April 2024

Progress Report on Interlinked Modelling

The Cross-Sectorial Integration of Energy System Planning

CONTENTS //

1 EXECUTIVE SUMMARY //

The European energy landscape is undergoing a transformative shift towards climate neutrality, transitioning from traditional oil and gas exploration to sustainable energy production methods. A notable focus has emerged in the development of the hydrogen sector, showcasing a rapid shift in Europe's energy priorities. Renewable energy plays a crucial role in hydrogen production, creating a strong interconnection between the electricity and hydrogen sectors.

This report delves into the intricate links between the electricity and hydrogen sectors, emphasizing the need to comprehend the reciprocal impacts and identify synergies. Understanding the interplay of assets in both sectors is essential for minimising overall energy costs and CO_2 emissions in Europe and neighbouring countries.

The key objectives of the report include:

- Exploring the integration of the power and hydrogen systems, particularly through electrolysers powered by low carbon electricity.
- Optimizing shared infrastructure, with a focus on shared renewables designed for hydrogen production, and their potential contribution to the power system.
- Assessing the social and economic welfare impact of projects involving electricity grids, electrolysers, and hydrogen pipelines in both the power and hydrogen systems.
- Evaluating the effect of such projects on CO_2 emissions and Renewable Energy Source (RES) integration in the hydrogen and power sectors.
- Providing recommendations for the further development and utilisation of the Interlinked Model.

This report aims to uncover the intricacies of these connections, offering insights into fair and accurate project valuation within the Ten-Year Network Development Plans (TYNDPs). It is anticipated that this exploration will contribute to understanding the impact of the energy transition on Europe's future gas and electricity networks.

Both associations await inputs from stakeholders to enrich the findings of this report. We anticipate that the recommendations provided will foster informed decision-making for a sustainable and integrated energy future in Europe.

2 INTRODUCTION //

2.1 Scope of the document

To efficiently meet the EU decarbonisation targets, it is recommendable to adopt a comprehensive perspective of the energy system. An Interlinked Model can play an important role in this context by striving to ensure that the mutual influence of the natural gas, hydrogen and electricity sectors are considered during the evaluation of infrastructure projects in the context of cost-benefit analysis (CBA) in the respective TYNDPs. This approach acknowledges the interconnected nature of energy systems and underlines the importance of comprehensive planning to optimise the development and sustainability of the European Union's energy infrastructure.

Based on the investigations carried out in the period 2019–2020 and implementing recently adopted European Regulations, ENTSO-E and ENTSOG have worked on the development of a consistent process for the inclusion of a dual infrastructure assessment in TYNDPs as well as of a methodology for its application.

The target of this exercise is to be able to explore methodologies for the development of an "Integrated Model" that shall provide consistency between single sector methodologies based on common assumptions including electricity, Methane and hydrogen transmission infrastructure. This report focuses on the development of a joint electricity and hydrogen model.

The aim of this report is therefore to describe the progress made by ENTSO-E and ENTSOG on the integration of their respective models and make it transparently available for stakeholders. This report also includes recommendations for use of an Interlinked Model in the respective TYNDPs and a set of recommendations for future improvements.

2.2 Background

According to Article 8(3)(b) of Regulation 714/2009 and Article 8(3)(b) of Regulation 715/2009, ENTSO-E and ENTSOG must publish their TYNDPs on a biennial basis.

Article 11(8) of Regulation (EU) 347/2013 required ENTSO-E and ENTSOG to submit by 31 December 2016 a consistent and interlinked electricity and gas market and network model including both electricity and gas transmission infrastructure as well as storage and LNG facilities, On 21 December 2016, ENTSO-E and ENTSOG submitted the ILM2016 to the European Commission and the Agency for the Cooperation of Energy Regulators (ACER) for approval. The key element of the model submitted by ENTSO-E and ENTSOG was the joint development of scenarios that constitute the basis for the cost-benefit analysis of Methane and electricity infrastructure projects.

In March 2017, ACER published its opinion on the ENTSO-E's and ENTSOG's draft consistent and interlinked electricity and Methane market and network model (so called "Interlinked Model" or "ILM"). The opinion stated that the following phenomena should have been investigated in further details: (1) Interaction of the price formation process for the Methane and electricity sectors; (2) Interaction (potential competition and synergies) of electricity and Methane infrastructure developments; (3) Cross-sectoral influence of Methane and electricity projects.

In September 2019 the "Investigation on the interlinkage between Methane and electricity scenarios and infrastructure projects assessment" Report commissioned by ENTSO-E and ENTSOG to Artelys, was published. Main objective of this focus study was to provide the elements to determine for which kind of projects a more thorough investigation of the impacts of interlinkages should be performed.

In 2020, the Interlinked Model Project Team has worked to test, develop, and implement a project screening methodology, considering the outcomes of the Artelys Focus Study as well as to test and develop a dual assessment methodology for electricity, methane and hybrid projects for its application as a pilot on the basis of the TYNDP 2020 data. The ILM Progress Report was then published in 2021.

Regulation (EU) 2022/869, adopted by the European Parliament and the European Council in May 2022, replaced Regulation (EU) 347/2013 and states in Article 11(10) that by 24 June 2025 ENTSO-E and the ENTSOG shall jointly submit to the Commission and ACER a consistent and progressively integrated model that will provide consistency between single sector methodologies based on common assumptions including electricity, natural gas and hydrogen transmission infrastructure as well as storage facilities, liquefied natural gas and electrolysers, drawn up in line with the principles laid down in Annex V.

Regulation (EU) 2022/869 also limits the project-specific cost-benefit analysis scope for PCI projects (Projects of Common Interest) within the TYNDPs to electricity transmission projects, energy storage facilities projects and hydrogen infrastructure projects.

DEVELOPMENT PERIOD	MODEL NAME	CODE	CARRIERS	MODEL TYPE	LINKS
2016 - 2018	TYNDP 2018 Scenarios	SCN2018	Electricity / Methane	Scenario Model	Link
2018 - 2020	Artelys investigation on interlinkages	ILM2018	Electricity / Methane	Report	Link
2020 - 2022	Interlinked Model Investigation	ILM2020	Electricity / Methane	Linked Model (output → Input)	Link
2022 - 2024	Interlinked Model Investigation: 2024 Progress Report	ILM2024	Electricity / Hydrogen	Cross Sectoral Integrated Model	In Progress

Table 1: History of interlinked model

2.3 ILM Progress Report 2020

In 2020, ENTSO-E and ENTSOG joined forces to further test, verify and develop project screening and dual assessment methodologies based upon the outcome of the report "Investigation on the interlinkage between Methane and electricity scenario and infrastructure projects assessment", produced by Artelys.

The aim was to test the methodologies on TYNDP 2020 data and to derive a set of recommendations to identify further improvements in view of the future TYNDP editions.

A final report called "Interlinked Model Investigation" was published by ENTSOG and ENTSO-E in spring 2021 (link). The outcome of this investigation has also provided input to the TYNDP scenarios development process.

The ILM Progress Report mainly focused on two types of interactions (called "conditions") where a Methane or an electricity project can have an impact on (or be impacted by) each other and the related energy systems: (1) interlinkages under significant presence of Methane-to-power; (2) interlinkages under significant presence of power-to-gas.

2.4 A New Approach

The European energy sector naturally evolves as new national, regional and global targets are ratified. Over the last 3 years, these evolutions have been rapid and substantial.

The development of various hydrogen strategies, as well as a focus to reduce extra-EU Methane dependencies, has shifted the direction of focus for interlinked modelling. ENTSOG has been called to run the first hydrogen project-specific CBA for the TYNDP 2022. Significant electrolyser capacity has been added to the TYNDP scenarios. Finally, the CBA process in future TYNDPs will explore benefits of projects which contain assets connecting to a combination of the electricity, hydrogen and methane systems. Such projects should be assessed by an Interlinked Model to determine their full system benefits as is legally required by Regulation (EU) 2022/869.

It is therefore the joint belief of ENTSOG and ENTSO-E that an Interlinked Model reflecting the increased importance of the coupling of the hydrogen, natural gas, and electricity sectors is a useful approach for future electricity, hydrogen, and natural gas TYNDPs.

The "Task Force Interlinked Model" is a group of experts from ENTSO-E and ENTSOG which have been tasked with the development of models and methodologies to be used for the next generation of TYNDPs. An Interlinked Model which connects the electricity and hydrogen systems at an EU level has been developed as well as new CBA methodologies which interact with the current ENTSO-E and ENTSOG methodologies.

The project screening and dual assessment methodologies from the ILM Progress Report 2020 has been replaced as it is a common consensus that most, if not all, projects could have a cross-sectoral impact, even if the assets are based in a single sector.

This report describes these new models and methodologies, presents key insights and sketches possible future developments of the ILM2024.

3 THE OVERALL PROCESS //

3.1 Governance structure for designing the methodology

The methodology presented in this document is the outcome of a joint development process from various experts from both Methane and electricity TSOs in the Task Force and Steering Group ILM.

Choices have been made giving priority to the accuracy of the model while still considering constraints such as complexity, timeline, data availability and computation time. The overall structure for the organisation of tasks and decisions related to the ILM2024 is pictured in Figure 1.

	ENTSOG	ENTSO-E
ILM STEERING GROUP	Kacper Zeromski (ENTSOG) Thilo Gruen (ENTSOG) Geert Smits (Fluxys) Jacques Reberol (GRTgaz)	Nils Schindzielorz (Tennet) Antje Orths (Energinet)
ILM CORE TEAM	Dante Powell (ENTSOG) Nils Melcher (Gascade)	Franck Dia Wagoum (ENTSO-E) Philipp Fortenbacher (Amprion)
ILM MODELLING TEAM / ILM TASK FORCE	Virginie Pison (Fluxys) Eglantine Kunle (GRTgaz) Satefano Pezzenati (Snam)	Jean-Marc Janin (RTE) (Modelling Team) Ana Clavero (REE) Pedro Carola (REN) Tobias Frohmajer (TenneT)

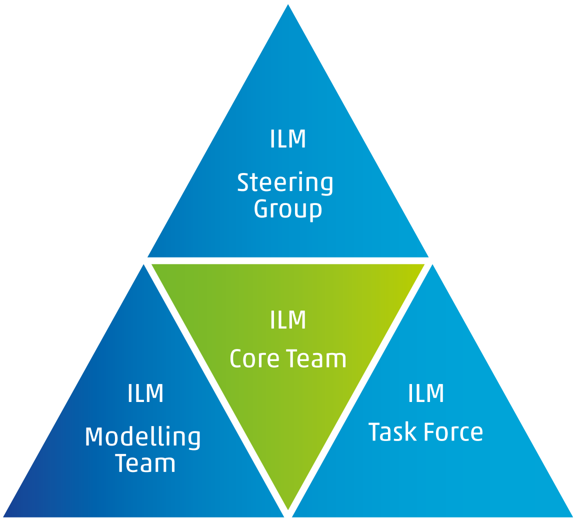

Figure 1: TF ILM Governance structure

3.2 Project assessment

Article 11 of Regulation (EU) 869/2022 requires that ENTSO-E and ENTSOG draft their own consistent single sector methodologies for a harmonised energy system-wide cost-benefit analysis at Union level for projects on the Union list falling under the energy infrastructure categories set out in point (1)(a), (b), (d) and (f) and point (3) of Annex II of this Regulation. These methodologies are also applied to the overall ENTSO-E and ENTSOG TYNDPs.

In line with their most recent CBA Methodologies, the current ENTSO-E and ENTSOG system assessment approach, which also represent the basis for the project assessment, can be represented as follows.

The ENTSO-E and ENTSOG TYNDP processes are largely similar and can be summarised in **four main steps**:

1. **Scenarios development**
2. **Project collection**
3. **System needs assessment**
4. **Project assessment**

The scenarios development is a process performed jointly by ENTSO-E and ENTSOG since TYNDP 2018.

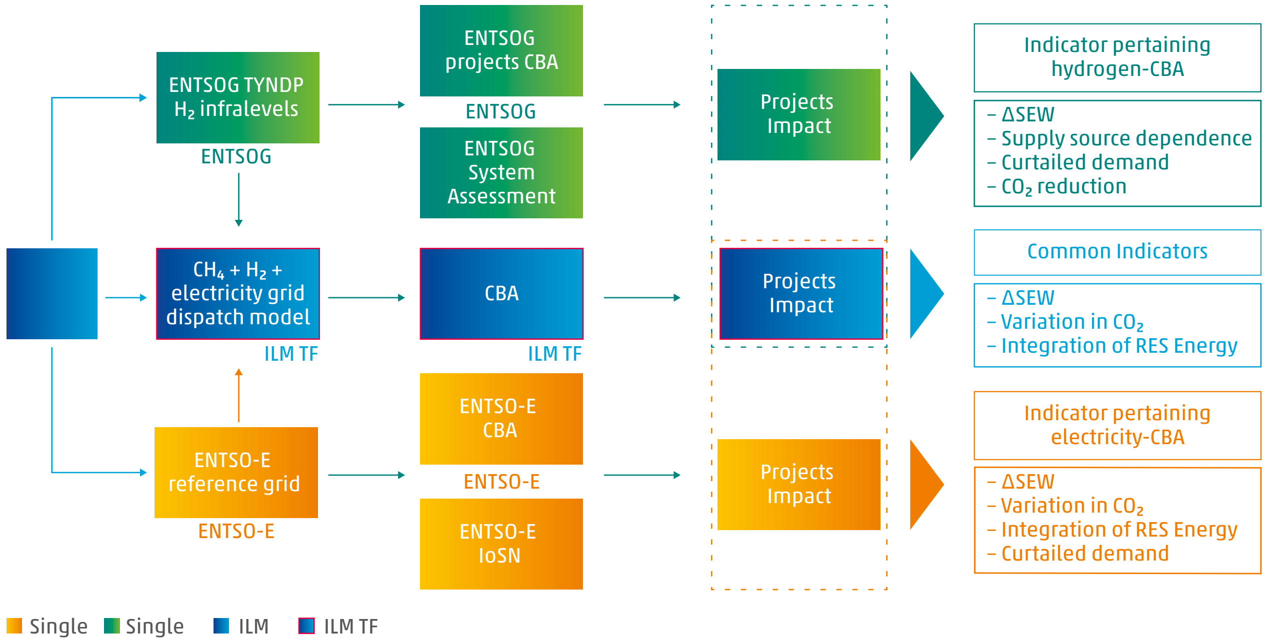

Figure 2: ENTSO-E/ENTSOG CBA approaches

Most of the interlinkages in the TYNDP are captured through the scenario development process. A TYNDP process that only assessed an individual sector after the scenario development process would show some limitations: It does not allow needs identification through the combined consideration of hydrogen, natural gas, and electricity "reference grids"[1] and their interaction, as well as cross-sectoral synergies in the respective project assessment phases. The Dual Gas Model developed by ENTSOG does however consider interactions between the Natural Gas and Hydrogen Sectors.

For this reason, a dual system and project assessment has been proposed and tested by ENTSO-E and ENTSOG as a first step.

3.3 Joint project assessment

The proposed dual sector project assessment captures interlinkages stemming from the interaction between hydrogen and electricity infrastructures of the respective assets under evaluation. **Improvements explored are based predominately on three elements:**

- **Common dispatch model**
- **Common reference grid considering projects from the electricity and hydrogen sector**
- **Commonality in capability of simulation tools**

The below process builds on the already well-developed TYNDP best practices and workstreams while allowing the identification of system needs and project impact under single and dual assessment and ensuring full comparability of results.

It also allows adequate flexibility to ENTSO-E and ENTSOG whose TYNDP processes do not fully match due to some intrinsic differences.

Application of an Interlinked project assessment approach allows to meet the following criteria:

- **To assess hydrogen and electricity projects under same common framework.**
- **To compare results from indicators assessed within the same hydrogen or electricity specific TYNDP (e.g. results for hydrogen project under single and dual assessment).**
- **More advancement towards assessing interlinkages and common "model".**
- **ENTSOG/ENTSO-E "way of doing" independence is preserved also for dual assessment.**

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[1] Differently from ENTSO-E, the ENTSOG TYNDP currently does not consider a single "reference grid" but it considers different possible development of infrastructure (so called "infrastructure levels") which are all used for the system assessment and needs identification.

4 MODEL DESCRIPTION //

In this section the topology of the ILM2024 will be explained. As the electricity and hydrogen topology do not follow the same zonal approach, the methodology of coupling both sectors to create a consistent integrated model must be explored and developed. The topology of the electricity and hydrogen systems including the underlying infrastructure used in the TYNDP model within ENTSO-E and ENTSOG will be discussed. The development of the model starting from the TYNDP 2022 scenario structure to the TYNDP CBA structure will also be discussed.

4.1 Base of the ILM2024 for the purpose of this report

The interlinked model is a market model using interconnectors to simulate flows between European bidding zones. Infrastructure internal to the bidding zones and their physical constraints are not represented in detail.

The models are made for the scope of the Ten Year Network Development Plan planning purposes e. g. infrastructure needs identification and cost benefit analysis at a pan-European scale but are limited with regard to some physical and locational constraints. However, some of these constraints are simplified through a series of processes within ENTSO-E and ENTSOG as well as within the TSOs.

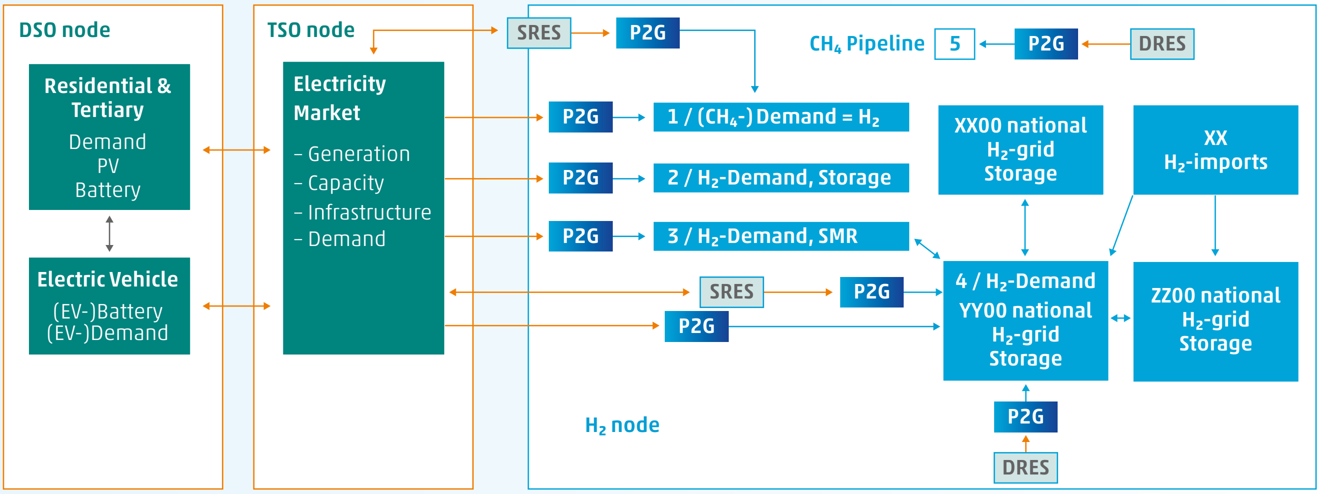

Figure 3: TYNDP 2022 Scenario topology

The ILM2024 is a simplified version of the TYNDP 2022 scenario model, which contains 3 electricity nodes and 5 hydrogen nodes per bidding zone as shown in Figure 3. It cannot be understated the importance of the work undertaken in the scenario development process as it pertains to the development of the ILM2024. A link to the TYNDP 2022 Scenario reports and data can be found here.

To test the ILM2024 within the timeframe available, the model must be simplified. One reason for this is that at least 2 modelling tools are required to compare the consistency of outputs, giving a greater level of quality control.

