TYNDP 2024

The Hydrogen and Natural Gas TYNDP

ANNEX D2

Hydrogen Infrastructure Gaps Identification Methodology

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1 INTRODUCTION

The objective of this Hydrogen Infrastructure Gaps Identification (IGI) methodology is to provide guidance on the different elements of relevance for the IGI report as part of the 2024 TYNDP cycle. The TYNDP 2024 IGI methodology thereby builds on the TYNDP 2024 Implementation Guidelines through cross-references. The TYNDP 2024 Implementation Guidelines specify the required elements of the project-specific cost-benefit analysis (PS-CBA) as part of the 2024 TYNDP cycle.

The TYNDP 2024 IGI methodology (TYNDP 2024 Annex D2) and the TYNDP 2024 Implementation Guidelines (TYNDP 2024 Annex D1) provide input to the PCI and PMI selection process. The TYNDP 2024 System Assessment methodology (**TYNDP 2024 Annex D3**) covers the methodology of TYNDP 2024 sections that are not of relevance for the PS-CBA process and the IGI report.

2 LEGAL BACKGROUND

Article 60 of the Regulation (EU) 2024/1789 on the internal markets for renewable gas, natural gas, and hydrogen (GHR) stipulates that

"The Union-wide network development plan for hydrogen shall include the modelling of the integrated hydrogen network, scenario development, a European supply adequacy outlook and an assessment of the resilience of the system. The Union-wide network development plan for hydrogen shall, in particular: […] c) identify investment gaps, in particular with respect to the necessary cross-border capacities, to implement the priority corridors for hydrogen and electrolysers as referred to in point 3 of Annex I to [the TEN-E Regulation]."

Point 3 of Annex I of the TEN-E Regulation defines the priority corridors for hydrogen and electrolysers:

"[…] Hydrogen interconnections […]: ***hydrogen infrastructure and the repurposing of gas infrastructure, enabling the emergence of an integrated hydrogen backbone, directly or indirectly (via interconnection with a third country), connecting the countries of the region and addressing their specific infrastructure needs for hydrogen supporting the emergence of an Union-wide network for hydrogen transport****, and, in addition,* ***as regards islands and island systems, decreasing energy isolation, supporting innovative and other solutions involving at least two Member States with a significant positive impact on the Union's 2030 targets for energy and climate and its 2050 climate neutrality objective, and contributing significantly to the sustainability of the island energy system and that of the Union.***

Electrolysers: supporting the deployment of power-to-gas applications aiming to enable greenhouse gas reductions and contributing to secure, efficient and reliable system operation and smart energy system integration and, in addition, as regards islands and island systems, supporting innovative and other solutions involving at least two Member States with a significant positive impact on the Union's 2030 targets for energy and climate and its 2050 climate neutrality objective, and contributing significantly to the sustainability of the island energy system and that of the Union."

Three such priority corridors are defined in the TEN-E Regulation:

- HI West: Belgium, Czechia, Denmark, Germany, Ireland, Spain, France, Italy, Luxembourg, Malta, Netherlands, Austria, Portugal.
- HI East: Bulgaria, Czechia, Germany, Greece, Croatia, Italy, Cyprus, Hungary, Austria, Poland, Romania, Slovenia, Slovakia.
- BEMIP Hydrogen: Denmark, Germany, Estonia, Latvia, Lithuania, Poland, Finland, Sweden.

In line with Article 60 of the GHR, the focus of ENTSOG's infrastructure gaps identification exercise is on the needed hydrogen interconnectors within the priority corridors for hydrogen and electrolysers.

The infrastructure gaps identification is complementarily addressed by Article 13 of the TEN-E Regulation. An identified infrastructure gap thereby translates into an equivalent infrastructure need. The identified infrastructure gaps shall be reported as a part of the TYNDP and follow the procedural requirements of Article 13 of the TEN-E Regulation.

Article 13(1) of the TEN-E Regulation directs the focus of the analysis at system level to the effect of possible infrastructure gaps on the completion of the EU's 2030 climate and energy targets and 2050 climate-neutrality objective. The TYNDP scenarios, established in line with Article 12 of the TEN-E Regulation, thereby comply with this requirement. In line with Article 13(1) of the TEN-E Regulation, these scenarios form the basis of the infrastructure gaps identification.

3 MODEL DESCRIPTION

The model description contained in section 2 of the TYNDP 2024 Implementation Guidelines is also valid for this TYNDP 2024 IGI methodology. Exceptions from this validity and specifications are described in this section:

- While as for the TYNDP 2024 PS-CBA process the Dual Hydrogen/Electricity Model (DHEM) and Dual Gas Model (DGM) are used, the same TYNDP 2024 scenario is considered (i.e., National Trends+), and the same years are modelled (i.e., 2030 and 2040), the benefit indicators described in the TYNDP 2024 Implementation Guidelines are not computed for the TYNDP 2024 IGI report. The TYNDP 2024 IGI report is based on own indicators.
- For the DGM, the same natural gas infrastructure level (i.e., Low natural gas infrastructure level) is prescribed in the TYNDP 2024 Implementation Guidelines for the TYNDP 2024 PS-CBA process as in the TYNDP 2024 IGI methodology for the TYNDP 2024 IGI report.
- In contrast to the TYNDP 2024 PS-CBA process, both hydrogen infrastructure levels (i.e., PCI/PMI hydrogen infrastructure level and Advanced hydrogen infrastructure level) are assessed within the TYNDP 2024 IGI report.

The DHEM market assumptions listed in section 3.2.4 and Annex III, the GHG emissions factors of power plants listed in Annex IV, the GCV/NCV ratios defined in Annex VII as well as the infrastructure information provided by Annex I and II of the TYNDP 2024 Implementation Guidelines are also valid for this TYNDP 2024 IGI methodology. The same stressful weather year is used for the curtailed hydrogen demand IGI indicator (see section 5.3) as detailed in section 3.2.10 of the TYNDP 2024 Implementation Guidelines. The remaining parts of section 3 as well as section 4, section 5, section 6.2, Annex IV, Annex V, and Annex VI of the TYNDP 2024 Implementation Guidelines are not relevant for this TYNDP 2024 IGI methodology as they are related to project-specific assessments.

All hydrogen-related values specified in this TYNDP 2024 IGI methodology are considering the GCV[1].

1 The TYNDP 2024 scenarios are using the NCV. For hydrogen, the NCV can be converted into the GCV by multiplication with 1.176.

4 GENERAL APPROACH

To identify the infrastructure gaps, the following elements must be defined:

Already defined in the TYNDP 2024 Implementation Guidelines in combination with the previous section:

- General modelling concepts.
- The simulation tools and models to be used.
- The TYNDP scenario(s) and years to be used.
- The level of the network development (infrastructure level) to be considered as a reasonable counterfactual situation on which to assess the system and identify possible infrastructure gaps.

Not defined in the TYNDP 2024 Implementation Guidelines:

- The indicators based on which infrastructure gaps will be identified (see section 5).
- The threshold value for each infrastructure gaps identification indicator (IGI indicator). The comparison of the intermediate indicator result with its threshold value allows the judgement whether i) an infrastructure gap does not exist or is less relevant, or ii) an infrastructure gap does exist (see section 5).
- The methodology to compare the results for different hydrogen infrastructure levels to derive project-related information about infrastructure gaps (see section 6).

