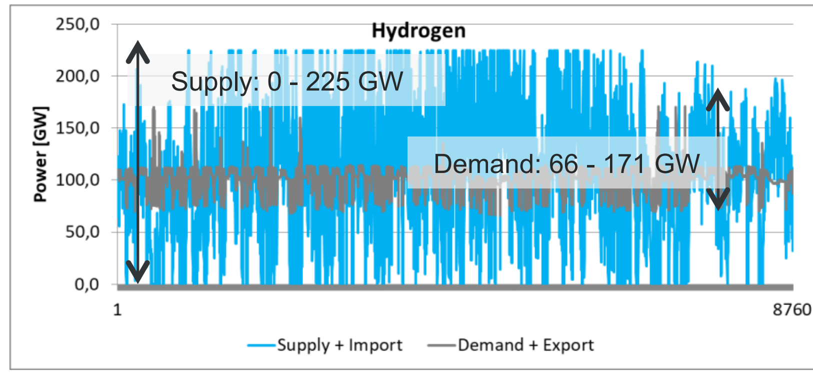
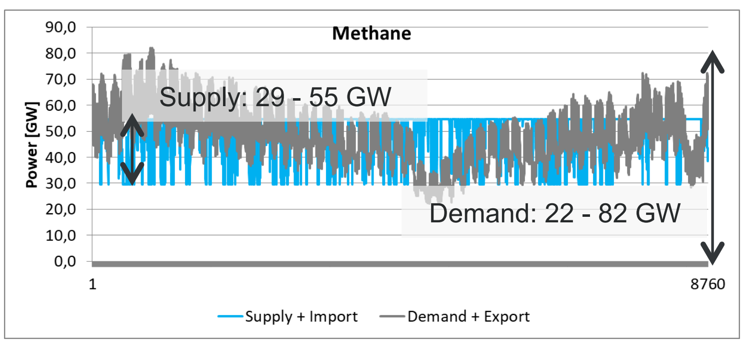
Regional scenario DE

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).

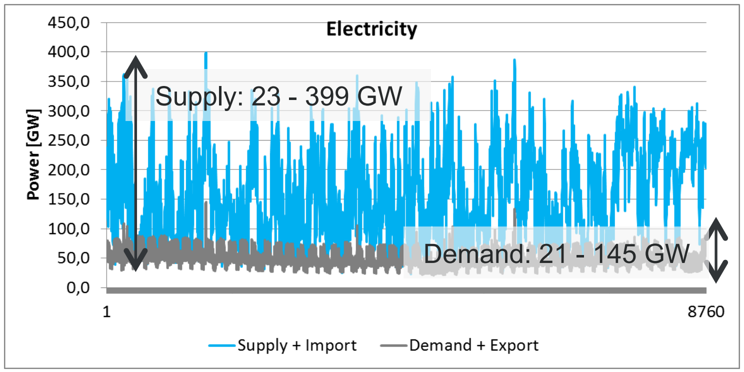
Regional Scenario DE

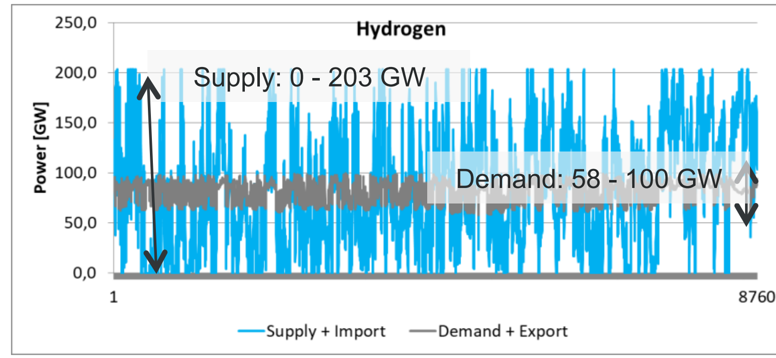
Supply and Demand main findings

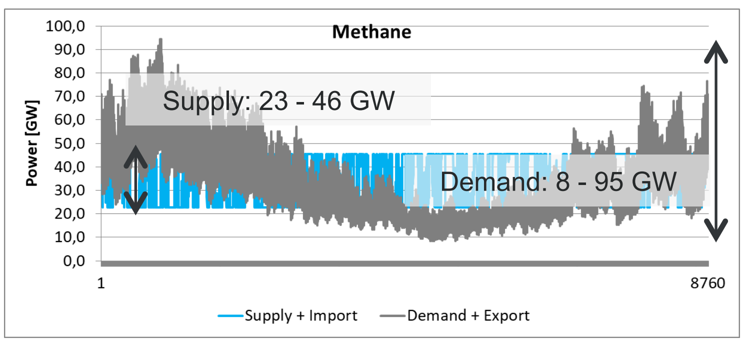
- **Significant mismatch between electrical supply and demand** due to high installed capacity and volatile infeed of wind and solar
- To fully integrate the RES infeed, a **combination of power-to-hydrogen („base flexibility") and battery storage („peak flexibility")** is used
- The high capacity of 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
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- Hydrogen: Supply volatility from power-to-H2. Demand stable (industry) except for peaks from gas power plants
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Supply = Total supply to the system including imports
Demand = Total demand from the system including exports

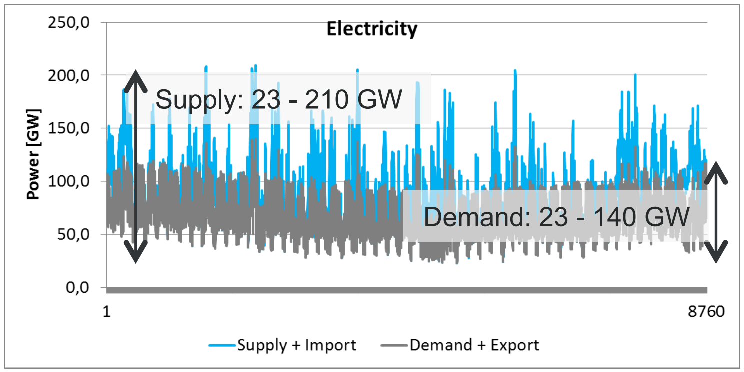
National Scenario DE

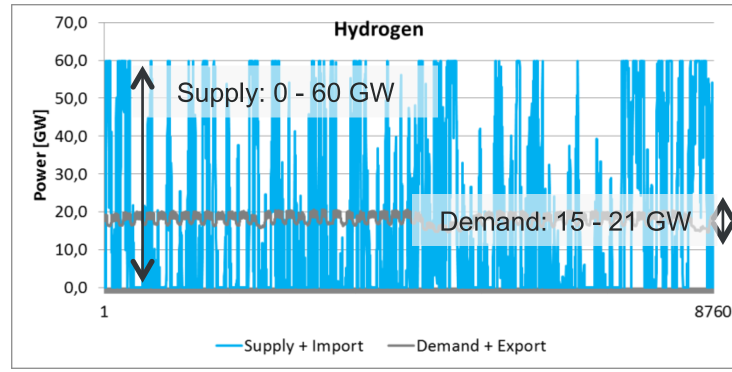
Supply and Demand main findings

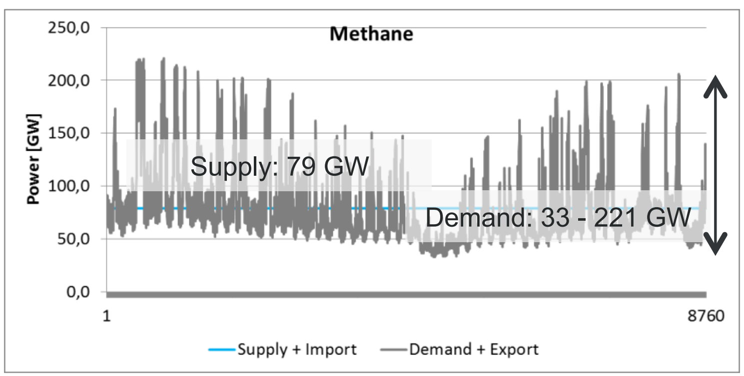
- Behaviour on the overall demand/supply view comparable to Regional Scenario
- Main Difference in different RES Supply structure (higher Wind (Onshore/Offshore) and less PV)
- Import of significant amounts of green liquid fuels

International Scenario-NL

Supply and Demand (original dena figures)







- 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

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

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)

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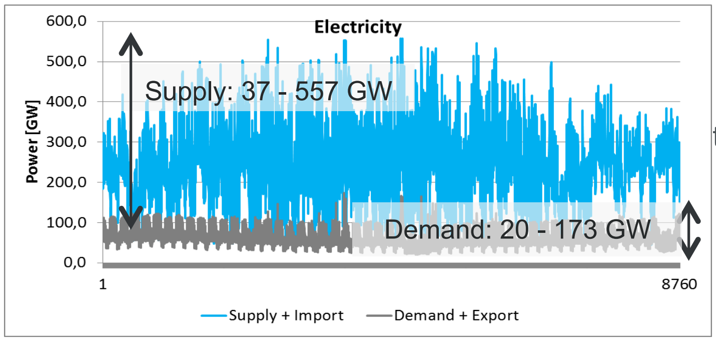
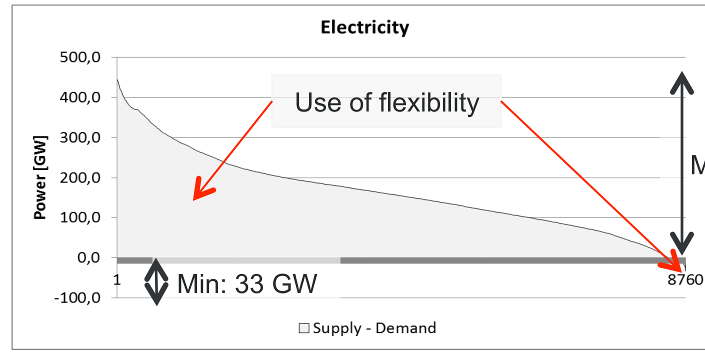
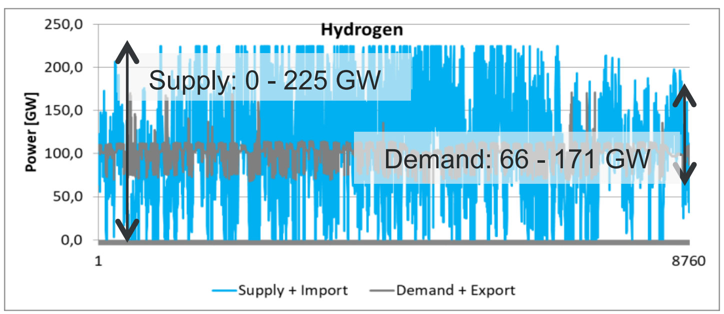
Regional Scenario DE

Charge and Discharge capacities (GW)

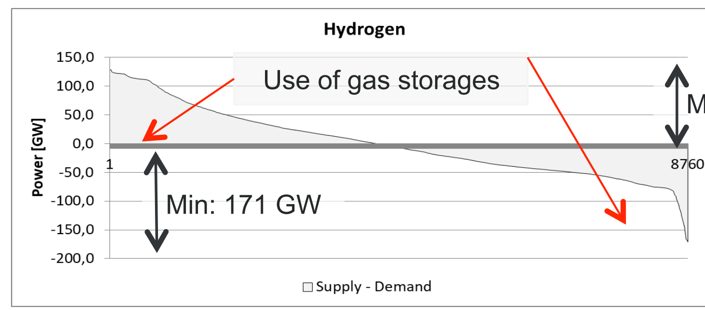


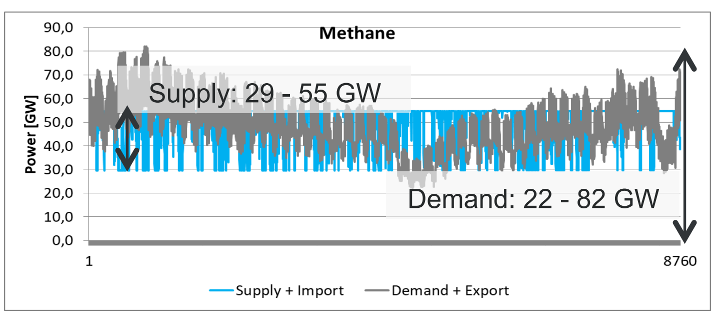
Flexible electricity demand through Power-to-hydrogen

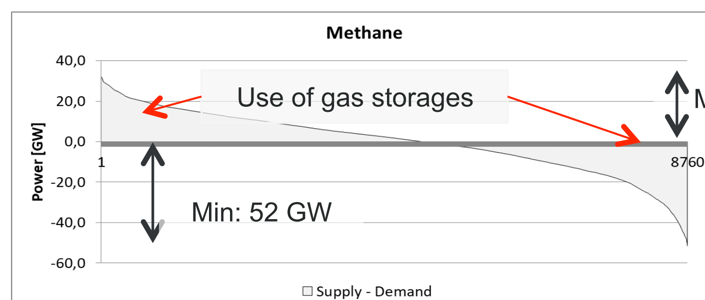




Balancing through gas storages

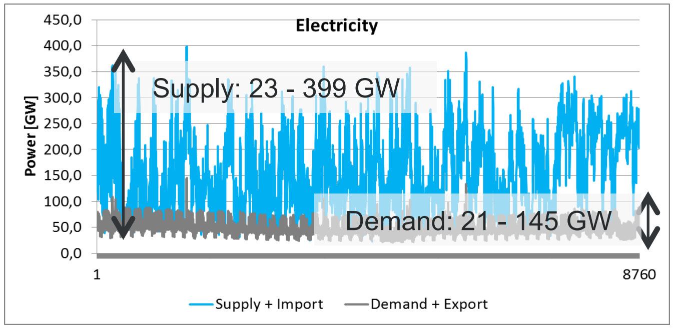


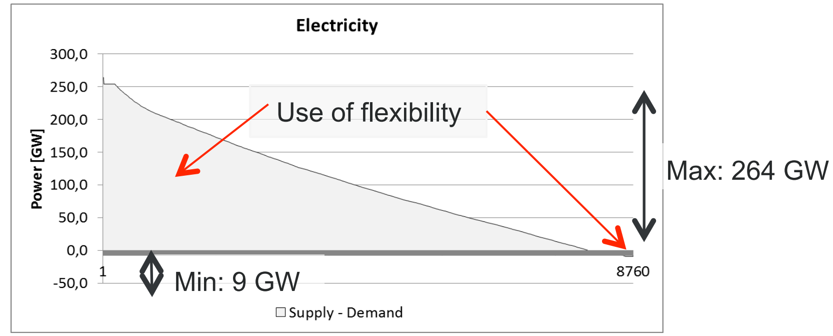


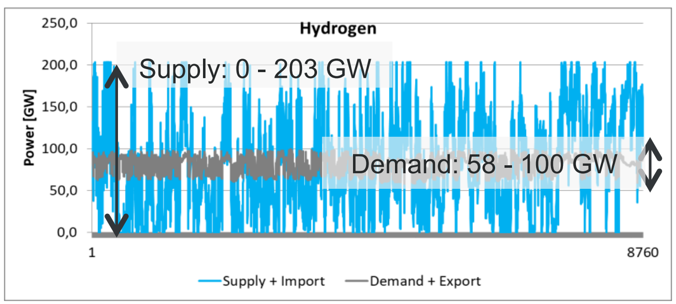


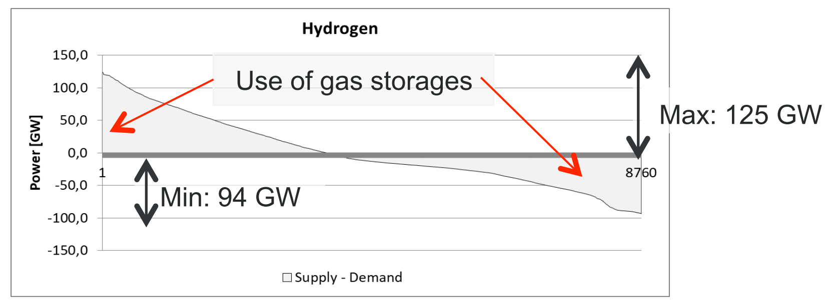
National Scenario DE

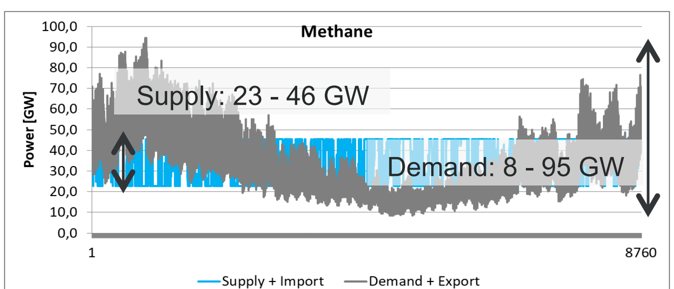
Charge and Discharge capacities (GW)

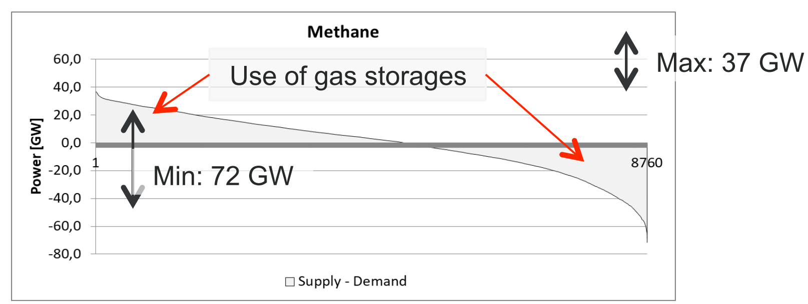






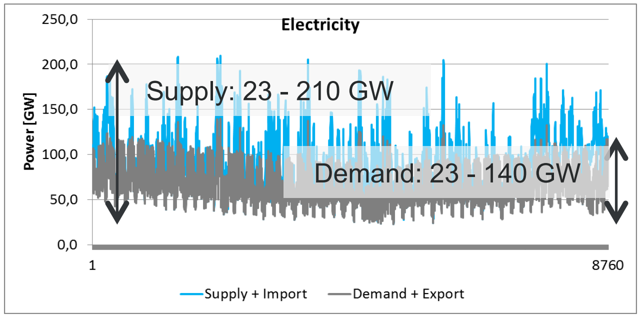


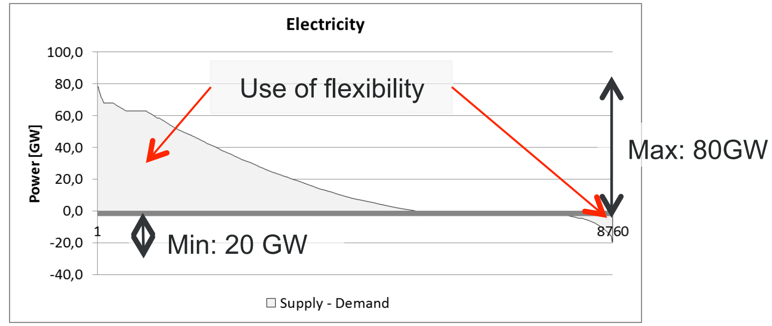


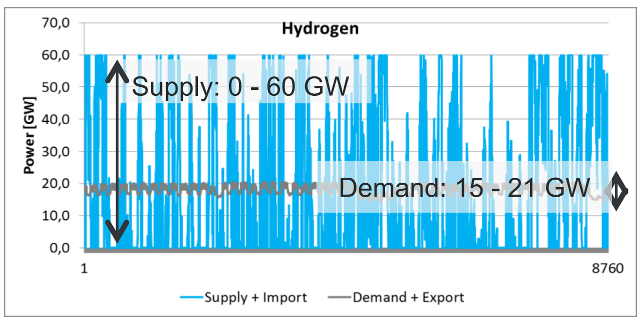


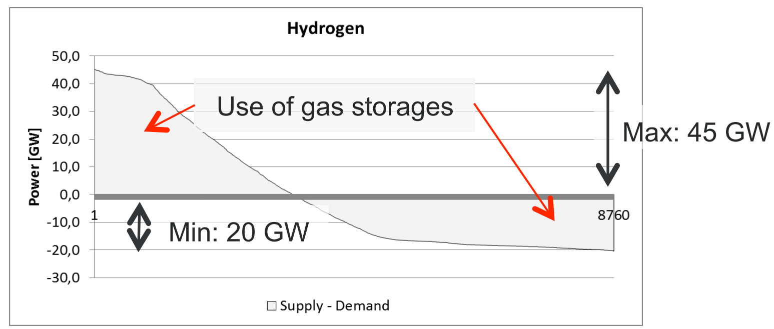
International Scenario DE

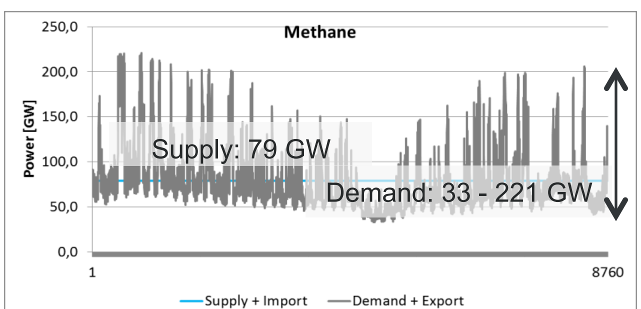
Charge and Discharge capacities (GW) – dena original

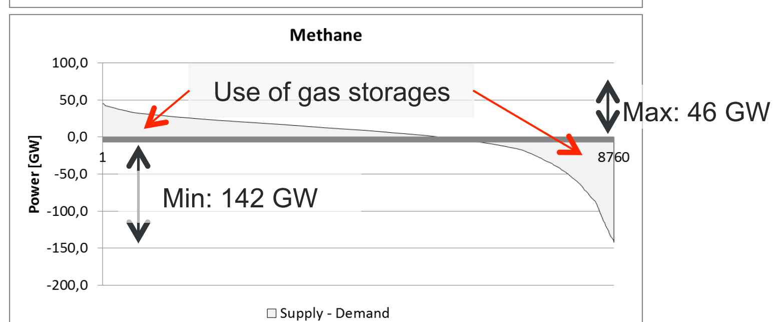










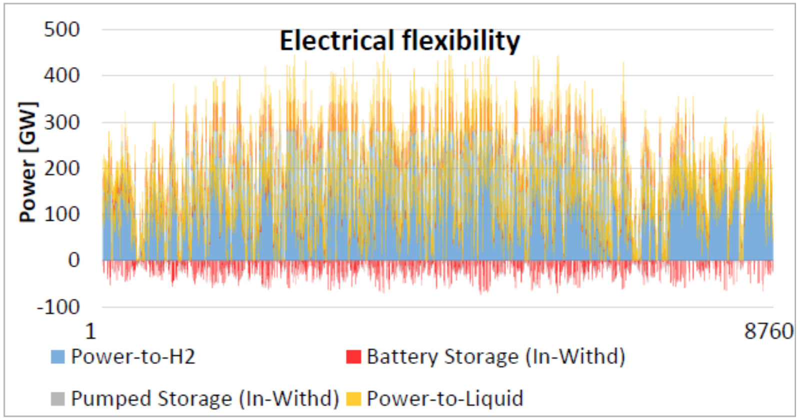


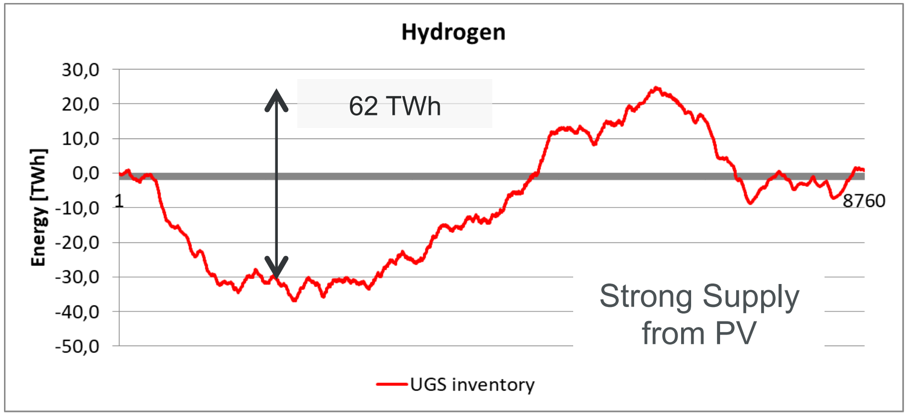
Storage requirements

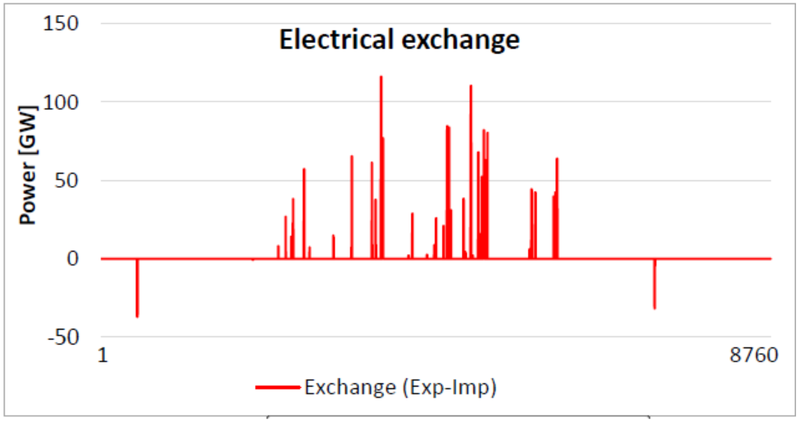
- Derived from ETM model and simulation from IAEW
- Storage volumes (TWh)