There are many benefits to reducing the size of the model, e.g. the time benefits of running several hundred projects can be significant. Reruns are a common practice for a multitude of reasons, e.g. a requested sensitivity study. The testing process puts further necessity on the need to reduce the size of the model as high-volume testing is required, thus simulation time must be reduced. However, the reduction in model size means simplifications must be made for better or worse. As the hydrogen system is yet to be developed it is unclear whether the ILM2024 or TYNDP 2022 scenario representation are closer to the future design of the hydrogen system. More detail on the Scenario model description can be found on the Scenario 2022 Website[1].

The ILM2024 follows ENTSO-E's TYNDP Study Team's electricity model, where the electricity system nodes are reduced from 3 to 1 node per bidding zone as shown in Figure 4. The "Residential and Tertiary" demand, PV and Batteries are absorbed into the electricity market. The electric vehicles are modelled as batteries in the scenarios, which enables the use of demand side management. This feature is not included in the interlinked model, which removes the "vehicle to grid" and demand side shifting capabilities of the model. This is the same approach, which is used within the electricity TYNDP, where the focus is cross border benefits.

The model reduces the hydrogen zones from 5 to 2:

- **Scenario Zone 1**, **2** and **3** represent dedicated zones for Production of synthetic fuels, industrial processes with steel tank storages and current hydrogen demand which use SMR. These Scenario Zones have been combined into 1 called "Zone 1" in the ILM2024.
- **Scenario Zone 4** in the scenarios represent the hydrogen market. This Stream is simply renamed to "Zone 2" in the ILM2024.
- **Scenario Zone 5** is a dedicated zone that exists outside both the electricity and hydrogen markets and therefore has no effect on the re-optimisation of the model with projects included.

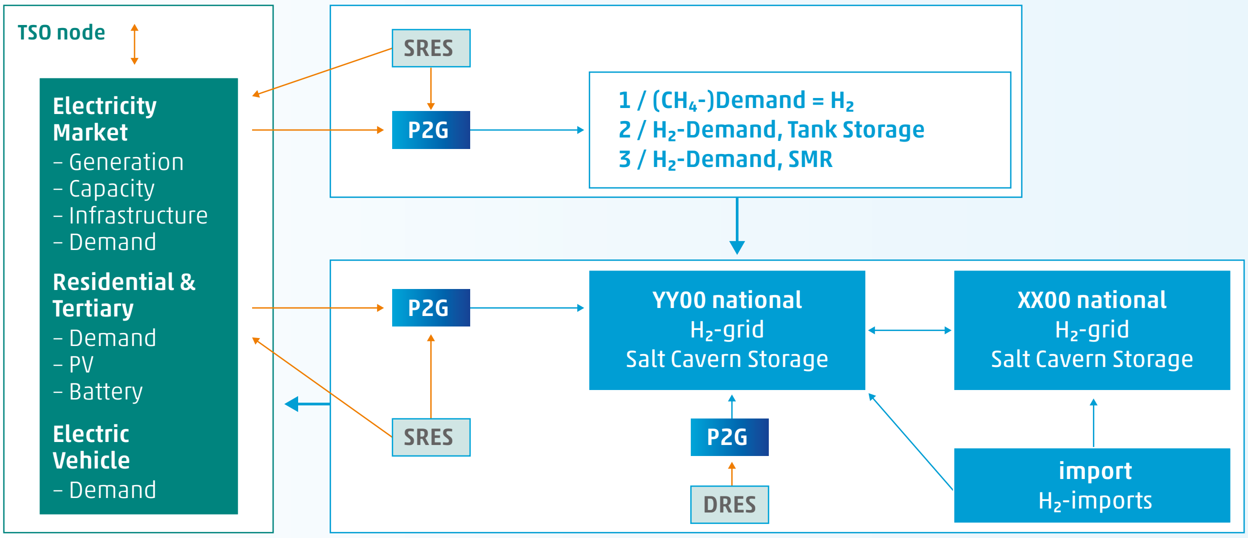

Figure 4: 2022 ILM model topology

The electricity reference grid mentioned here refers to cross-border infrastructures with a high probability (certainty) of availability by a particular date. As such, the reference grid does not represent national grid infrastructures and their physical limitations. This date changes based on the target year considered for the project assessment (typically 2030, 2040, 2050) and the certainty criteria is often based on project status. The hydrogen reference grid is based on the relevant projects submitted to ENTSOG's TYNDP and the respective PCI call. The infrastructure grid topology for electricity and hydrogen can be seen in Figure 5 on the following pages.

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[1] https://2022.entsos-tyndp-scenarios.eu/

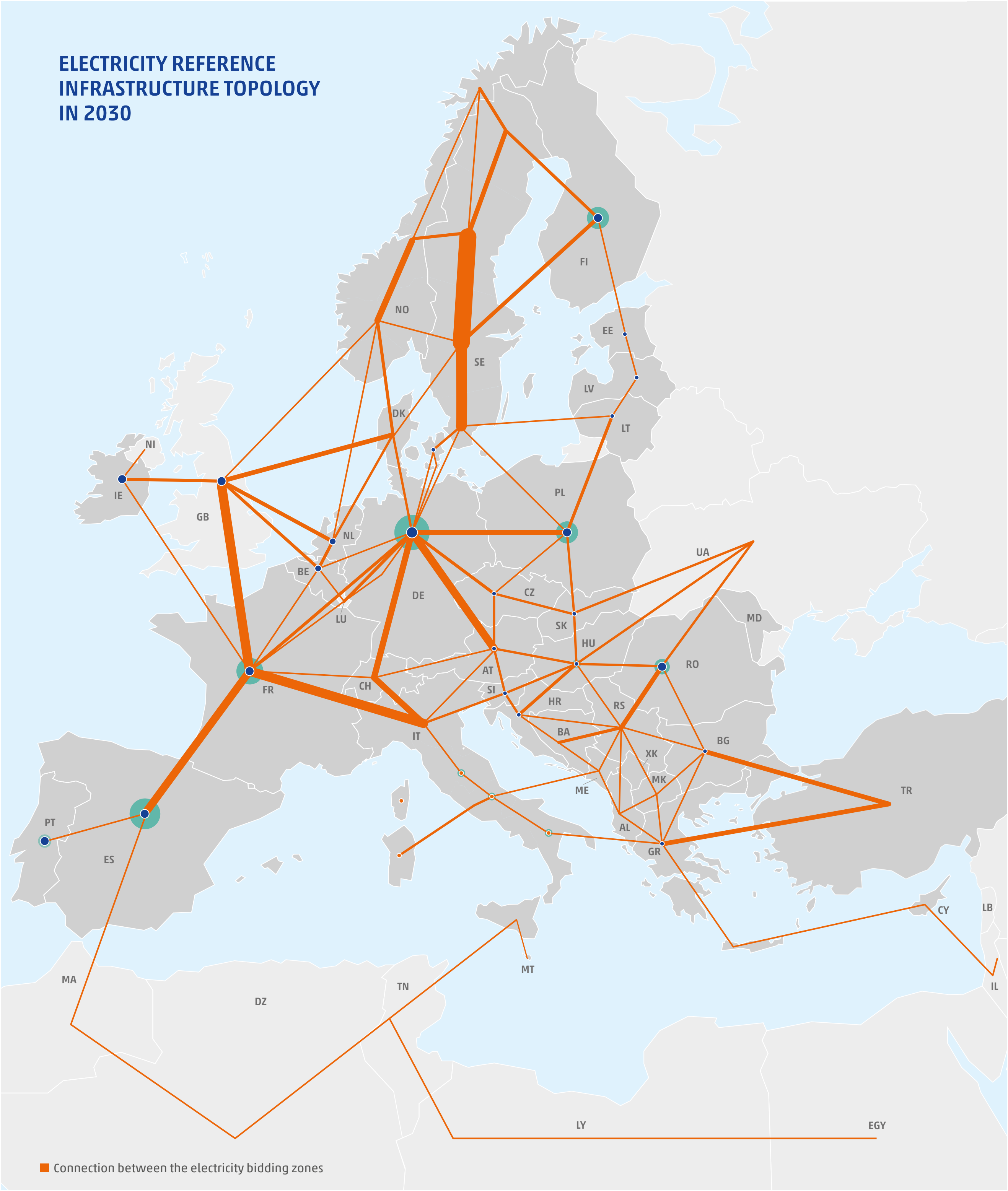

Figure 5a: Electricity reference infrastructure topology in 2030

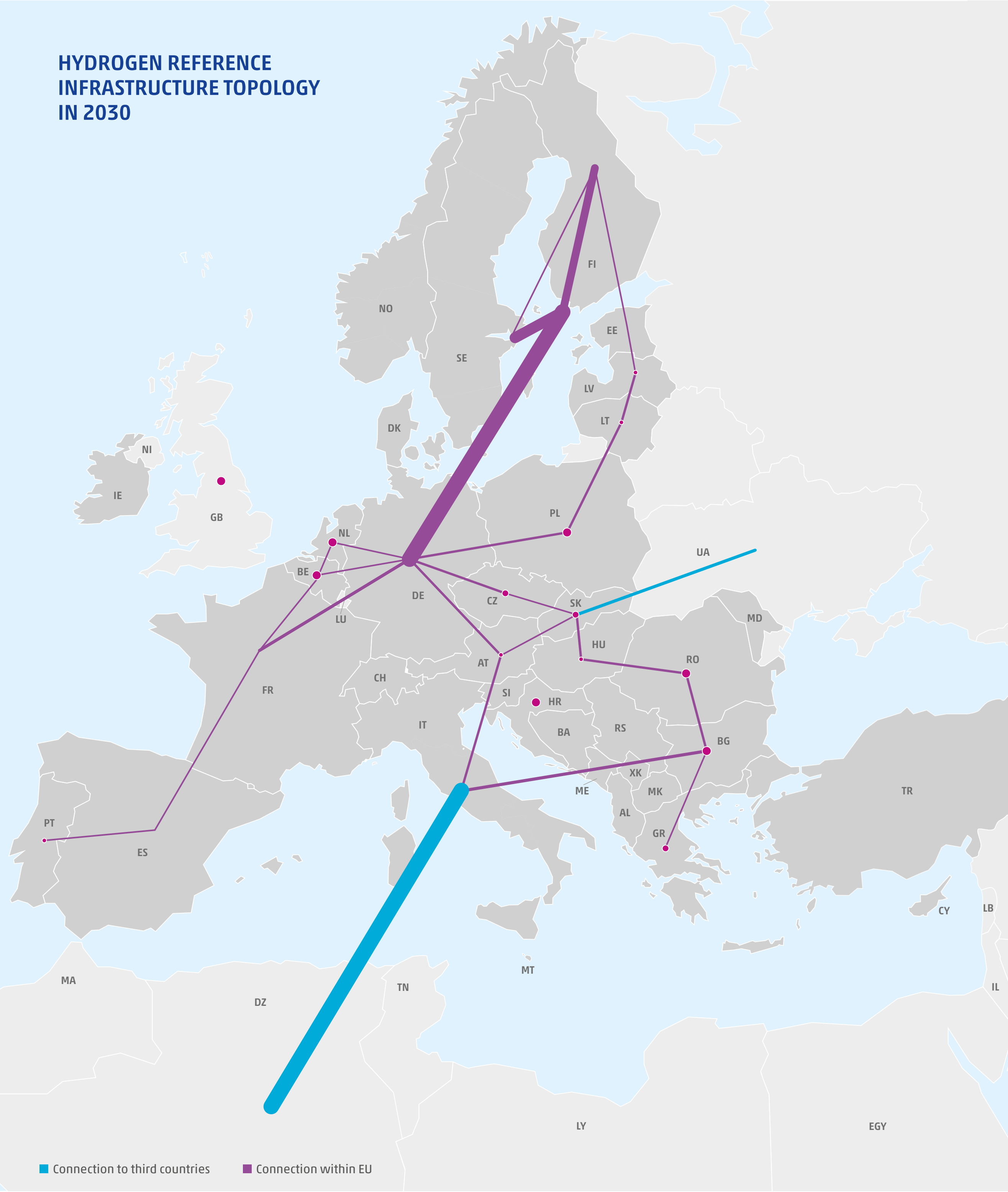

Figure 5b: Hydrogen reference infrastructure topology in 2030

4.2 Electricity topology

The electricity model contains supply and demand from all sectors. Each node represents 1 EU bidding zone. Hence, model nodes are aligned with the design of current electricity markets bidding zones across Europe. Most countries only use 1 bidding per country and therefore 1 node per country, but there are 7 countries which use additional nodes.

Italy: 7 bidding zones

Sweden: 4 Bidding Zones

Denmark: 2 Bidding Zones

Norway: 3 bidding zones

Greece: 2 Bidding Zones

Luxemburg: 4 Bidding Zones

United Kingdom: 2 Bidding Zones

Any countries outside of the EU27 countries, with the exception of Norway, are represented as 1 node.

4.2.1 Supply and Demand

Generation capacities, including electrolysers are aligned with the scenarios. One difference between the scenario model and the ILM2024 is the way electric vehicles are modelled including the reduction in flexibility from V2G. It also means that transport profiles are modelled as charging profiles rather than the driving profiles used in the scenario process. This approach is in alignment with the models used for the TYNDP.

4.2.2 Infrastructure

In the scenario model, infrastructure is based on the reference grid taken from the previous TYNDP, with additional capacity added based on the expansion model. The main purpose of the scenario development process is to determine the locations of new renewables and electrolysers; once this target has been reached the expanded grid is abandoned within the TYNDP process.

A new reference grid collected for the 2022 cycle of the TYNDP is used to replace all electricity infrastructure from the scenario building process.

4.2.3 Prices

All prices are taken from the scenarios. This includes the CO_2 price, fuel prices, VO&M costs and any other additional prices which are used to determine the merit order of the electricity and hydrogen markets.

4.3 Hydrogen topology

4.3.1 Zones

The hydrogen system is developed with each country represented as 2 Zones (Zone 1 and Zone 2) with 1 node per Zone. The Zone 1 represents off grid hydrogen production and demand. This means that there may be inconsistencies between the electricity and the hydrogen sectors in the countries mentioned in section 4.2. If there are multiple nodes in the electricity system, all electricity nodes connected to Zone 1 will funnel into the single Zone 1 H_2 node and all electricity nodes connected to Zone 2 will funnel into the single Zone 2 H_2 node as shown in Figure 6. H_2 CCGTs are connected to the H_2 node, in the case of inconsistent topologies, the H_2 will be sourced from the holistic H_2 node.

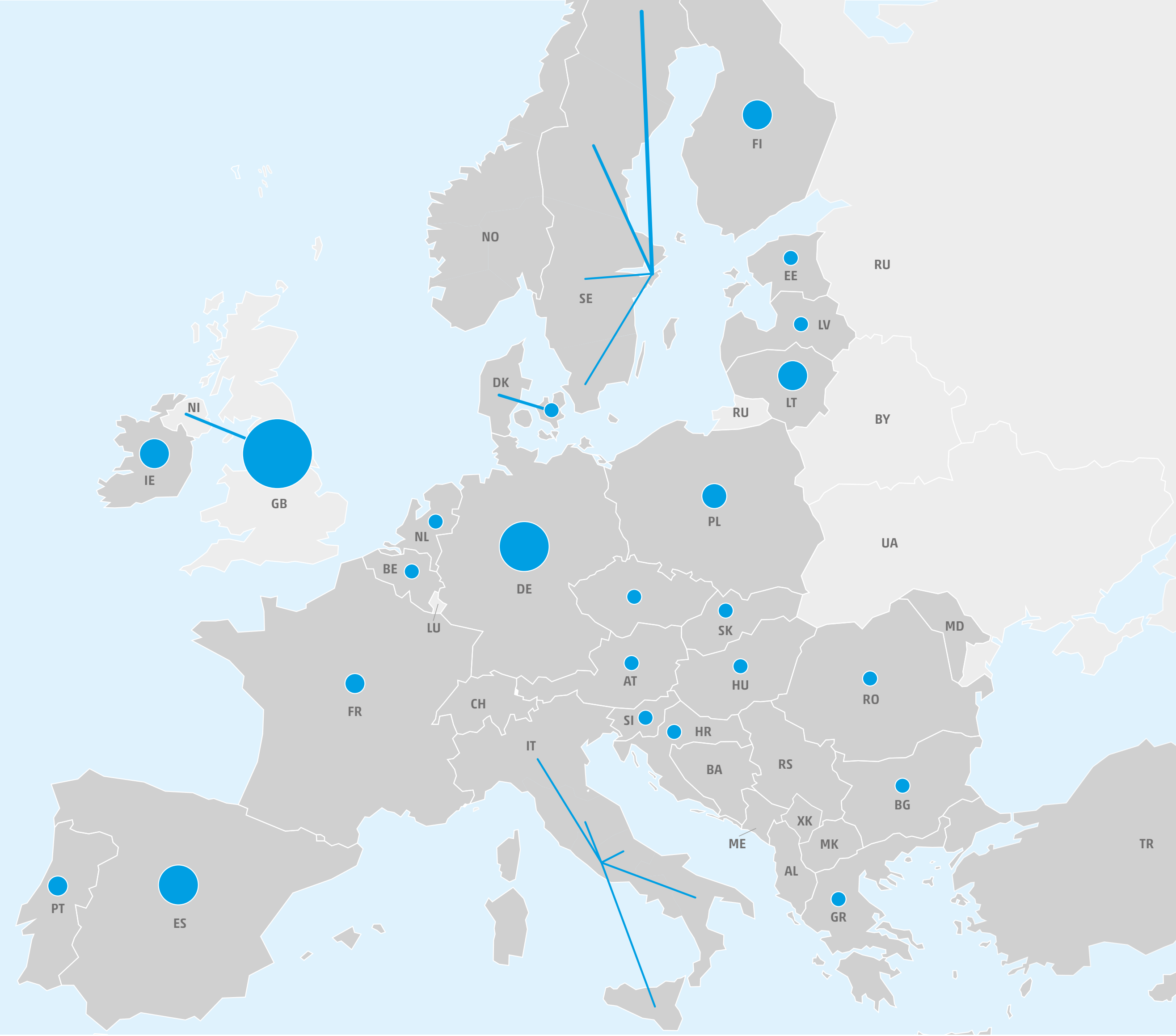

Figure 6: Intersection between hydrogen and electricity

4.3.2 Supply and Demand

As the ILM2024 has been reduced from the scenario model, some of the Scenario Zones from the scenario model must be combined to create the ILM2024 structure. ILM Zone 1 contains demand from the first 3 Scenario Zones and ILM Zone 2 represents Scenario Zone 4.

The supply sources and flexibilities included in Zone 1 are:

- Electrolysers connected to the electricity market.
- Electrolysers connected to dedicated renewables which can subsequently be added to the electricity market (then becoming shared renewables).
- Steam Methane Reformers which exist today. The assumption is that they will be retrofitted with CCS.
- Steel Tanks with the capacity of two days demand from Scenario Zone 2.

All Electrolyser capacities are taken from the scenarios.

The supply sources and flexibilities included in Zone 2 are:

- Electrolysers connected to the electricity market.
- Electrolysers connected to dedicated renewables.
- Pipeline Imports.
- Pipelines (Infrastructure Level 1 of ENTSOG's TYNDP 2022).
- Salt Cavern Storages (Infrastructure Level 1 of ENTSOG's TYNDP 2022)[2].

4.3.3 Infrastructure

The hydrogen infrastructure level is taken from "Infrastructure Level 1" from ENTOSG's TYNDP 2022. Hence, only interconnections between countries, but no national grids will be modelled. As modelled in the electricity sector, the additional investments in pipeline capacities made by the scenario are removed and replaced with the infrastructure levels. There are traditionally multiple Infrastructure levels used in the ENTSOG TYNDP for different purposes. The ILM2024 uses only Infrastructure Level 1. There is an additional set of technical pipelines which have been taken from the scenarios. This is the connection between ILM Zone 1 and ILM Zone 2 and represents the possibility that hydrogen production outside of the market may be eventually connected into the market.