The results of the TYNDP 2024 IGI report are only related to infrastructure gaps that are based on the considered infrastructure levels. Therefore, the TYNDP 2024 IGI report cannot find that an infrastructure that is part of the smallest considered infrastructure level (i.e., the PCI/PMI hydrogen infrastructure level) is not addressing any infrastructure gap. Therefore, all the projects constituting the PCI/PMI hydrogen infrastructure level are to be treated as equally and jointly necessary for addressing the infrastructure gaps considered in the analysis.

Infrastructure gaps identified in ENTSOG's hydrogen-related TYNDP 2024 IGI report may in some cases also be addressable by energy infrastructure solutions in other sectors like the electricity sector[2] or the natural gas sector. This is the case for any infrastructure gaps identification that is focused on a specific energy vector.

No generic hydrogen infrastructure projects are used in this TYNDP 2024 IGI methodology. Instead, only real projects that were submitted by project promoters are considered.

2 While for example imports of hydrogen produced from natural gas with CCS or renewable energy imports by ship from distant production locations cannot be achieved by the electricity sector.

5 INFRASTRUCTURE GAPS IDENTIFICATION INDICATORS

The IGI indicators identify the existence of an infrastructure gap through the existence of effects of such infrastructure gap. The effect of this infrastructure gap is either expressed at a border for IGI indicator 1 (see section 5.1) or at a country for IGI indicators 2.1 and 2.2 (see section 5.2 and section 5.3). For each simulation case (see section 7), the TYNDP 2024 IGI report presents each relevant IGI indicator on a map and/or in a table.

Thereby, the following information is provided:

- the calculated value of relevance for the thresholds (i.e., hydrogen market clearing price spread for IGI indicator 1 and hydrogen demand curtailment rate for IGI indicators 2.1 and 2.2);
- the information if the threshold was reached or not.

The reason for an infrastructure gap is an infrastructure bottleneck. An infrastructure bottleneck is a physical congestion of the network that can be observed based on full utilization rates of all relevant transmission infrastructure during certain periods of time. If a limited cooperation mode is used among countries in situations of hydrogen scarcity (see section 3.2.4 of the TYNDP 2024 Implementation Guidelines), the dominant infrastructure bottleneck is not necessarily located at a border of the country through which the IGI indicators demonstrated the existence of an infrastructure gap (see examples below).

Also, besides the dominant bottleneck, non-dominant bottlenecks may exist at other locations that only unfold their effect once the dominant bottleneck is addressed. Additionally, an infrastructure bottleneck can in principle be solved by different projects and via different routes. Therefore, the infrastructure gaps identified by the IGI indicators identify regional infrastructure gaps, as the potential solution to it is not limited to the border of IGI indicator 1 or the country of IGI indicator 2. The regional aspect of the infrastructure gap can be further investigated at project level (see section 6).

5.1 IGI INDICATOR 1: HYDROGEN MARKET CLEARING PRICE SPREADS IN DHEM

This IGI indicator aims at identifying hydrogen infrastructure gaps by assessing Zone 2 nodes of different countries based on differences in hydrogen market clearing prices between these nodes. When assessing hydrogen infrastructure gaps with this IGI indicator, it should be noted that it depends on scenario assumptions about supply prices that are currently uncertain in the early stages of the hydrogen market development.

The indicator is established

- based on outputs of the objective function of the DHEM,
- for the considered scenario (i.e., NT+),
- for each considered year of assessment (i.e., 2030 and 2040),
- for the reference weather year (i.e., 1995),
- for each considered combination of hydrogen and electricity infrastructure levels (i.e., PCI/PMI hydrogen infrastructure level coupled with the electricity infrastructure level from the NT+ scenario; Advanced hydrogen infrastructure level coupled with the electricity infrastructure level from the NT+ scenario).

The DHEM thereby provides hourly hydrogen market clearing prices per hydrogen node. The hydrogen market clearing price spreads between different hydrogen nodes thereby allows to internalise information about several aspects that are listed below.

1. COMPETITION AND MARKET INTEGRATION:

Undersized hydrogen cross-border capacities are cross-border trade barriers. These trade barriers limit the access of the hydrogen producers with the lowest marginal production cost to hydrogen consumers. This results in hydrogen market clearing price spreads. On the other hand, a perfect market integration would result in a full hydrogen market clearing price convergence between Member States.

Example of how IGI indicator 1 captures competition and market integration:

Case: Country A is neighbouring country B. There is no direct or indirect hydrogen transport capacity between them. There is no curtailment in country A and country B. Country A and country B are producing and/or importing hydrogen from various sources. The most expensive supply source in country A that must be used to satisfy demand is less expensive than the most expensive supply source in country B that must be used to satisfy demand. This difference in hydrogen supply prices is captured by IGI indicator 1:

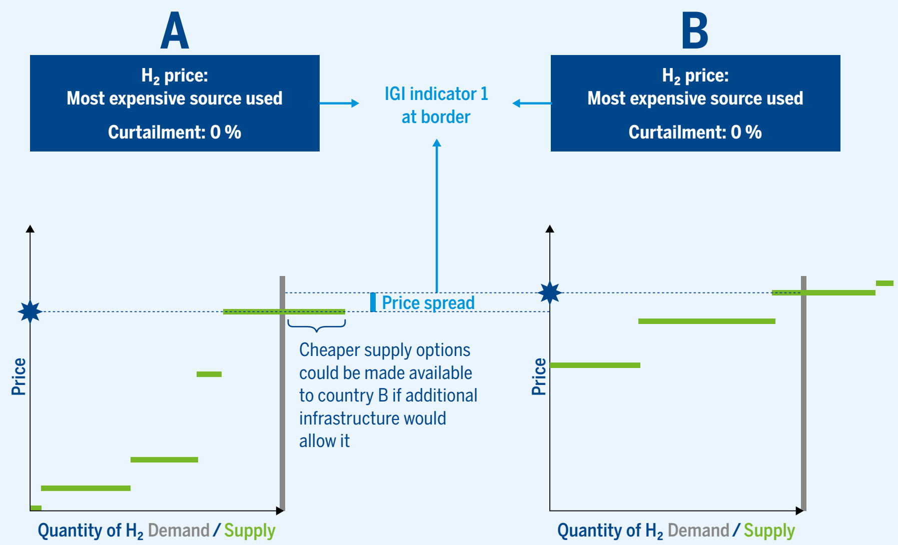

Figure 1: Example of IGI indicator 1 without hydrogen demand curtailment.

2. HYDROGEN DEMAND CURTAILMENT[3]

Hydrogen demand curtailment in a certain node is a last resort. It is characterized by a hydrogen market clearing price at the level of the willingness to pay for hydrogen (WTP_{H2}). The WTP_{H2} is higher than the price of the most expensive hydrogen supply source. This creates hydrogen market clearing price spreads between nodes with and nodes without hydrogen demand curtailment.

Example of how IGI indicator 1 captures hydrogen demand curtailment:

Case: Country C is neighbouring country D. There is no direct or indirect hydrogen transport capacity between them. There is hydrogen demand curtailment in country C but no hydrogen demand curtailment in country D. Country C and country D are producing and/or importing hydrogen from various sources.