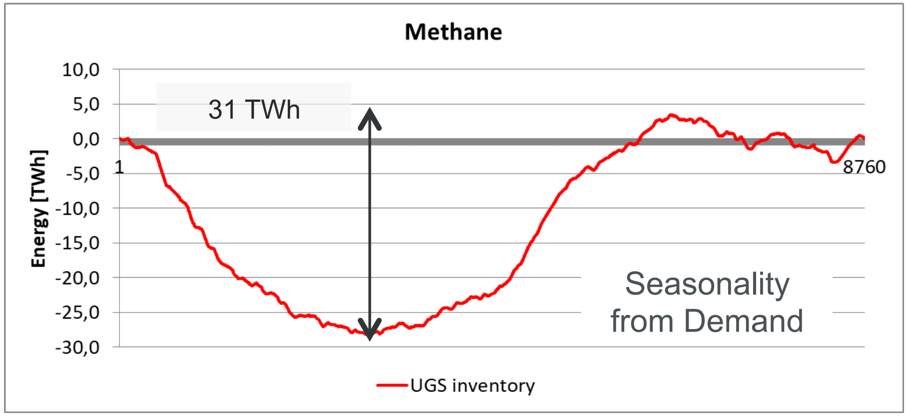
Decentral scenario DE

Storage volumes (TWh)



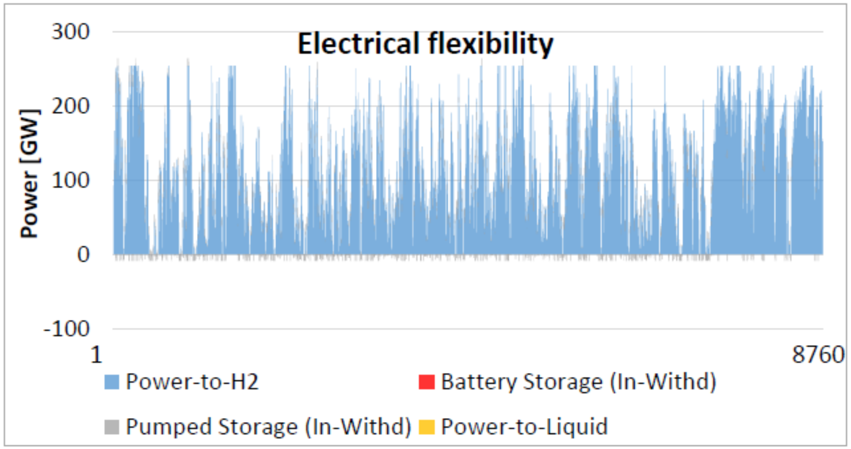


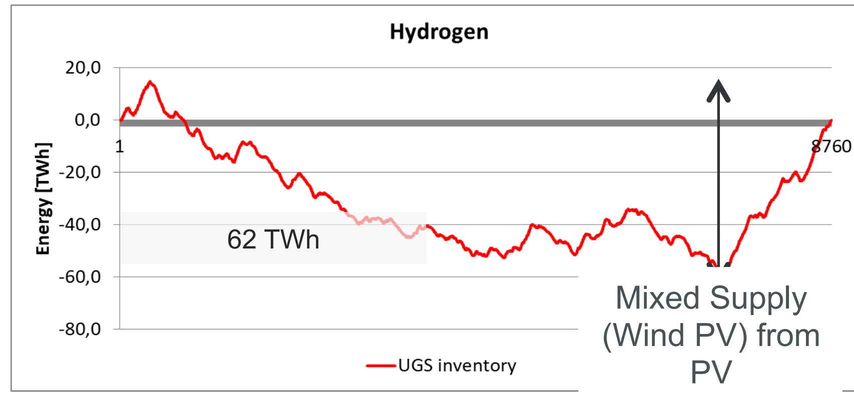


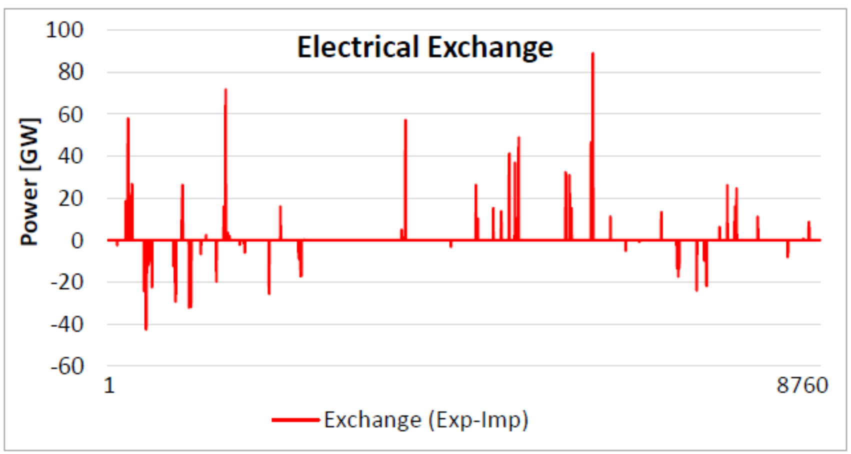


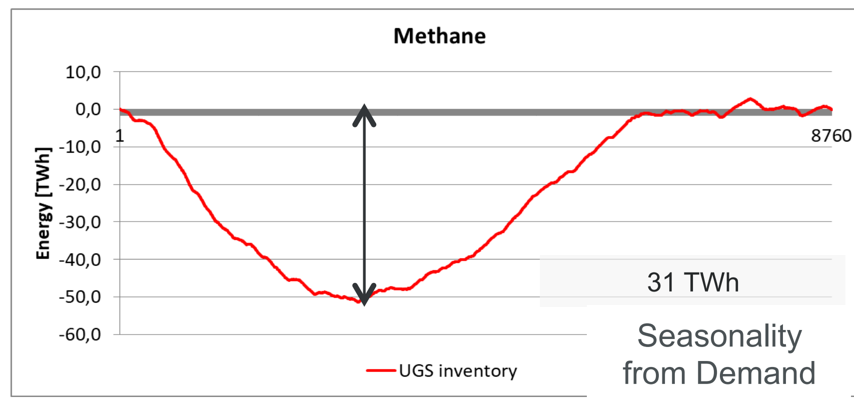
National Scenario DE

Storage volumes (TWh)



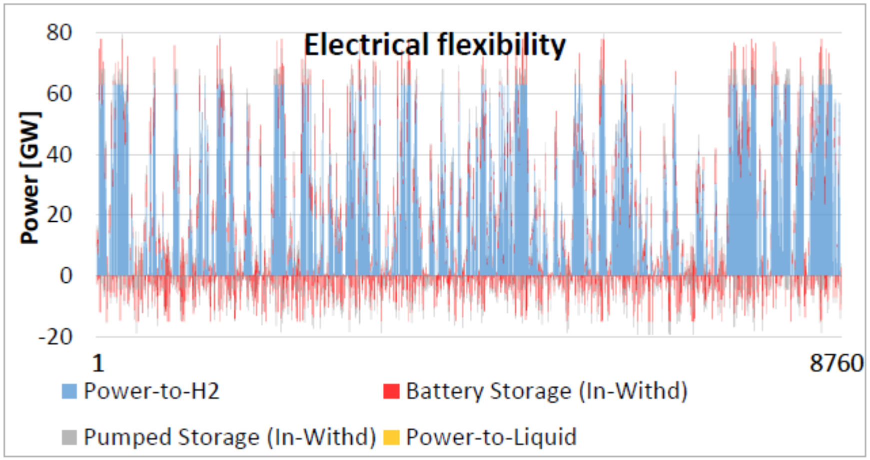


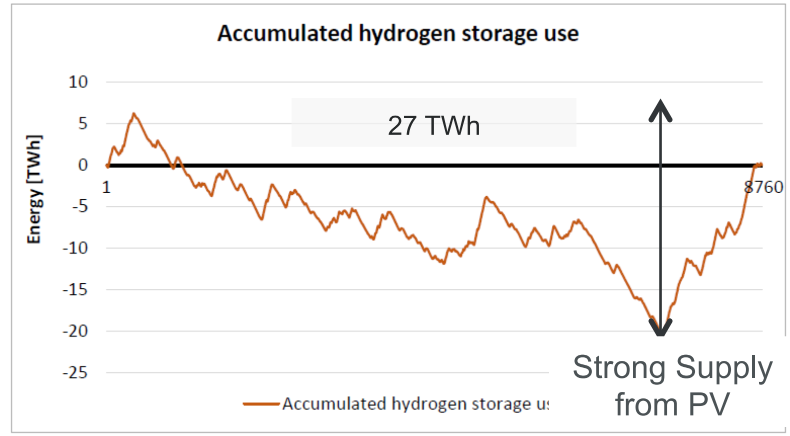


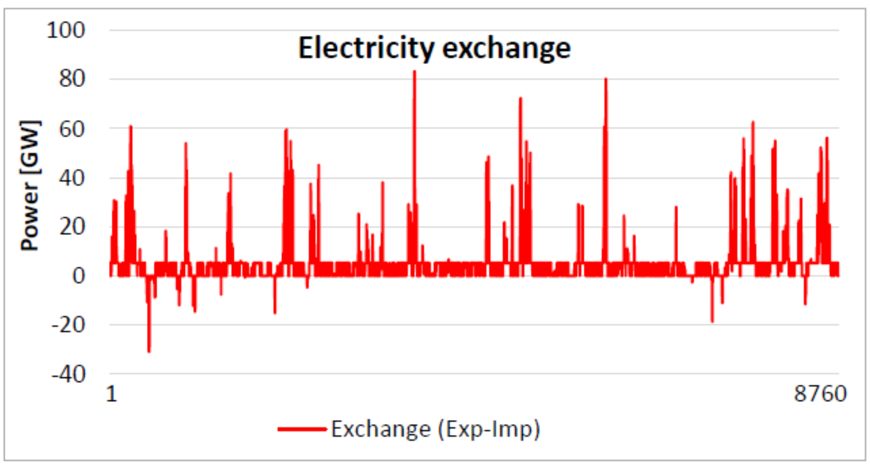


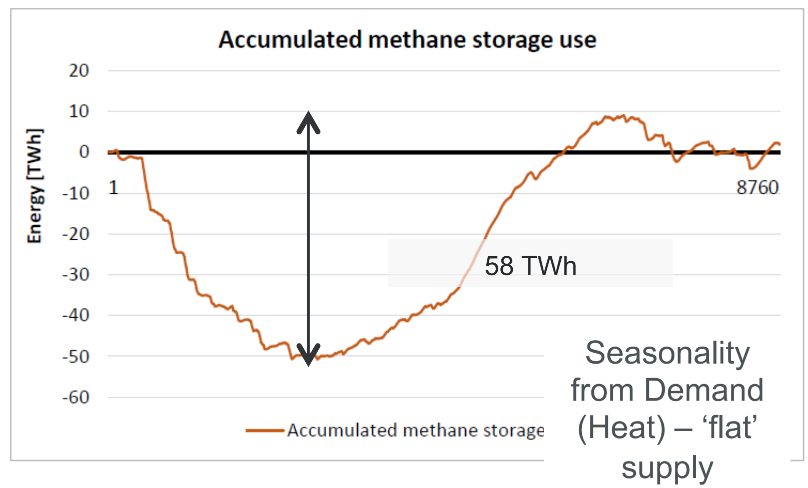
International Scenario DE

Storage volumes (TWh) (original dena figures)









Infrastructure Calculations

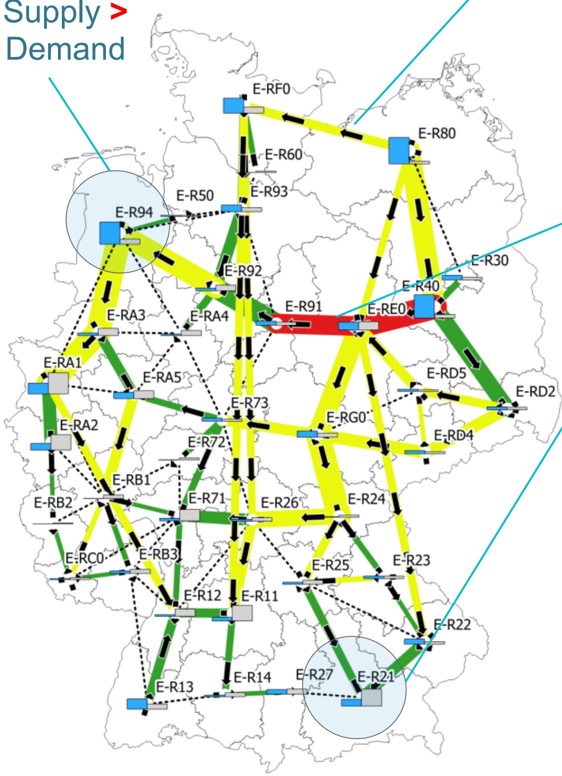
- Regional Szenario (Enervis)

Infrastructure Calculations: Introduction

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

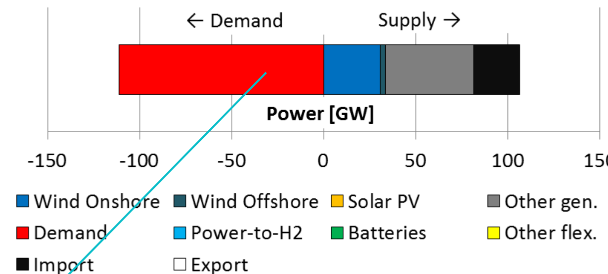
∑ Supply > ∑ Demand

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

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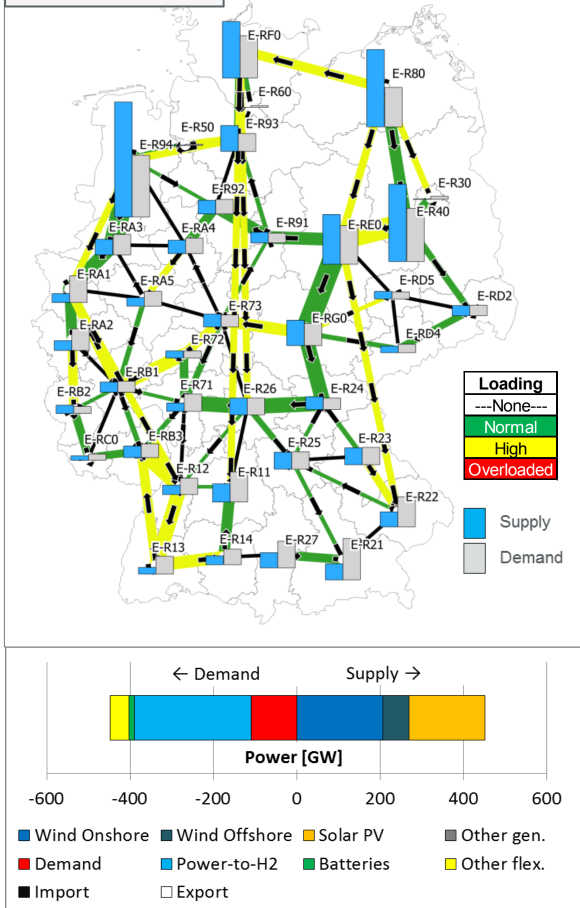
Infrastructure calculations (DE)

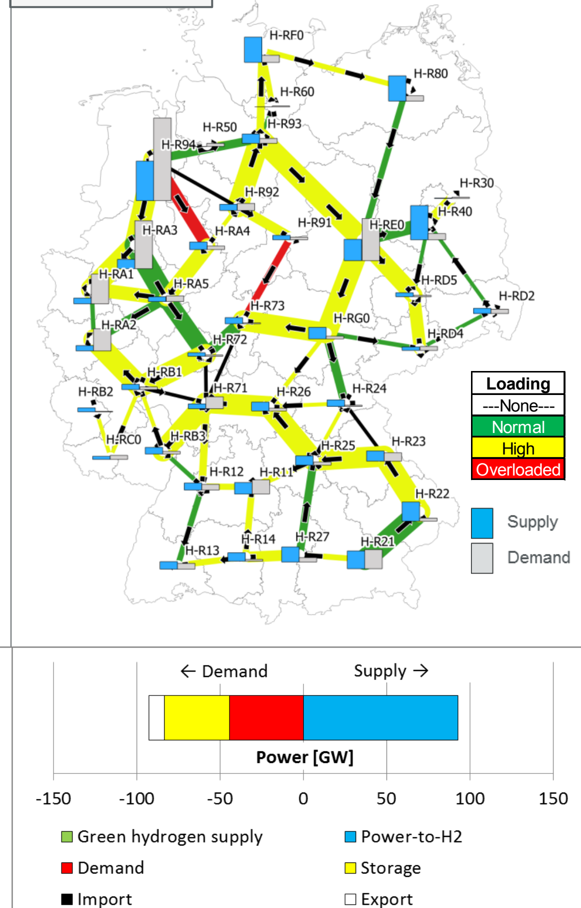
High RES + low electrical demand

Base cases (Enervis_1450)

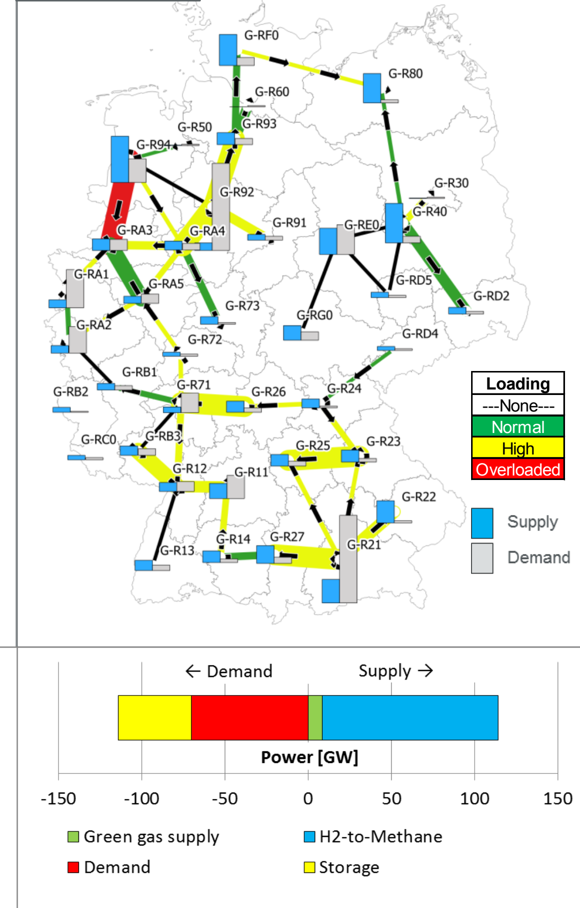
Electricity



Hydrogen



Methane



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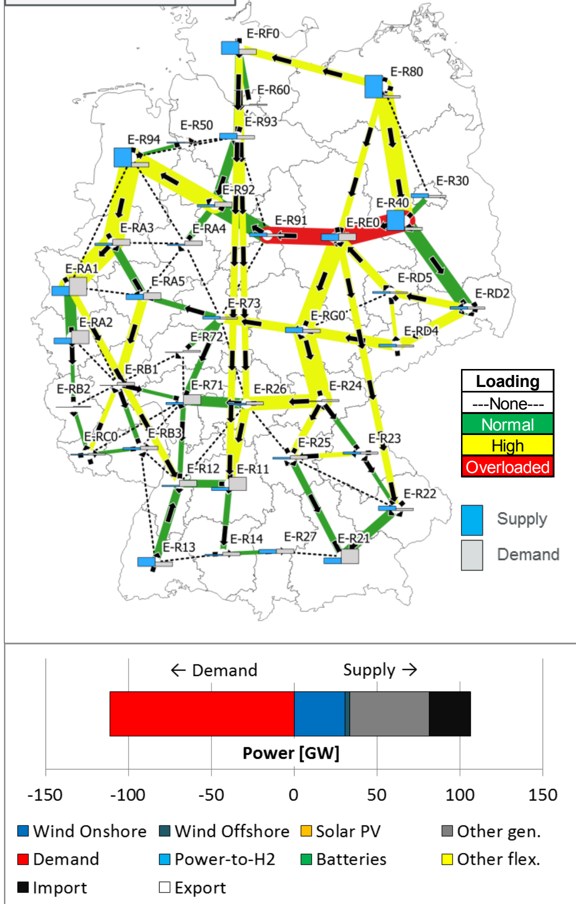
TenneT Taking power further

Infrastructure calculations (DE)

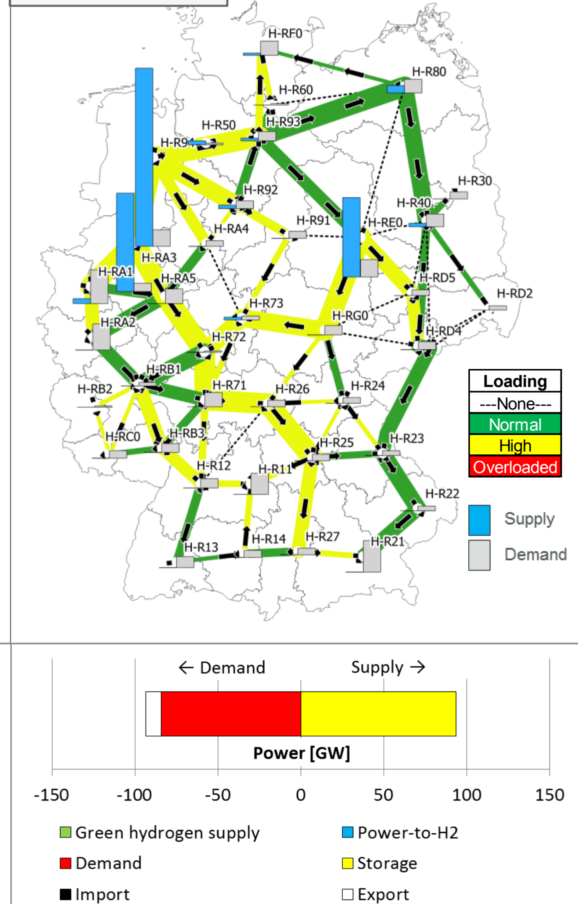
Base cases (Enervis_473)