4.3.4 Storage

As with the hydrogen pipelines, the reference storage levels represent Infrastructure Level 1 of ENTSOG's TYNDP 2022 is considered.

4.3.5 Prices

The model contains prices for SMR and imports. These prices are taken from the scenarios. Hydrogen market prices are determined endogenously in the model.

4.4 Interlinkages

4.4.1 Electrolysers

The electricity and the hydrogen sectors are connected via electrolysers. The ILM2024 contains three electrolysers (P2G in the figures).

- **Zone 1 Electrolyser.** Connected to the electricity market and shared RES.
- **Zone 2 Electrolyser.** Connection to the electricity markets.
- **Zone 2 Dedicated RES Electrolyser.** Renewables are physically connected to electrolysers on-site.

The electrolysers are connected in the model and constraint to allow only zero carbon electricity to be used for hydrogen production.

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[2] This is considered only for a few areas.

4.4.2 Hydrogen to power

The hydrogen and electricity sectors are also connected via hydrogen-fired CCGTs and fuel cells , although Fuel Cell generation capacity is very limited within the model.

Capacities for both of these assets have been submitted by TSOs in relation to their national plans. The hydrogen fuel is linked to the hydrogen node, which then fuels the CCGTs and fuel cells in the electricity side of the model. The marginal pricing of these plants will be contingent on the cost of fuel in the hydrogen node. Hydrogen CCGTs are only available from 2040 in the scenario models, however in the scenario model the hydrogen CCGTs are not connected to the hydrogen market. In the ILM2024 (starting from the 2040 horizon) there will be a direct connection between the hydrogen CCGTs and the hydrogen nodes.

4.5 Climatic Years

The number of climatic years considered by the models will impact the renewable production. It is therefore necessary to select a limited combination of years while ensuring the representativeness of the climatic variability of the last 30 years. A statistical analysis performed on the last 35 years have helped to identify the most representative combinations of years.

In the case of definition of representative climate years, the approach is as follows:

(1) **Definition of hourly time series of residual load** (final demand minus wind and solar power generation) on a regional level, to capture the temporal and spatial variability of the system state due to climatic conditions.

(2) **Compute delta indicators** to assess how years compare to the 30-year average on a regional level.

(3) **Selection of most representative combination** of 3 years for the study

The weights are calculated based on the Pan European Climate Database (PECD) according to their representativeness in terms of the solar infeed, wind infeed, hydro inflows, and load parameters. The PECD is made available through the following link.

The years 1995, 2008 and 2009 will be the years used in the ILM2024.

4.6 Value of Lost Load (VoLL)

The value of lost load refers to the cost of curtailing demand. It is possible that this cost could be different within the hydrogen and electricity sectors. Currently, there is no defined cost for the hydrogen system.

The costs traditionally referenced for the electricity markets are € 3,000 and € 10,000. For TYNDP 2022, ENTSO-E has considered a VoLL of € 3,000 in its CBA assessment for all indicators besides the adequacy indicator (more information is provided in ENTSO-E TYNDP 2022 CBA Implementation guidelines[3]). A similar as sumption is made for the ILM2024.

In a cost benefit analysis, this price can have a strong effect on project benefits, especially if the project reduces the amount of demand curtailed. In the ILM2024, a methodology for assigning the VoLL price in the hydrogen system has been developed and will be discussed in section 5.3.

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[3] Link

4.7 Commodity prices and emission factors

Commodity prices include both fuel and CO_2 prices. The emission factors quantify how much CO_2 is emitted during fuel combustion. Therefore, they are used to measure in which extent CO_2 price impacts fuel prices. The emission factors are derived from JRC and summarised below.

Methane and hydrogen emission factors depend on the composition of different sources:

- **Methane:** fossil natural gas, biomethane and synthetic methane.
- **Hydrogen:** electrolysis, hydrogen imports, and SMR / ATR production.

The composition of the methane mix is dependent on scenarios and time horizon. The emission factors of electrolysis-based products (hydrogen, synthetic methane, and synthetic liquids) are an output of the electricity modelling.

Some commodity prices are common to all scenarios and dependent either from local drivers (shale oil and lignite) or from a very specific and slow evolving value chain (nuclear). Table 2 shows fuel price common to all scenario storylines. Table 3 shows storyline-based fuel prices.

Other commodities have a price depending either on the global energy context (Methane, oil, coal) or European regulation (CO_2). As scenario storylines reflect different European and global storylines, it is necessary to define prices reflecting their respective storyline.

FUEL	EMISSION FACTOR (TCO$_2$/MWH)
OIL	0.267
SOLIDS	0.354
METHANE	0.202

Table 2: Emission factor of fuels

FUEL	SUB FUEL	2025	2030	2040	2050
METHANE	Methane	23.89	20.74	16.94	13.97
SHALE OIL	Shale oil	1.56	1.86	2.71	3.93
LIGNITE	**Group 1** (BG, MK and CZ)	1.4			
LIGNITE	**Group 2** (SK, DE, RS, PL, ME, UK, IE and BA)	1.8			
LIGNITE	**Group 3** (SI, RO and HU)	2.37			
LIGNITE	**Group 4** (GR and TR)	3.1			

Table 3: Fuel prices common to all scenarios (€/GJ)

COMMODITY	UNIT	SCENARIO STORYLINES	2030
CO_2	€/tonne	NT	78
HARD COAL	€/GJ	NT	1.967
LIGHT OIL	€/GJ	NT	10.09
GAS	€/GJ	NT	5.911
H_2 IMPORTS	€/GJ	NT	17.11

Table 4: Fuel and CO_2 prices per scenario and horizon

4.8 Tools description and comparison

There are two models which participate in this process: ANTARES and PLEXOS. There will be an underlying level of variability between these models as the achieving of the objective function will depend on the solver used and the mathematical approach used by each solver. Therefore, the variability of some of the parameters such as storage use or grid activity have less impact and are allowed more variability than the main indicators System Costs, RES Integration and CO_2 Reduction.

The comparison will be made for Distributed Energy in 2030.

5 INTERLINKED MODELLING INSIGHTS //

5.1 Specific issues for green hydrogen

5.1.1 Shared RES management

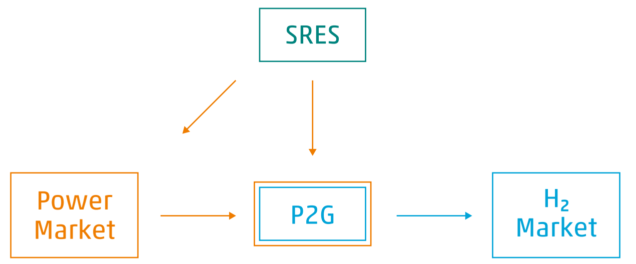

Figure 7: Shared RES connexion to both electricity and hydrogen markets

SCENARIO	P2G CAPACITY	SRES GENERATION	H_2 DEMAND
DE-2030	49 GW	700 TWh	310 TWh
DE-2040	138 GW	1,800 TWh	1,220 TWh

Table 5: Hypothesis for DE models

For shared RES, two operation modes have been studied:

- **Mode 1:** freely optimised sharing of RES between the power and hydrogen.
- **Mode 2:** favouring the RES for hydrogen production.[1]

In **Mode 1**, decarbonisation of electric power takes priority over P2G, which means that electrolyser facilities will only run if the marginal price where they are located corresponds to fully carbon-free power generation at that time.

Mode 2, even with the constraint of guaranteeing the production of hydrogen only from carbon-free electricity sources, an insufficient decarbonisation of the power generation system could have negative effects on the overall volume of emissions. SRES would result insufficient to serve both P2G and the power system. This effect is reinforced by the optimisation of the Steam Methane Reforming (SMR) process which, in our modelling, includes a 90 % Capture rate and provides a low emission alternative for hydrogen production when the green hydrogen produced by electrolysers is insufficient to serve the demand. This operation significantly increases the load-factor of electrolysers and makes them more profitable. The emissions replacement process from hydrocarbon based fuels to hydrogen is inherently considered within the scenario development process . These emission reductions are not considered within the PS-CBA process but would indeed lead to significant emissions reduction which would change the balance of the change in emissions from the CBA assessment.

The shared RES was intended to be modelled in Mode 2, but as this is not the case in the scenario development process, it leads to unintended effects in the model, namely higher CO_2 emissions. A recommendation of the ILM2024 is to adopt the same approach as the scenario which the model is based on. Therefore, Mode 1 is considered in the ILM2024 in order to align with the European delegate act which states, "RES used to produce hydrogen will not deprive the Power system of part of the RES". Mode 2 could be considered during the scenario development process in order to align with the true nature of shared RES.

In the distant future, the two modes should converge as the whole power generation fleet will be decarbonised, but for the next decade, a remaining large fleet of thermal power plants must be considered and consequently significant differences in the P2G load factor between the two modes, as can be seen in Figure 8 on the following page for 2030 with the green profile representing electrolyser production.

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[1] This Mode can be particularly relevant in a future where electrolysers projects would rely a lot on PPAs for producing hydrogen.

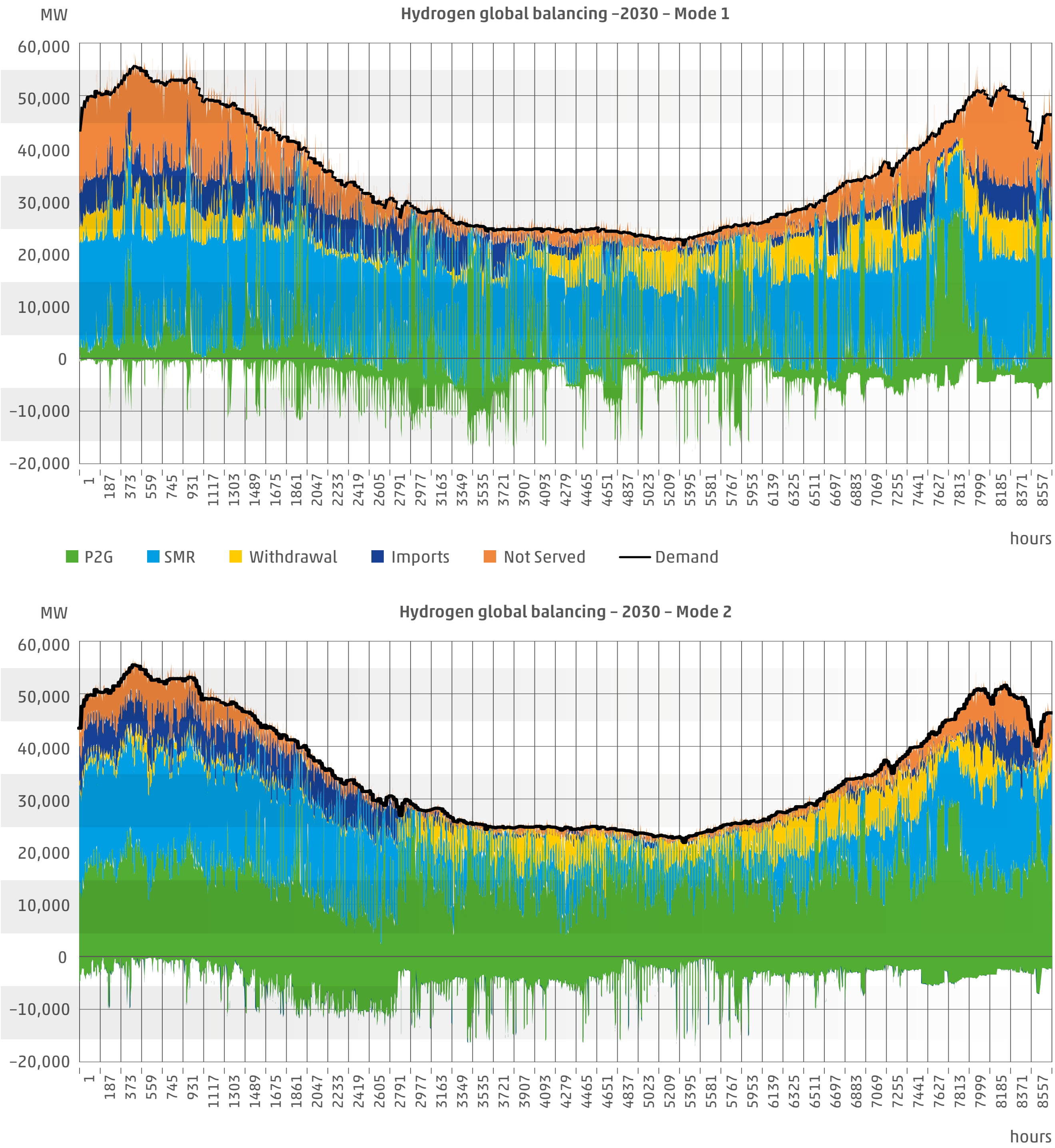

Figure 8: H_2 production DE2030 – Mode 1 (above), Mode 2 (below)

The impacts on P2G load factors, emissions and curtailed H_2 demand can be seen below in Table 6.

DE2030	P2G LOAD FACTOR	CO_2 EMISSIONS	H_2 NOT SERVED
MODE 1	22 %	413 Mtons	55 TWh (17 %)
MODE 2	45 %	473 Mtons	13 TWh (4 %)

Table 6: Shared RES modal analysis – DE2030

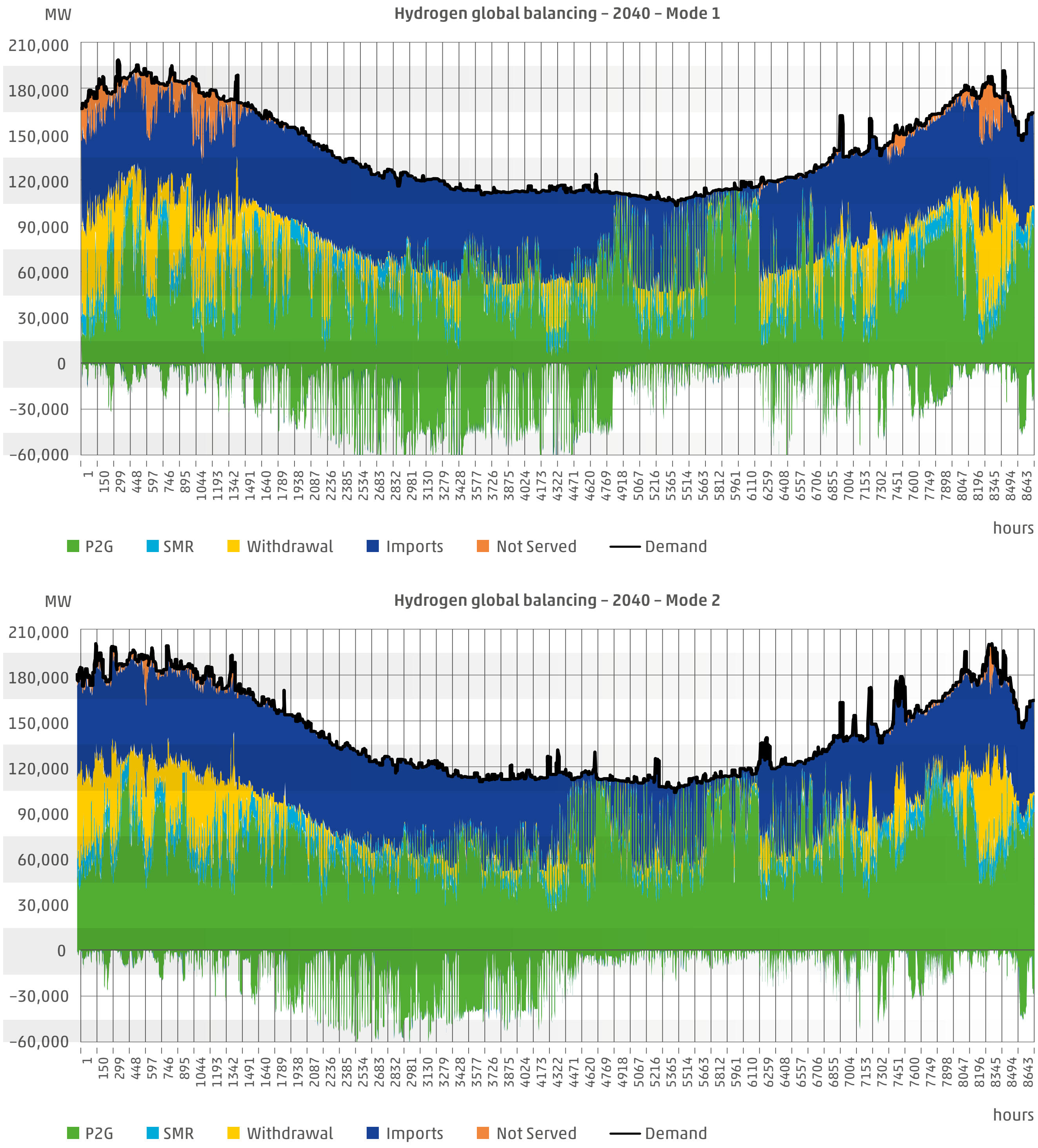

Figure 9: H_2 production DE2040 – Mode 1 (above), Mode 2 (below)

In 2040, there is a better convergence of the two modes, with the decommissioning of most of the thermal power plants in Europe, as can be seen in Figure 9. The forced capture of shared RES with mode 2 will less often induce an increase of CO_2 emissions on the power grid.

DE2040	P2G LOAD FACTOR	CO_2 EMISSIONS	H_2 NOT SERVED
MODE 1	53 %	220 Mtons	34 TWh (3 %)
MODE 2	61 %	255 Mtons	9 TWh (1 %)

Table 7: Shared RES modal analysis – DE2040

5.2 Emissions due to opportunities for thermal power plants to produce hydrogen

In such global adequacy model, attention must be paid to eliminate all emission impacts due to opportunities for thermal power plants to produce hydrogen, to ensure that the hydrogen produced in the simulation will be fully carbon-free. These opportunities can be broken down into two terms, the first is due to linear valuation, the second is due to non-linear valuation of the thermal power plant generation. These terms will be examined one after the other.

5.3 Linear valuation of thermal power plants and impacts on unserved hydrogen demand

A simplified first representation of this valuation is to consider a power plant as a unit with only proportional costs, also called marginal costs (in €/MWh), that can run at any time between 0 and a maximum capacity. These marginal costs which include fuel costs, operating costs and emission costs are those generally considered to establish in a simplified way the "merit order" for power generation.

Fortunately, those power plants that generate emissions are the ones with the highest marginal costs. Thus, a simple way to avoid any opportunity to produce hydrogen with such a plant in the model is to cap the marginal price of hydrogen in all hydrogen nodes.

A common way of capping this price is to set the unserved hydrogen demand penalty (or hydrogen curtail demand price) to this ceiling value, considering that this penalty is the ceiling price any hydrogen consumer undertakes to pay its supply.

Therefore, to avoid any opportunity for CO_2-emitting thermal power plants to produce hydrogen, the cost of producing 1 MWh of hydrogen with such power plants must be higher than this ceiling price. This hydrogen production cost is the combination of the marginal cost described above plus the P2G energy conversion cost (efficiency).