The hydrogen market clearing price in country C is equivalent to the WTP_{H2}. The hydrogen market clearing price in country D is equivalent to the most expensive supply source of hydrogen that must be used to satisfy the demand, which is lower than the WTP_{H2}. This difference in hydrogen market clearing prices is captured by IGI indicator 1:

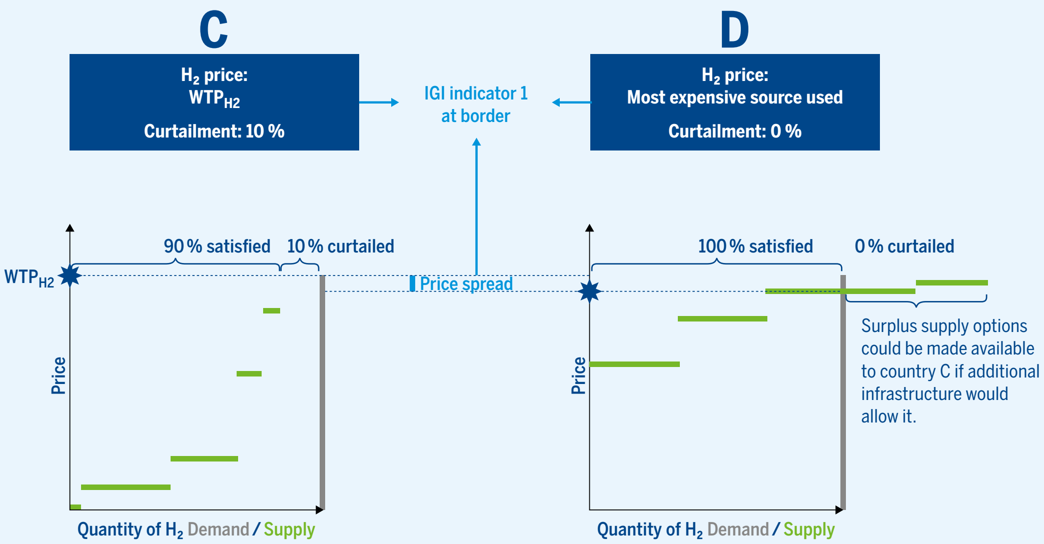

Figure 2: Example of IGI indicator 1 with hydrogen demand curtailment.

3 Selecting the curtailed hydrogen demand as single indicator would not allow to consider other listed aspects of relevance for the identification of hydrogen infrastructure gaps.

3. CURTAILED ELECTROLYTIC HYDROGEN PRODUCTION WITHIN THE EU:

Curtailed renewable electricity production would as a symptom show an electricity market clearing price of 0. Thus, there would be a business case for producing electrolytic hydrogen from this curtailed renewable electricity at a very low marginal cost if in another country more expensive hydrogen sources were used (e.g., hydrogen production from electricity produced by nuclear power plants, hydrogen production from natural gas, hydrogen imports from non-EU countries, etc.). If there was insufficient hydrogen transport capacity between the country with the curtailed renewable electricity production and a country that uses more expensive hydrogen sources, this will be displayed as a hydrogen market clearing price spread.

Example of how IGI indicator 1 captures competition and market integration in case of curtailment of renewable hydrogen production:

Case: Country E is neighbouring country F. There is no direct or indirect hydrogen transport capacity between them. There is no curtailment in country E and country F. Country E experiences high electricity generation from RES that results in an electricity market clearing price of 0. Country E has sufficient electrolyser capacity to satisfy its own hydrogen demand with this inexpensive electricity, i.e., it defines the hydrogen market clearing price of country E. Country F is producing and/or importing hydrogen from various sources. At the same time, some renewable hydrogen production is curtailed in country E due to limited offtake and/or export options. The most expensive supply source in country E that must be used to satisfy demand is less expensive than the most expensive supply source in country F that must be used to satisfy demand. This difference in hydrogen supply prices is captured by IGI indicator 1:

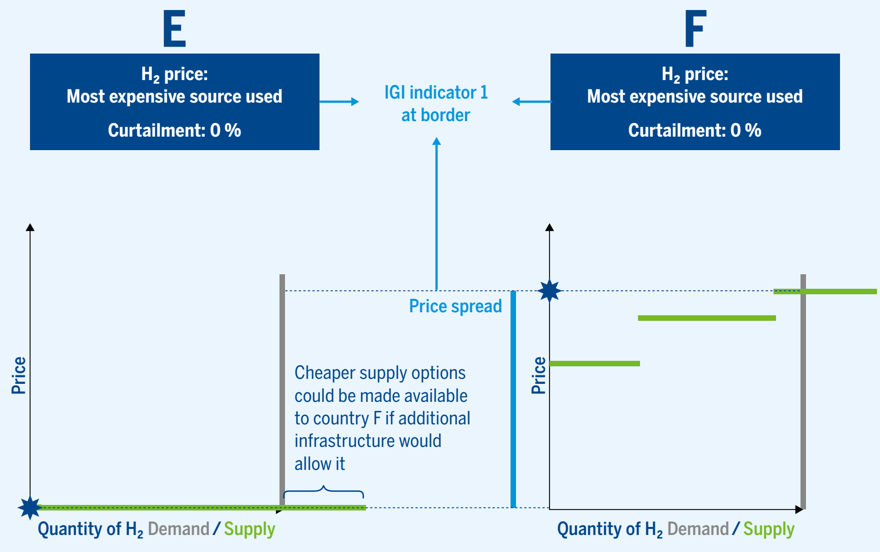

Figure 3: Example of IGI indicator 1 with renewable hydrogen production curtailment.

4 . RENEWABLE HYDROGEN OR LOW-CARBON HYDROGEN IMPORT OPTIONS:

Hydrogen price spreads can also be calculated between the hydrogen market clearing price in a Member State and relevant import prices of import options of renewable hydrogen (e.g., imports by ship or hydrogen from North Africa or Ukraine) or of low-carbon hydrogen (e.g., hydrogen from Norway) as established in the NT+ scenario. Such price spread shows which non-EU country or region could be an attractive potential supply source.

Example of how IGI indicator 1 can be used to indicate attractive import options:

Case: Country G is an island. Country G is an island and cannot produce sufficient hydrogen in any hour along the year to satisfy its hydrogen demand. The hydrogen market clearing price is therefore equivalent to the WTP_{H2}. Hydrogen import by ship is assumed to be available along the entire year in case its supply potential as established in the TYNDP 2024 draft Scenario Methodology Report is not fully used. In this example, there is still remaining supply potential of shipped ammonia. IGI indicator 1 then captures the difference between the WTP_{H2} and the price of hydrogen imports by ship.

To define which hydrogen market clearing price spreads are a significant indication of a hydrogen infrastructure gap, one of the following thresholds must be passed:

- Threshold 1: A hydrogen market clearing price spread as the yearly average of the absolute hourly hydrogen market clearing price spread between two Zone 2 nodes of different countries of more than 4 €/MWh_{H2}[4]; OR
- Threshold 2: A hydrogen market clearing price spread as the absolute average daily[5] hydrogen market clearing price spread between two Zone 2 nodes of different countries of more than 20 €/MWh_{H2} for more than 40 days per year.

If there is a hydrogen market clearing price spread above one of the thresholds, this indicates an infrastructure gap for the given assumptions.

4 In ENTSO-E's implementation guidelines for TYNDP 2024 of 4 March 2024, several interconnection target recommendations to contribute to EU energy targets are listed. Amongst them is the price differential: "Market studies simulations will serve to account price differentials per border as the yearly average of absolute hourly price differentials. This indicator is computed per border in €/MWh. In those borders where this indicator is greater than 2 €/MWh will mean that further interconnectors should urgently be investigated." The hydrogen market clearing price spreads indicator allows for a similar approach, while a more conservative threshold value is chosen.

5 By using daily average values, intra-day changes of the transport direction are tending to equalize each other, being more conservative than working with absolute average hourly hydrogen market clearing price spreads.