High RES + low electrical demand

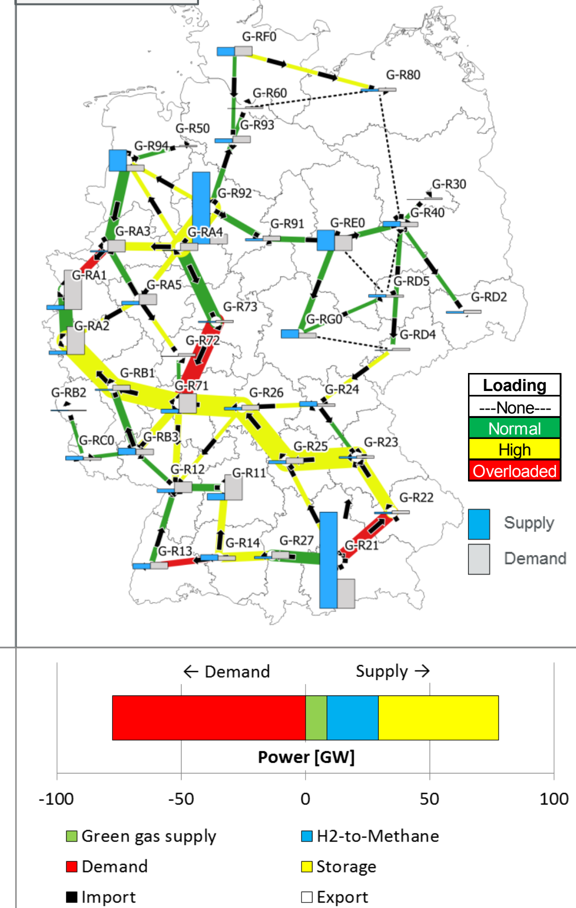
Electricity



Hydrogen



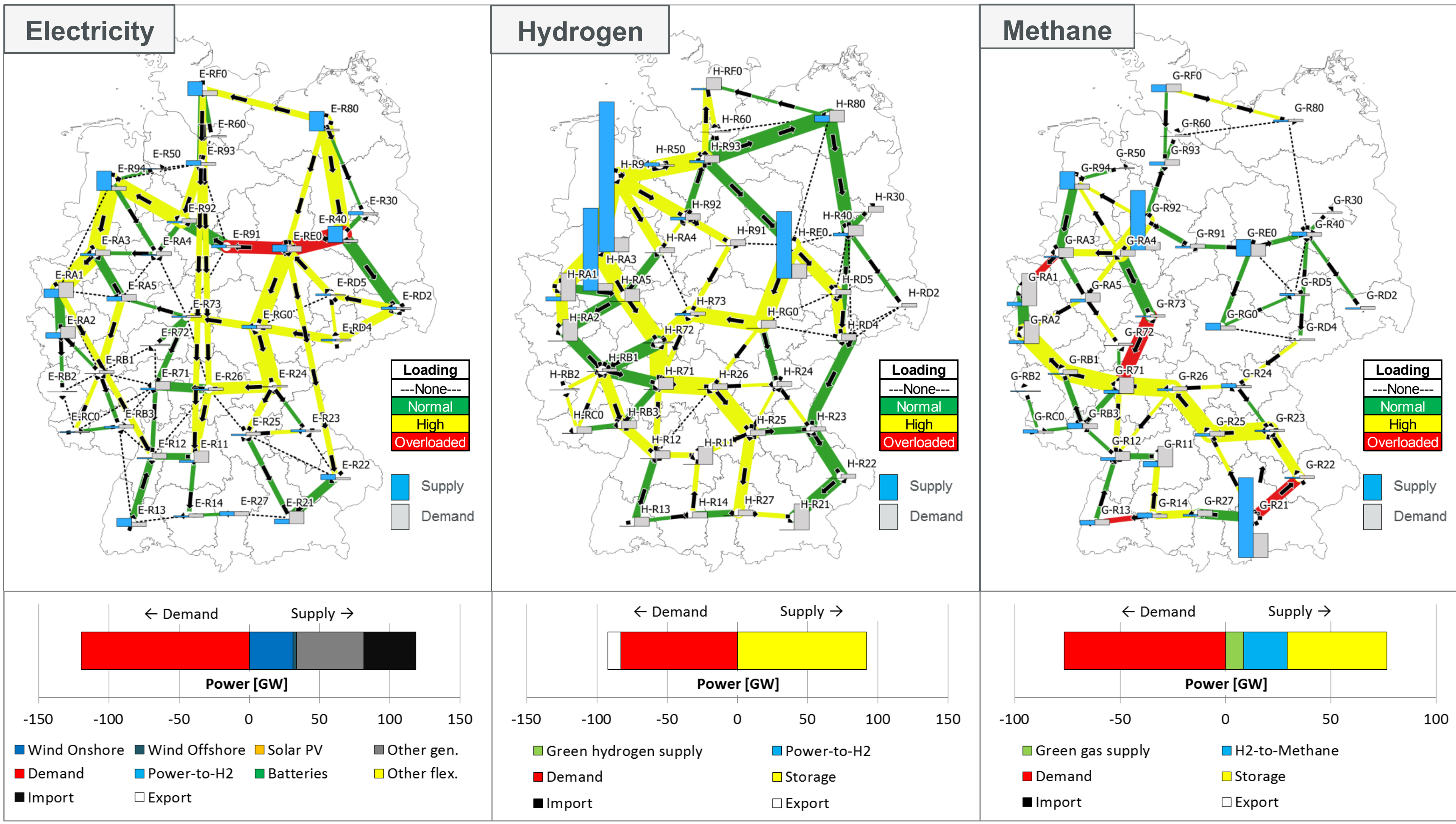
Methane



Infrastructure calculations (DE)

High RES + low electrical demand

Base cases (Enervis_474)



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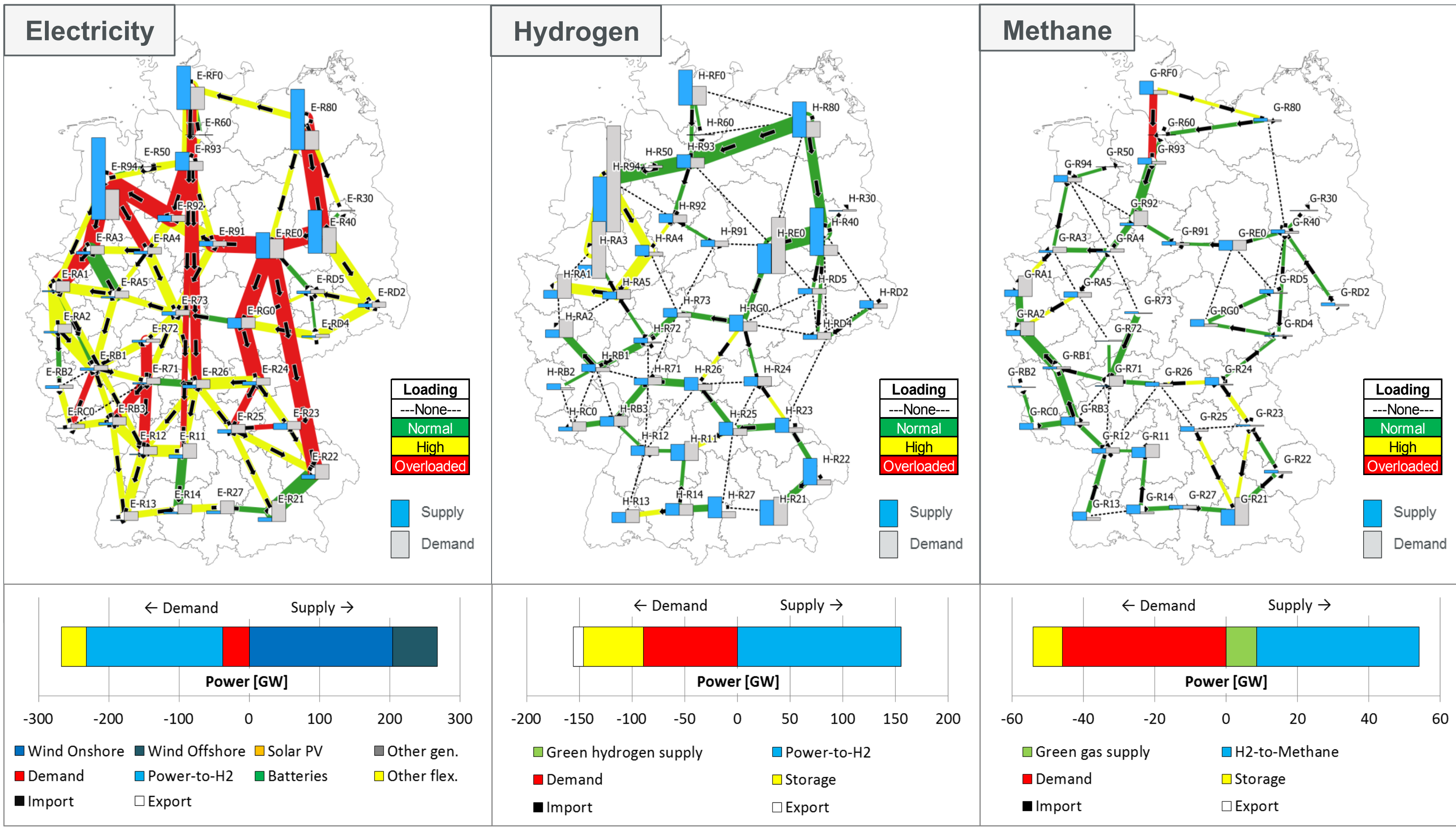
TenneT Taking power further

Infrastructure calculations (DE)

Base cases (Enervis_916)

High RES + low electrical demand



gasunie crossing borders in energy

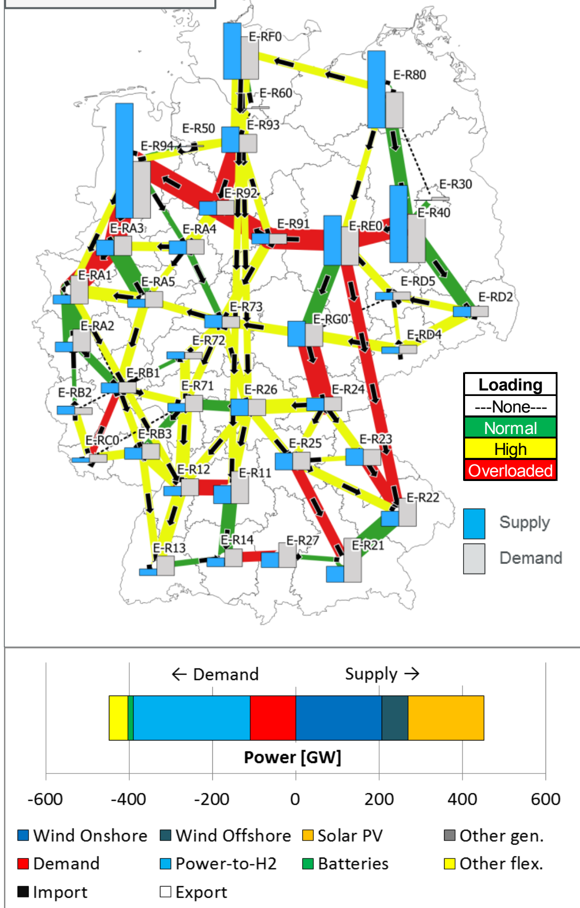
TenneT Taking power further

Infrastructure calculations (DE)

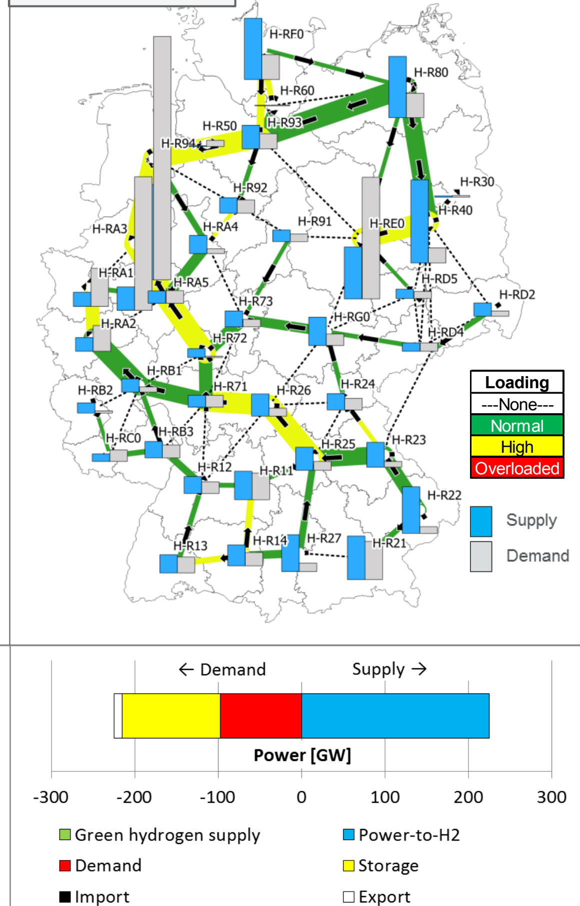
Base cases (Enervis_1450)

High RES + low electrical demand

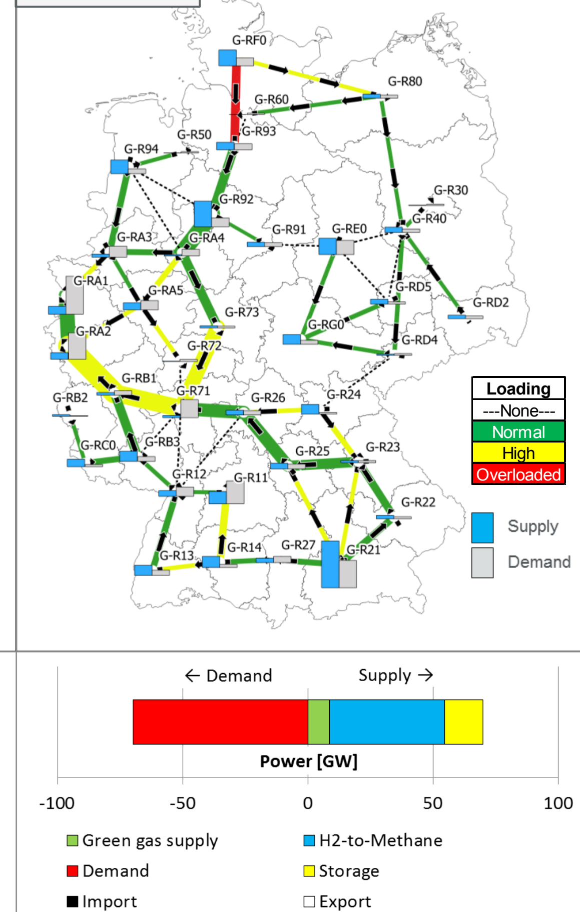
Electricity



Hydrogen



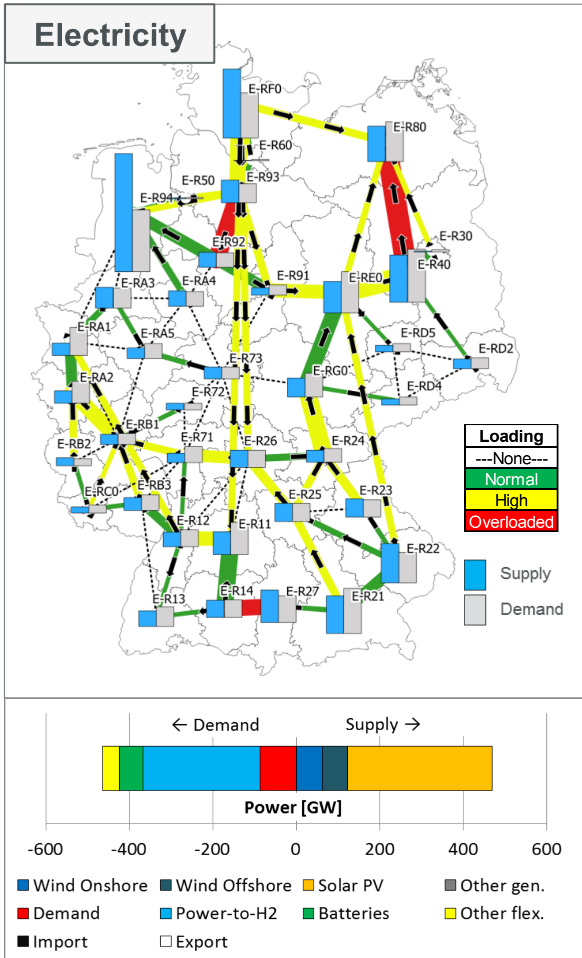
Methane

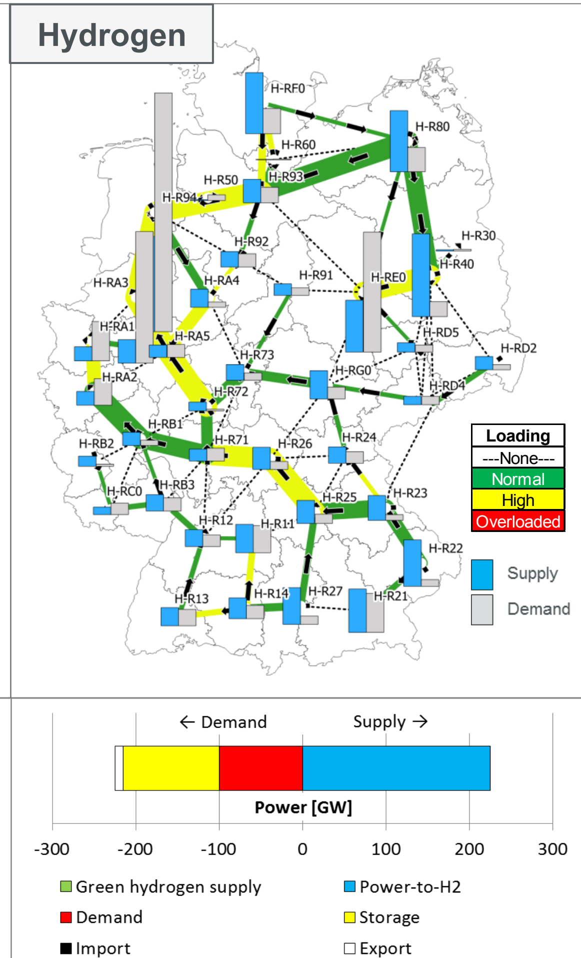


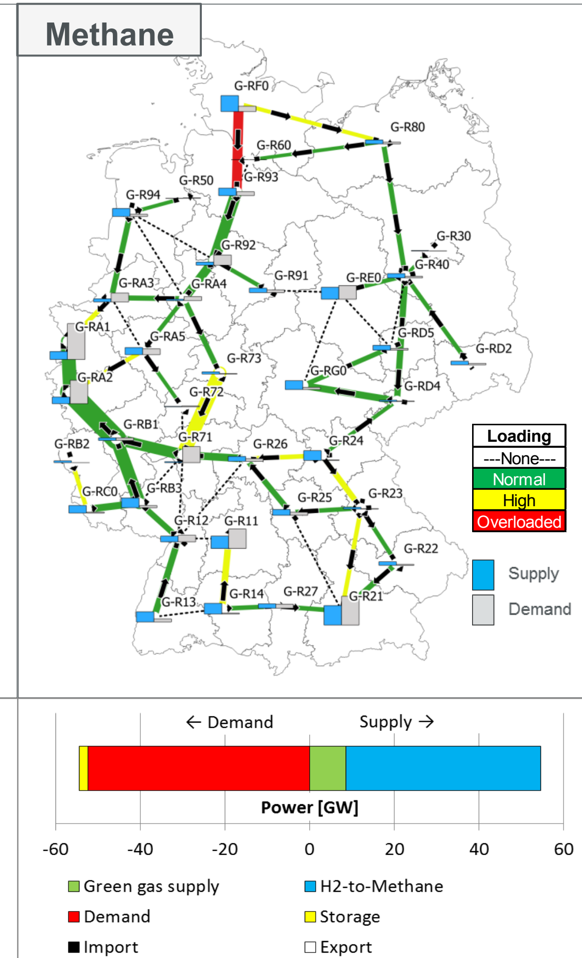
Infrastructure calculations (DE)

Base cases (Enervis_4358)

High RES + low electrical demand







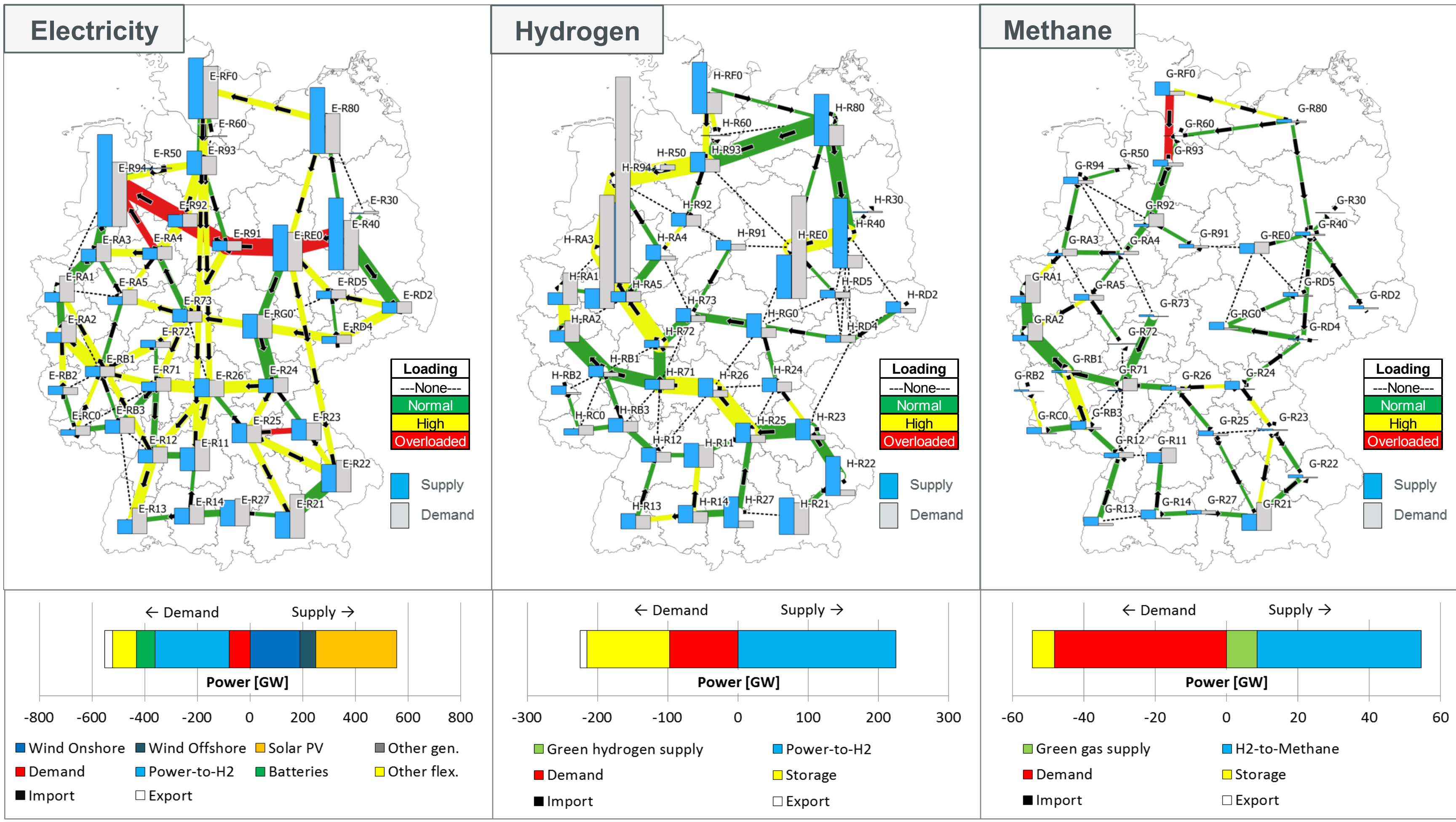
gasunie crossing borders in energy

TenneT Taking power further

Infrastructure calculations (DE)