This ceiling (or shortage) price for hydrogen demand should fulfil the following condition:

$$H_2 \text{ demand shortage price} \times \text{P2G efficiency} < \min(\text{Marginal costs of the cheapest } CO_2 \text{ emitting TPP})$$

Considering a P2G efficiency of 70% for all simulations and the condition written above, the hydrogen shortage prices for the DE2030 and DE2040 scenarios can respectively be chosen as follows:

ILM-DE2030	
CHEAPEST CO_2-EMITTING THERMAL POWER PLANT (TPP)	Methane CCGT
MARGINAL COST OF THE CHEAPEST CO_2-EMITTING TPP	61 €/MWh
H_2 COST OF PRODUCTION FROM CHEAPEST CO_2-EMITTING TPP	87 €/MWh
H_2 SHORTAGE PRICE CHOICE	80 €/MWh

Table 8: H_2 shortage price selection – DE2030

ILM-DE2040	
CHEAPEST CO_2-EMITTING THERMAL POWER PLANT (TPP)	Methane CCGT
MARGINAL COST OF THE CHEAPEST CO_2-EMITTING TPP	83 €/MWh
H_2 COST OF PRODUCTION FROM CHEAPEST CO_2-EMITTING TPP	118 €/MWh
H_2 SHORTAGE PRICE CHOICE	115 €/MWh

Table 9: H_2 shortage price selection – DE2040

Thus, insofar as linear valuation approximation is considered, with such hydrogen curtail demand prices, thermal power plants will never contribute to generating hydrogen. Note, however, that these prices do not represent the economic cost of not satisfying hydrogen demand and that indeed this cost is not considered in the models.

Unfortunately, these thermal power plants also have non-linear valuation contributions to consider, which will be explained in the next section.

This methodology has several downfalls. The first is that it only works if the prices of the supply sources within the hydrogen system are lower than what it would cost to produce hydrogen using gas turbines. This fortunately was the case in the 2022 TYNDP scenarios but this may not be the case in for future TYNDP scenarios. The issue could be rectified by post processing the output data but is not an ideal approach. An alternative approach that would allow blocking the electrolysis when prices in the electricity side exceed the marginal cost of CCGTs while dispatching more expensive production means in the hydrogen system would need to be investigated.

5.4 Non-linear valuation of the production of thermal power plants

The modelling of thermal power plants includes 3 non-linear parameters in the adequacy model:

1. **Start-up costs (in €/start-up):** these costs are paid when a plant is switched-on.

2. **Minimal Stable Power (PMIN in MW):** when a plant is operating its production must be greater than PMIN.

3. **Minimal Duration (DMIN in hours):** there must be at least DMIN hours between changes of status on/off.

One easy way to appreciate the effects of such non-linear parameters is to compare the results of two simulations that differ from each other only by extended P2G capacities in a single area. This was done by adding P2G capacities only in Germany (the most ambitious country in Europe in terms of development of P2G assets). Consequently, 700 MW of additional P2G capacities led to an additional emissions contribution of 43 ktons in the simulation results. How can such results be explained?

One parameter that is easily explained is the reduction of "stop and go" sequences. For such a sequence, there is a trade-off between these two options:

1. Maintain the plant at its Minimum Stable Power and pay for the fuel consumed during this period,

   or

2. stop it, restart it later and pay the start-up costs.

The difference in costs between the two options may be small and a small difference in the valuation of the power produced with "Option 1" can modify the result of this trade-off.

The expansion of electrolysers increases the load opportunities for the power sector and therefore the marginal price of electricity. This provides "Option 1" an added advantage and may make it slightly more often more profitable than "Option 2". Finally, as "Option 1" generates more emissions, the expansion of electrolysers leads to generating slightly more emissions.

To confirm a significant contribution of start-up costs in the non-linear opportunities for a thermal power plant to generate H_2, a combination of two simulations was calculated which differs only with 700 MW of P2G capacity in Germany, but we set start-up costs of all thermal power plants to 0 € for both simulations. In that case, an additional contribution of 18 ktons resulted from the simulation including 700 MW of additional P2G capacities, which is much lower than what was obtained considering start-up costs.

The two other non-linear parameters may also contribute to some non-linear opportunities by disrupting the "merit order": it can happen that a more expensive unit is operating while a cheaper one is not fully activated.

5.5 Carbon Capture and Storage considerations for SMR

When a thermal power plant is operating and contributes to P2G, the reduction of emissions due to a partial substitution of SMR generation by P2G generation must be considered.

However, this reduction is very small since in this study we assume that all SMR generation induces a rate of Carbon Capture and Storage of 90 %. Of course, if this rate were lower, one would obtain greater moderation on the emissions induced by thermal power plants opportunities.

5.6 Introduction of a Carbon budget with a PINT approach: methodology

As mentioned before, the objective of these models is to carry out the CBA of various hybrid projects coupling power and hydrogen grids. For this, the approach described above to explain the sensitivity to start-up costs on thermal power plant opportunities is suitable as it consists of doing two simulations that differ from each other by the presence (or not) of the hybrid project.

The reference case is the one that does not include any of the hybrid projects to evaluate and then, through a "Put IN one at the Time" (PINT) approach, the projects are successively assessed.

Thus, the reference case is executed with only optimal curtail demand prices to cancel the "linear" opportunities for the thermal power plant to generate hydrogen, as explained in section 5.3. From this simulation one obtains daily emissions in the entire domain.

This information can be forwarded to all project-specific simulations that each include a project via a PINT approach, by adding an additional constraint in the modelling which caps daily emissions to those obtained with the reference case simulation.

This methodology was a test case which was used to explore how the model reacts to CO_2 constraints. It does not provide us with a model that is representative of reality and therefore not discussed further in the report.

6 CBA METHODOLOGY //

6.1 Basic principles of Dispatch Models

The purpose is to minimise the production costs across the sectors modelled considering the commodities prices. This optimisation is subject to constraints that are the available infrastructure capacities and the limits of production assets and flexible assets. The aim is to minimise the following objective function:

$$\sum_{System} Variable\ OPEX + \sum_{System} Fuel\ cost + \sum_{System} CO_2\ emissions\ cost + \sum_{System} VoLL$$

Equation 1: Objective function for the dispatch model optimisation (variable costs of the electricity system)

6.2 CBA Indicators

Many indicators have been proposed and developed over time for an improved and more equitable appraisal of the contribution of infrastructure projects to the energy system in relation to the energy transition and societies. The existing and well renown indicators feed into the discussion of relevant CBA indicators for an Interlinked Model.

Therefore, in the scope of projects assessed in the ILM2024, there are two main categories of indicators:

- Common indicators
  - Socio-economic welfare
  - GHG emissions
- Sector-specific indicators
  - Curtailed hydrogen demand
  - Electricity RES curtailment
  - Share of electricity RES integrated into the system
  - Share of low-carbon hydrogen integrated into the system

Common indicators are essentially made of a shared impact from the linked sectors. In principle, common indicators can be split into sector specific information, however this study shows that not all common indicators can be split between sectors while sending the right signals. In such a case, it is therefore preferable to look at results at the system level, given that the cost optimisation is performed for the whole system. More details are found in section 7.

Sector-specific indicators are indicators that are characteristic of one sector. Nevertheless, these indicators are not independent from the other sectors' specific indicators, as each element of the problem has an effect on the system as a whole. It is a better exercise to try to understand the potential link between sector-specific indicators. Commonly known examples of sector specific indicators are RES curtailment, curtailed hydrogen demand, low-carbon hydrogen and RES integrated into the system.

In the following sections, the methodology for the assessment of the different indicators outlined above are described. An important focus is put on the Socio-Economic Welfare indicator in this report. Some results are also presented for illustrative purposes based on the simulation outputs obtained from the models built in ANTARES and PLEXOS. Comparison and insights on the results are provided in each subsection.

6.2.1 Variation of GHG emissions

This benefit indicator measures the reduction in GHG emissions because of implementing a project and thereby covers the "contribution of a project to greenhouse gases emissions reductions in various end-use applications" of Annex IV(5)(a) of the TEN-E Regulation.

This benefit indicator considers the change of GHG emissions because of changing the generation mix of the electricity sector or the supply source used to meet hydrogen demand. This indicator is expressed in quantitative terms in tonnes of CO_2 equivalent emissions savings (tCO_2e/y).

The assessment of the variation in CO_2 emissions due to the presence of an infrastructure project is there computed as:

$$\Delta CO_2\ Emissions = CO_2\ Emissions_{with\ project} - CO_2\ Emissions_{without\ project}$$

Source of CO_2 are Thermal Power Plant and Steam Methane Reformers. Given its nature, this indicator can be assessed in each sector separately and can also be gathered into one information for the system as a whole.

6.2.2 RES and Low-Carbon Hydrogen Integration

6.2.2.1 Renewable Energy Sources Integration

This benefit indicator measures the reduction of renewable generation curtailment (avoided spillage) because of implementing a project. This indicator quantifies two important impacts that an electricity infrastructure project can have which are:

- Bring additional RES capacity to the system that can be used to serve demand.
- Facilitate the integration of more RES energy into to power system that can be used to serve supply demand at a lower cost.

The effect of more RES energy integrated into the system is a reduced need for expensive fuel, for which the monetised value is captured in the B Socio-Economic Welfare indicator described in section 6.2.2.1. This B2.1 RES integration benefit is expressed quantitatively in terms of energy (MWh/year).

The RES integration benefit therefore stems from a difference in dump energy of the system from a situation where the project is considered in the system to a situation where the latter will not be considered. To this, should be added also the additional renewable energy provided to the system due to additional RES capacity connect by the project, if any.

This can be summarised are follows:

$$\Delta RES\ Energy = E_{project} - (E_{dump\ with\ project} - E_{dump\ without\ project})$$

Where:

- $E_{project}$ corresponds to the yearly energy produced by the additionally connected RES source.
- E_{dump} corresponds to the yearly dump energy in the electricity system.

6.2.2.2 Low-Carbon Hydrogen Integration

This benefit indicator measures the increase of green hydrogen because of implementing a project. This indicator quantifies the extent to which any infrastructure project with cross-sectoral impact is going to play a role in the decarbonisation of the hydrogen sector.

Increasing the integration of low-carbon hydrogen into the system will participate in reducing the need for CO_2-intensive H_2 production means and the monetised value of this is well captured in the Socio-Economic Welfare benefit. This Low-Carbon Integration benefit is expressed quantitatively in terms of energy (MWh/year or GJ/year), which represent the amount of hydrogen produced over the year in a green manner (here through electrolysis).

This can be assessed as follows:

$$\Delta LowcarbonH_2 = (\Delta LowcarbonH_{2\,with\,project} - \Delta LowcarbonH_{2\,without\,project})$$

Where $GreenH_2$ corresponds to the total amount of low carbon H_2 produced.

6.2.3 Variation of Curtailed Hydrogen Demand

This benefit indicator measures the impact of an infrastructure project on the reduction of curtailed H_2 demand. The deployment of infrastructure assets (at any part of the energy system) can provide more potential for converting electricity into hydrogen. Some projects will have a non-negligible impact while the impact of some other projects will be marginal. In any case, they are not expected to negatively impact the system when it comes to coupling sectors.

The indicator quantifies the extent to which any infrastructure project with cross-sectoral impact is going to play a role in fulfilling more of the H_2 demand. This indicator is expressed in MWh/year or GJ/year.

$$\Delta Curtailed\ H_2 = Curtailed\ H_{2\,with\,project} - Curtailed\ H_{2\,without\,project}$$

Where $Curtailed\ H_2$ corresponds to the total amount of H_2 demand curtailed over the year.

6.2.4 System-wide Socio-Economic Welfare (SEW)

When it comes to power markets analysis, the SEW is defined as the sum of the short run economic surpluses of electricity consumers, electricity producers and transmission owners (this sum is also called the Total Surplus). The first two elements of the equation are easy to illustrate as the first element represents the difference between the consumers' willingness to pay and the market clearing price and the second element corresponds to the difference between the market clearing price and the producers' offered/bid prices, in other words the margin made by the producers on the produced energy[1].

This definition goes beyond power markets as it also applies to any other common good that can be exchanged through an auction cleared market. The SEW presented above can therefore be appraised also in the Hydrogen market, making use of the same surpluses applied to the Hydrogen consumers, Hydrogen producers, and Hydrogen pipeline owners.

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[1] With the assumption of a perfectly competitive market in the model, the offer/bid price for each generator corresponds to its actual cost of generation.

When sectors are coupled, the surpluses mentioned above are not sufficient to appraise the complete SEW of the system. In fact, when systems are linked a new arbitrage potential appears for the owners of the sector-coupling assets, where they can buy an exchanged good in one of the markets at a cheap price and sell it after conversion in another market at a higher price. These are additional components to what would be observed in a single sector assessment, where the additional electricity demand stemming from this coupling would have to be explicitly considered in the load profile. Typical coupling assets in an Interlinked Model could be electrolysers, hydrogen CCGTs, hybrid heat pumps (Heat pumps, H_2 Boilers and CH_4 Boilers).

When it comes to energy system planning, especially over large regions such as Europe, this SEW indicator is one of the most sought-after monetary benefits to guide the deployment and/or the improvement of infrastructure assets that makes the system able to supply more demand with cheaper generations. A proper assessment of this indicator is therefore of utmost importance, as this is one of the main bases of comparison between projects, and even across sectors.

If the assumption of energy demand inelasticity is made (constant demand in each time step) and if from one simulation to another the energy demand stays constant considering the whole system, it is proven in theory and in practice that the change in SEW in the system is equivalent to the change in total cost in the system. If one assumes that the only thing that changes from one run to another in the CBA simulations is the inclusion or exclusion of projects in the reference grid, the assumption of total energy demand inelasticity is fully met. This process of putting one project in the reference grid or taking it out of the reference grid during the CBA runs are labelled as PINT and TOOT approaches respectively.

It is important to mention that the matching between change in total cost and change in total SEW when energy demand is inelastic is true only when considering the whole system. Only by doing so, one properly accounts for the effects of changing flows between sectors and between borders where additional generation in one area would help meeting the demand of another area at least cost. If cross (sector) border flows are allowed and one investigates just one (sector) area, the change in cost in that (sector) area is not fully representative because this change will lead to the opposite effect in the neighbouring (sector) area which is then being overlooked if the changes are looked at independently for each (sector) area. It is only when the effects are considered all together that a real value of the change in SEW can be extracted and the match with the change in total costs is obtained.

In subsection 6.2.4.1, the Total Cost (TC) approach for assessing the SEW is described. This is followed in subsection 6.2.4.2 by the description of the second approach for assessing the SEW, namely the Total Surplus (TS) approach. In contrast to the change in TC, the change in TS gives more insight onto how the surpluses are being shared amongst the agents of the market and can also be used to split the SEW benefit at regional level without losing information. This can be very helpful when it comes to limiting the benefits to regions such as the European Union area. This will be discussed later in the text.

6.2.4.1 Total Cost Approach

As mentioned above, when the assumption of inelastic load is fulfilled, the change in Social Economic Welfare (SEW) in a system when one project is removed from (or included in) the reference grid is in theory equal to the change in total cost of that system. This is the traditional approach of calculating SEW in both ENTSO-E and ENTSOG.

The total cost of a system corresponds to the sum of all costs of generation/production in the system, added to it the cost of Energy Not Served (ENS). In practice, this therefore encompasses the cost of the fuel used, the cost of CO_2 emissions, the cost of energy imports and the cost of ENS.

This total cost is computed for all the hours of the year in all the sectors considered and can be mathematically expressed as follows:

$$Total\ cost = \sum_{s \in \boldsymbol{S}} \sum_{g_s \in \boldsymbol{G_s}} \sum_{n=1}^{8760} (MC_n^{g_s} * \ Gen_n^{g_s} + ENS_n^s * \ VoLL^s)$$

Where:

$\boldsymbol{S}$	is the set of sectors under consideration
$\boldsymbol{G_s}$	is the set of all production means in sector s
$MC_n^{g_s}$	corresponds to the marginal cost of production mean g_s in sector s at time step n. As described earlier in the report, marginal cost includes cost of fuel, operational cost and emissions costs.
$Gen_n^{g_s}$	corresponds to the dispatched generation of production mean gs in sector s at time step n. This information is an output on the market simulation.
ENS_n^s	corresponds to the energy not served at time step n in sector s. This item is also part of the output datasets from the simulations.
$VoLL^s$	corresponds to the Value of Lost Load considered in sector s. In the hydrogen system for instance, Methane would also be imported from outside of the EU. This import potential would be part of the set where g would therefore represent the import mean (direct pipeline, ship, …).

From the equation presented above, it is easy to see that computing the TC of a system is a relatively simple exercise, as the information required for its computation are straightforward and half of them are input to the model.

6.2.4.2 Total Surplus Approach

The total Surplus approach is based on original SEW decomposition method.

The decomposition of the Social Economic Welfare (SEW) aims to assess the benefit of an investment, by analyzing the welfare gains and the costs that this induces. Its ambition is to understand, measure and quantify all the expected economic effects of an investment by dissociating them to allow analysis of the aspects in which this investment brings value. This decomposition is important when carrying out socio-economic evaluation studies of investment. It provides elements of analysis:

- To objectify the effects of an investment on the well-being of all the agents affected by this investment to assess its ability to meet an identified need, by assessing the expected gains with regard to the costs incurred.
- To compare various investment options based on sizing and different technical choices.
- To provide elements which help to choose between competing investments.

The first step for the generalisation of the decomposition of the SEW to multi-energy systems is the definition of the set C of components that interact with each energy sectors of multi-energy systems. Consequently, a decomposition of each unit u of the system into its sectoral components is necessary for the definition of the set C. For example, a P2G unit can be decomposed into two components: an incoming electrical component and an outgoing hydrogen component[2].

Figure 10: Interaction of a P2G unit with the two systems

Each component $c \epsilon C$ belongs to a single sector $j_c \epsilon S$, a single area $a_c \epsilon A$ and to a single technology u_c of the set of technologies of the system U. Since a component is the smallest part of a multi-energy system, the overall SEW is the sum of all Producer and Consumer Rents of each component.

To consider all rents appearing in an interconnected multi-energy system, the general formula for the decomposition of the SEW is written as follows[3]:

$$SEW = \sum_{c \in C} R_c^{CSR} + R_c^{prod} + R_c^{cons} + R_c^{flex} + R_c^{cong}$$

With:

R_c^{CSR}: Cross-Sector Rent is the rent associated to the components of the sector-coupling which belong to the same area and to two different sectors (e.g. the rent of an owner of an electrolyser installation which produces hydrogen from electricity).

R_c^{prod}: Producer rent is the profit that the producer obtains by selling at a price higher than the price that covers his variable costs. This rent is generated by the components linked to the production facilities except those which ensure flexibility, sectoral coupling and congestion included in other rents.

R_c^{cons}: Consumer Rent is the difference between what a consumer is willingness to pay for a good and the amount actually paid.

R_c^{flex}: Flexibility Rent is the rent linked to the components that ensure the flexibility of production within one unique sector (example: the rent of an owner with a hydraulic storage installation, batteries, etc.). In our model, most of this Rent comes from storage assets.

R_c^{cong}: Congestion Rent corresponds to the difference between the gains induced by injecting an energy vector into an import area and the costs induced by withdrawing the same energy vector from an export area (example: the rent of an owner of an electricity transmission line that links two regions).

Given that this approach is just an extension of the commonly known sector specific SEW decomposition, it can be perfectly applied to assess the impact on total system SEW of projects that are specific to each of the sectors considered (e.g. electricity transmission projects in the electricity grid, hydrogen pipeline projects in the hydrogen grid…), when systems are coupled. On the other hand, this approach is the unique approach that allows to assess the impact of sector coupling assets on the total value of SEW of the system (e.g. hybrid projects consisting of a mix of sector specific assets, electrolyser capacity between the electricity sector and the hydrogen sector).

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[2] T. Felling and P. Fortenbacher, "Extended Social Welfare Decomposition for Multi-Energy Systems," 2022 18th International Conference on the European Energy Market (EEM), Ljubljana, Slovenia, 2022, pp. 1–7, doi: 10.1109/EEM54602.2022.9921010.

[3] ENTSO-E TYNDP 2024 CBA Implementation Guidelines

7 PROJECT ASSESSMENT //

This section will explore the differences between models and tools. It is important to state the difference between models and tools. Models represent the methodology of how the inputs are used. A specific type of model can be implemented into different tools. In this case, the tools are ANTARES and PLEXOS. The models are the Interlinked Model, the electricity model, the hydrogen model etc.