Example 1 of the application of the thresholds:

Case: Country H is neighbouring country I. There is no direct or indirect hydrogen transport capacity between them. Country H is producing all its hydrogen with electrolysers from renewable electricity at a marginal cost of 30 €/MWh_{H2} along the entire year. Country I is producing hydrogen with electrolysers from nuclear power at a marginal cost of 40 €/MWh_{H2} along the entire year.

- Result for Threshold 1: The yearly average of the absolute hourly hydrogen market clearing price spread between country H and country I is 10 €/MWh_{H2}. As this is more than 4 €/MWh_{H2} Threshold 1 is passed.
- Result for Threshold 2: The absolute average daily hydrogen market clearing price spread between country H and country I is above 20 €/MWh_{H2} for 0 days. Therefore, Threshold 2 is not passed.
- Result: As one of the thresholds is passed, an infrastructure gap is identified based on the IGI indicator 1 between country H and country I.

Example 2 of the application of thresholds:

Case: Country G is an island and cannot produce sufficient hydrogen in any hour throughout the year to satisfy its hydrogen demand. The hydrogen market clearing price is therefore equivalent to the WTP_{H2}, e.g. 154 €/MWh_{H2}. Hydrogen import by ship is assumed to cost 116.5 €/MWh_{H2} and to be available throughout the entire year.

- Result: Both thresholds are passed. As at least one threshold is passed, an infrastructure gap is identified based on the IGI indicator 1.

Addressing an identified infrastructure gap by addressing the underlying dominant infrastructure bottleneck does not exclude the existence of non-dominant infrastructure gaps based on non-dominant infrastructure bottlenecks that would unfold an effect on other nodes once the identified dominant infrastructure gap was addressed. This is explained by the following example.

The approach to investigate the role of projects is described in section 6.

Example of a non-dominant infrastructure gap:

Initial case: Country A is neighbouring country B, country B is neighbouring country A and country C, and country C is neighbouring country B. There is no hydrogen transport capacity between these three countries. Country A has surplus hydrogen supply options while country B and country C have no hydrogen supply option but hydrogen demand.

- Result of the hydrogen market clearing price spread indicator: The hydrogen market price spread indicator will indicate an infrastructure gap based on the IGI indicator 1 between country A and country B. There is no such indication between country B and country C as both show the high hydrogen market clearing price associated with hydrogen shortage.

Case after identified infrastructure gap was addressed: There would still be the non-dominant infrastructure gap between country B and country C as there is still no connection between them, so the non-dominant infrastructure bottleneck remains, and country C remains with the high hydrogen market clearing price associated with hydrogen shortage.

Picture courtesy of Gas Connect Austria

5.2 IGI INDICATOR 2.1: CURTAILED HYDROGEN DEMAND IN DHEM AND DGM WITHOUT STRESS CASE

This IGI indicator identifies infrastructure gaps by measuring the hydrogen demand curtailments of individual nodes during the reference weather year (i.e., 1995), and without infrastructure or source disruptions.

The following simulation logic is applied for each combination of simulation year and hydrogen infrastructure level:

1. A DHEM simulation is run with the reference weather year data (i.e., the same simulation is used for IGI indicator 1).
2. The DHEM outputs from step 1 that influence the natural gas demand, hydrogen production, and hydrogen consumption are transferred into the DGM (see sections 2.4.5 and 2.4.6 of the TYNDP 2024 Implementation Guidelines).
3. A DGM simulation is run based on step 2.
4. Per node, the combined hydrogen demand curtailment from the DHEM simulation and the additional hydrogen demand curtailment from the DGM are provided.

To define which hydrogen demand curtailments are a significant indication of a hydrogen infrastructure gap, the following threshold must be passed:

- Threshold: A yearly average hydrogen demand curtailment rate of more than 0 %.

If there is a hydrogen demand curtailment above the threshold, this indicates an infrastructure gap for the given assumptions.

As there is only a limited cooperation mode considered for hydrogen in the DHEM and in the DGM (see section 3.2.4 of the TYNDP 2024 Implementation Guidelines), the infrastructure bottleneck causing the hydrogen demand curtailment rate to be above the threshold defined above in a certain country does not need to be located at the border between this country and its direct neighbours. This is explained by the following examples.

Example of the identification of an infrastructure bottleneck under full cooperation mode:

Country J is neighbouring country K, country K is neighbouring country J and country L, and country L is neighbouring country K. Country J has a surplus of hydrogen supply options, while country K and country L are depending on supplies from country J. Under a full cooperation mode, the model will try to reach equal hydrogen demand curtailment rates in all three countries. Under this full cooperation mode, a difference between hydrogen demand curtailment rates between neighbouring countries can only be caused by fully utilized (or non-existing) infrastructure. The infrastructure that was fully utilized (or was non-existing) and thereby caused this difference is defined as the dominant infrastructure bottleneck.

If as a result of this cooperation country K and country L have the same hydrogen demand curtailment rates, which are higher than the one of country J, the dominant infrastructure bottleneck is located between country J and country K. If country J and country K have the same hydrogen demand curtailment rates, which are higher than the one of country L, the dominant infrastructure bottleneck is located between country K and country L. If country J has a lower hydrogen demand curtailment rate than country K and the one of country K is lower than the one of country J, there are dominant infrastructure bottlenecks between country J and country K as well as between country K and country L.

Picture courtesy of terranets bw

Example of the identification of an infrastructure bottleneck under the limited cooperation mode applied for the hydrogen infrastructure gaps identification:

Country J is neighbouring country, country K is neighbouring country J and country L, and country L is neighbouring country K. Country J has a surplus of hydrogen supply options, while country K and country L are depending on supplies from country J and have no potential access to hydrogen import options. Under the limited cooperation mode, the model will try to first satisfy the hydrogen demand of country J, then of country K, and only then of country L (as cross-border flows are penalized with a small hurdle cost).

If only country L is curtailed, this does not mean that the infrastructure bottleneck, defined as the fully utilized (or non-existing) infrastructure causing the curtailment, is located at the border between country K and country L. While this is a possible explanation, the infrastructure bottleneck could also be linked to the infrastructure from country J to country K. In latter case, not sufficient hydrogen can be sent out of country J to satisfy the hydrogen demand of both country K and country L. This would then be the dominant infrastructure bottleneck. If it were not, the total supply options of the three countries would be too limited, so the dominant infrastructure bottleneck would be the import infrastructure into country J.

The example above shows that the infrastructure bottleneck with a limited cooperation mode does not need to be at the node where the infrastructure gap is identified. The approach to investigate the role of projects is described in section 6.

5.3 IGI INDICATOR 2.2: CURTAILED HYDROGEN DEMAND IN DHEM AND DGM UNDER STRESSFUL WEATHER YEAR

This IGI indicator identifies infrastructure gaps by measuring the hydrogen demand curtailments of individual nodes under stressful weather conditions (i.e., 2009).

The stressful weather year data is aligned with the stressful weather year proposed to be used for the calculation of the reduction in exposure to curtailed hydrogen demand indicator (B5) within the TYNDP 2024 Implementation Guidelines.

The following simulation logic is applied for each combination of simulation year and hydrogen infrastructure level:

1. A DHEM simulation is run with the stressful weather year data.
2. The DHEM outputs from step 1 that influence the natural gas demand, hydrogen production, and hydrogen consumption are transferred into the DGM (see sections 2.4.5 and 2.4.6 of the TYNDP 2024 Implementation Guidelines).
3. A DGM simulation is run based on step 2.
4. Per node, the combined hydrogen demand curtailment from the DHEM simulation and the additional hydrogen demand curtailment from the DGM are provided.