High RES + low electrical demand

Base cases (Enervis_4526)



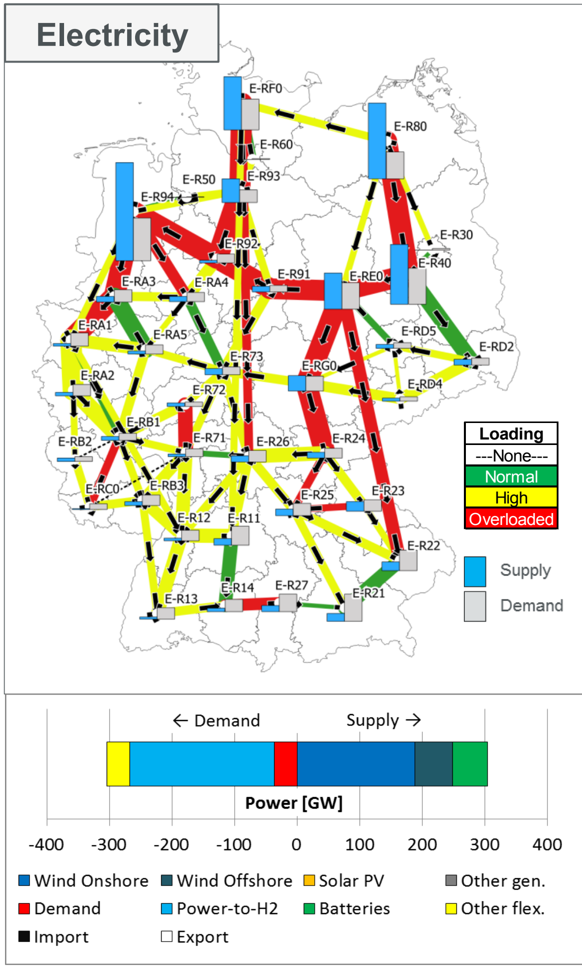
gasunie crossing borders in energy

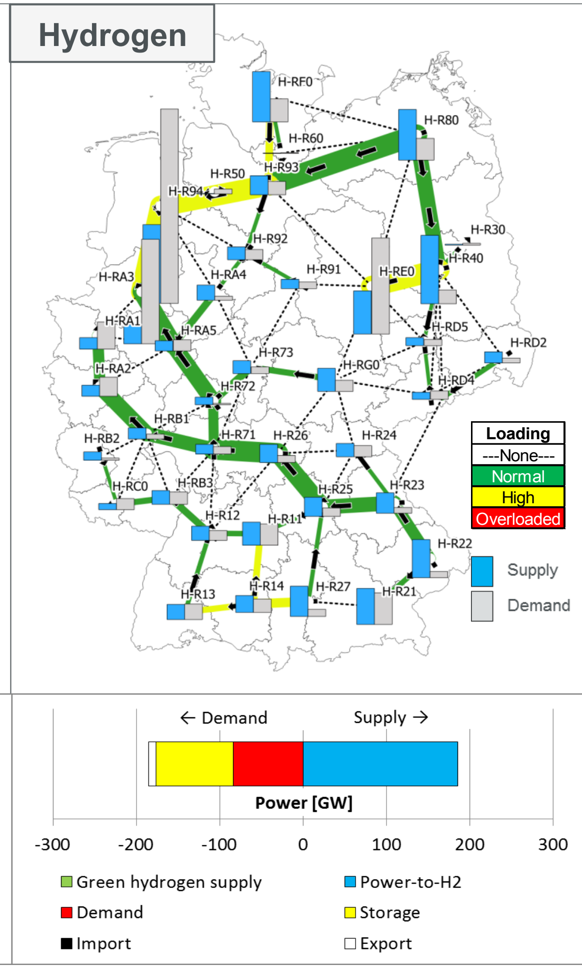
TenneT Taking power further

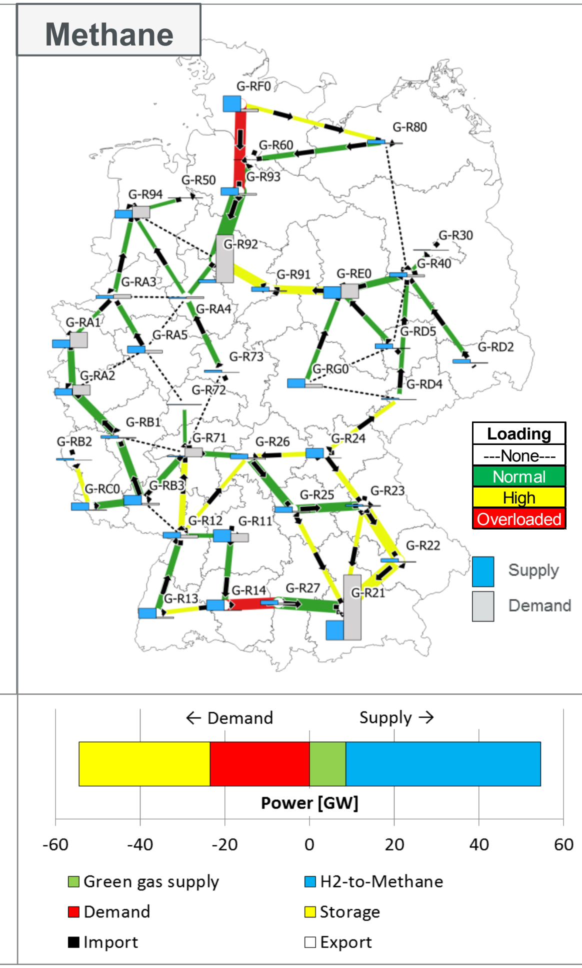
Infrastructure calculations (DE)

Base cases (Enervis_4943)

High RES + low electrical demand





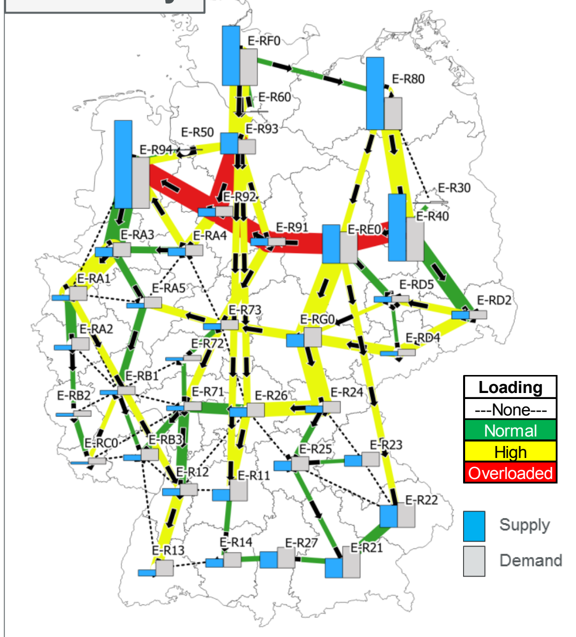


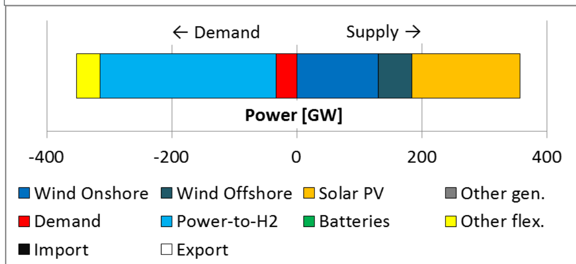
Infrastructure calculations (DE)

Base cases (Enervis_4953)

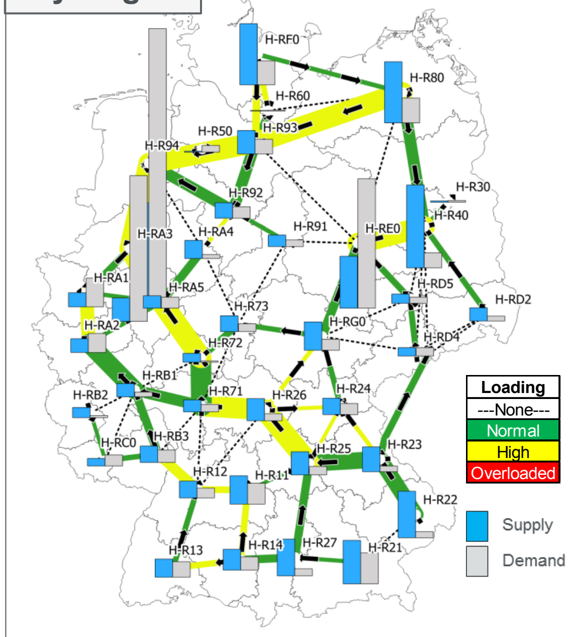
High RES + low electrical demand

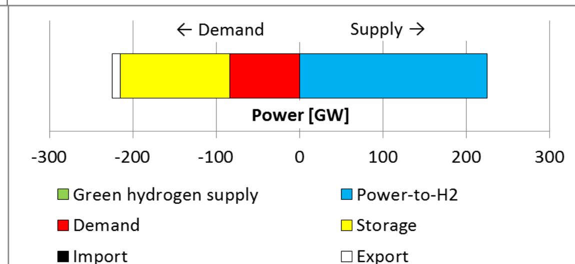
Electricity



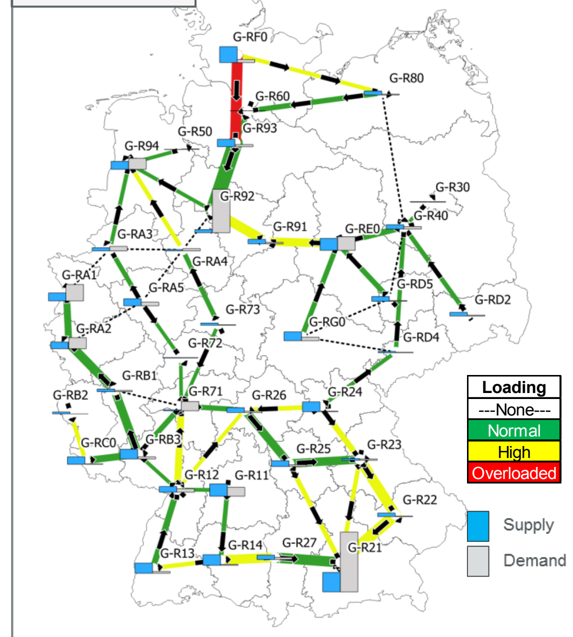


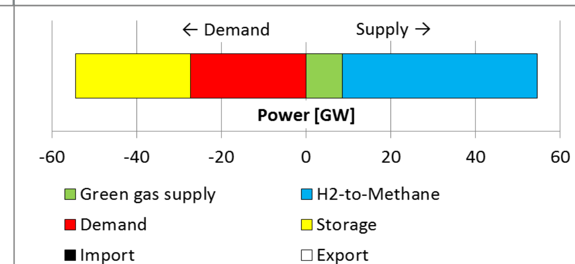
Hydrogen





Methane



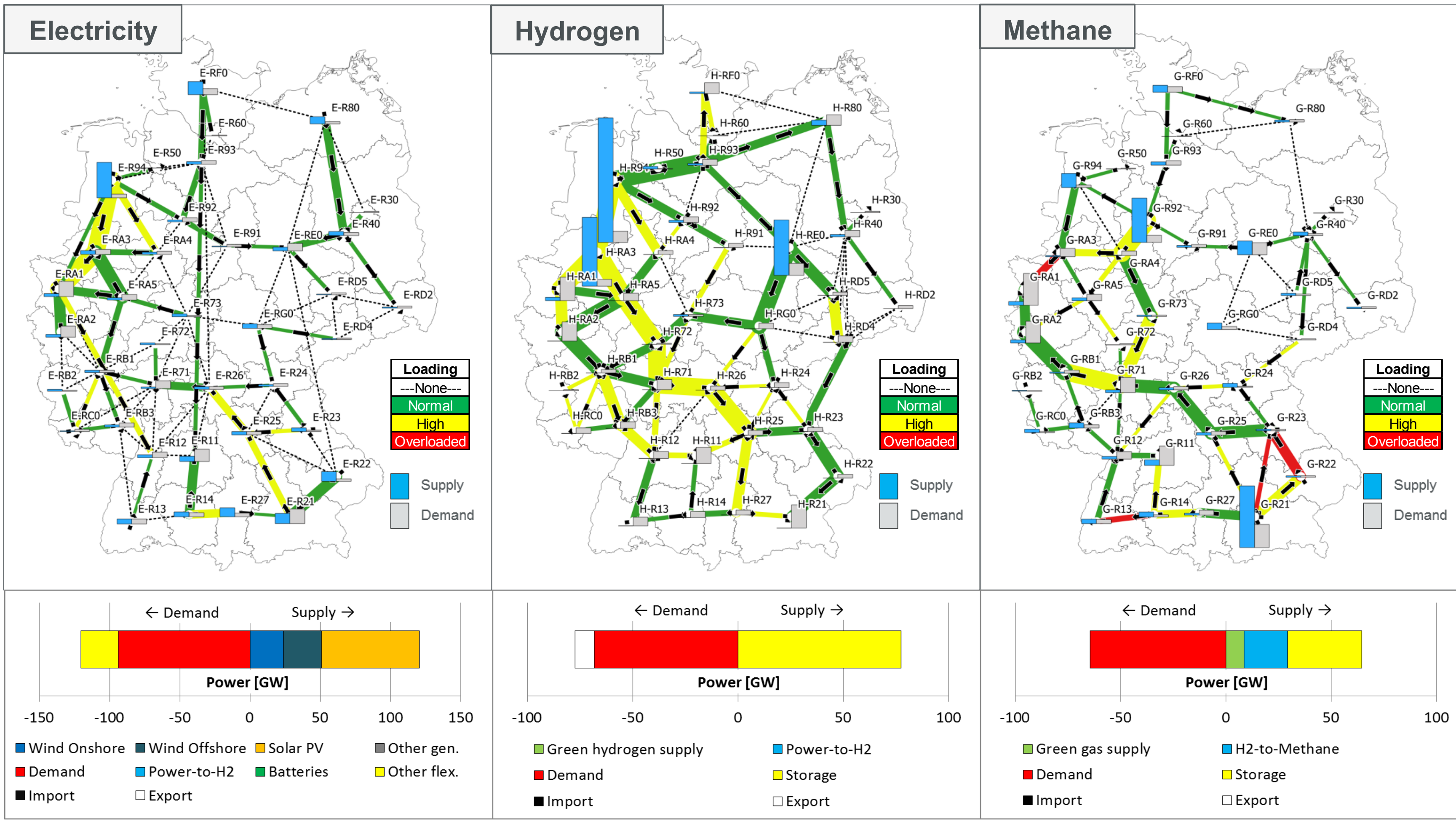


gasunie crossing borders in energy | TenneT Taking power further

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

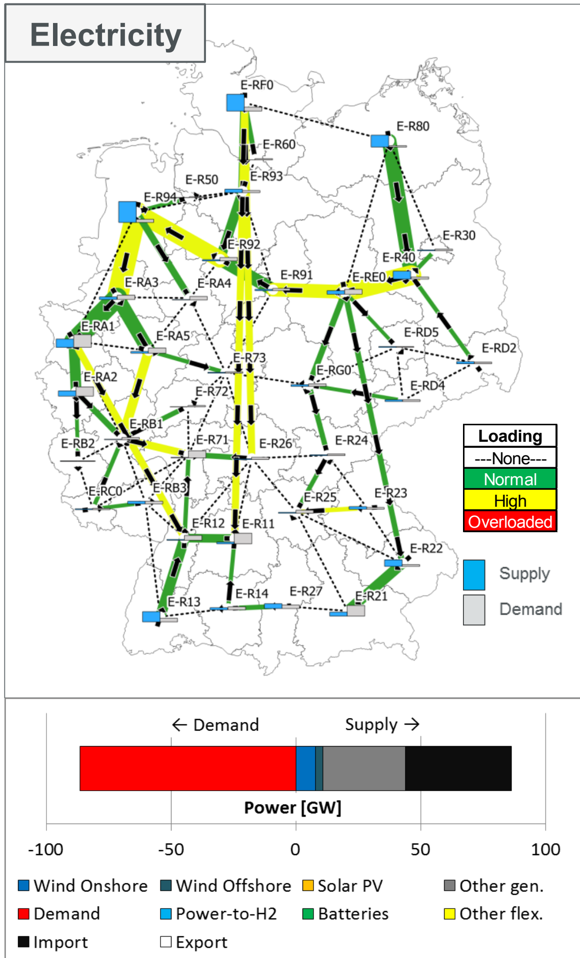
gasunie crossing borders in energy

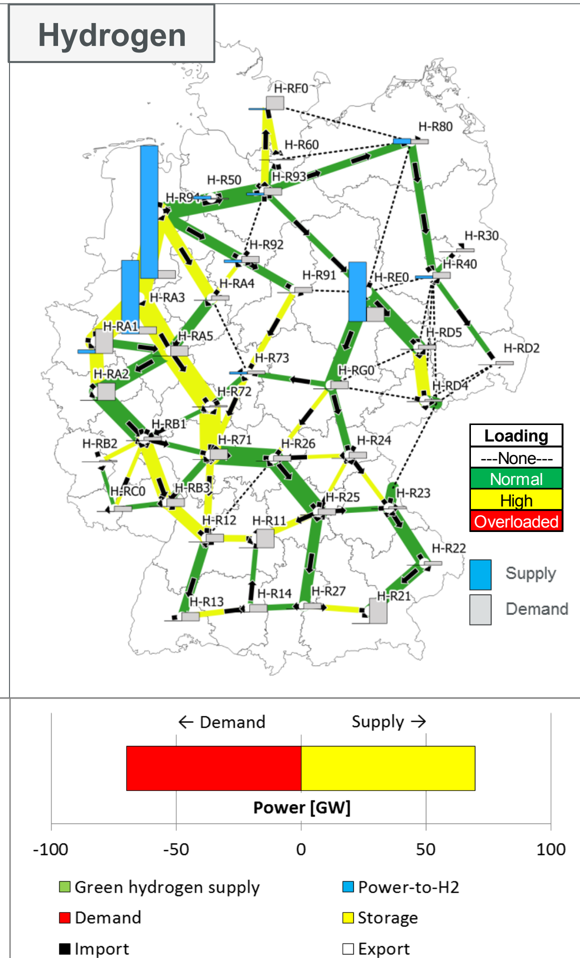
TenneT Taking power further

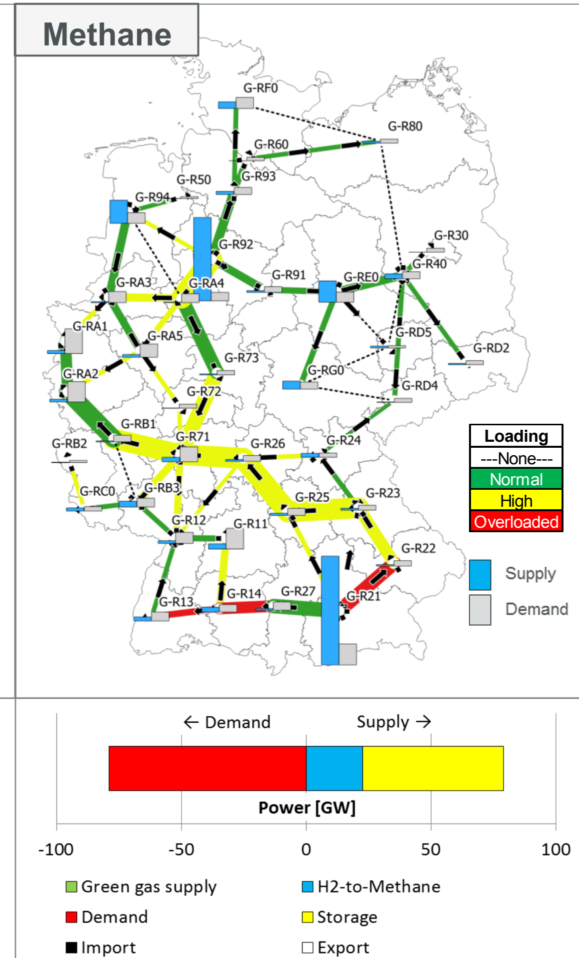
Infrastructure calculations (DE)

High RES + high electrical demand

Base cases (FNB_474)







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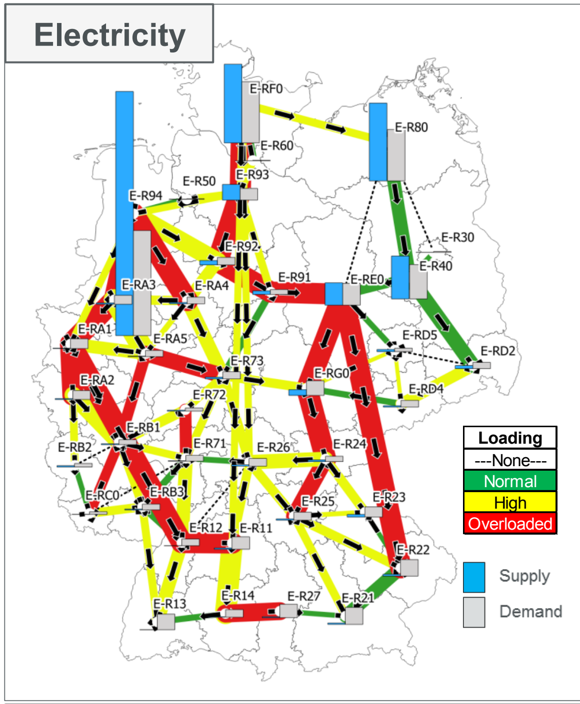
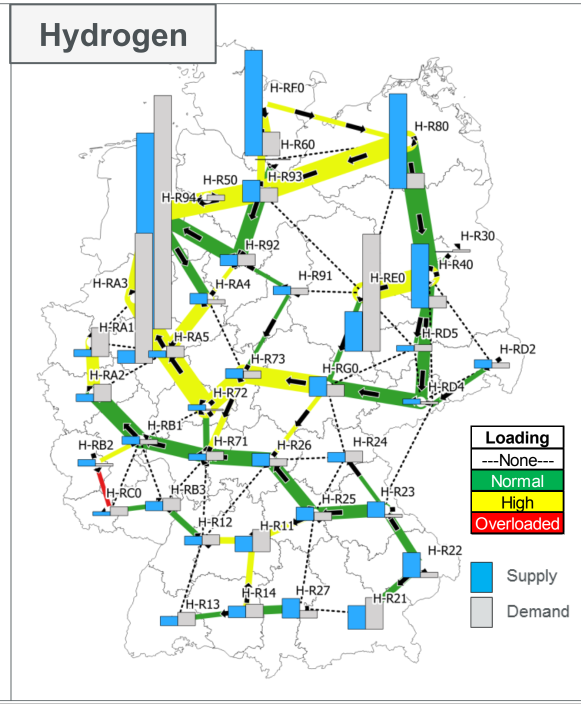
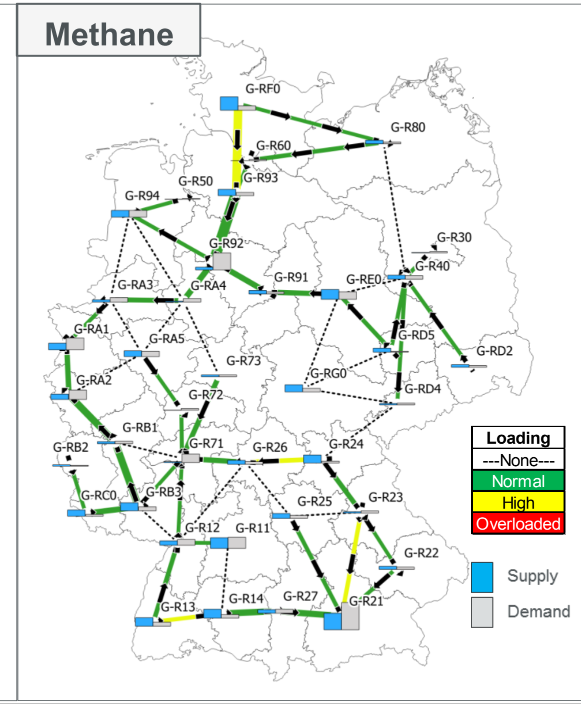
Infrastructure calculations (DE)