The CBA results presented hereafter are yearly results. It is important to note that these results should be interpreted as a methodology test and are not destined for usage.

7.1 Electricity Projects Assessment

7.1.1 Electricity Grid Projects

There are two types of assets which are typically submitted into the electricity TYNDP:

- Electricity transmission infrastructures (lines, transformers, …), with cross-border impact. This impact is considered in the Net Transfer Capacities (NTC).
- Storages (Hydro and Compressed Air).

For projects with cross-border impact, the NTC change brought by the project in both directions of the relevant borders must be submitted. Promotors can submit internal projects, projects considering a connection between EU countries and projects between an EU and a non-EU country. Storage project promotors must submit Reservoir capacity, Turbine Capacity and Pumping Capacity of a project. More data is required for compressed air storage (CAES) projects.

The electricity TYNDP is a mature process, where the reference grid has been well established. This means that both PINT and TOOT projects can be assessed for electricity projects in alignment with what is done within the electricity TYNDP.

7.1.2 TST Model vs ILM Model

ENTSO-E's TST Model are predominately electricity models which have been built and aligned using several tools, in a similar way to what is being done for the ILM2024 model. The models do not consider the hydrogen sector but do consider a simplification of electrolyser loads by allowing hydrogen production where there is excess renewable energy, essentially assuming a hydrogen copperplate. The TST model alignment is a well-developed process which has been seasoned over many years and would be considered state of the art in model alignment. The models are therefore very reliable and a good starting point for the ILM2024 model. The ILM2024 model's electricity sector replicates the TST model and builds the hydrogen system onto it, therefore we can say, the electricity parts of the models are aligned. In this section the aligned Models and the aligned TST model will be compared.

7.1.3 Electricity Projects for assessment

A small subset of the projects which have been submitted to ENTSO-E in the TYNDP 2022 is considered for the assessment of this alignment. These projects can be seen in Table 10.

PROJECT BORDER	COUNTRY 1	COUNTRY 2	CAPACITY (MW)
BG-GR	Bulgaria	Greece	930 / 600
DE-NL	Germany	Netherlands	600 / 600
IE-UKNI	Ireland	Northern Ireland	950 / 900
CZ-DE	Czechia	Germany	500 / 500
DE-FR	Germany	France	300 / 300
BG-RO	Bulgaria	Romania	600 / 600
PT-ES	Portugal	Spain	800 / 1,500
FI-SE	Finland	Sweden 03	900 / 800
DE-PL	Germany	Poland	500 / 1,500
FR-IE	France	Ireland	700 / 700
LI-PL	Lithuania	Poland	500 / 1,000
UK-NO	United Kingdom	Norway South	1,400 / 1400
BE-NL	Belgium	The Netherlands	1,000 / 1,000
UK-DE	United Kingdom	Germany	1400 / 1,400
AT-DE	Austria	Germany	2,000 / 2,000
DE-LU	Germany	Luxemburg	1,000 / 1,000
DE-SE	Germany	Sweden	700 / 700
ES-FR	Spain	France	2,200 / 2,200

Table 10: TYNDP 2022 Electricity Projects

7.1.4 SEW Results Comparison for electricity transmission projects

The results between ANTARES and PLEXOS show a relatively good alignment and results follow the same trend. As mentioned, it is not expected that the tools will be 100 % aligned. There are three projects which follow the same trend in both tools but present a slightly larger deviation (in line also with their order of magnitude); these are project 190 (NorthConnect), 309 (NeuConnect) and 313 (between Germany and Austria) as shown in Figure 11. The last two projects have a connection with the UK; therefore, the UK modelling could be further analysed as it is likely that the hydrogen system is creating this deviation between tools. However, for both tools and similarly for TST, the projects connecting to the UK show the highest benefits in the selected subset of projects.

The only project for which the outcome seems to be much less aligned compared to the other projects is project 94 (GerPol Improvement) for which the Cost Savings (SEW) in PLEXOS is much higher compared to the value obtained from ANTARES. One also notes the alignment of this PLEXOS value with the Average value from TST.

Figure 11 shows therefore a very interesting results in this sense that the SEW benefits observed for electricity transmission projects with the ILM2024 model correlate very strongly with the results of the same assessment performed with the single sector models used by the ENTSO-E TST.

It can be observed that in general, the average cost savings brought by projects tends to be slightly higher in the ILM2024 model compared to the average values obtained by TST. This is even more pronounced for the few projects mentioned before which connects the EU to the UK. This is an immediate consequence of the increased market opportunities created by the linkage of sectors.

It is important to note that on the ENTSO-E TST side, the results are communicated for the electricity system only, while here for the ILM2024 the results are communicated for the whole system. With an interlinked model, splitting the SEW benefit into sectoral components could potentially lead to unproper communication and wrong signals sent to the market. The following paragraphs focus on this aspect based on PLEXOS results and with the proof that the total cost approach and the total surplus approach are aligned.

The changes in the surpluses that make up the SEW in the electricity sector and in the H_2 sector will shift from one to another, within and across the sectors. Thanks to the total surplus approach of the SEW decomposition, these surpluses shifts can be assessed one by one to understand more on the model's behaviour. By aggregating these surpluses, one ends up with three main components that compose the Total dSEW. These elements are the $dSEW_{elec}$, $dSEW_{h2}$ and CSR, standing respectively for change in SEW in the electricity sector, in the hydrogen sector and the Cross-sectoral rent.

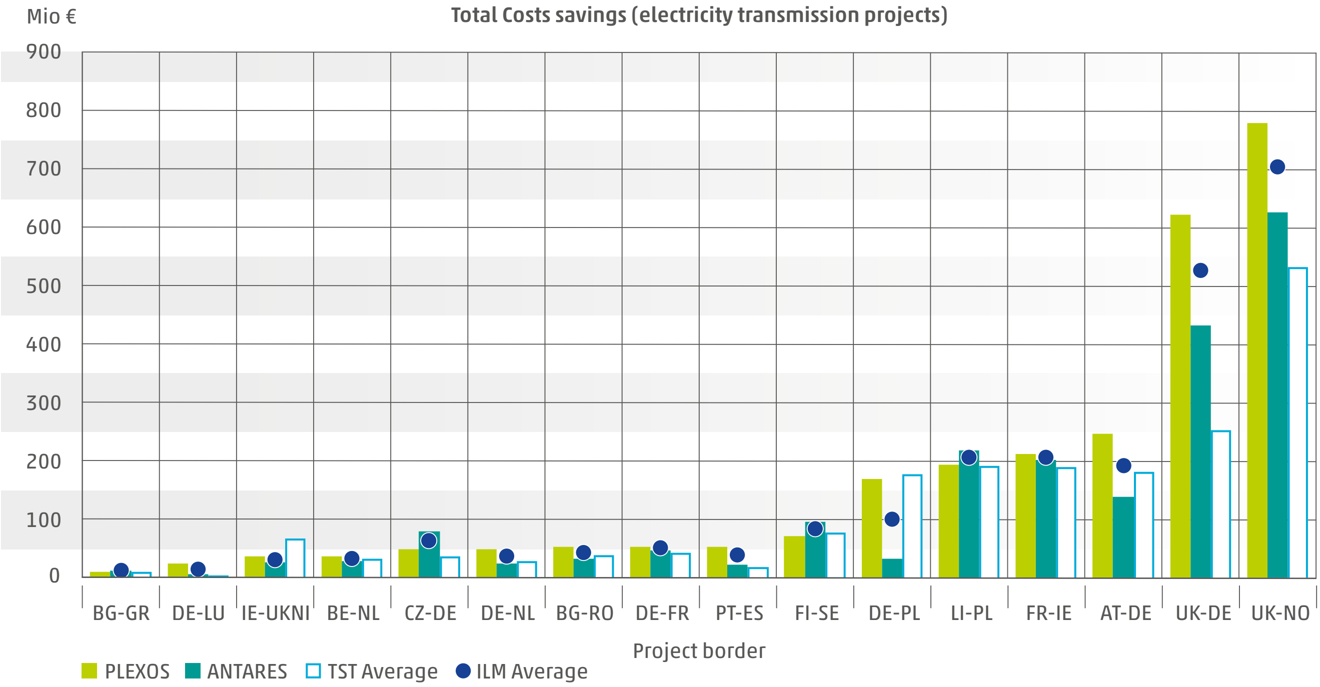

Figure 11: Total costs savings – PLEXOS vs ANTARES tool comparison for electricity projects

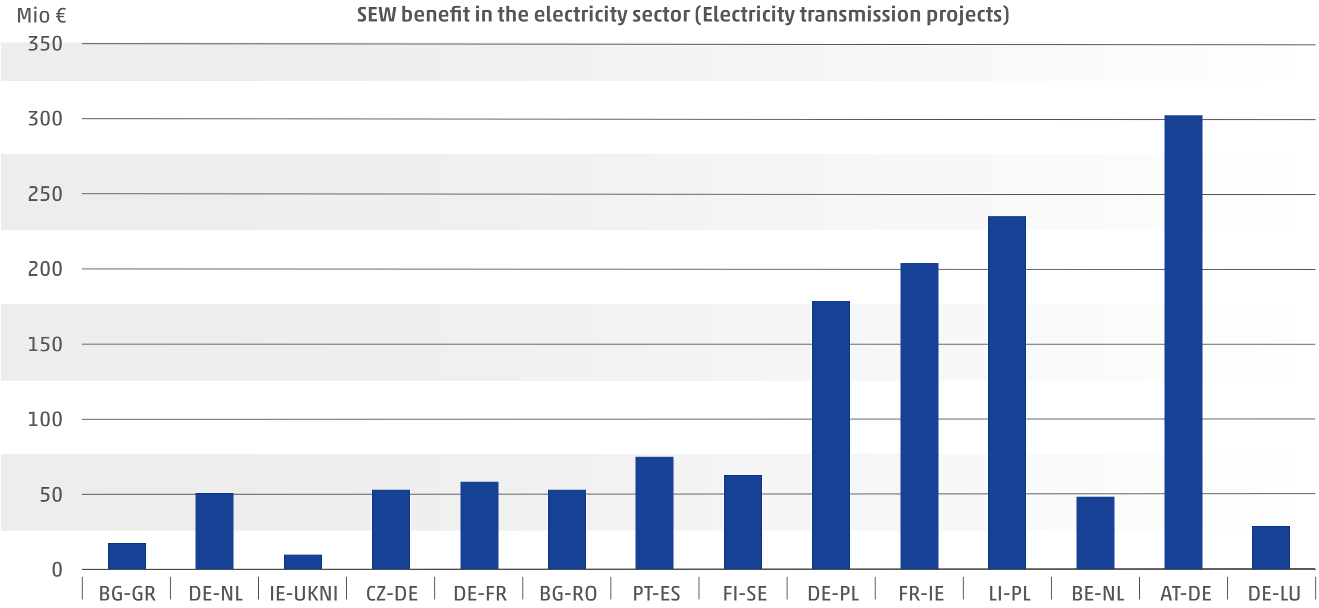

Figure 12: SEW benefit in the electricity sector – Electricity transmission projects (PLEXOS)

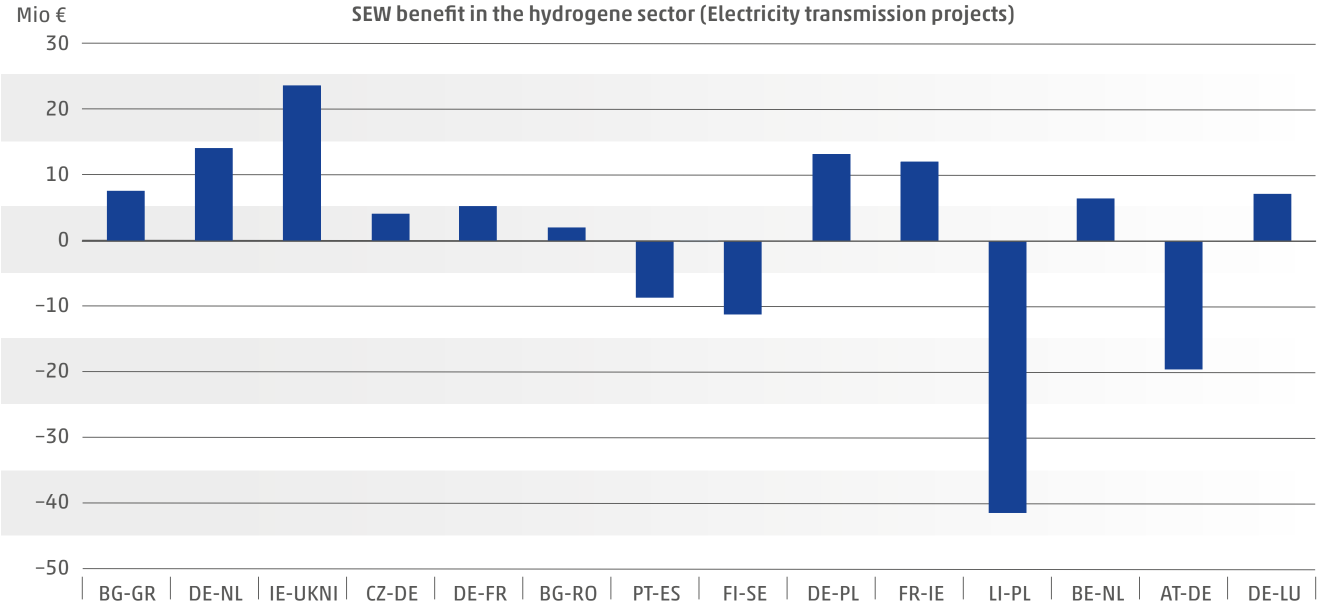

Figure 13: SEW benefit in the hydrogen sector – Electricity transmission projects (PLEXOS)

For a few projects from the subset of electricity transmission projects, the dSEWelec is shown in Figure 12. In general, the values are very close to those observed in Figure 11, meaning most of the SEW benefit brought by the electricity projects mainly stem from an increased SEW in the electricity system.

Similar information is extracted for the hydrogen system and the results can be observed in Figure 13. A big difference in the order of magnitude can be first observed and the value is not always positive like what is observed in the electricity sector. Some projects will indeed reduce the SEW in the H_2 sector while optimising the cost for the overall system.[1]

One should note also that the VoLL of the H_2 being set to a value just below the marginal cost of the cheapest CO_2-emitting thermal power plant undervalues the cost of H_2 demand not served. This would lead to different values of the $dSEW_{h2}$ if another price is considered ex-post, for case where the project brings changes for the H_2 demand curtailed.

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[1] It is important to remember that change in SEW equals change in costs only when the whole system is considered. Therefore, a reduction of SEW "in the hydrogen sector" is not synonym to an increased cost of production in the hydrogen sector.

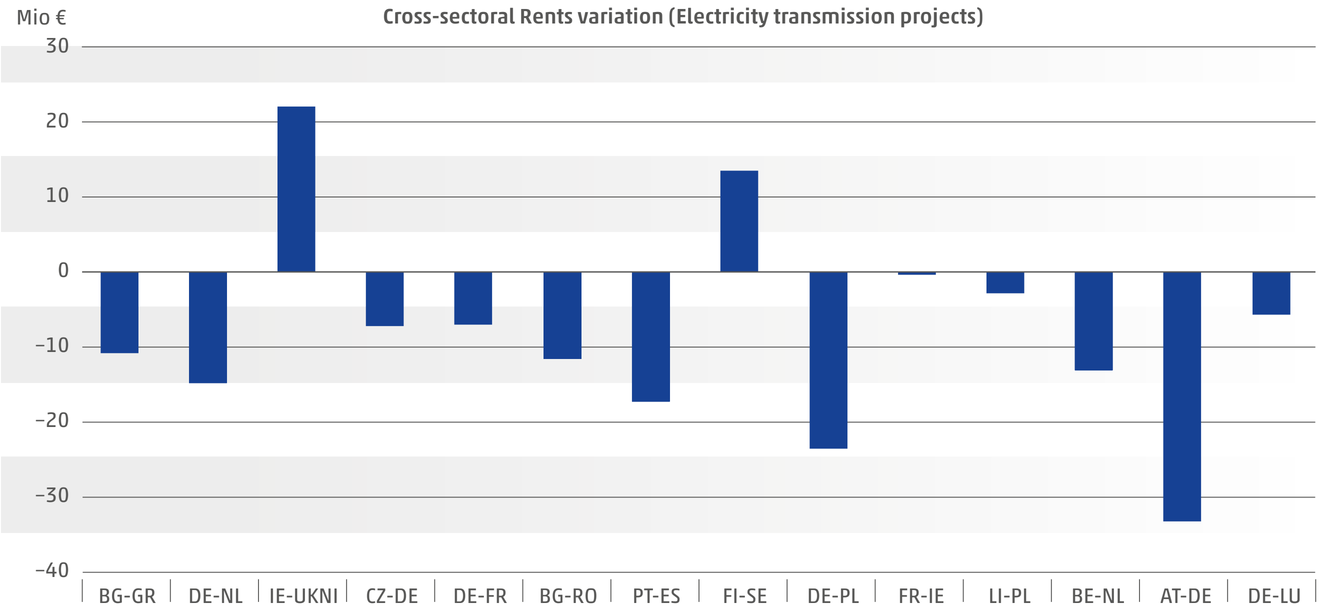

Figure 14: Cross-sectoral rents variations – Electricity transmission projects (PLEXOS)

Figure 14 shows the impact of each of the projects on what is called the cross-sectoral rent. The cross sectoral rent in simple words represent the profit made by the owners of sector coupling assets. In the ILM2024 Model the change in CSR due to the inclusion (or exclusion) of an infrastructure project will be affected by two main aspects which are:

- The change in installed capacity and/or load factor of the sector coupling assets.
- The price convergence between the sectors.

An increase in load factor of electrolysers combined with a much bigger price convergence between the electricity and the hydrogen sector could therefore lead to a decrease in CSR. The various combinations of the two aspects mentioned above will lead to different behaviours in the CSR; this is therefore also influenced by the optimiser used.

In Figure 14, the picture in quite varied. It is important to note the order on magnitude of this change in CSR, which is once again very low compared to the absolute value of CSR in each of the simulation which has billions as order of magnitude.

One could attempt to split the CSR between the sectors with an agreed rate. However, it would make it difficult to give a physical meaning to that split because as mentioned, the CSR represent the profit earned by owners of sector coupling assets, here electrolysers. One could then argue that this CSR itself is beneficial to neither of the coupled sectors and could be put aside. This would be true; however, this would overlook the fact that in a coupled sector approach, sector coupling assets' owners become agents in the market just as much as any other agent of the considered sectors and therefore, they should not be put aside. Moreover, an increased CSR rhymes here with a decarbonisation of the hydrogen sector and a better integration of RES from the electricity system.

Sharing the results of the SEW benefit per sector can be detrimental for some projects as the cross sectoral rent is then being overlooked with such approach. This is particularly true for the sector coupling assets (and therefore hybrid projects also). The total system SEW provides a stronger insight on the value added by an infrastructure project to the system.

Considering the total SEW with the total surplus approach, the results can also be clustered to look at the benefits brought by each project to the European Union. This is what is shown in Figure 15. For some of the projects, the SEW benefit brought to the European Union Member States is higher in comparison to the SEW benefit brought to the whole domain. This would mean that some of the non-EU Member States are seeing a decrease in their SEW benefit.