To define which hydrogen demand curtailments are a significant indication of a hydrogen infrastructure gap, one of the following thresholds must be passed:

- Threshold 1: A yearly average hydrogen demand curtailment rate of more than 3 %; OR
- Threshold 2: A hydrogen demand curtailment rate of more than 5 % for at least one month per year.

If there is a hydrogen demand curtailment above one of the thresholds, this indicates an infrastructure gap for the given assumptions.

The effect of the limited cooperation mode considered for hydrogen in the DHEM and in the DGM (see section 3.2.4 of the TYNDP 2024 Implementation Guidelines) is identical for IGI indicator 2.2 and IGI indicator 2.1 (see section 5.2). The approach to investigate the role of projects is described in section 6.

6 COMPARISON OF THE INDICATOR RESULTS FOR DIFFERENT HYDROGEN INFRASTRUCTURE LEVELS

As stated in previous sections, the IGI indicators are used to identify regional infrastructure gaps that are indicated by the passing of one threshold of one IGI indicator.

By comparing the results of different hydrogen infrastructure levels for simulations that are identical concerning all other parameters, the effect of including additional infrastructure can be identified. The Advanced hydrogen infrastructure level contains the exact PCI/PMI hydrogen infrastructure level as well as additional projects.

If an infrastructure gap is indicated in the PCI/PMI hydrogen infrastructure level but is not observed in the Advanced hydrogen infrastructure level, the additional projects contained in latter infrastructure level removed it. Thereby, they addressed a certain infrastructure bottleneck.

To identify which of the additional projects removed the infrastructure bottleneck that caused the infrastructure gap, the results of the IGI indicator simulations are interpreted. Thereby, infrastructure bottlenecks are identified by assessing which hydrogen demand curtailments are caused by all relevant transmission infrastructure being used at their maximum capacity (i.e., infrastructure bottleneck). Then, it can be stated that one solution to address the respective infrastructure gap is described by the identified projects (in addition to the PCI/PMI infrastructure level) with their respective capacities.

It is important to notice that this does not falsify the fact that various combinations of additional infrastructure at various locations may be able to address this gap. Attention should be given to the possible contribution of storage and extra-EU import capacity, since the following methodology prioritizes the identification of intra-EU pipelines to address the infrastructure gap.

An infrastructure gap can also be reduced by bringing the parameters captured by the IGI indicator closer to the threshold value. In this case, the comparison is following the same steps, but the projects and their respective capacities were not sufficient to remove the relevant infrastructure bottlenecks. Nevertheless, they partially address the identified regional infrastructure gap.

If an infrastructure bottleneck is identified, this is an indication that projects addressing the respective transport need and that are part of the assessed infrastructure level are not in competition. This information may be used for the PS-CBA process.

In the TYNDP 2024 IGI report, the comparison will be performed in the following steps for each simulation year (i.e., 2030 and 2040) and hydrogen infrastructure level (i.e., PCI/PMI hydrogen infrastructure level and Advanced hydrogen infrastructure level):

1. Displaying maximum interconnection usage (as percentage of technical capacity) per interconnection and listing unconnected (groups of) countries (or nodes) for both hydrogen infrastructure levels and both weather years (i.e., 1995 and 2009).[6]
2. Displaying which hydrogen demand curtailment is caused by limited intra-EU hydrogen transport capacity, calculated as follows on EU level based on the DHEM results:
   a. For each hour, the absolute EU-wide hydrogen demand curtailment is calculated based on the simulation result:

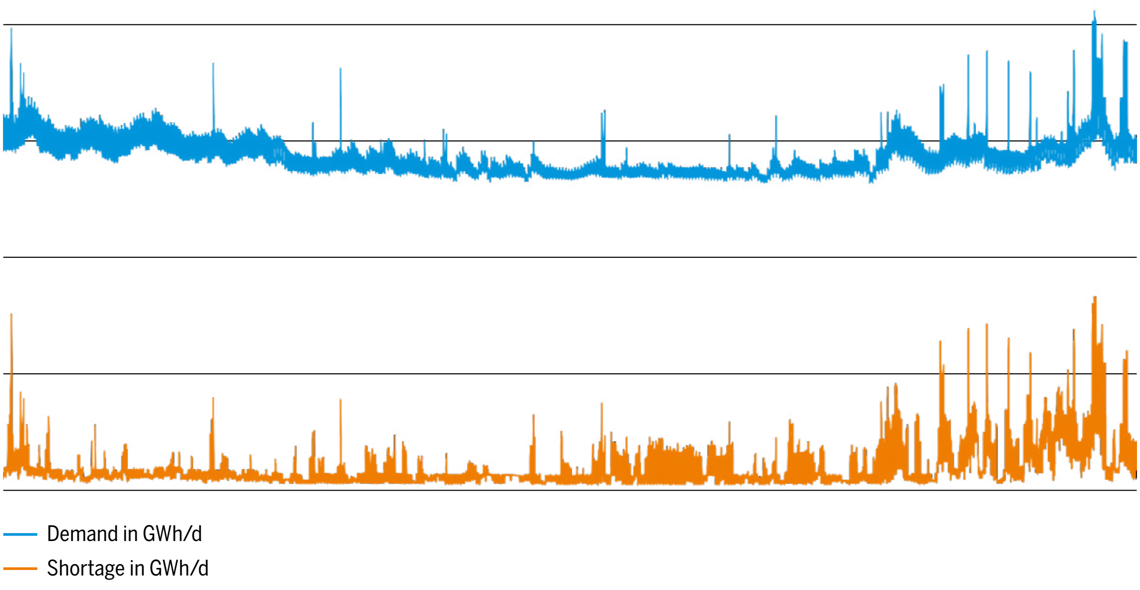

Figure 4: Example of the hourly, absolute EU-wide hydrogen demand curtailment along a year.

6 Some hydrogen transmission projects aim at connecting offshore electrolysers. If those projects are represented in the topology as an individual arc, their usage is available. If the project is not represented in the topology as an individual arc, the maximum interconnection usage is estimated by first calculating which share of the relevant country's Zone 2 electrolyser capacity (e.g., 10 GW_{el}) is enabled by the project (this information was collected during the project collection phase) (e.g., 20 %) and then calculating the ratio between i) the maximum hourly electrolyser utilization rate of the country (e.g., 98 %) times the share of enabled electrolyser production (e.g., 20 %) times the relevant country's Zone 2 electrolyser capacity (e.g., 10 GW_{el}) times the electrolyser efficiency (e.g., 69 %) and ii) the project's technical capacity (e.g., 5 GW_{H2}, resulting in a maximum utilisation of 27 %).

b. For each hour, the unused import potential is calculated by subtracting the simulated import flows from the import capacity. The import potential is in this context defined as the minimum of i) a sources' supply potential and ii) the capacity of the import infrastructure connecting it. Thereby, no additional import infrastructures are considered beyond those that are already part of the hydrogen infrastructure level.

(i) In general, additional import infrastructures can mitigate certain hydrogen demand curtailments even without additional intra-EU transport capacity or additional storage capacity. The effect of adding certain additional import infrastructures can be observed when comparing the assessments of the two different hydrogen infrastructure levels.