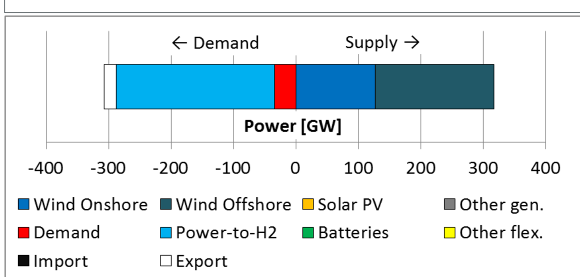
High RES + high electrical demand

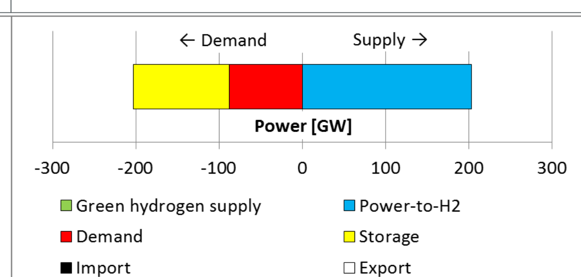
Base cases (FNB_914)

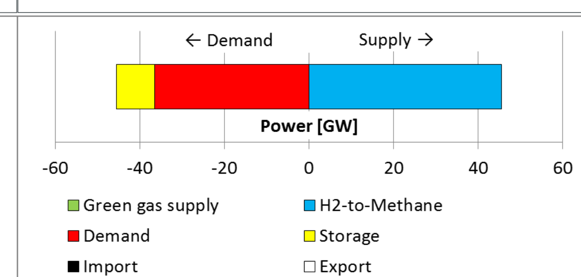








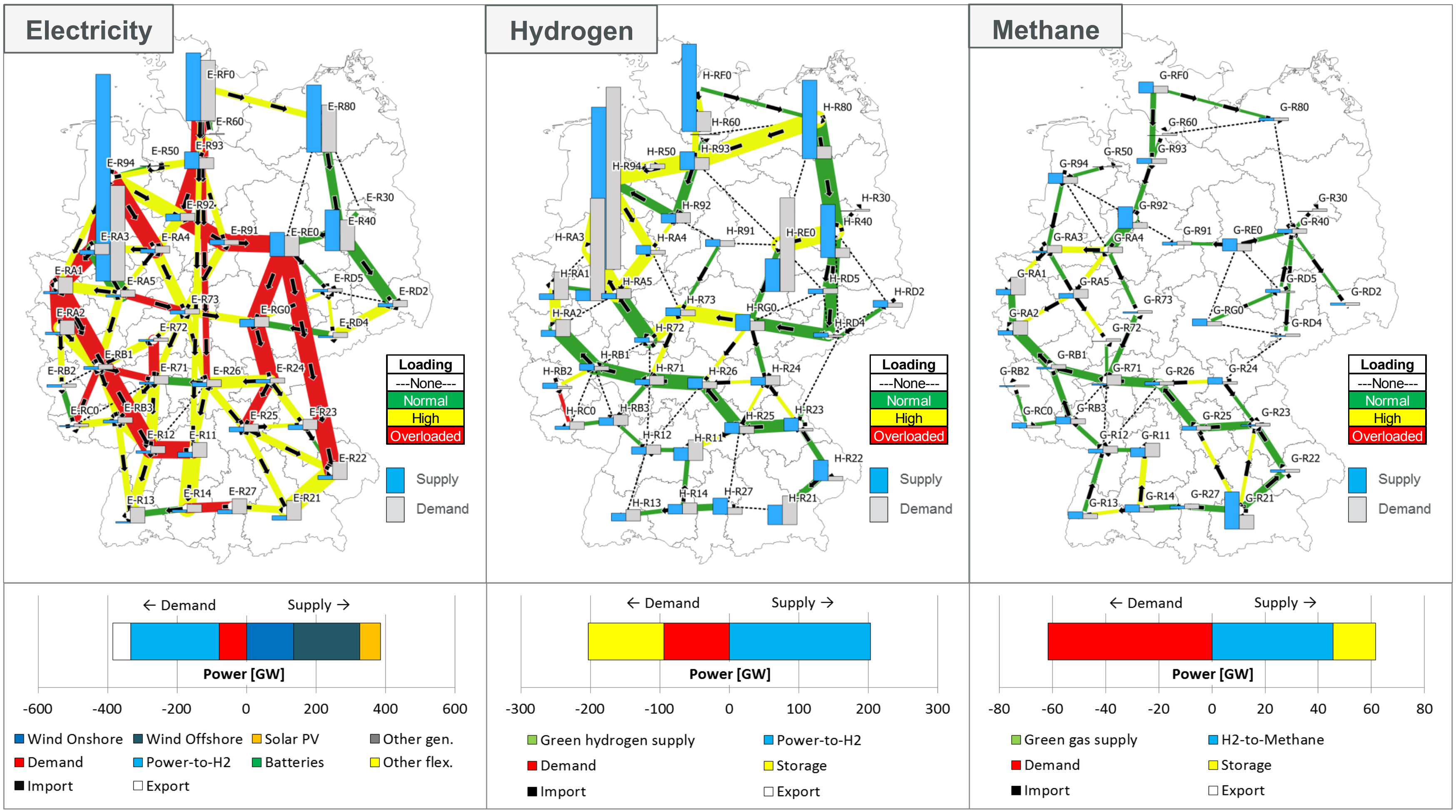




Infrastructure calculations (DE)

High RES + high electrical demand

Base cases (FNB_1450)



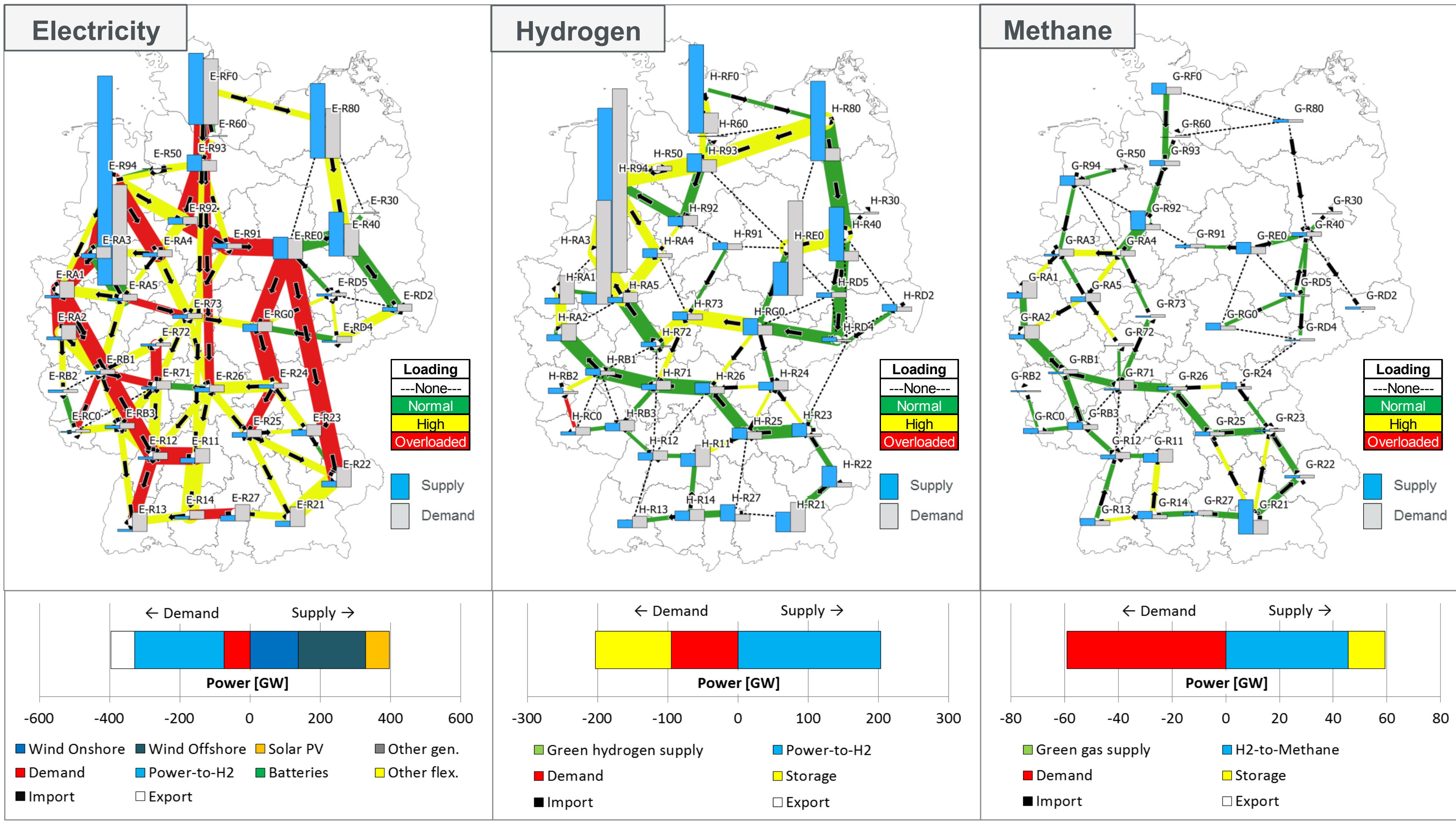
gasunie crossing borders in energy

TenneT Taking power further

Infrastructure calculations (DE)

High RES + high electrical demand

Base cases (FNB_41451)



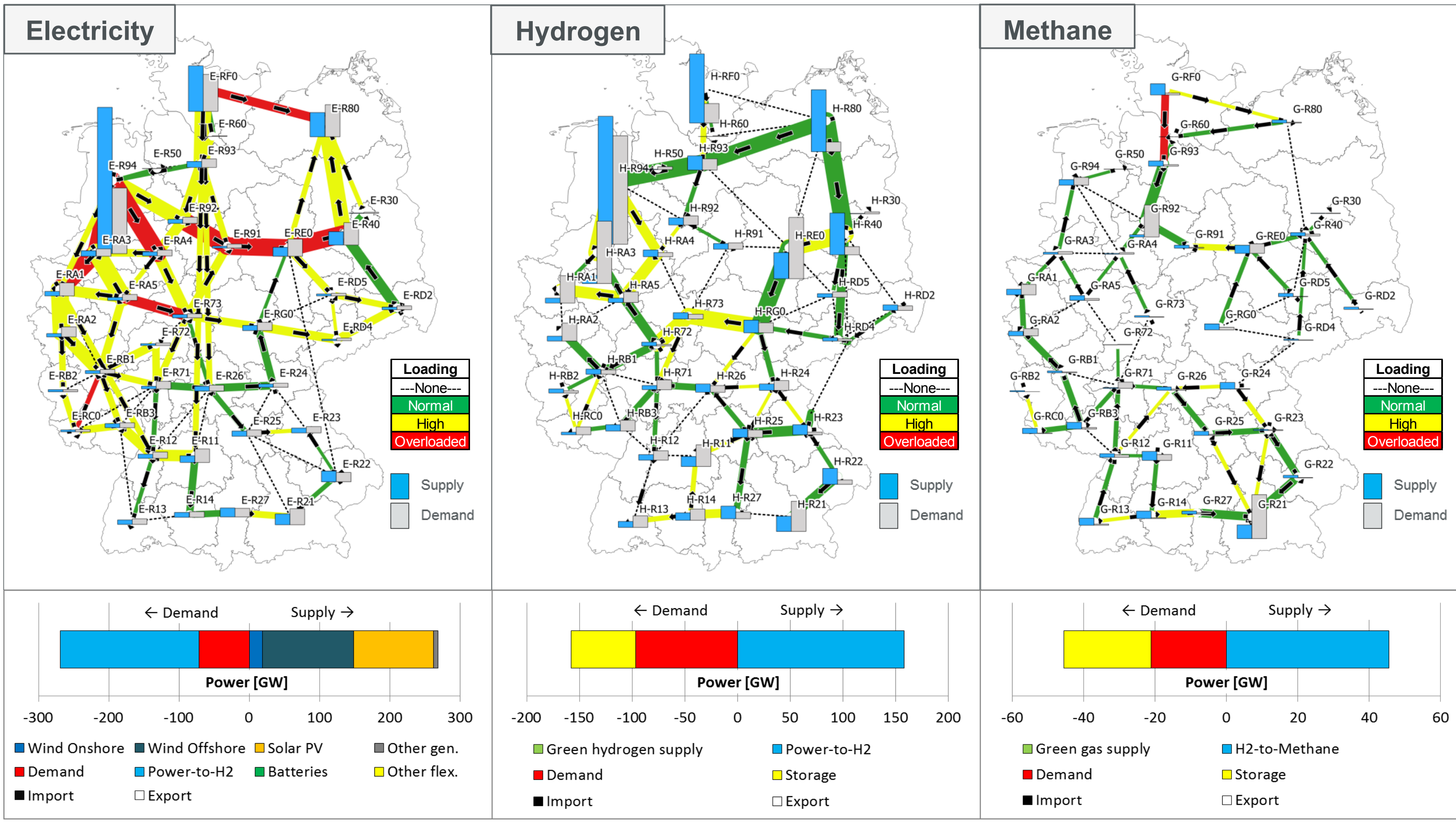
Infrastructure Outlook 2050

gasunie crossing borders in energy

TenneT Taking power further

Infrastructure calculations (DE)

Base cases (FNB_4358)



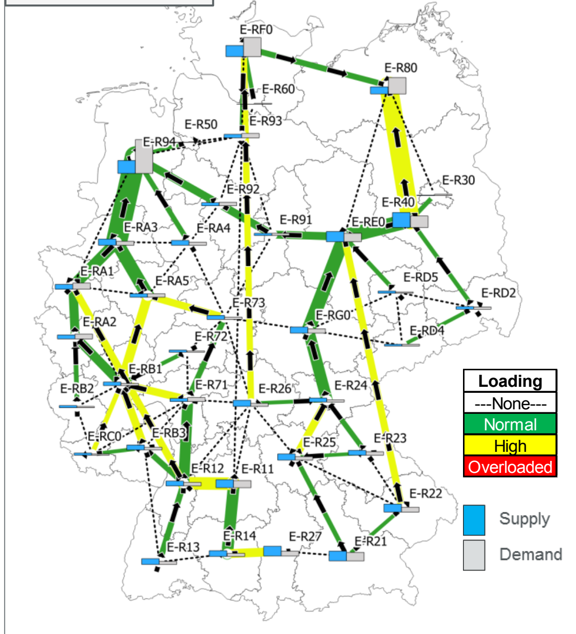
gasunie crossing borders in energy

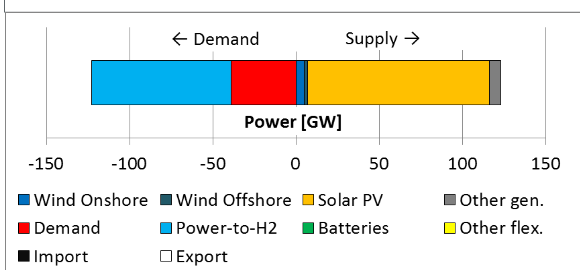
TenneT Taking power further

Infrastructure calculations (DE)

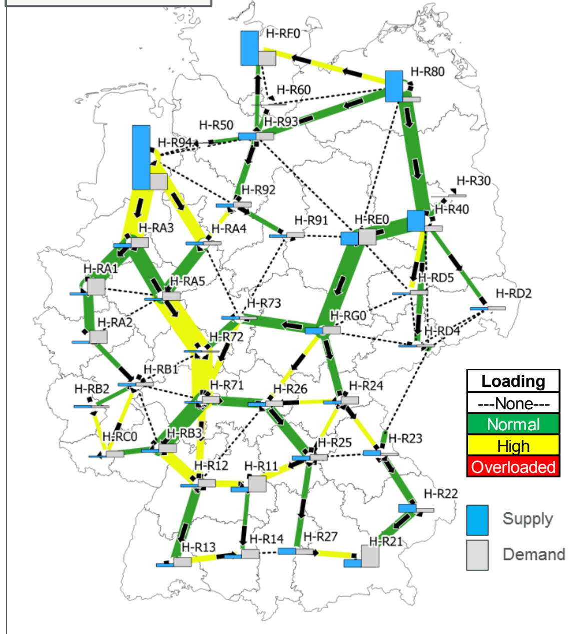
Base cases (FNB_5126)

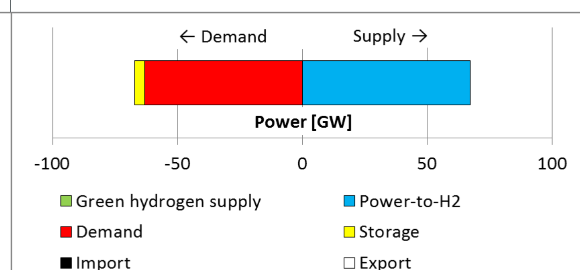
Electricity



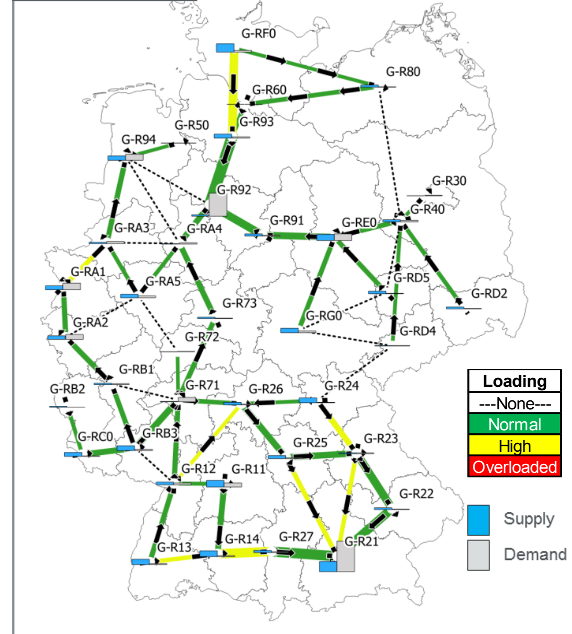


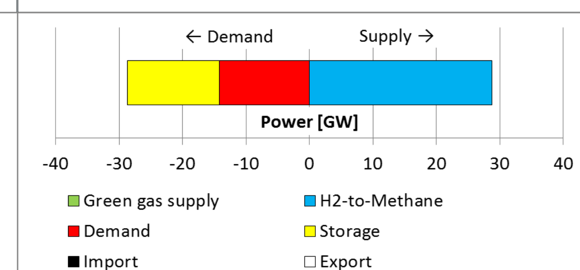
Hydrogen





Methane





Infrastructure Calculations

- International Szenario (dena)

Infrastructure calculations (DE)

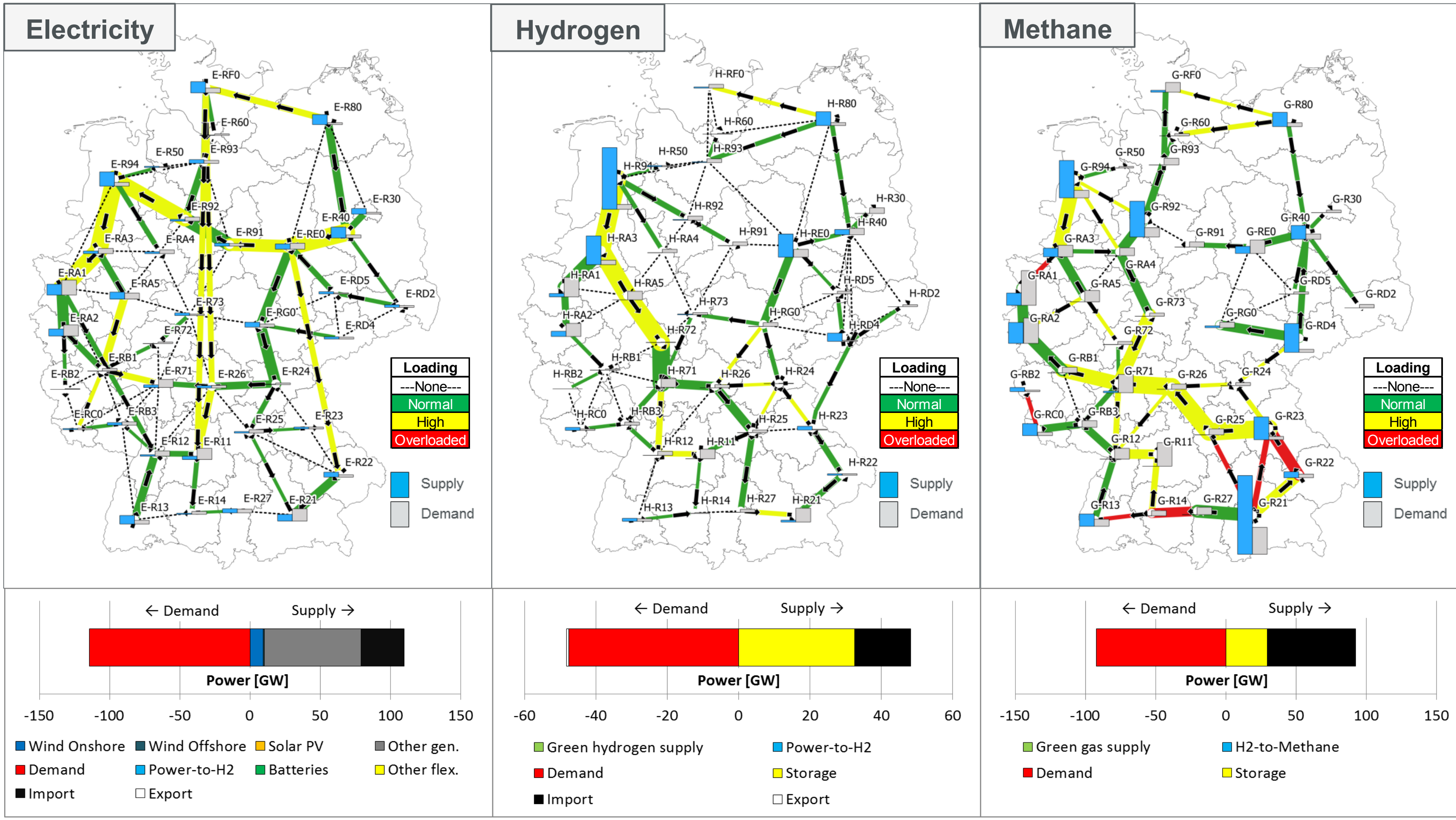
Overview snapshot base cases

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

Infrastructure calculations (DE)

High RES + high electrical demand

Base cases (dena_474)