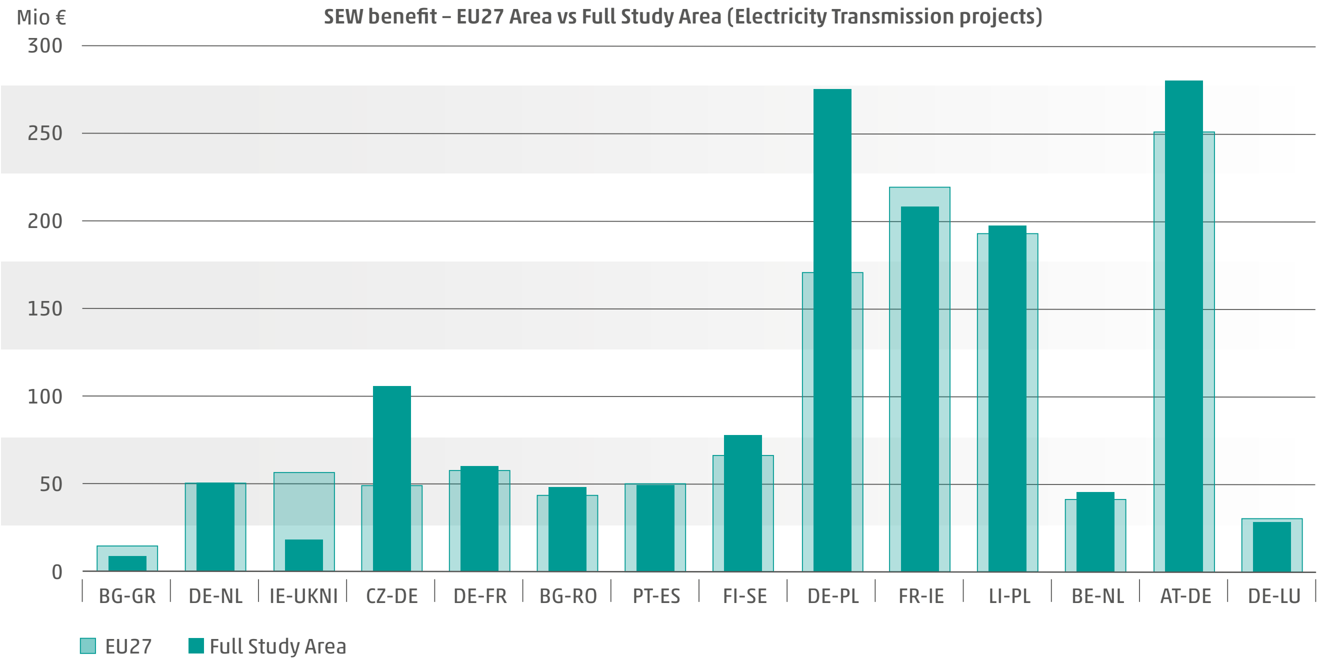

Figure 15: SEW benefit – EU27 Area vs Full Study Area (electricity transmission projects) (PLEXOS)

7.1.5 Sectoral SEWs trends in ANTARES

Similar to what is observed in PLEXOS (shown above), results show that in 2030, for the DE scenario, the impact of the hydrogen subsystem on the value of electricity projects is still limited. This result is confirmed by the SEW decomposition of these projects on both Electricity and Hydrogen subsystems. As shown in Figure 16, for all the projects, the share of this value on the Electricity subsystem is much higher than that on the Hydrogen subsystem. In the electricity subsystem on one hand, the value in terms of SEW for many projects exceed 100 M€ up to almost 680 M€. In the hydrogen on the other hand, these same values oscillate between −30 Mio € and +15 Mio €.

Figure 16: SEW electricity vs SEW Hydrogen (Antares) – Electricity transmission projects

7.1.6 Curtailed RES

The alignment in reduction in RES curtailment is not as close as the alignment of social economic welfare, the PLEXOS model seems to integrate more RES into the system. This indicator is not an economic indicator as the amount of RES integrated into the system will be inherently monetised within the Social economic welfare indictor. This is additional information for the project.

7.1.7 Emissions reduction (Power Generation)

There is a very close relationship between the tools in regard to reduction in GHG emissions. The shape of the emission reduction is very similar to the shape of the RES integration chart which shows a strong correlation between the two. This is of course expected as if thermal generation is replaced by renewable generation this will in turn effect the emissions unless a large proportion of renewables are replacing nuclear or biofuel generation.

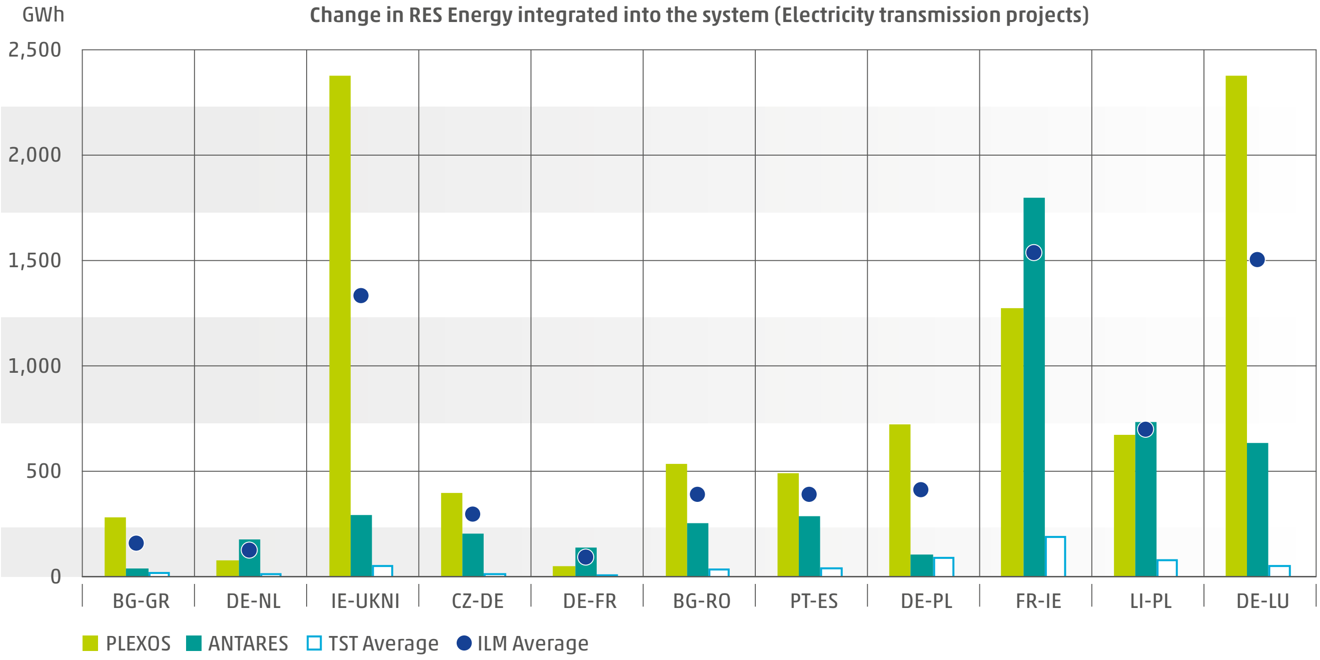

Figure 17: Change in RES integration from electricity transmission projects (PLEXOS vs ANTARES)

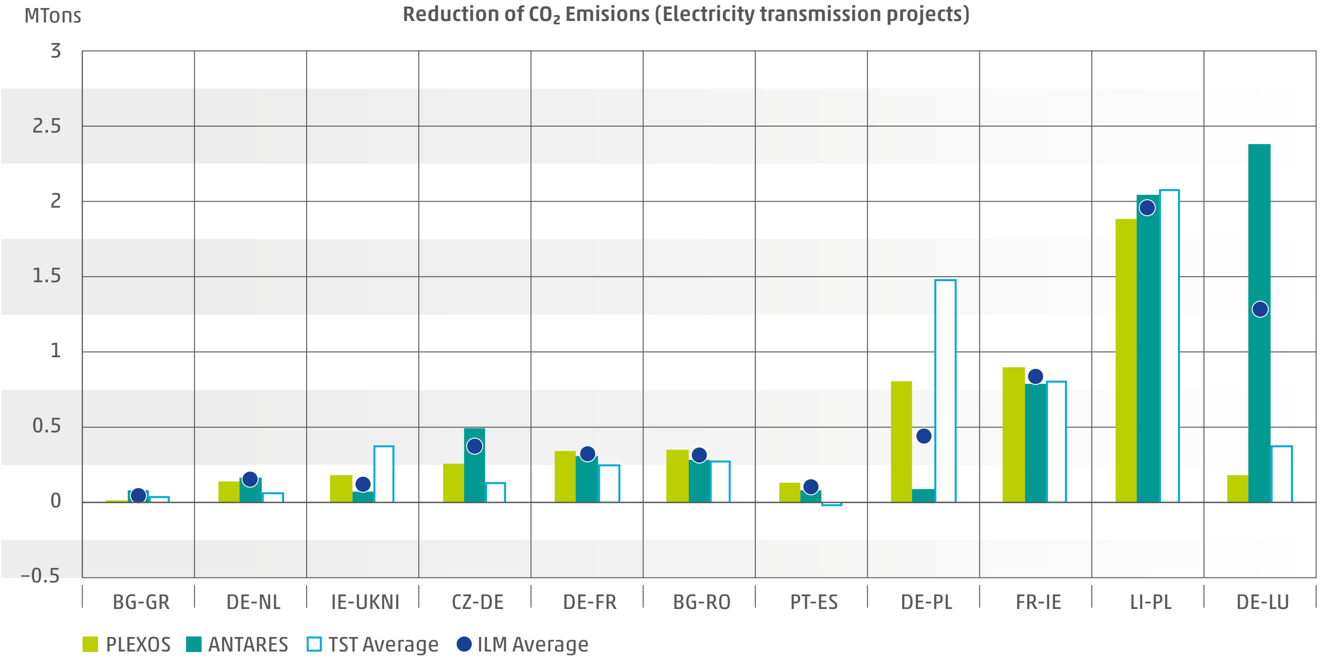

Figure 18: Reduction of GHG emissions by electricity transmission projects (PLEXOS vs Antares)

7.2 Electrolyser Assessment

Electrolyser projects do not fall within the mandate of the TYNDP performed within ENTSOG and ENTSO-E. The ILM2024 however is a useful tool for assessing them. Electrolysers are conversion technologies using electricity to split the molecules in water into their fundamental elements, hydrogen, and oxygen. As there is no reference infrastructure level for electrolysers, a supply disruption case is modelled instead, where the capacities are halved in the base case to address the impact of the reduction.

Electrolyser projects are a useful asset to assess as they transfer benefits from one sector to another. This transfer will be discussed below.

7.2.1 SEW Results Comparison for electrolysers projects

As with the other asset classes, there is generally alignment in SEW when comparing PLEXOS and ANTARES. In this case there is a misalignment in France, as with the other countries the reasons for this misalignment can be complex and will need to be further explored.

Electrolysers often result in a negative benefit in the electricity sector and a positive benefit in the hydrogen sector. This is because the increased power demand means increased market opportunities which results in additional costs being incurred in the electricity sector through the dispatch of expensive generators (Nuclear or Bio), which increases the system costs. In a single sector model, there would typically be a high net positive through producer rent and in contrast to this, the consumer rent is likely to decrease a lot as the unit dispatched would set higher market clearing prices that the consumers in the electricity sector would have to pay. When considering a coupled model, those consumer and producer benefits are reaped within another sector, in this case hydrogen sector where the effects in this sector are opposed to what was mentioned above in regard to the electricity sector. The cross-sector rent is typically a positive

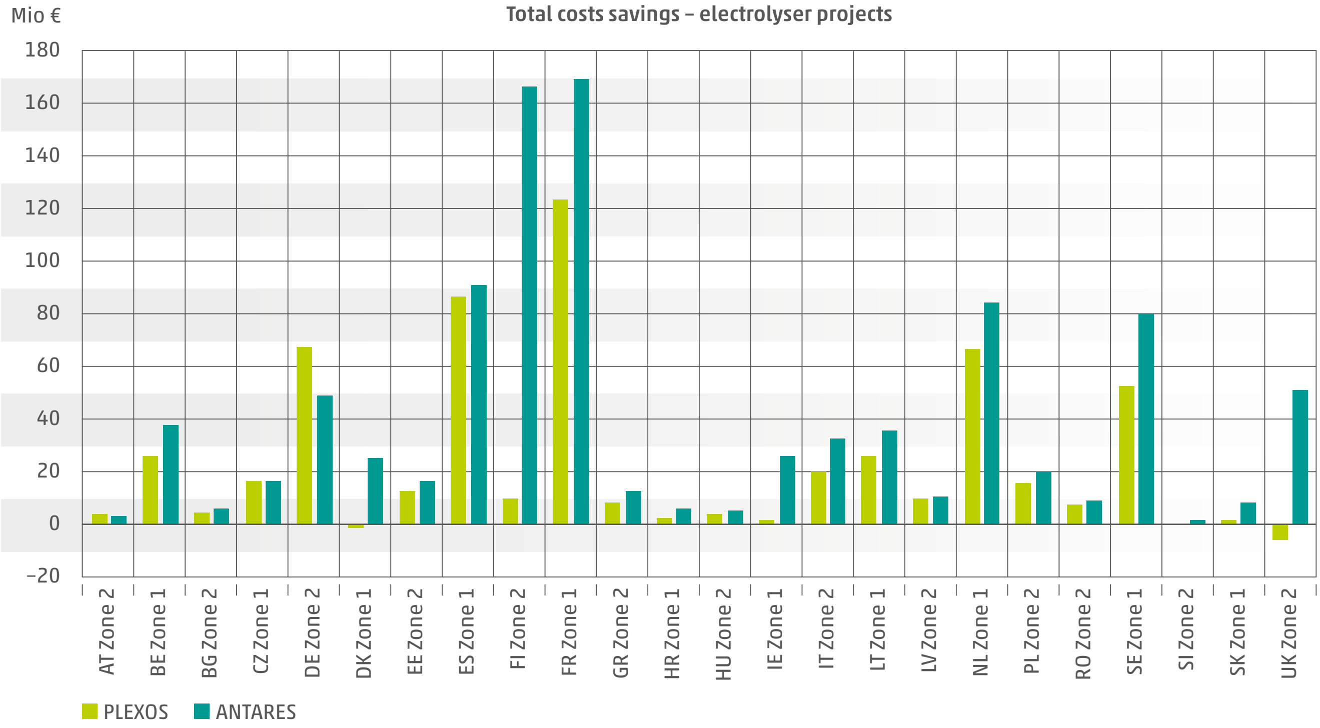

Figure 19: Total costs savings – PLEXOS vs ANTARES tool comparison for electrolyser projects

benefit and one can attempt to split it between the 2 sectors. This increases the overall SEW benefits attributed to the electricity sector but does not necessarily mean that the electricity sector will obtain a net positive benefit. The sum of the rents in and across the sectors however will typically lead to net positive benefits in the energy system. Figure 20 shows how these benefits manifest across the electricity and hydrogen systems. The x axis represent power and shows that around 50 % of projects show a negative SEW whilst the other 50 % is positive thanks to this cross sectoral rent. The hydrogen benefits are shown on the y axis and except for two electrolyser projects the SEW benefits are always positive. These benefits attributed to the hydrogen sector also contain 50 % of the cross sectoral rent.

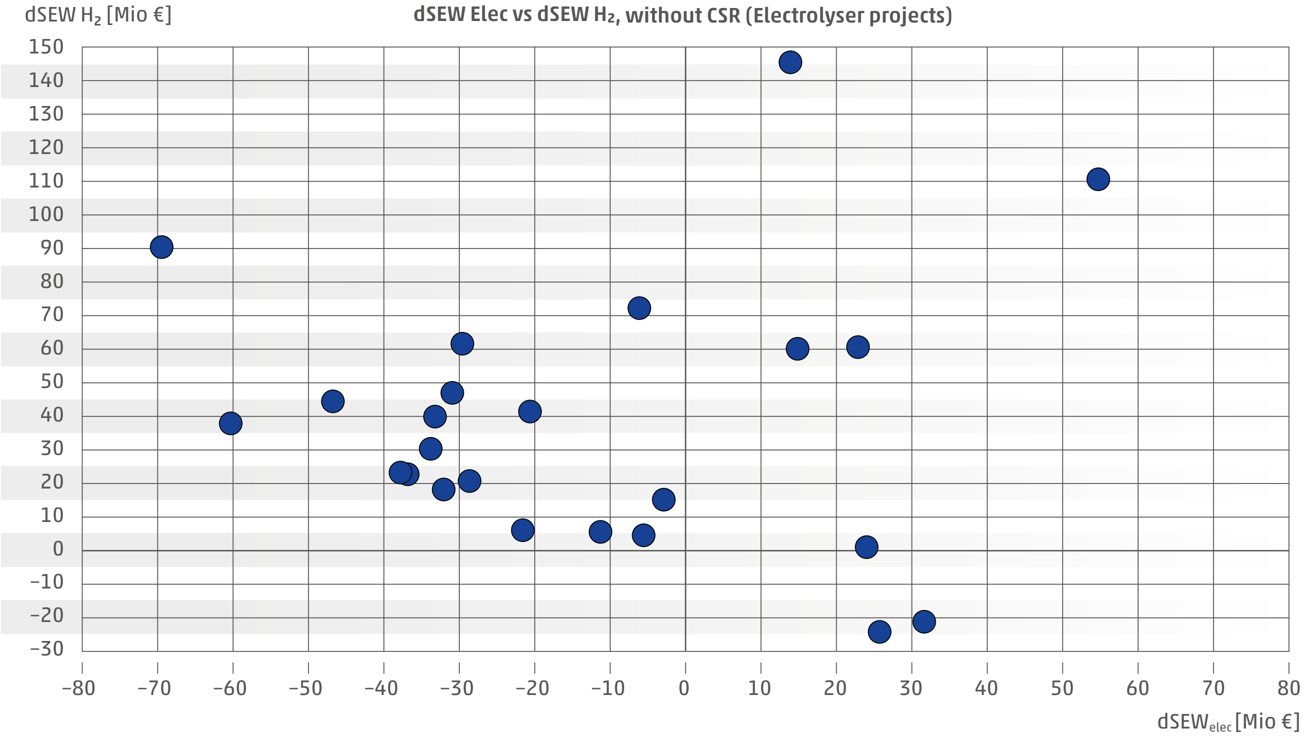

Figure 20: SEW electrictiy vs SEW hydrogen with 50 % CSR split (ANTARES) – P2G projects

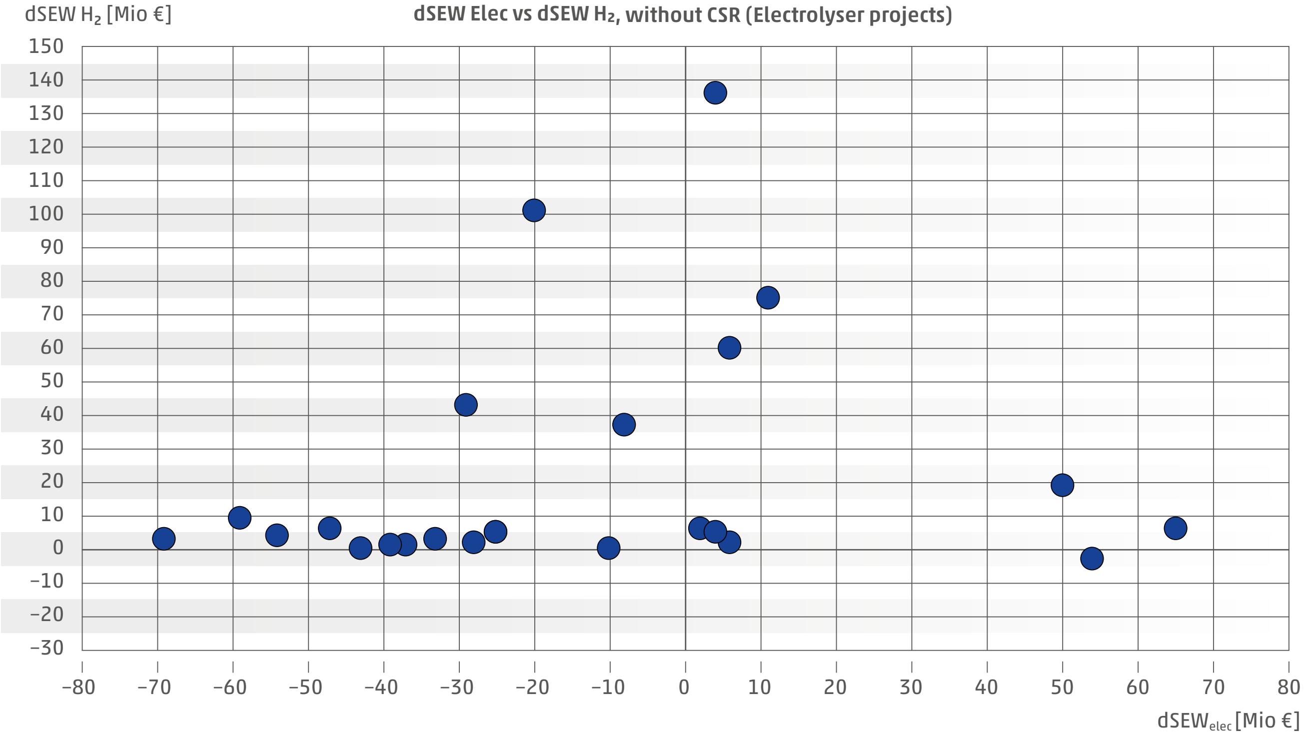

Figure 21: SEW electrictiy vs SEW hydrogen without CSR (ANTARES) – P2G projects

When looking at the results not considering the cross sectoral rent Figure 21, the electricity SEW remains around 50 % positive and 50 % negative. The hydrogen benefits similarly remain overwhelming positive, but the magnitude of this benefit float around the 0 line. This could be interpreted as the cross sectoral rent taking the lion's share of the benefits. Indeed, the surplus will be assigned to the electrolysers rather than the H_2 system. It also could be interpreted as the electrolytic hydrogen production is being used to mainly serve domestic demand rather than being used to serve demand across borders. If a larger proportion of electrolysers were removed from the model, there would likely be more cross border flows.