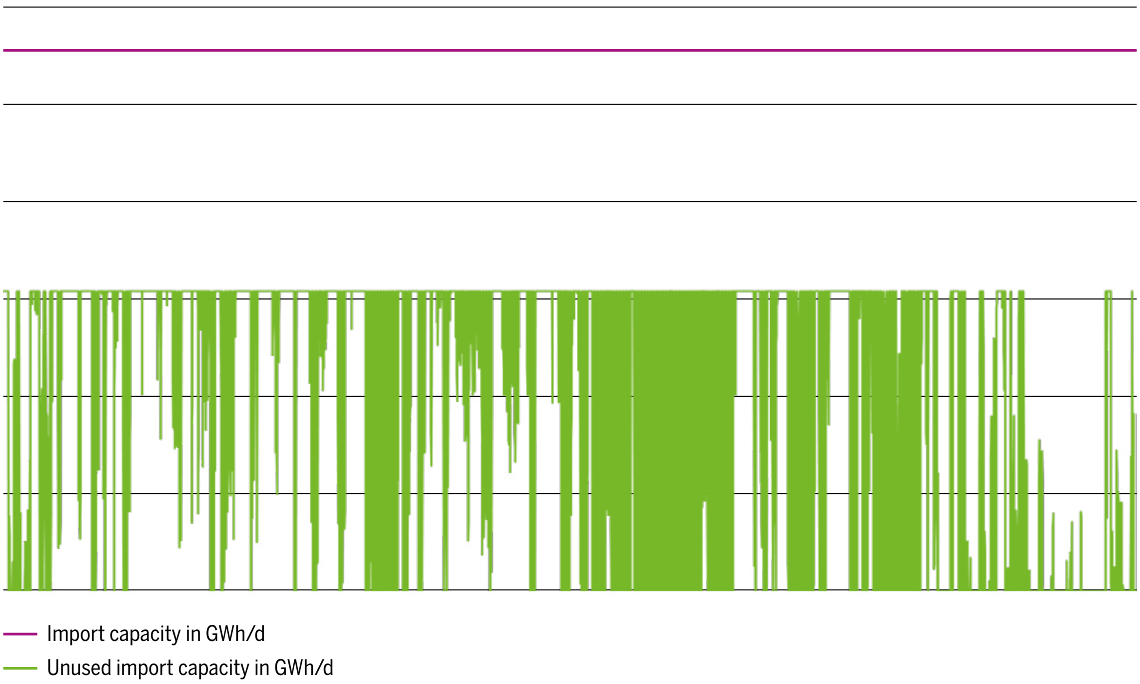

Figure 5: Example of the hourly, absolute EU-wide hydrogen import potential and its unused part.

c. For each hour, the unused electrolysis potential is calculated by assessing if there is unused RES and/or unused nuclear power generation in an electricity bidding zone and at the same time there is unused electrolyser capacity connected to it[7] (see point 3 of section 5.1). The value of the unused electrolysis potential is expressed after the application of the electrolyser efficiency.

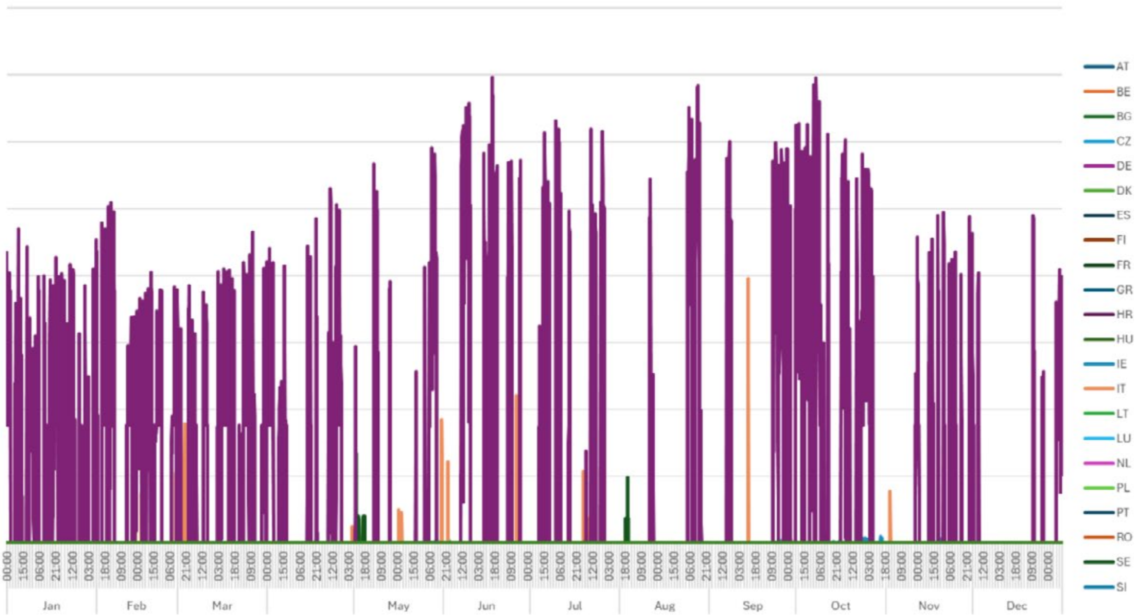

Figure 6: Example of the hourly, absolute EU-wide unused electrolysis potential per country.

7 While adding additional electrolyser capacity in electricity bidding zones with significant unused RES and/or unused nuclear power generation could further increase the hydrogen production and thereby mitigate hydrogen demand curtailment, the electrolyser capacity is considered as an input from the TYNDP 2024 scenarios that remains unchanged in the TYNDP 2024.

d. For each hour, the hypothetical absolute minimum EU-wide hydrogen demand curtailment is calculated that would be achievable if there was unlimited intra-EU transport capacity but no variation in storage capacity and no variation in the production of hydrogen from natural gas in the EU. It indicates the minimum hydrogen demand curtailment situation that could be achieved by adding only intra-EU pipeline connections (without allowing more unabated hydrogen production from natural gas to reach other nodes). **If it is lower than the hydrogen demand curtailment of step a, additional intra-EU hydrogen pipelines that are not part of the assessed hydrogen infrastructure level could mitigate hydrogen demand curtailments.**

   This assessment can be further broken down into (groups of) countries. The calculation is the following:

   (i) Calculate the maximum hourly value of i) 0 and ii) the EU-wide hydrogen demand curtailment minus the unused import potential minus the unused electrolysis potential.

   This represents the reduced hydrogen demand curtailment enabled by unlimited intra-EU interconnections but without an optimisation of the usage of the storages contained in the hydrogen infrastructure level.

   (ii) Calculate an improved usage of storages contained in the hydrogen infrastructure level by allowing them to store the remaining unused import potential and/or unused electrolysis potential after step (i) and to withdraw hydrogen to satisfy the reduced hydrogen demand curtailment after step (i). To make sure that the requirement of 50 % storage filling level in the last hour of the year is fulfilled, the withdrawal from the storages is limited after the last hour of the year in which the storages reach a filling level of 100 % or from the first hour of the year if a filling level of 100 % cannot be reached.

   (iii) Calculate the remaining hydrogen demand curtailment after step (i) and step (ii).