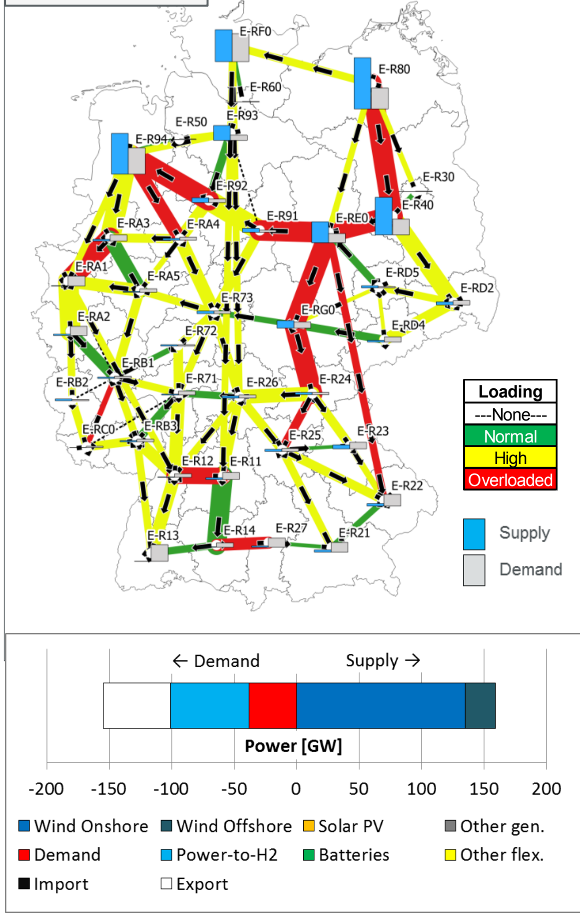
gasunie crossing borders in energy

TenneT Taking power further

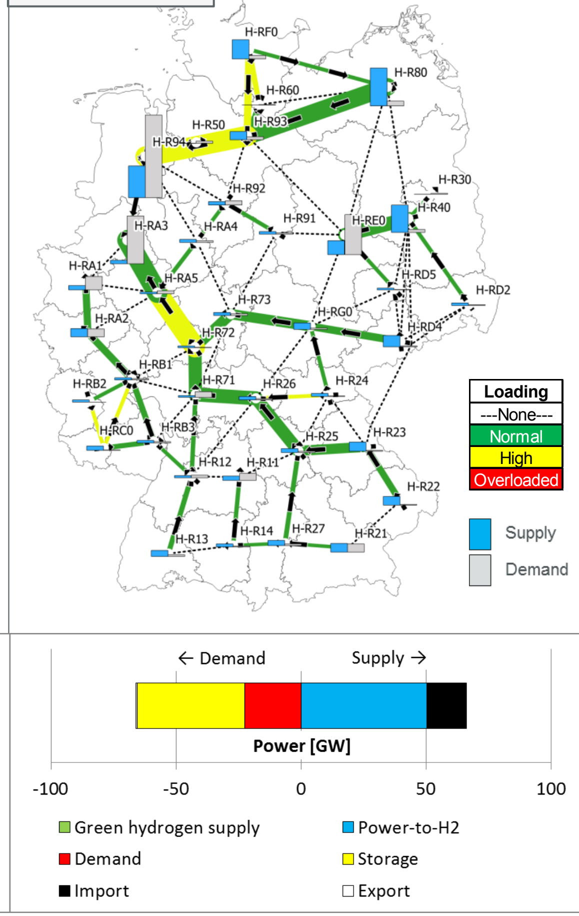
Infrastructure calculations (DE)

Base cases (dena_915)

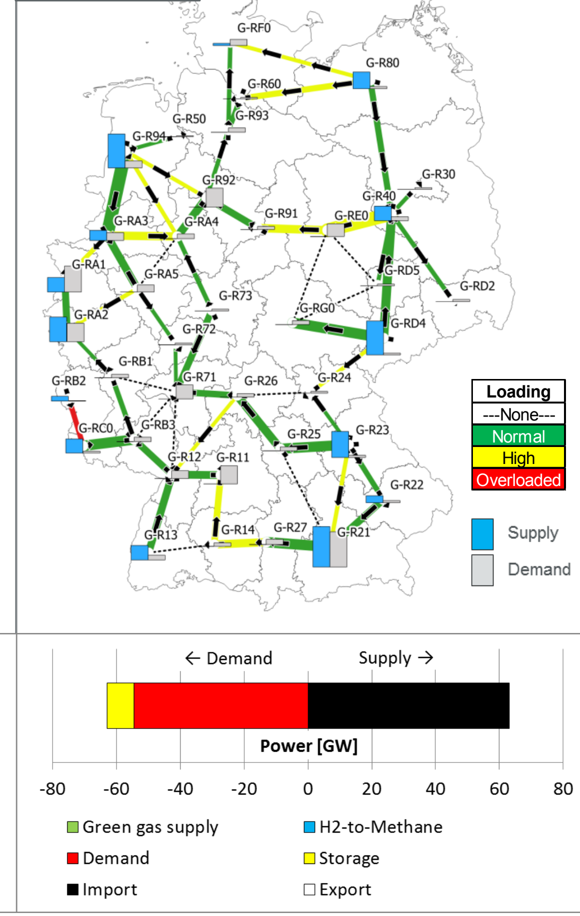
Electricity



Hydrogen



Methane



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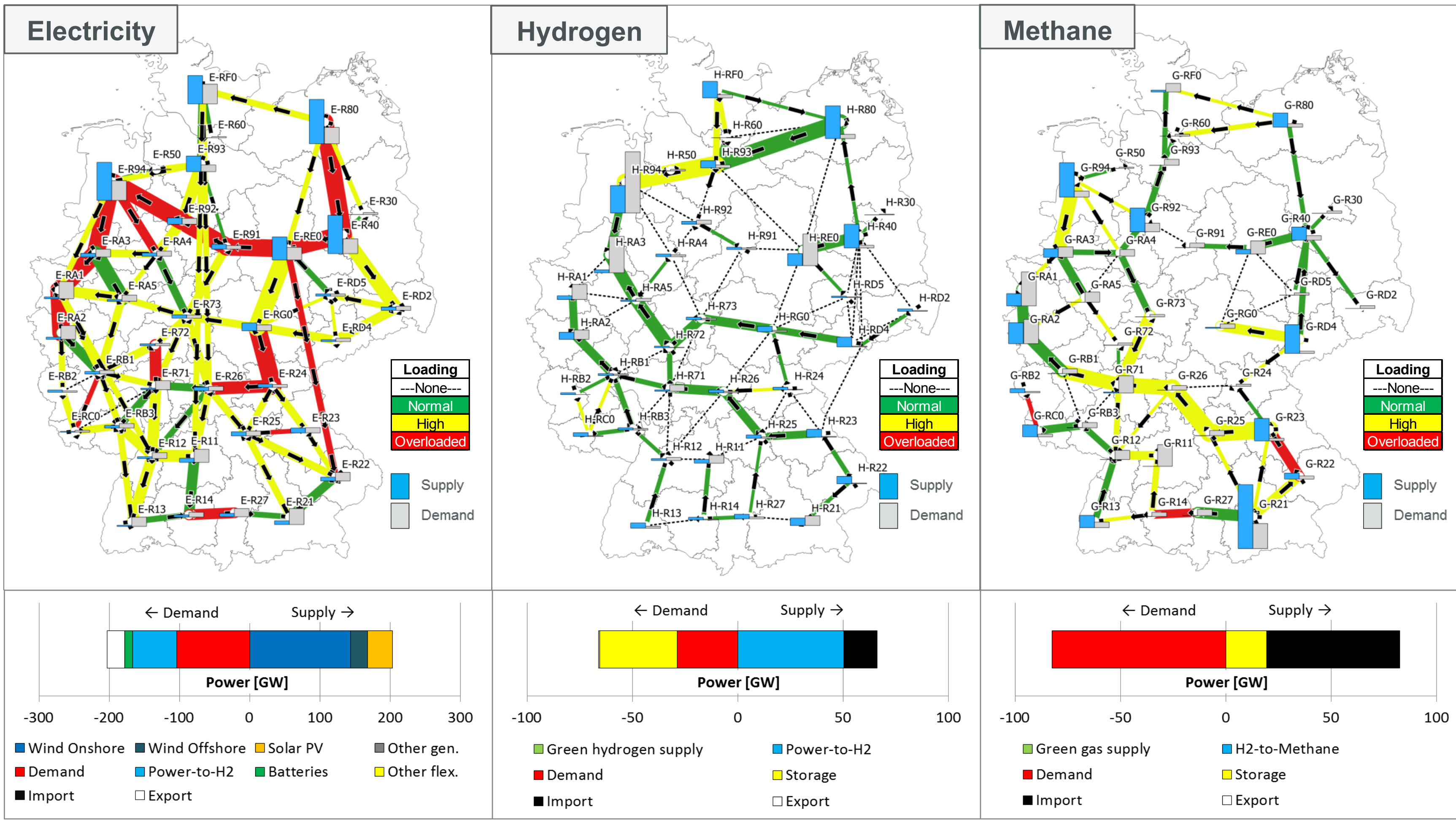
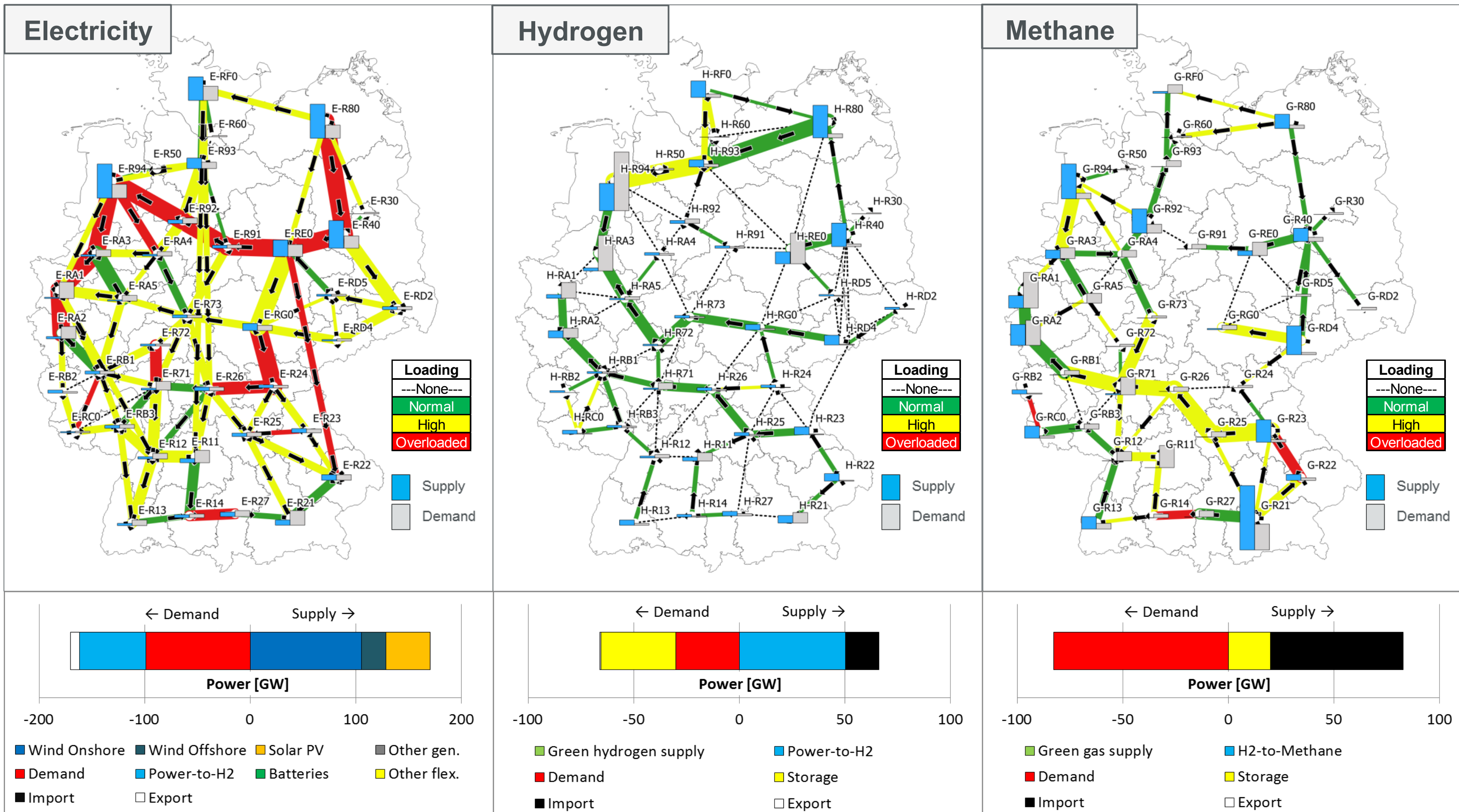
Infrastructure calculations (DE)

Base cases (dena_1450)



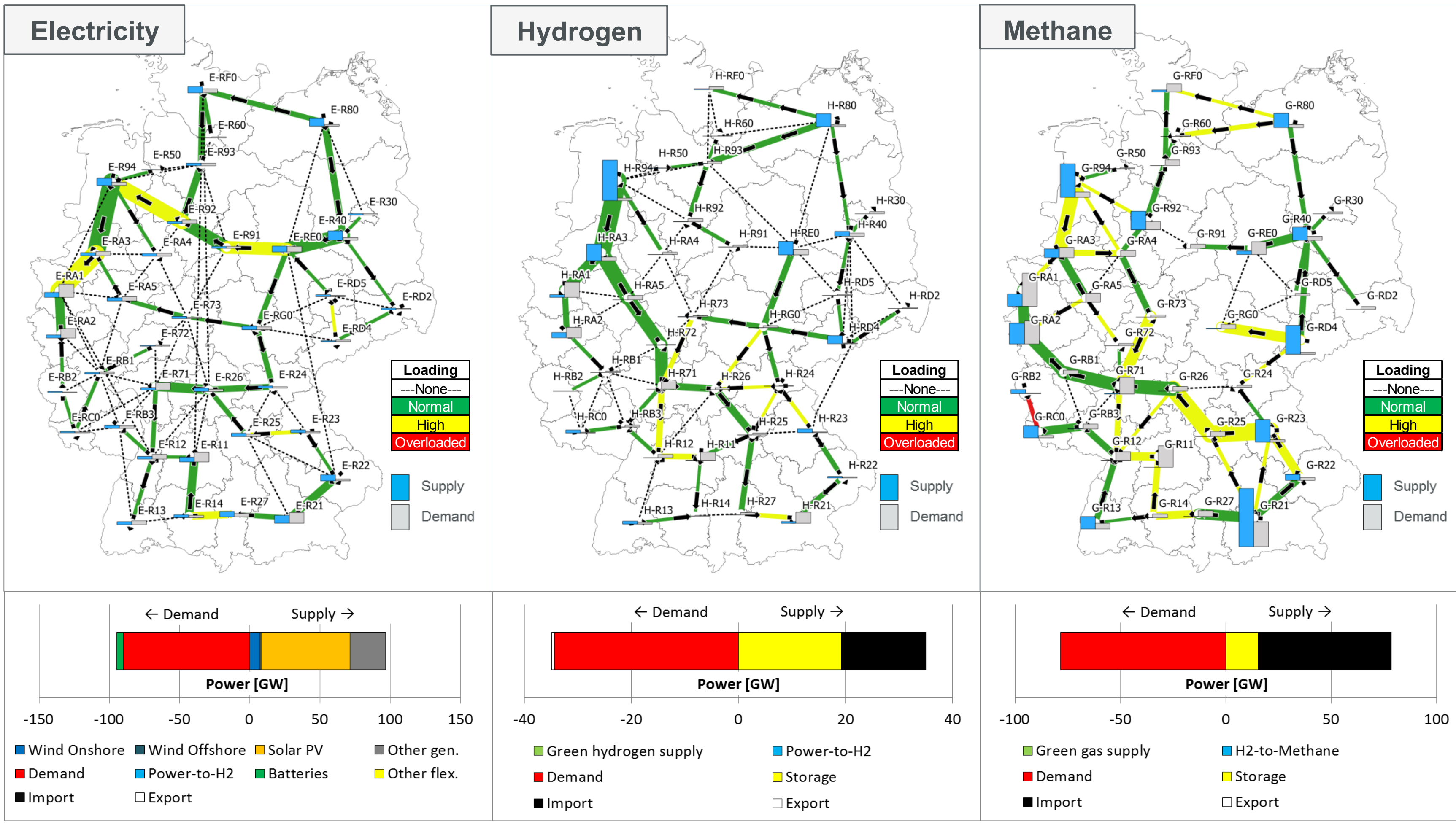
Infrastructure calculations (DE)

Base cases (dena_1477)



Infrastructure calculations (DE)

Base cases (dena_1884)



gasunie crossing borders in energy

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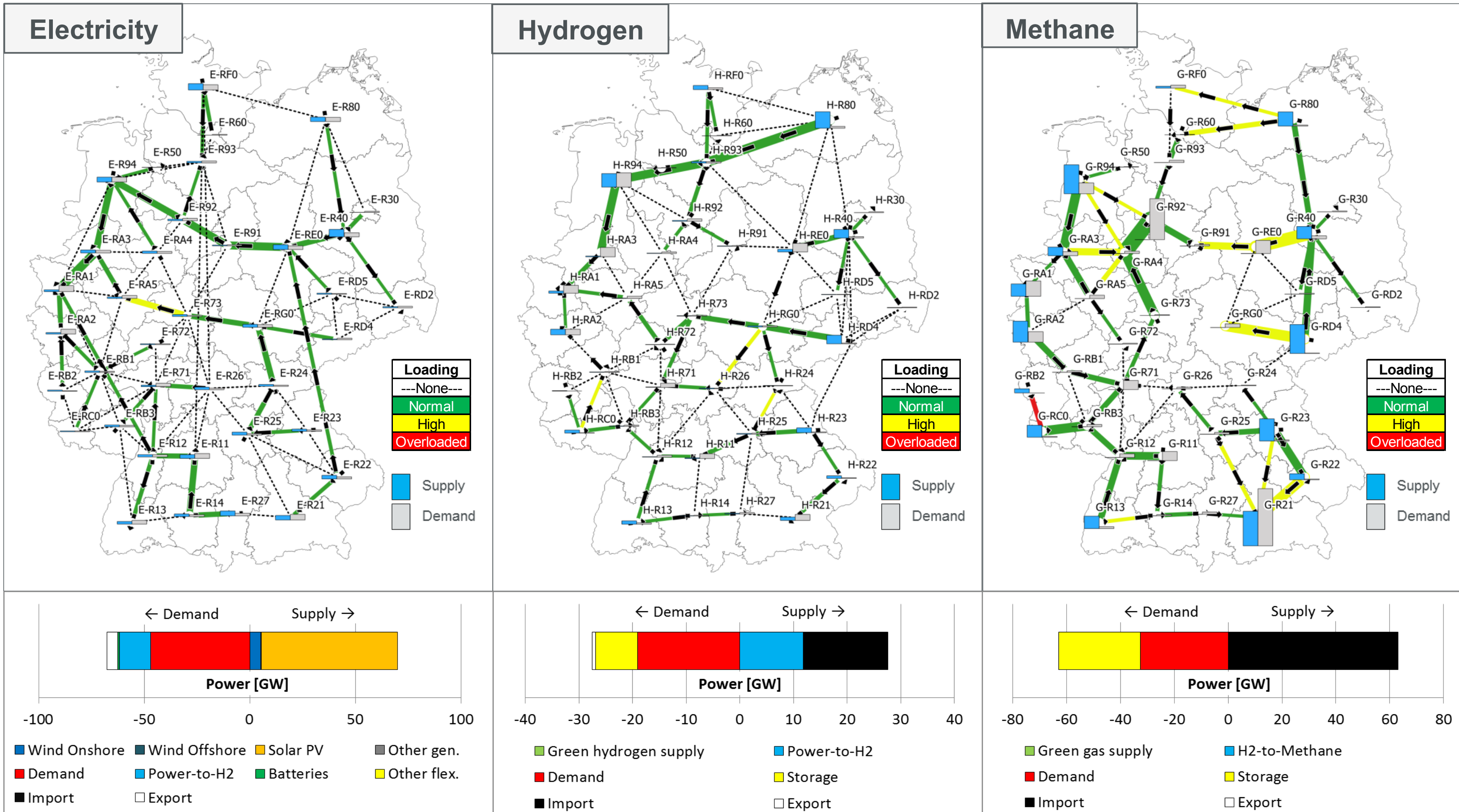
Infrastructure calculations (DE)

Base cases (dena_5126)



Infrastructure Calculations

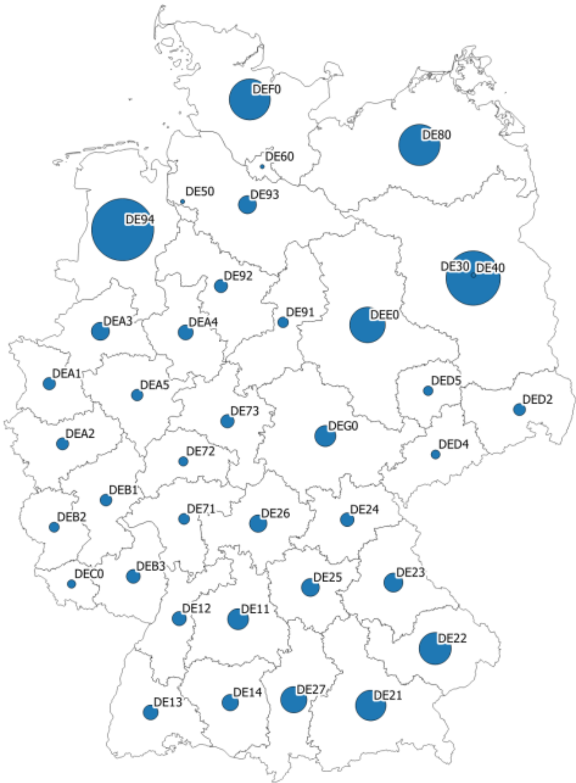
Sensitivity electrolyser

Infrastructure calculations (DE)

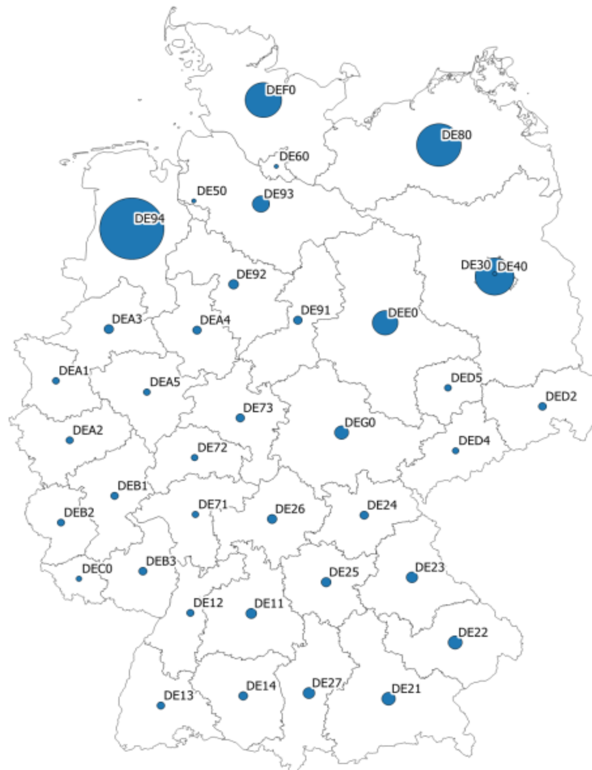
RES-capacity weighted regional distribution key