7.2.2 Reduction in CO_2 emissions

The non-linear constraints are discussed in section 5.4, where there are constraints which will need to be met by the model. This can vastly change the outcomes of the models. The charts below show how electrolyser projects can flip the change in CO_2 produced from positively or negatively depending on the project. This can be seen below for both tool and in a sporadic fashion. This is because the objective function of the model is cost minimisation and the balance between where energy is used changes as the model creates an endogenous demand for hydrogen. Once power plants are turned on, they must be run for a certain amount of time and at a minimum level of production. This issue can be overcome by implementing a CO_2 constraint which limits the amount of CO_2 that can be produced in the project case to what was produced in the base case. Implementing this constraint however may lead to negative effects in social economic welfare producing overall negative economic benefits for the project. One method to reduce these effects is to change the objective function of the model to CO_2 minimisation. This may have adverse effects on the economic indicators as it could also have a large effect on unserved energy. Another method would be to run the model using linear programming rather than mixed integer programming, although this would create a less realistic dispatch of generators.

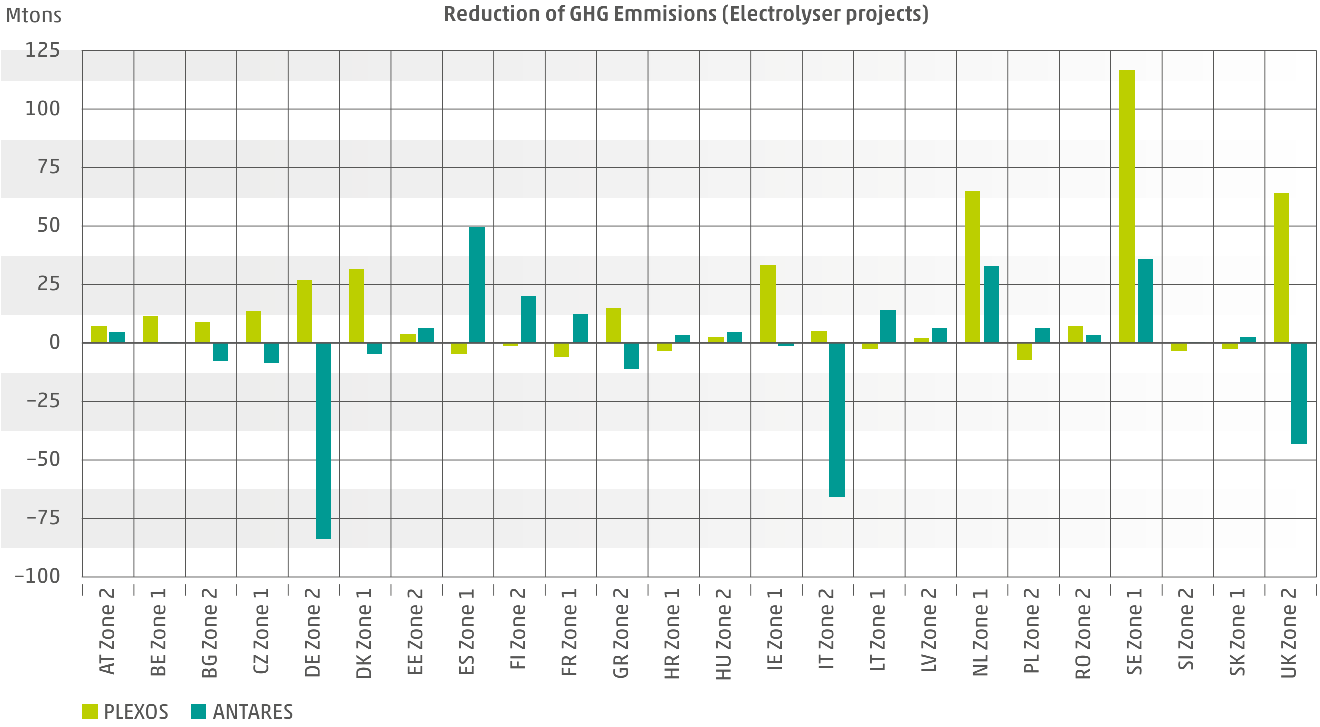

Figure 22: Reduction of GHG emissions by electrolyser projects (PLEXOS vs ANTARES)

7.2.3 Reduction of RES curtailment

Unlike with electricity projects, the Reduction in Curtailed RES does not follow the pattern as the reduction of CO_2 emissions. Despite the non-linear constraints for thermal plants, the model has been developed using a constraint which does not allow electrolysers to produce energy using CO_2 emitting power plants, and thus the only option for the model is to use renewable energy, giving the energy that was curtailed a load to follow. The magnitude of the RES integration is quite different between tool although the shape of the profiles in both tools are almost the same. This phenomenon will be further explored to see the reason for this. The largest difference between the 2 tool is 6.75x (661 TWh vs 4464).

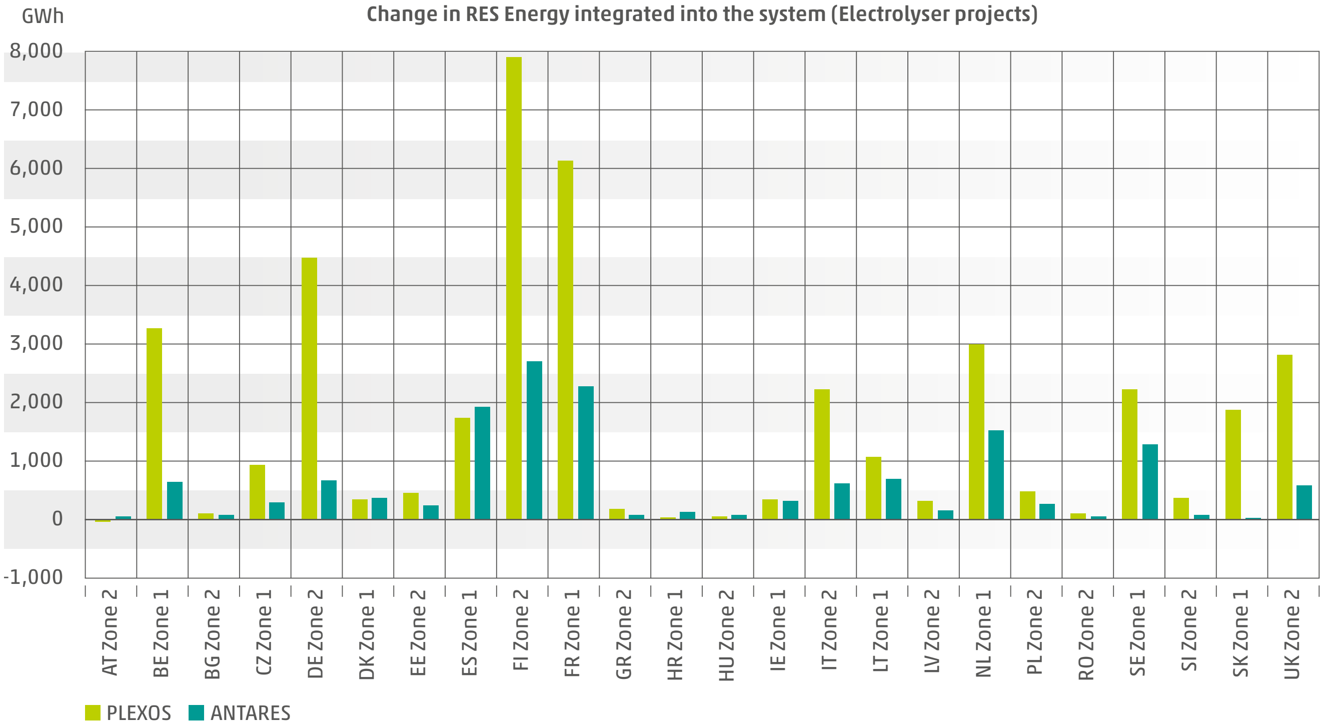

Figure 23: Change in RES integration from electrolyser projects (PLEXOS vs ANTARES)

8.2.4 Pipeline Projects

There are two category of assets which are typically submitted into the hydrogen TYNDP, Pipelines and Storages.

The cross-border capacities in both directions must be submitted for pipeline projects. Promotors can submit projects considering a connection between EU countries, between an EU and a non-EU country or import pipelines. Storage project promotors must submit Working Gas Volume, Injection Capacity and Withdrawal Capacity of a project.

In the TYNDP 2022, as the hydrogen infrastructure is in its infancy stage all the projects were assessed using the TOOT methodology, all project submitted to the gas TYNDP constructed the reference infrastructure levels. Therefore, the tests done for this report have been based on this approach.

7.3 Dual Gas Model vs ILM2024

In the 2022 TYNDP the Dual Gas Model (DGM) was used. This model which contains both the hydrogen and methane carriers. In comparison to the ILM2024 model, it is a simplified model which makes it very useful for running sensitivities such as supply disruptions and peak case analysis in respect to security of supply.

The DGM model is run at a monthly granularity. It is standard practice for the Gas models built within ENTSOG to use very coarse granularities due to the way the system is run i. e. historically does not rely on high granularity climate data such as solar radiation or wind speed. The ILM2024 however is run at an hourly granularity and connects electricity and hydrogen sectors. The ILM2024 model is therefore very useful for sustainability and economic indicators, as well as security of supply.

7.3.1 Hydrogen Projects for assessment

The selected subset of the projects which have been submitted to ENTSOG in the TYNDP 2022 can be seen in Table 11.

PROJECT	COUNTRY 1	COUNTRY 2	CAPACITY DIRECTION 1 [GW]	CAPACITY DIRECTION 2 [GW]
GROUP 10	**GR**	BG	2.92	2.92
GROUP 11	**DE**	CZ	6	6
GROUP 13	**FI**	SE	6.75	6.75
GROUP 14	**EE**	LV	8.33	4.167
GROUP 14	**LV**	LT	8.33	4.167
GROUP 21	**DK**	DE	12.08	21.08
GROUP 23	**PL**	DE	8.33	4.167
GROUP 24	**FI**	EE	8.33	4.167
GROUP 26	**ES**	PT	3.375	3.375
GROUP 28	**ES**	FR	9	9
GROUP 37	**DE**	FR	8	8
GROUP 38	**NL**	DE	15.625	0.5
GROUP 39	**FR**	DE	0.5	8

Table 11: Hydrogen projects assessed

7.3.2 SEW Results Comparison for hydrogen pipeline projects

The results between ANTARES and PLEXOS are relatively well aligned. Three projects show relatively large deviations, Group-11 a connection between Germany-Czech Republic, Group-14 a connection between Estonia and Latvia and Group-21 a connection between Denmark and Germany as shown in Figure 24. A fourth project (not in Figure 24 to keep a good scale for the visual) also shows a deviation between the two models. This is Group 28 a connection between Spain and France, which brings a total SEW benefit of 369 Mio € and 168 Mio € in PLEXOS and ANTARES respectively. Despite the large deviation for the latter project, one can note very similar trends in the SEW surpluses of the two tools.

Unfortunately, only a comparison between tools can be performed here, as the Dual Gas Model would not be an appropriate model to compare with due to the granularity of the model and the fact that these indicators were not reported for that model. The misalignments between these projects will in any case be further explored to see if a closer alignment can be made.

The results for 2030 shows that a limited number of these projects generate significant value for the dual-energy system studied by ILM2024. A few projects only allow an overall cost reduction of more than € 20 million/year as shown in Figure 24. A reason for this is the flat merit order of supply sources within the hydrogen system. **There are essentially only 4 cost levels:**

- **Green Hydrogen**
- **Pink Hydrogen**
- **Blue Hydrogen and Import**
- **Shortage Price**

This flat merit order leads to very low-price arbitrages between countries, which in turn will lead to low benefits for pipeline projects and little price signal for underground storages which will lead to less activation of seasonal storage. An important recommendation would be to increase the price differences in supply sources.

Similar to what was proposed in the section dedicated to the electricity projects assessment, one can look at the total SEW benefit brought by hydrogen pipeline projects for the whole domain and for the EU27 Area. We observe in Figure 25 that Group-21 leads to a slight decrease of SEW in the EU27 Area.

Considering the output results from the PLEXOS ILM2024 Model, these benefits can be split into sectoral components. Figure 26 shows the $dSEW_{elec}$, Figure 27 shows the $dSEW_{h2}$ and Figure 28 on page 46 shows the change in CSR brought by the hydrogen pipelines projects.

One can observe that some hydrogen pipeline projects reduce the SEW in the hydrogen sector while they would increase the electricity sector SEW. Once again, this shows the complexity of the problem and brings light again on the fact that splitting the SEW benefit between sectors may not be the best approach for sending the right signals to the market participants. These projects bring much more benefit to the system than the effects on the hydrogen system only. When systems are optimised together, the benefit should be reported for the whole system.

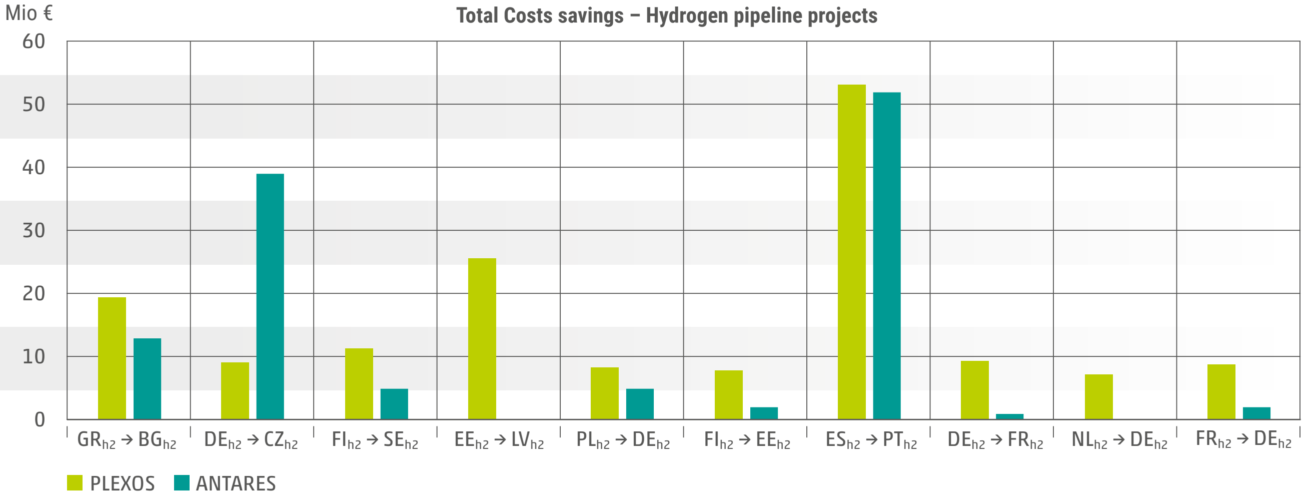

Figure 24: Total costs savings – PLEXOS vs ANTARES Tool Comparison for hydrogen pipeline projects

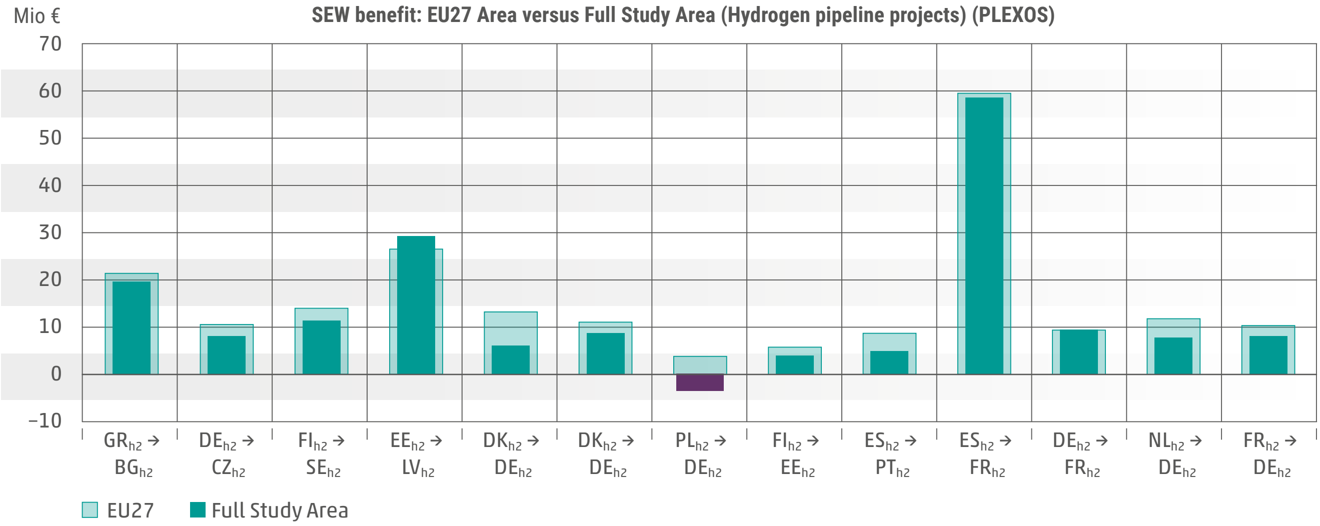

Figure 25: SEW benefit – EU27 area vs full study area (hydrogen pipeline projects) (PLEXOS)