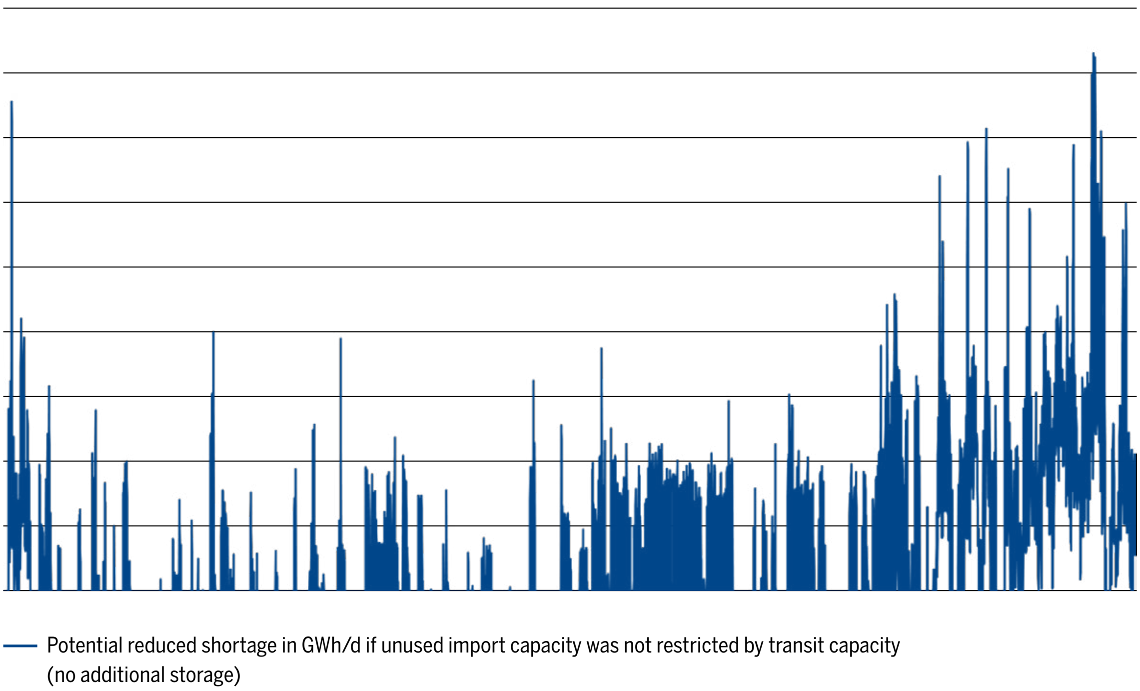

Figure 7: Example of the hourly, minimum hypothetical EU-wide hydrogen demand curtailment for unlimited intra-EU hydrogen transport capacities but no changes of storage behaviour.

3. Displaying which additional hydrogen demand curtailment is caused by limited intra-EU hydrogen storage capacity, calculated as follows on EU level based on the DHEM results:

    a. In step 2.d, still not all unused import potential and/or unused electrolysis potential may be utilised. For this, additional hydrogen storages would be needed. The needed additional storage capacity can be estimated by using the fact that each consecutive hour, i) the still unused import capacity can be injected into a hypothetical additional hydrogen storage or ii) hydrogen stored therein can be withdrawn to satisfy the already reduced hydrogen demand curtailment of step 2.d. Thereby, the injection and withdrawal capacities are limited by the maximum injection and withdrawal capacities that are defined on the basis of the working gas volume of the hypothetical additional hydrogen storage.

The location of this storage thereby is irrelevant as the EU-internal interconnections are considered as unlimited. These limitations are identical with those imposed on the real projects contained in the hydrogen infrastructure level. The hypothetical additional hydrogen storage level can never be negative or higher than the assumed working gas volume. Furthermore, the filling level must be identical in the first and in the last hour of the year (steady-state requirement). The delivery of this step is the hypothetically needed additional hydrogen storage capacity. It can be displayed as a factor of additional hydrogen storage need compared to the actual hydrogen storages in the hydrogen infrastructure level (e.g., factor 5.2). As no intra-EU transit restrictions are considered that could affect the optimum usage of hydrogen storages, this additional storage size is minimised.

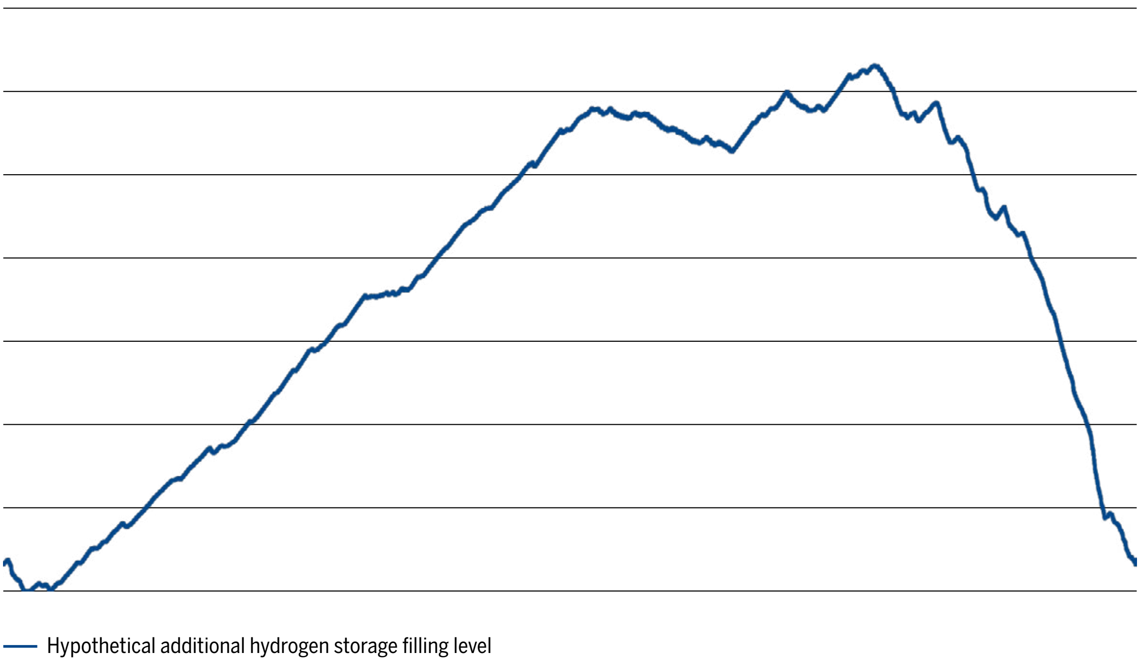

Figure 8: Example of the filling level of a hypothetical additional hydrogen storage to make full use of the import potential.

Picture courtesy of Fluxys Belgium

b. There can still be remaining hydrogen demand curtailment after step 3.a. This remaining hydrogen demand curtailment is equivalent to a structural undersupply of hydrogen that cannot be solved by making full use of all hydrogen import potentials (as defined in step 2.b) as described in the previous steps. It is the sum of all hourly deltas between the reduced hydrogen demand curtailment of step 2.c and the storage withdrawals of step 3.a.

   This supply gap can only be satisfied by additional supplies. As the electrolyser capacities of each country are limited by the TYNDP 2024 Scenario Report, the remaining option is additional extra-EU hydrogen supply potentials according to the TYNDP 2024 Scenario Report. The supply gap is therefore quantifying the minimum need of additional hydrogen import potential (as the hydrogen supply potential of the hydrogen infrastructure level is already used to its maximum).

4. Overview of infrastructure gaps that could be solved by the additional projects of the Advanced hydrogen infrastructure level (i.e., one threshold is passed for the PCI/PMI infrastructure level, and no threshold is passed for the Advanced hydrogen infrastructure level).

5. Identification of projects responsible for solving hydrogen infrastructure gaps by addressing hydrogen infrastructure bottlenecks.[8]

6. Overview of regional hydrogen infrastructure gaps that could be partially mitigated by additional projects in the Advanced hydrogen infrastructure level compared to the PCI/PMI hydrogen infrastructure level.

7. Identification of projects responsible for partially mitigating hydrogen infrastructure gaps by addressing hydrogen infrastructure bottlenecks.

8 As the IGI is based on a limited number of simulation cases (i.e., two different weather years), there might be other cases that would result in the identification of additional projects being responsible for solving or partially mitigating hydrogen infrastructure gaps.