Variation of PtG locations

Distribution keys according to RES Capacity



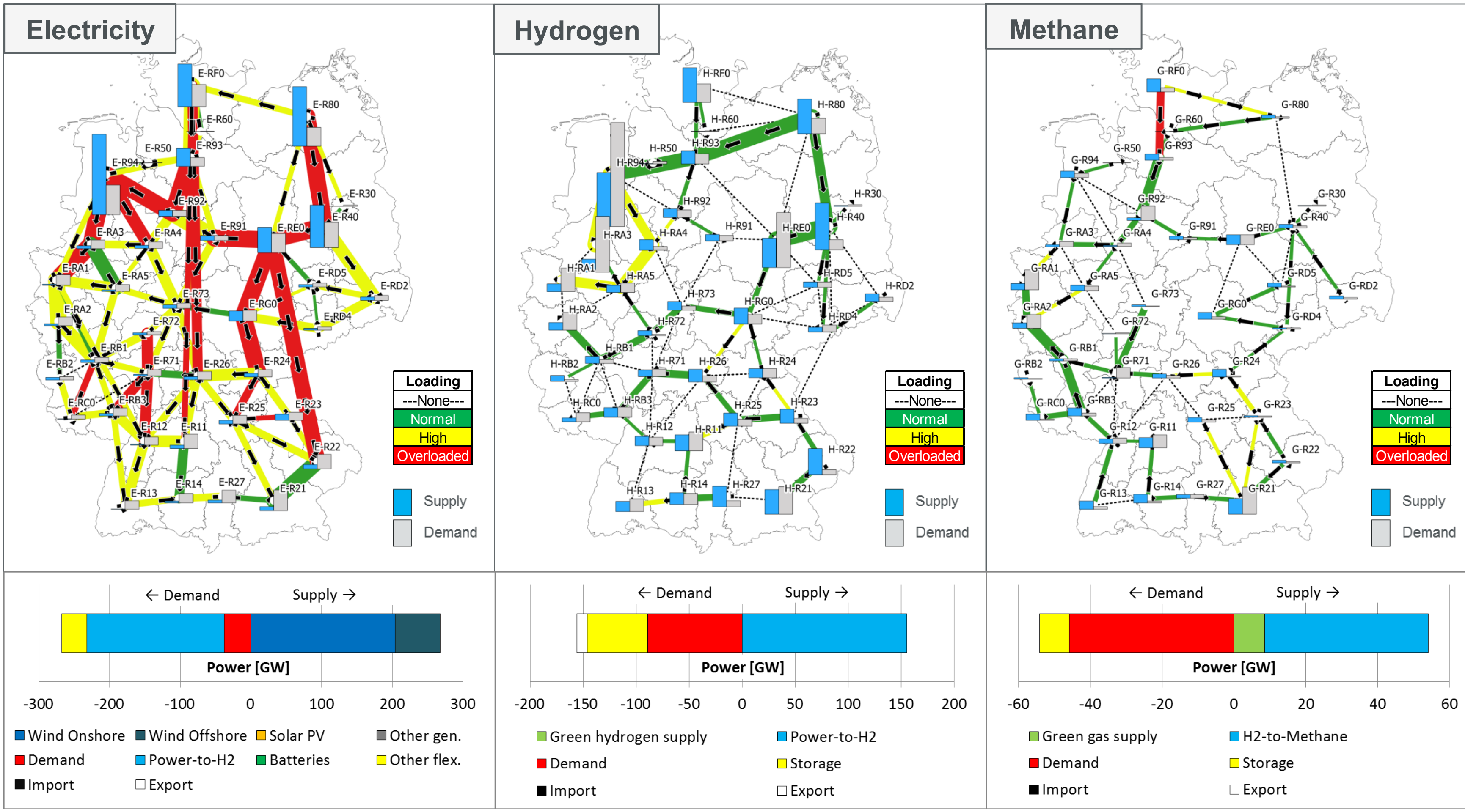
Distribution keys according to RES Energy



Infrastructure calculations (DE)

RES-capacity weighted regional distribution key

Base cases (Enervis_916)



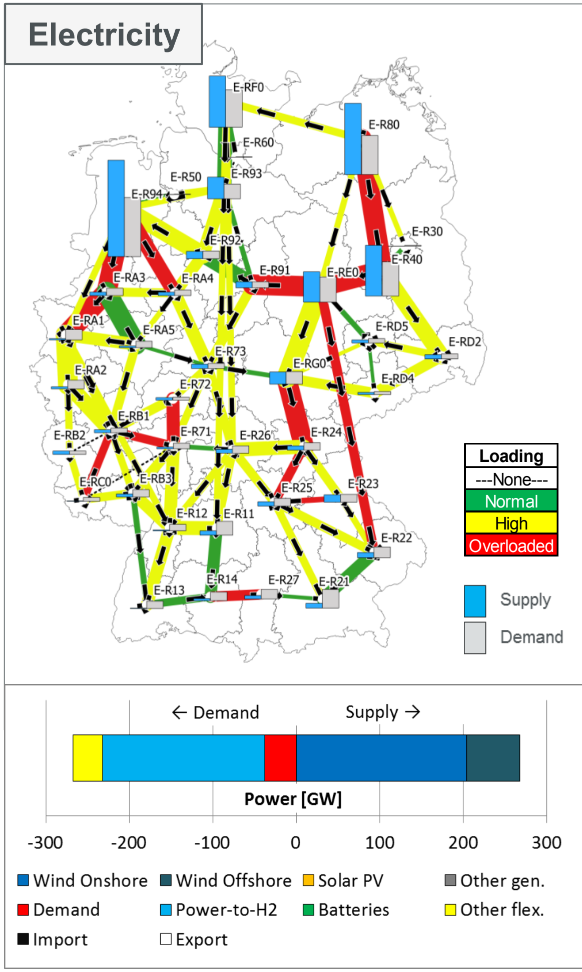
gasunie crossing borders in energy

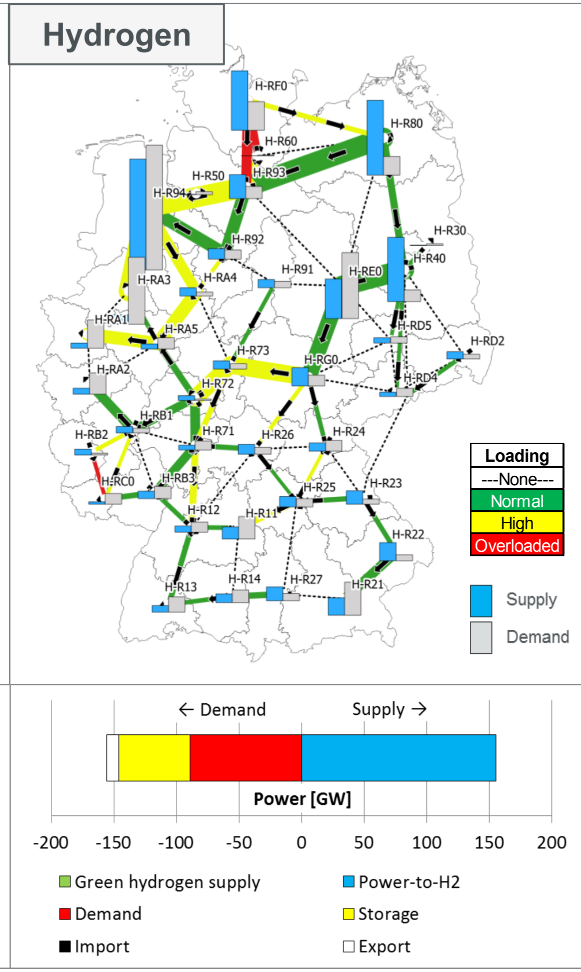
TenneT Taking power further

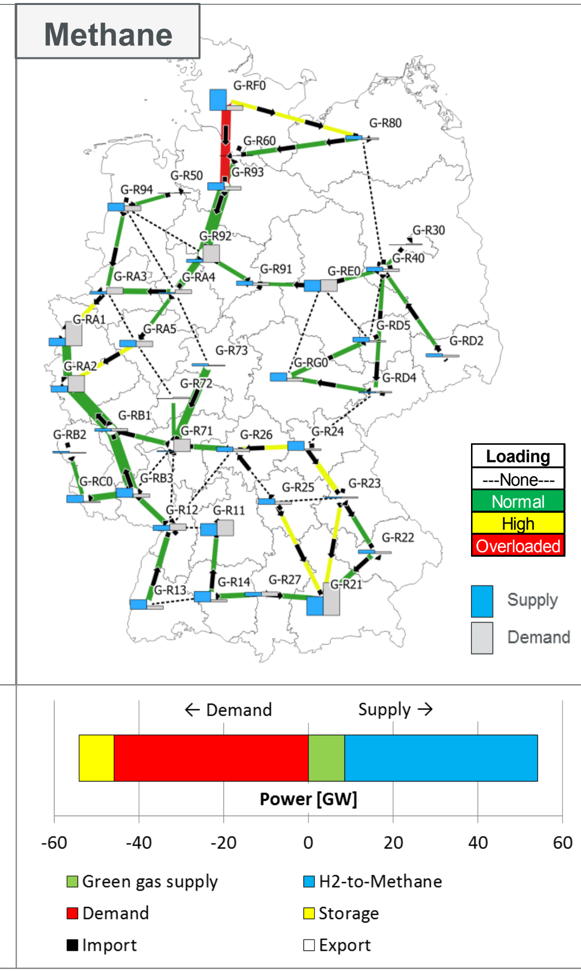
Infrastructure calculations (DE)

RES-energy weighted regional distribution key

Sensi cases (Enervis_916)







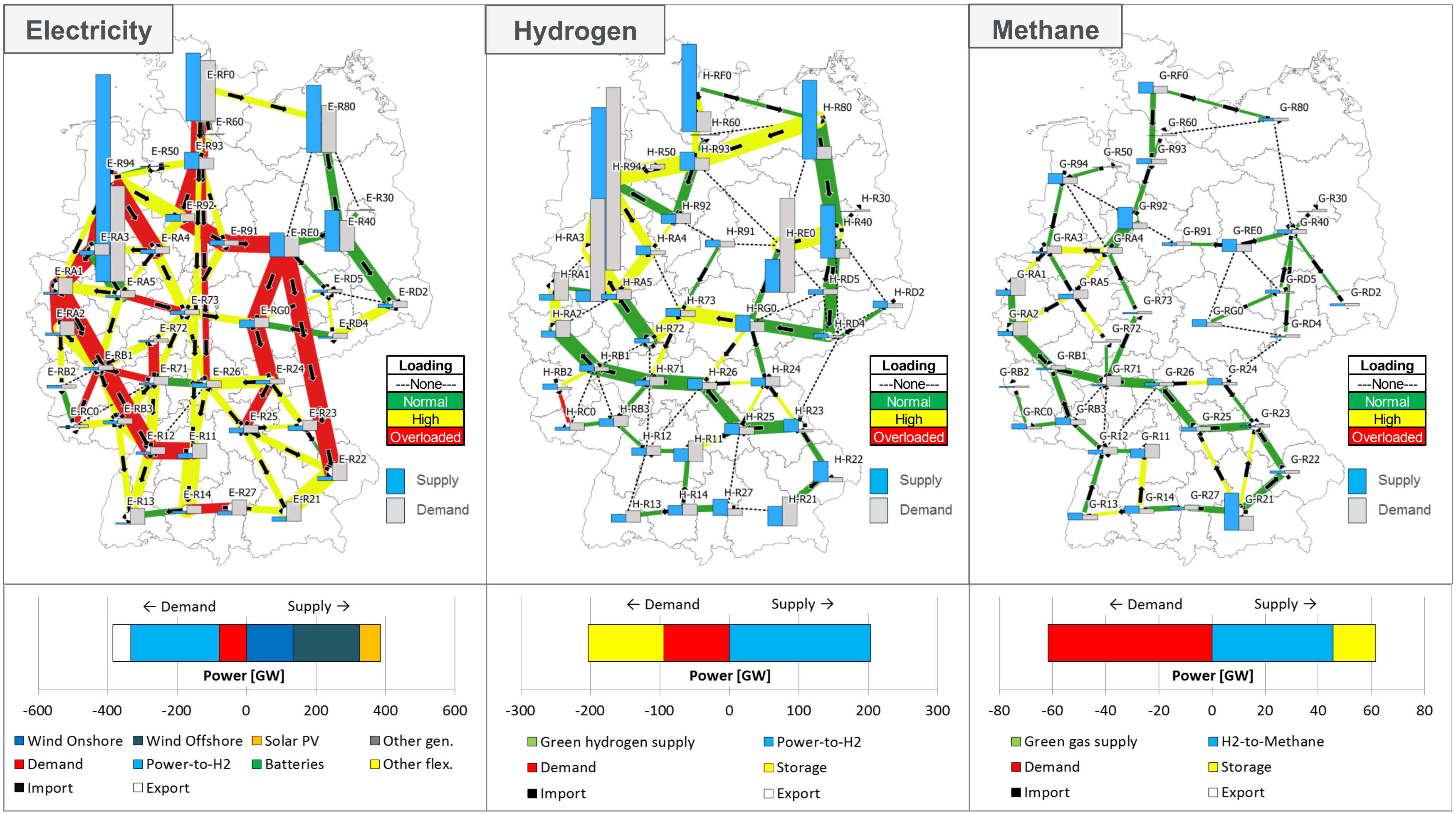
gasunie crossing borders in energy

TenneT Taking power further

Infrastructure calculations (DE)

RES-capacity weighted regional distribution key

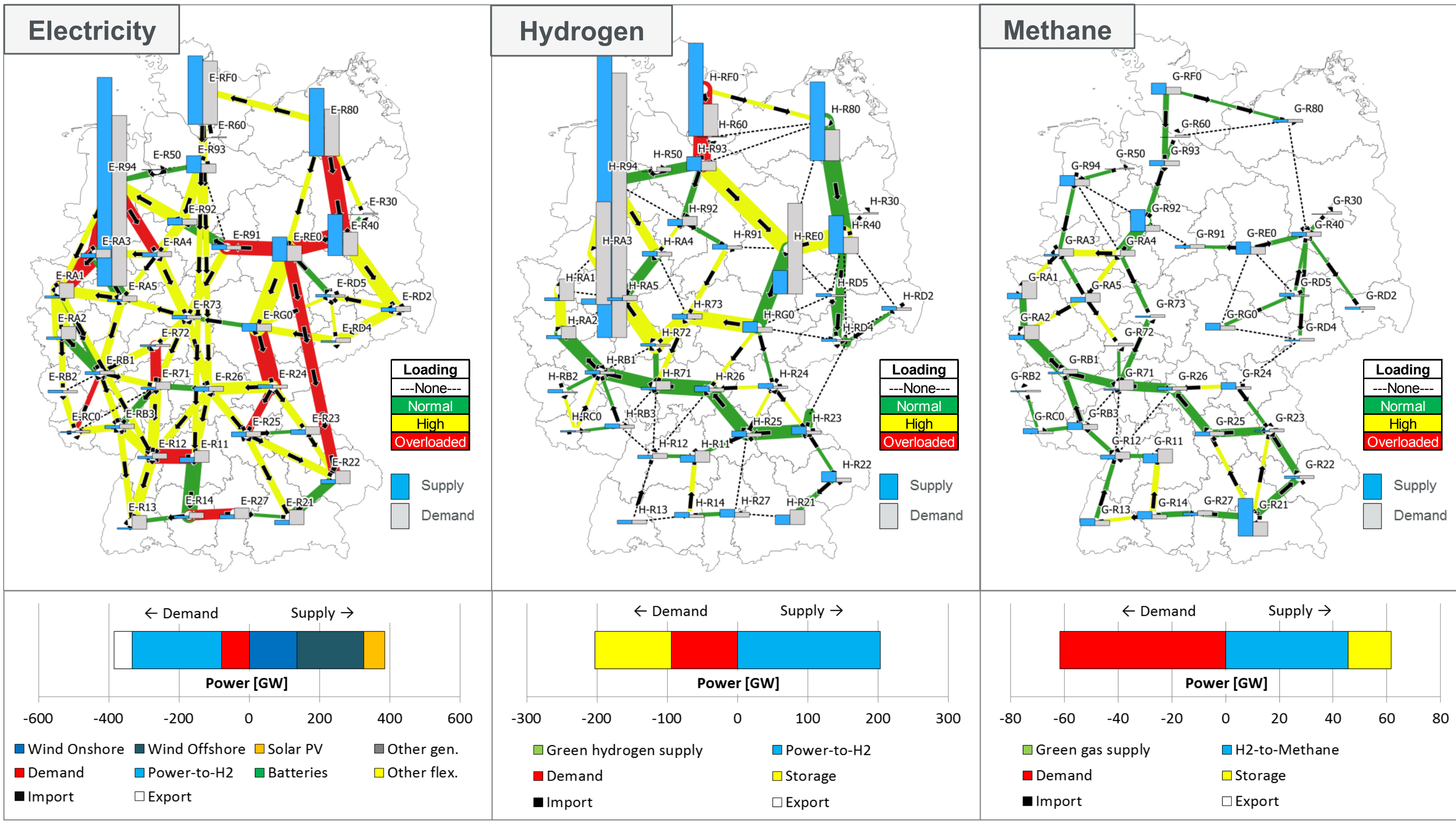
Base cases (FNB_1450)



Infrastructure calculations (DE)

RES-energy weighted regional distribution key

Sensi cases (FNB_1450)



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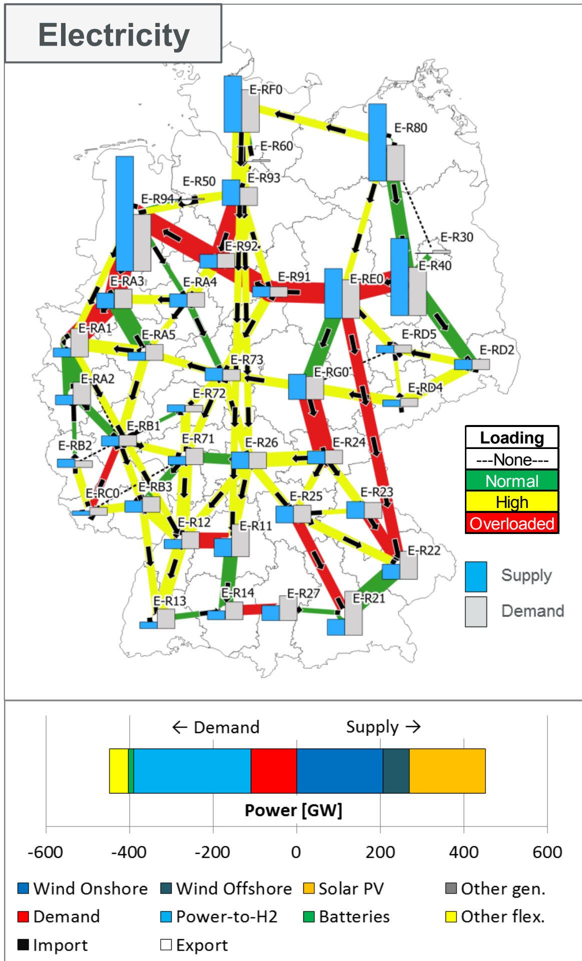
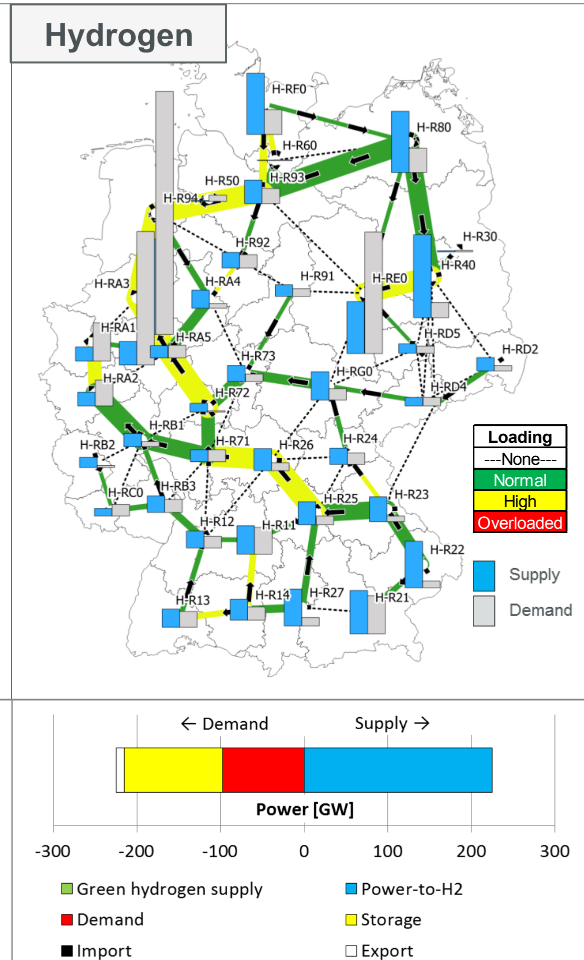
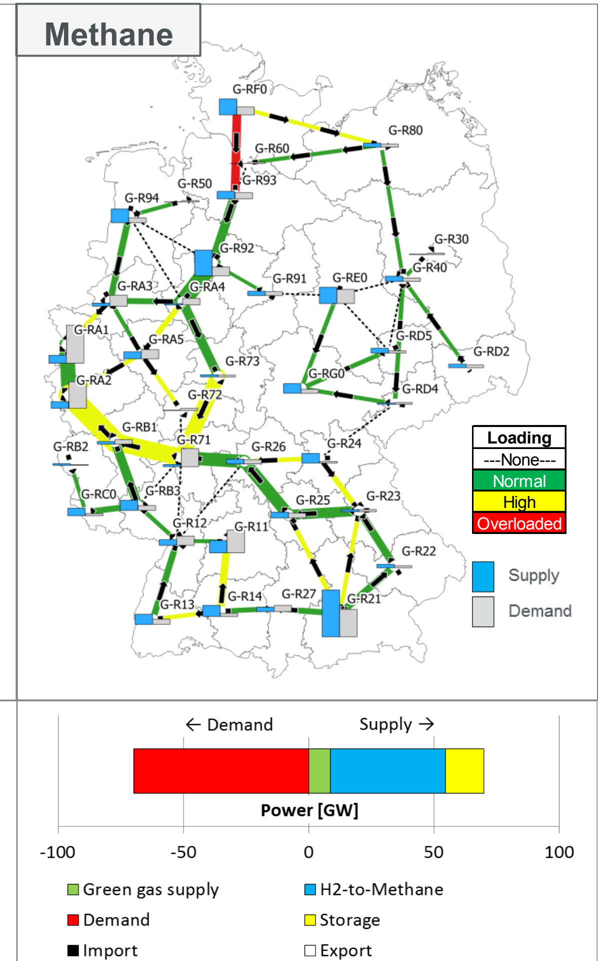
Infrastructure calculations (DE)

RES-capacity weighted regional distribution key

Base cases (Enervis_1450)







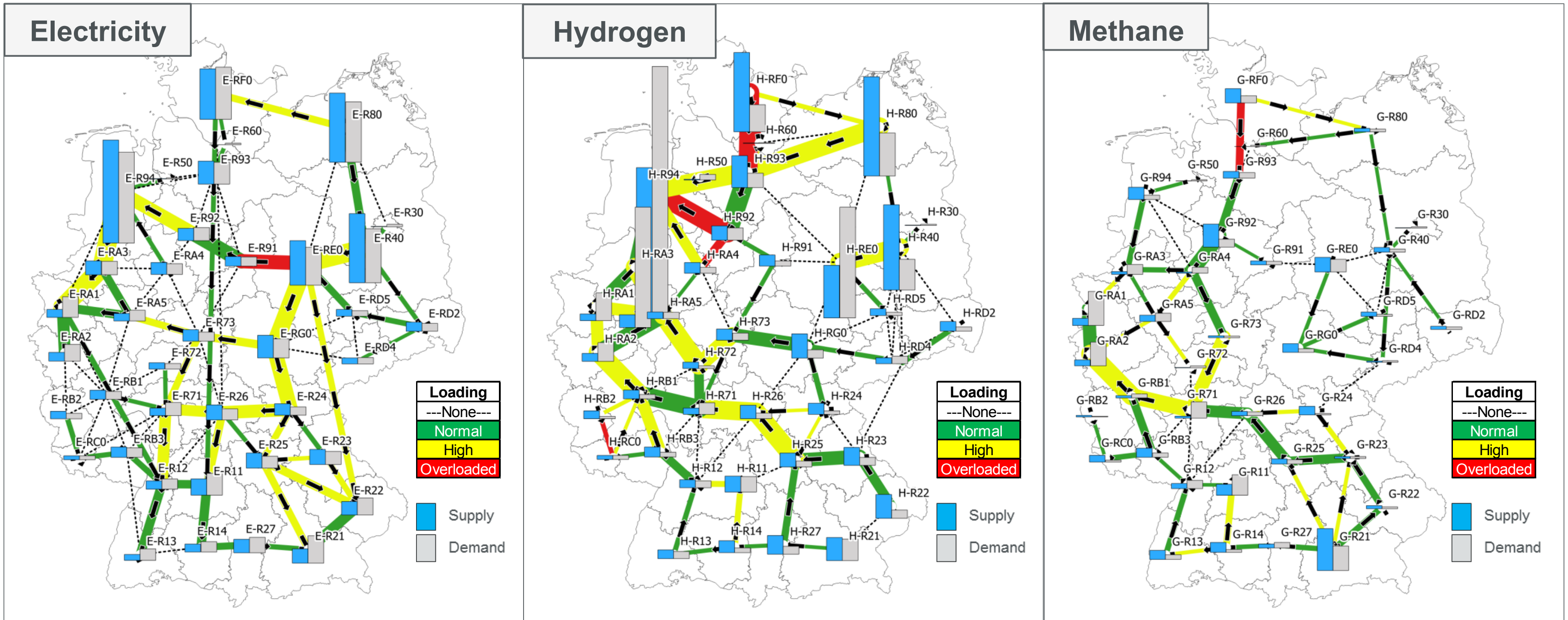
gasunie crossing borders in energy

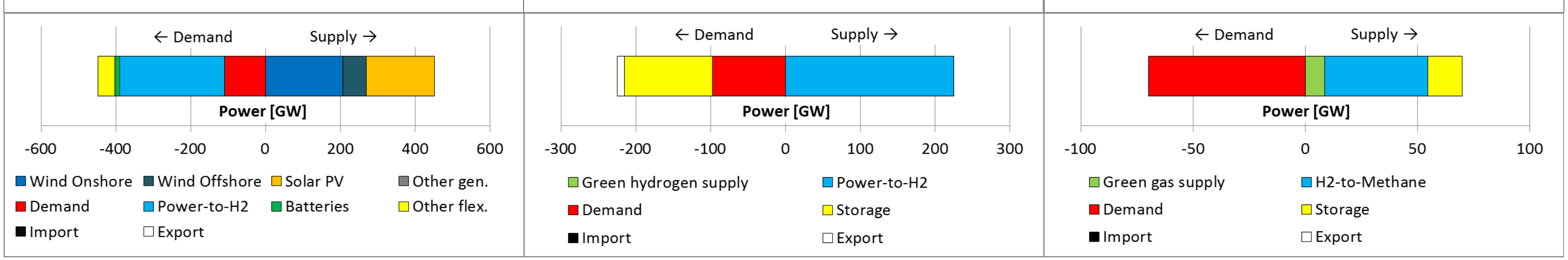
TenneT Taking power further

Infrastructure calculations (DE)

RES-energy weighted regional distribution key

Sensi cases (Enervis_1450)





gasunie crossing borders in energy

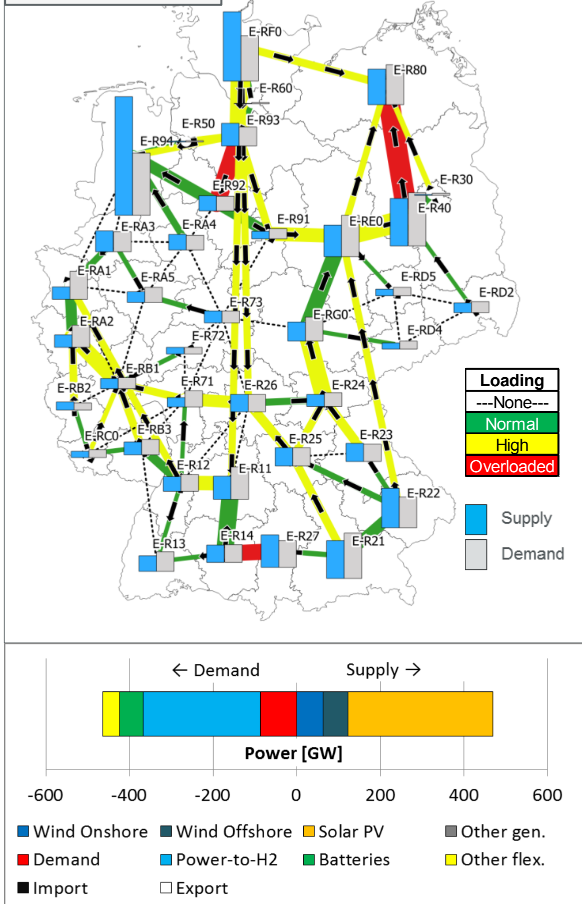
TenneT Taking power further

Infrastructure calculations (DE)

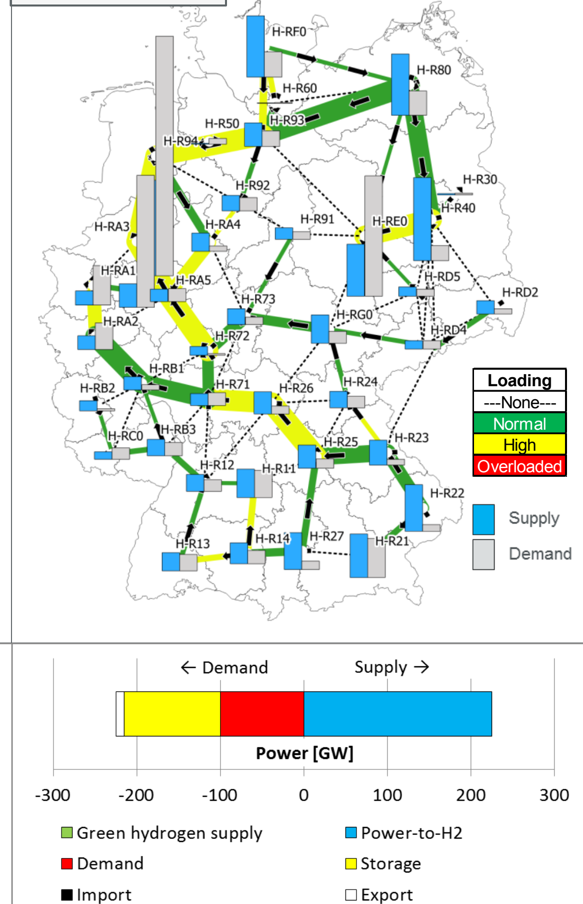
RES-capacity weighted regional distribution key

Base cases (Enervis_4358)

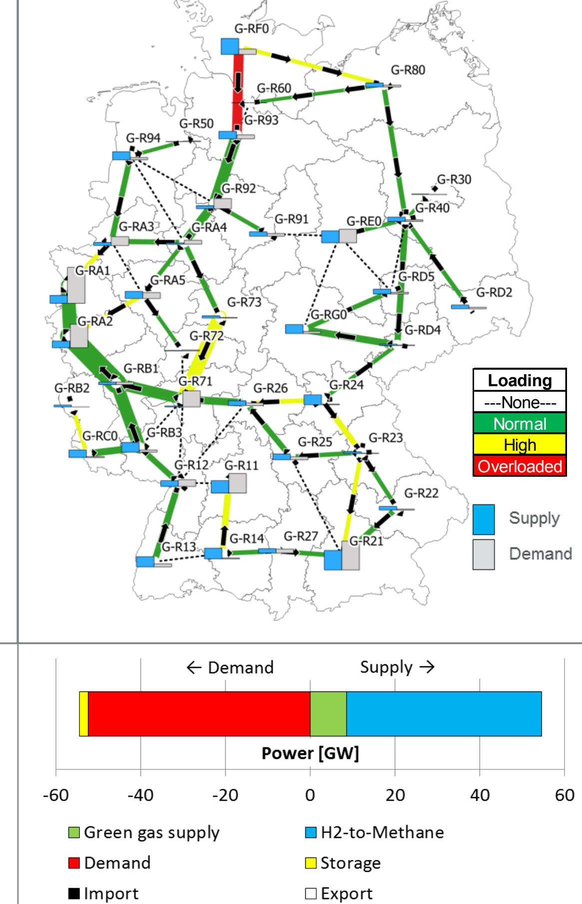
Electricity



Hydrogen



Methane



gasunie crossing borders in energy

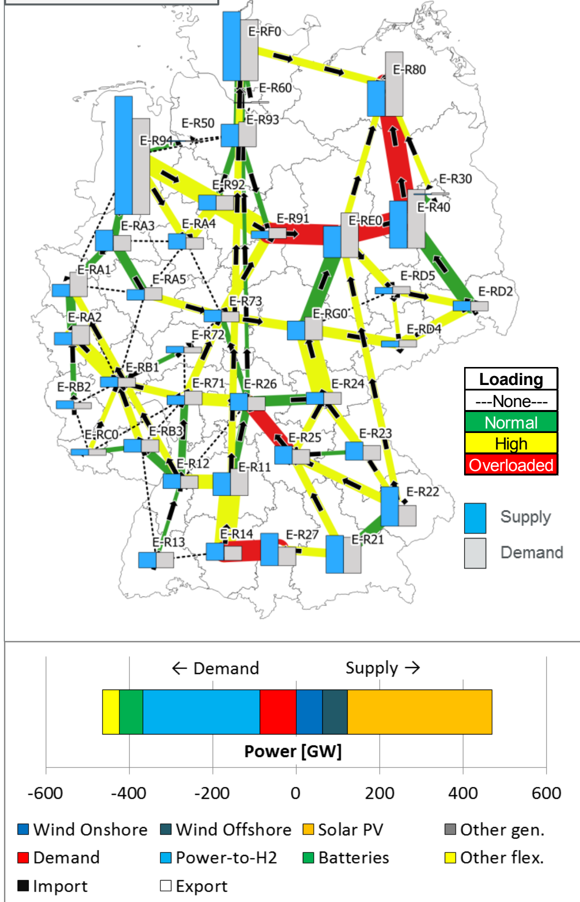
TenneT Taking power further

Infrastructure calculations (DE)

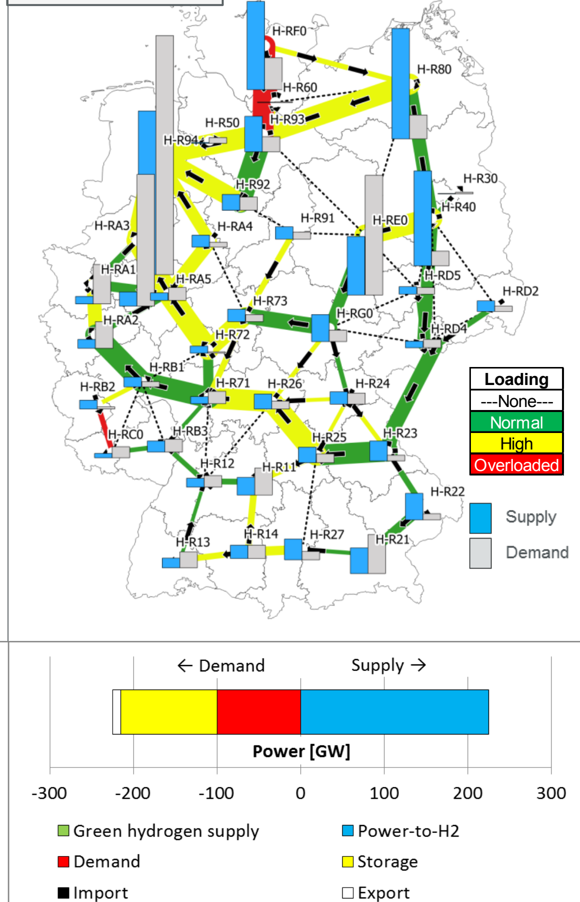
RES-energy weighted regional distribution key

Sensi cases (Enervis_4358)

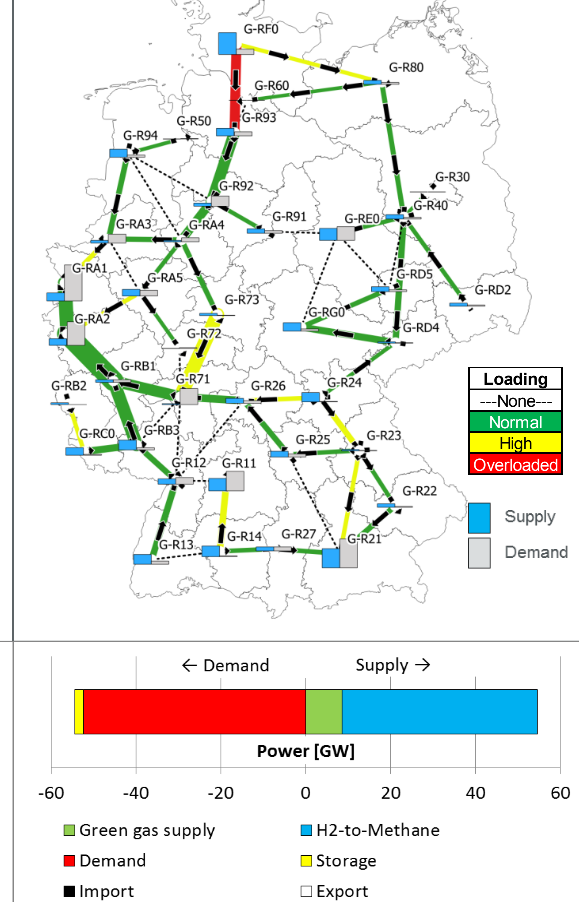
Electricity



Hydrogen



Methane



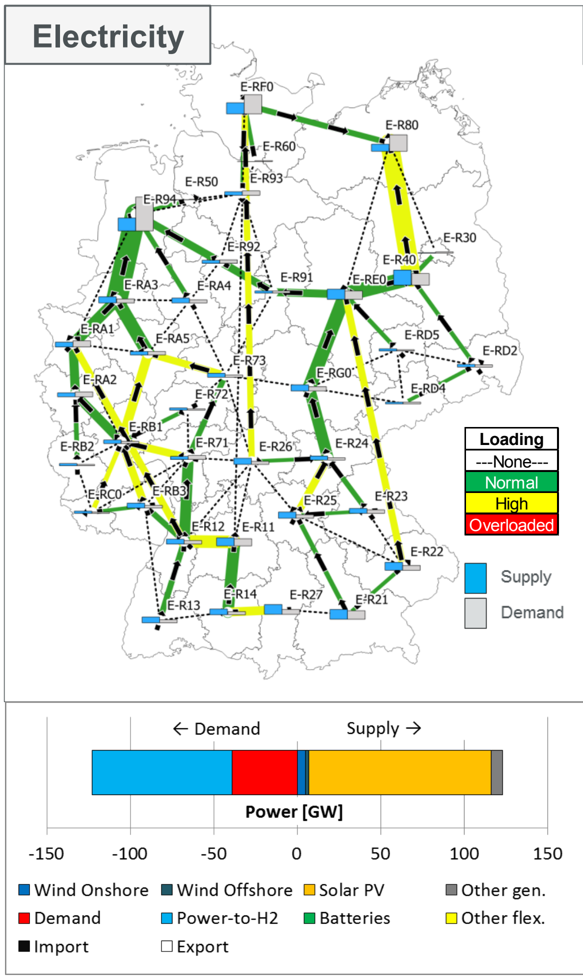
gasunie crossing borders in energy

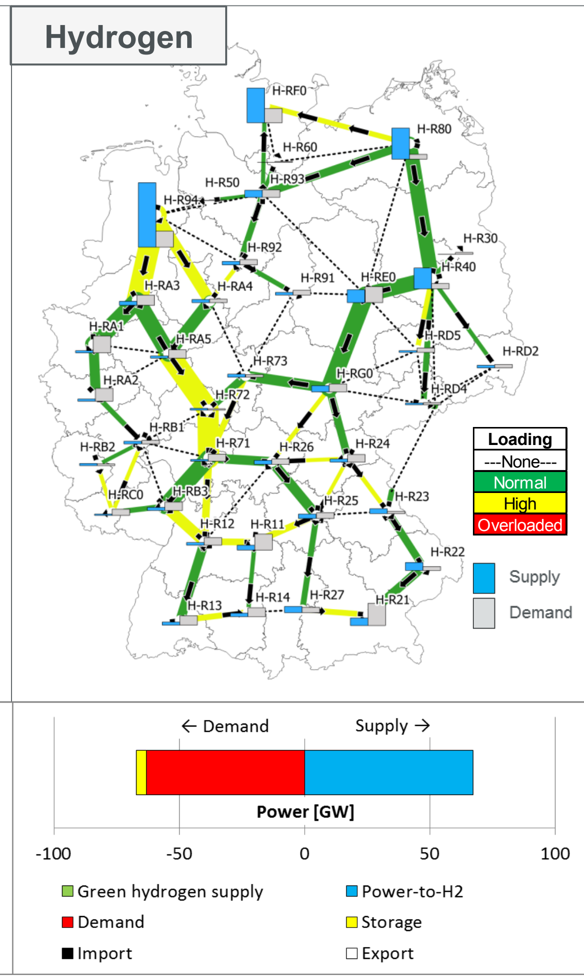
TenneT Taking power further

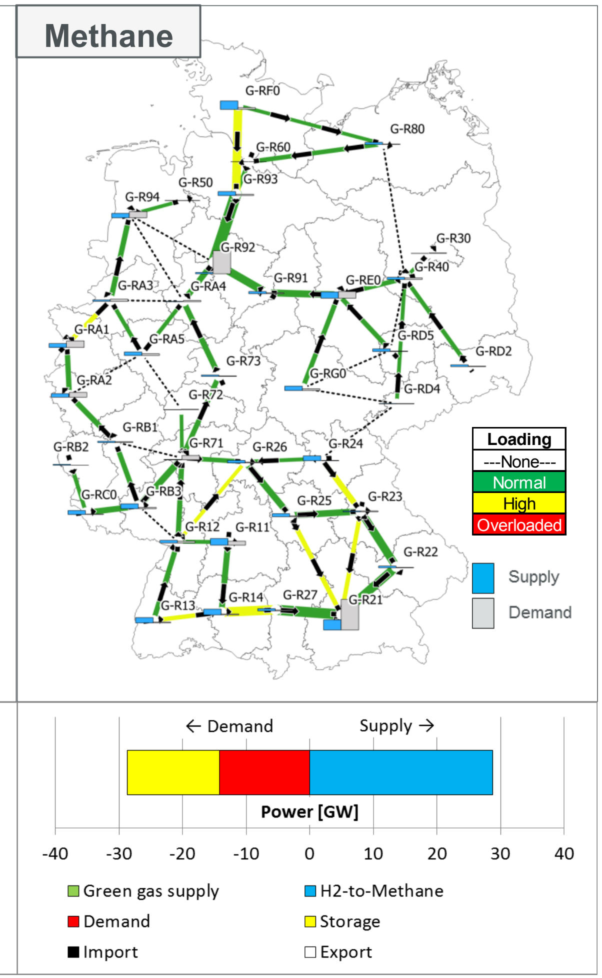
Infrastructure calculations (DE)

RES-capacity weighted regional distribution key

Base cases (EFNB_5126)







Infrastructure Outlook 2050

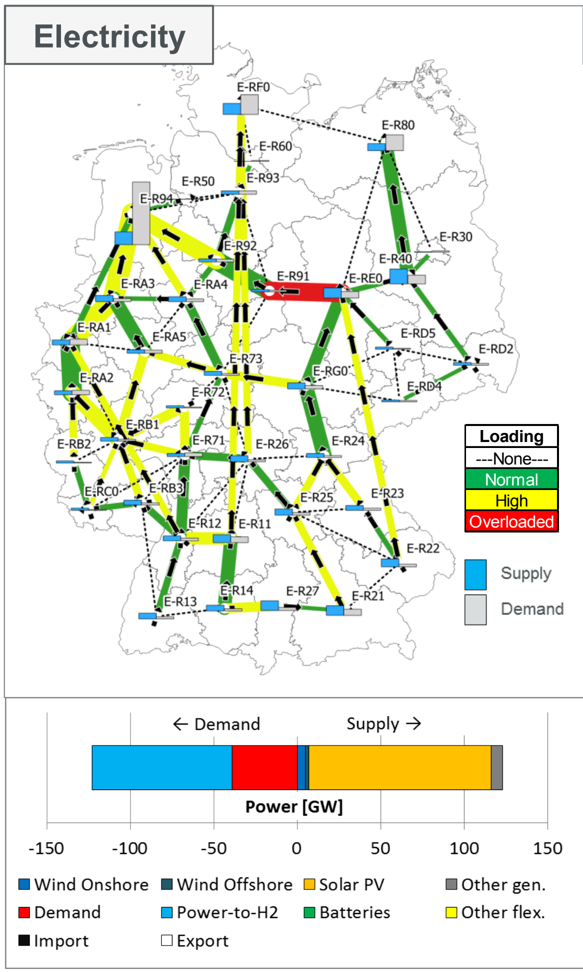
gasunie crossing borders in energy

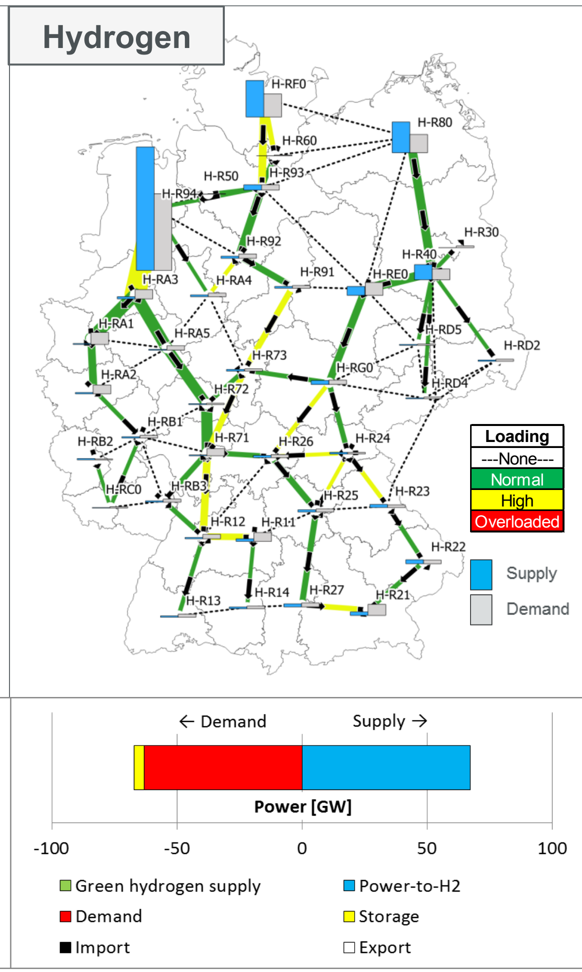
TenneT Taking power further

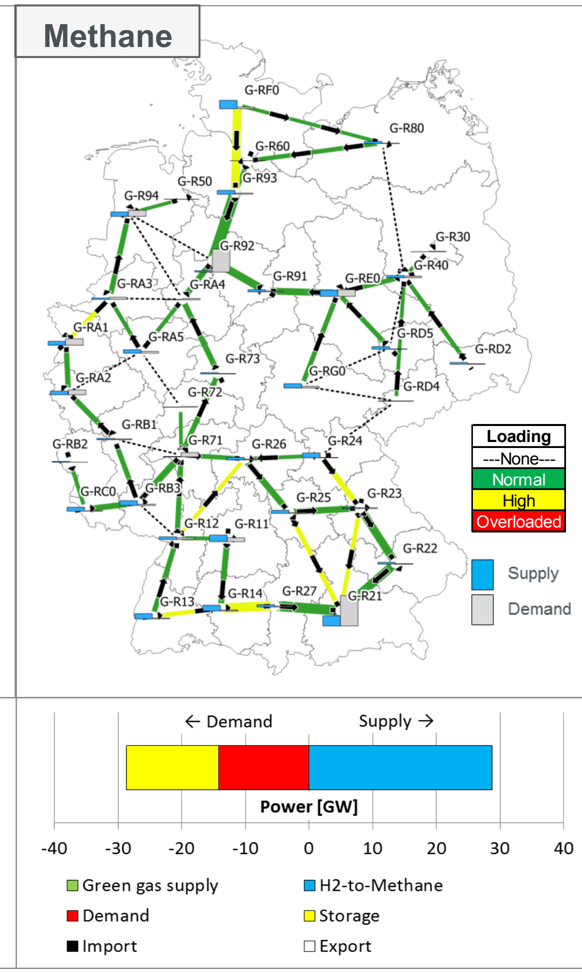
Infrastructure calculations (DE)

RES-energy weighted regional distribution key

Sensi cases (EFNB_5126)







gasunie crossing borders in energy

TenneT Taking power further

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