7 OVERVIEW OF SIMULATION CASES FOR THE INFRASTRUCTURE GAPS IDENTIFICATION REPORT

No.	Scenario	Infrastructure levels			Weather year	Model	IGI indicator
		Electricity	Hydrogen	Natural gas			
1	NT+ 2030	NT+ 2030	PCI/PMI	–	Reference	DHEM	1 and 2.1
2	NT+ 2030	NT+ 2030	PCI/PMI	–	Stressful	DHEM	2.2
3	NT+ 2030	–	PCI/PMI	Low	Stressful	DGM	2.2
4	NT+ 2030	NT+ 2030	Advanced	–	Reference	DHEM	1 and 2.1
5	NT+ 2030	NT+ 2030	Advanced	–	Stressful	DHEM	2.2
6	NT+ 2030	–	Advanced	Low	Stressful	DGM	2.2
7	NT+ 2040	NT+ 2040	PCI/PMI	–	Reference	DHEM	1 and 2.1
8	NT+ 2040	NT+ 2040	PCI/PMI	–	Stressful	DHEM	2.2
9	NT+ 2040	–	PCI/PMI	Low	Stressful	DGM	2.2
10	NT+ 2040	NT+ 2040	Advanced	–	Reference	DHEM	1 and 2.1
11	NT+ 2040	NT+ 2040	Advanced	–	Stressful	DHEM	2.2
12	NT+ 2040	–	Advanced	Low	Stressful	DGM	2.2

Table 1: Combinations of scenarios, years, infrastructure levels, cases, models, and indicators for the infrastructure gaps identification of hydrogen infrastructure.

8 IMPLEMENTATION OF THE ENERGY EFFICIENCY FIRST PRINCIPLE IN THE INFRASTRUCTURE GAPS IDENTIFICATION

The introduction part of section 6 as well as section 6.1 of the TYNDP 2024 Implementation Guidelines are also valid for this TYNDP 2024 IGI methodology. Furthermore, the

Inclusion of options for better utilisation of existing infrastructure

- The existing infrastructure considered in the TYNDP 2024 topology is updated with information that is provided by the infrastructure operators. This provides the option to update the underlying energy infrastructure capacities which are the main parameter capturing the ability of better utilisation through operational improvements, including by digital solutions. Also, the consideration of infrastructure of multiple energy sectors like hydrogen, electricity, and natural gas allows an optimisation of the utilisation of the existing infrastructure's capacities in the model through flexibility provisions across energy sectors.

Inclusion of options to include more energy-efficient technologies

- The TYNDP 2024 IGI report is prepared based on the NT+ scenario that includes energy efficiency measures as described in the section 6.1 of the draft TYNDP 2024 Implementation Guidelines. Thereby, a decisive share of the measures (e.g., renovations of buildings) have been set at the highest level that can be considered as feasible and realistic under current targets, policies, and expected technological advancements. Thereby, in line with the energy efficiency first principle, the most energy efficient solution does not have to prevail but should be considered within the decision-making process and be preferred if being similarly cost-efficient, and beneficial for security of supply. By already being part of the NT+ scenario, the selected energy efficiency measures are not associated with additional investments in the simulations for the TYNDP 2024 IGI report and their usage is always an option alongside the identification of infrastructure gaps.

Inclusion of options to make better use of the market mechanisms

- By considering perfect competition only limited by infrastructure constraints between nodes, as well as by allowing demand side response to be acting without infrastructure or market restrictions (e.g., if the demand side response is located at DSO level) within a whole zone, the market behaviour is optimistic regarding the effects of demand side management. Several demand side responses are therefore considered. The pattern of the total demand is not simply transferred from the NT+ scenario to the TYNDP, but the underlying assets are used within their specifications to allow their optimised utilisation.
- Concerning the DHEM-based assessments, this relates to
  - assets coupling the sectors through conversion (i.e., electrolysers and hydrogen-fired power plants);
  - demand shedding (e.g., reduction of industrial demand for a limited time that is triggered by a certain market clearing price).
- Concerning the DGM-based assessments, this relates to
  - the calculation of monthly profiles for the DGM, which is not only a simplification, but also assumes the possibility of significant temporal flexibility of natural gas and hydrogen demand, interpretable as demand-shifting possibilities within a sector and/or additional availability of storage options and/or further optimisation of existing infrastructure's utilisation. This prioritises all relevant alternatives to new infrastructure, while being agnostic concerning the actual solution;
  - assets coupling the sectors through conversion (i.e., hydrogen production from natural gas);
  - the model being allowed to investigate the optimal solution for each stress case with several degrees of freedom (i.e., usage of hydrogen supply sources and natural gas supply sources).

Aiming at balancing security of supply, quality of energy supplied, and cost-efficiency

- The wider benefits of investments are addressed from a system efficiency and societal perspective.
- Concerning the DHEM-based assessments, this relates to
  - monetising unserved energy demand (i.e., VoLL and WTP_{H2});
  - penalising energy losses contributing negatively to life cycle efficiencies (e.g., reflection in marginal costs of fuels, conversion losses of electrolysers, conversion losses of power plants, efficiencies of energy storages);
  - penalising of emissions (e.g., reflection in marginal costs of fuels and thereby in the merit order);
  - simulating with an integrated model covering the hydrogen and the electricity sector.
- Concerning the DGM-based assessments, this relates to
  - penalising unserved energy demand (i.e., reflection in merit order list and usage to identify infrastructure gaps);
  - penalising energy losses contributing negatively to life cycle efficiencies and emissions (e.g., conversion losses of hydrogen production from natural gas, reflection in merit order);
  - simulating with an integrated model covering the hydrogen and the natural gas sector.

LIST OF **ABBREVIATIONS**

The list of abbreviations of the **TYNDP 2024 Implementation Guidelines** is also valid for this document. Additionally, the following abbreviations apply:

ENNOH	European Network of Network Operators for Hydrogen
BEMIP Hydrogen	Hydrogen and electrolyser priority corridor containing Denmark, Germany, Estonia, Latvia, Lithuania, Poland, Finland, Sweden
GHR	Regulation of the European Parliament and of the Council on the internal markets for renewable gas, natural gas and hydrogen, amending Regulations (EU) No 1227/2011, (EU) 2017/1938, (EU) 2019/942 and (EU) 2022/869 and Decision (EU) 2017/684 and repealing Regulation (EC) No 715/2009 (recast)
HI East	Hydrogen and electrolyser priority corridor containing Bulgaria, Czechia, Germany, Greece, Croatia, Italy, Cyprus, Hungary, Austria, Poland, Romania, Slovenia, Slovakia
HI West	Hydrogen and electrolyser priority corridor containing Belgium, Czechia, Denmark, Germany, Ireland, Spain, France, Italy, Luxembourg, Malta, Netherlands, Austria, Portugal

Picture courtesy of terranets bw

COUNTRY CODES (ISO)

AL	Albania
AT	Austria
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BE	Belgium
BG	Bulgaria
BY	Belarus
CH	Switzerland
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
DZ	Algeria
EE	Estonia
ES	Spain
FI	Finland
FR	France
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxembourg
LV	Latvia
LY	Libya
MA	Morocco
MD	Moldova
ME	Montenegro
MK	North Macedonia
MT	Malta
NL	Netherlands
NO	Norway
PL	Poland
PT	Portugal
RO	Romania
RS	Serbia
RU	Russia
SE	Sweden
SI	Slovenia
SK	Slovakia
TM	Turkmenistan
TN	Tunisia
TR	Turkey
UA	Ukraine
UK	United Kingdom

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