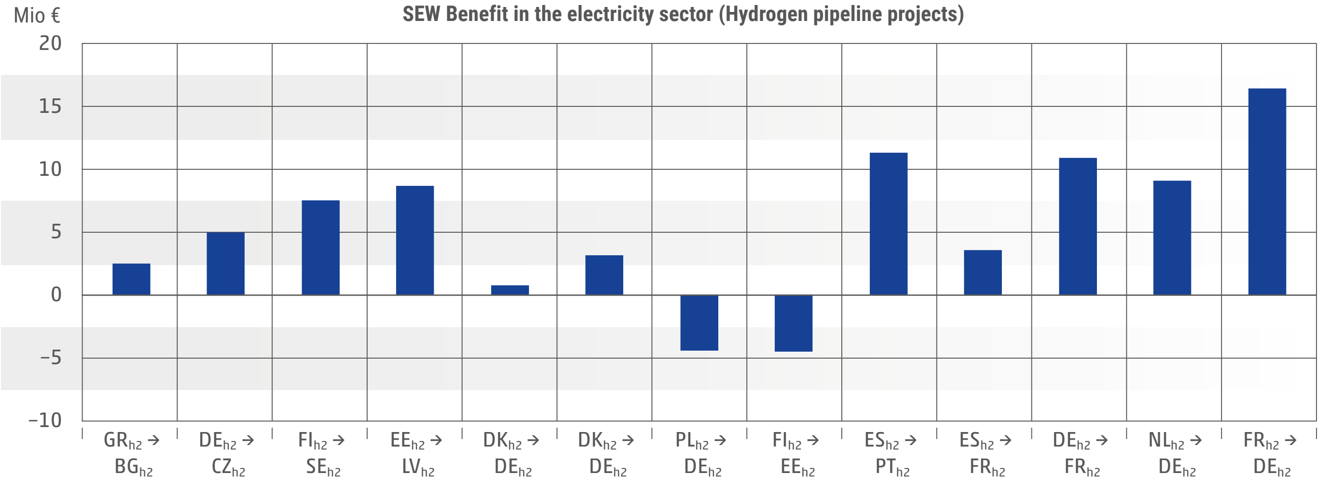

Figure 26: SEW benefit in the electricity sector – Hydrogen pipeline projects (PLEXOS)

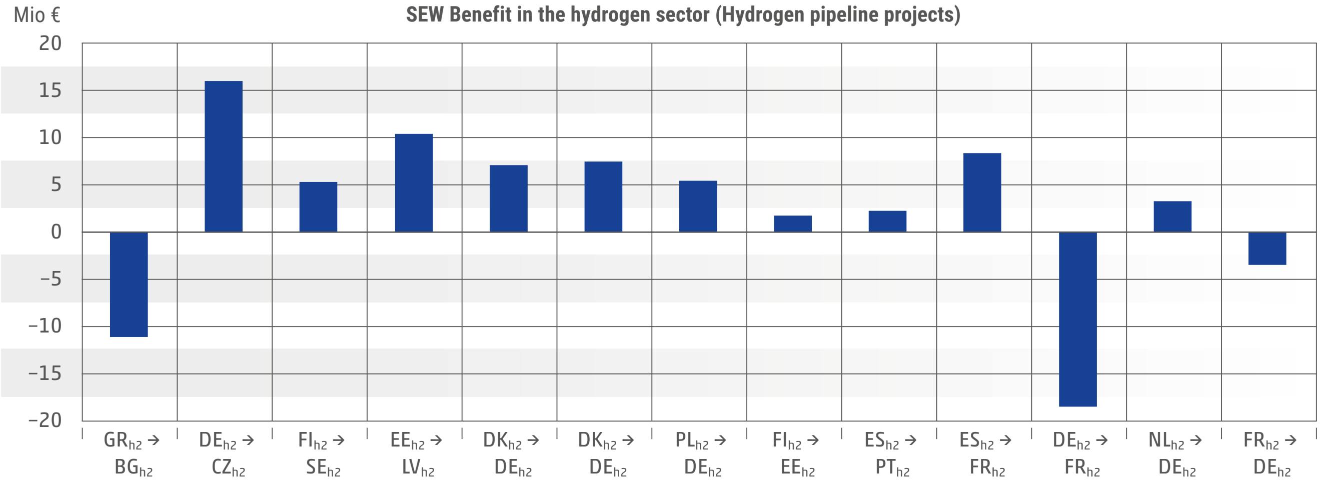

Figure 27: SEW benefit in the hydrogen sector – Hydrogen pipeline projects (PLEXOS)

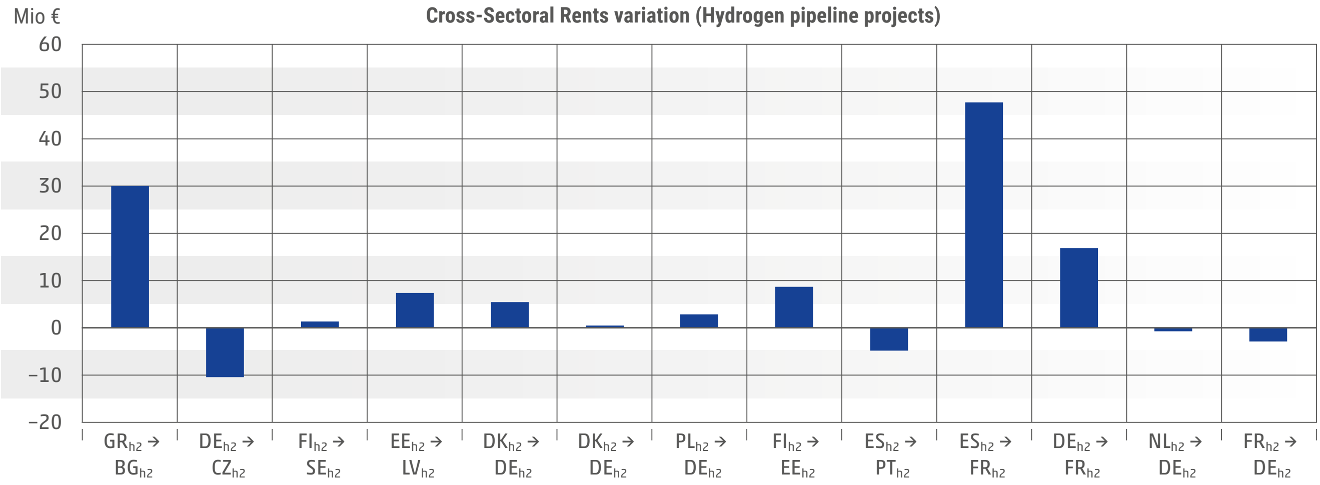

Figure 28: Cross-sectoral rents variations – Hydrogen pipeline projects (PLEXOS)

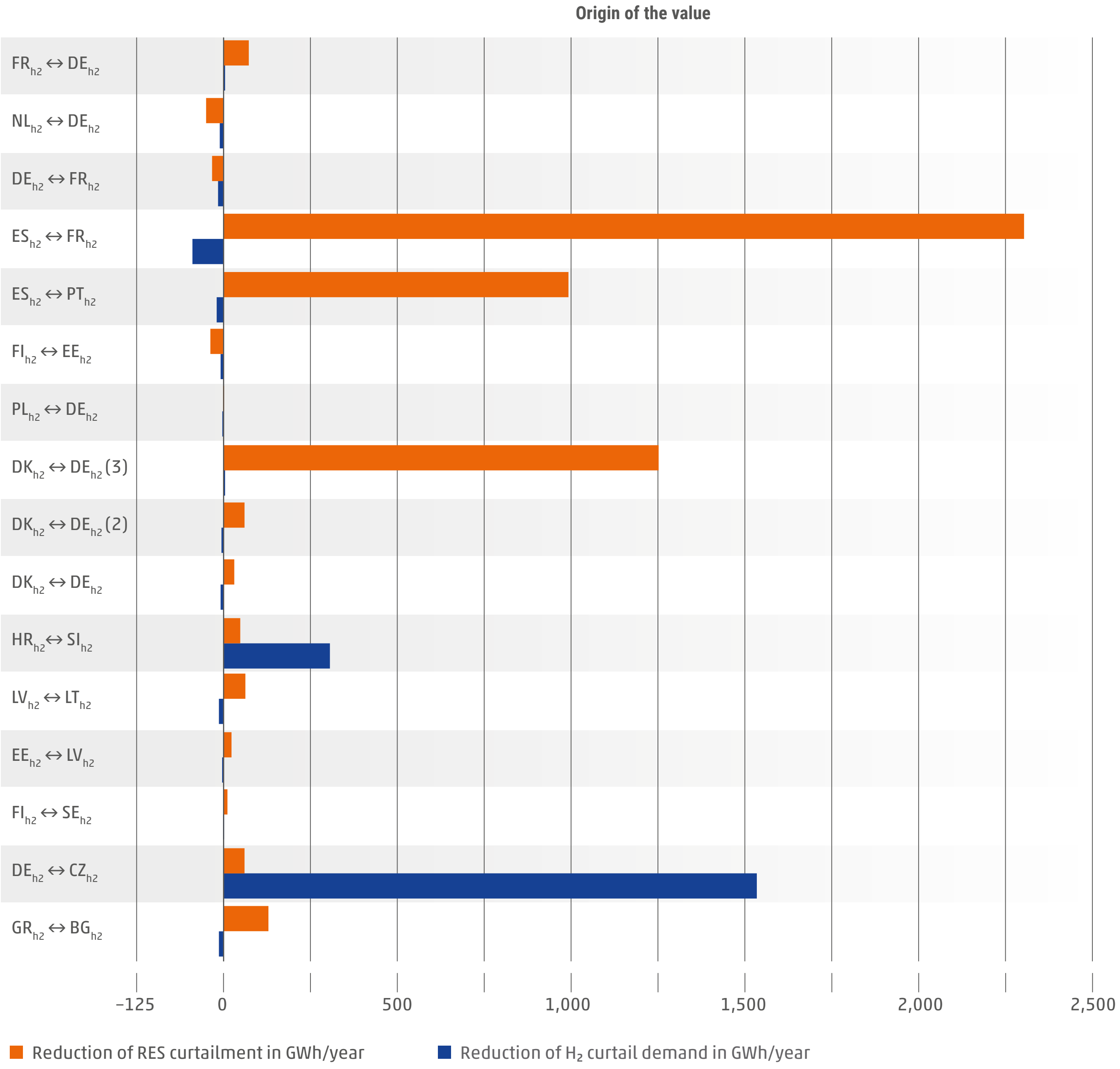

Figure 29: Origin of SEW Benefits (ANTARES)

The projects which lead to the largest SEW benefits can be further analysed to identify where these benefits stem from. For the project connecting Spain to neighbouring country, benefits stem from a significant reduction of RES curtailment. Additional capacity on these borders makes it possible to transform curtailed RES into Hydrogen in Spain for export.

The Germany and Czech Republic pipeline leads to a significant reduction of curtailed H_2 demand mainly located in Eastern Europe supporting the Hydrogen supply deficit in Eastern Europe.

An analysis in the cost difference between borders over 8,760 hours of the year has been performed to identify where opportunities lie based on a model with low price differences and low amount of hydrogen curtailment in the base case. It can be seen in Figure 30 that most borders show little to no price differences at any time during the year. The largest benefits are concentrated around eastern Europe which supports to analysis above which leads to the project between DE and CZ creating benefits due to hydrogen curtailment rates.

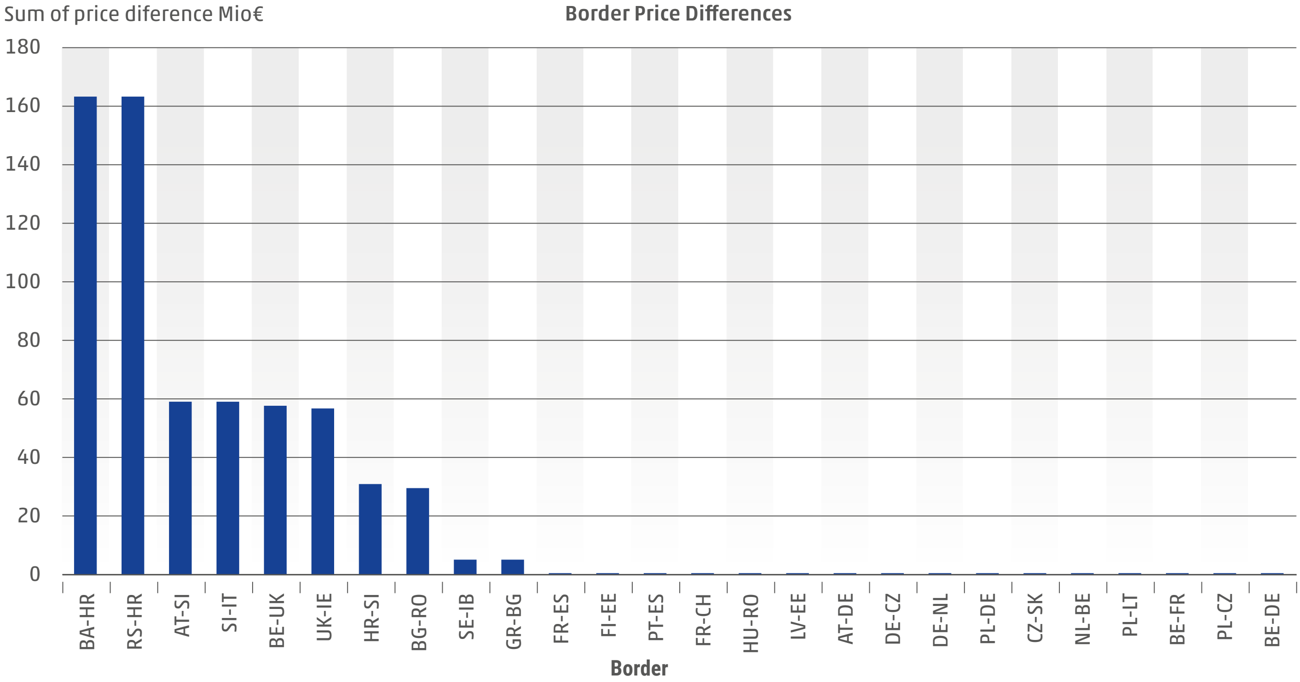

Figure 30: Sum of cross border price differences DE2030

7.3.3 Reduction of GHG Emissions

As can be seen in Figure 31, there is not a strong correlation between the GHG emissions in ANTARES and PLEXOS. As we saw in the electrolyser CBA section, the change in CO_2 emissions with and without electrolyser projects show high variability across projects and models. The introduction of pipelines can affect how electrolysers are operated and optimized; this therefore can lead to high variability when assessing electrolyser projects. The magnitude of this variability is not as high as when assessing on electrolyser projects, which is logical as there is only an indirect effect on electrolysers through assessing pipeline projects.

The hydrogen system is interlinked to the electricity system through electrolysers. The main variation in GHG emissions derives from the electricity sector as the dispatch of thermal power plants emits most of the emissions in the model. The change in emissions which derive from the hydrogen sector comes from the SMR plants, but as the SMRs are fitted with CCS at a 90 % capture rate, replacing SMRs with other generation may not lead to significant reductions. An interesting outcome of the model shows that the introduction of hydrogen projects reduces the emissions within the power sector, which could be due to the pipelines creating additional flexibility within the hydrogen sector and within the whole model allowing the electricity dispatch to become more efficient.

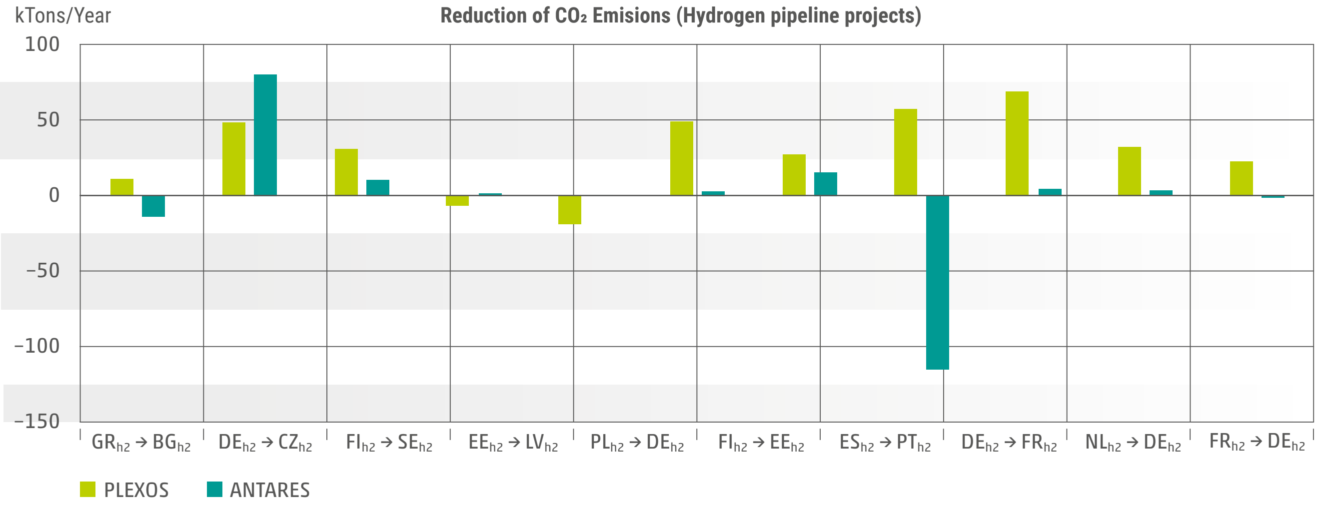

Figure 31: Reduction of GHG emissions by hydrogen pipeline projects (ANTARES vs PLEXOS)

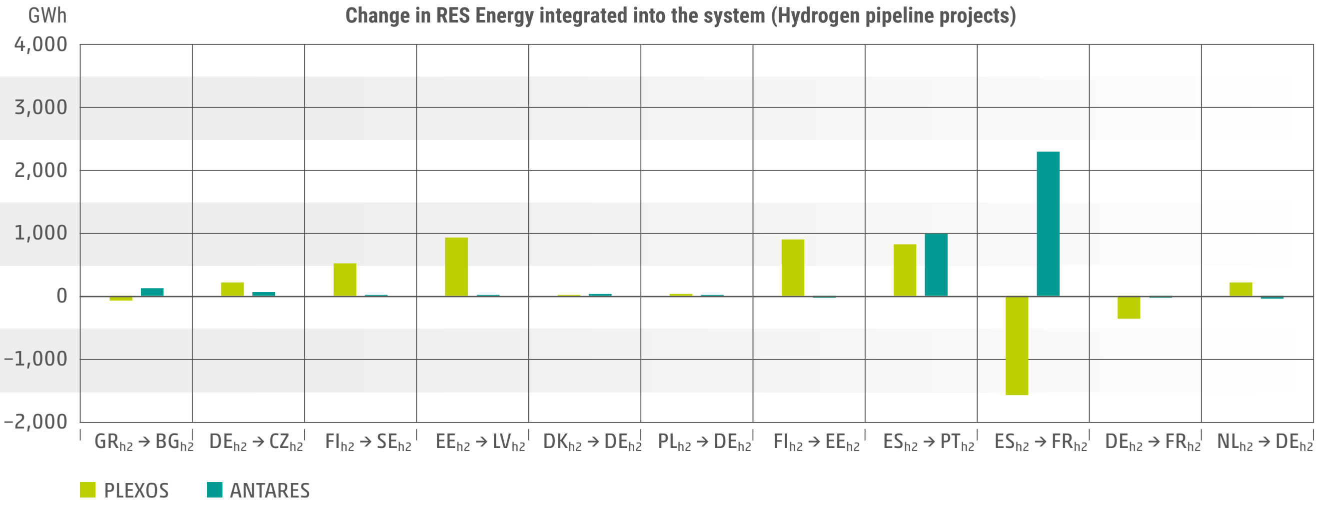

Figure 32: Change in RES integration from hydrogen pipeline projects (PLEXOS vs ANTARES)

8 RECOMMENDATIONS ILM MODEL USE FOR CBA //

8.1 **Recommendation 1:** SEW Approach

It is recommended that the SEW decomposition methodology is used for the assessment of projects using an Interlinked Model. This approach is particularly useful as it gives more insights on how the benefit is distributed to the different participants of the market. For full domain analysis the total cost approach will always provide equal results faster.

Thanks to analysis made on the total surplus approach which led to the insights shared in this report, the TF recommends that the SEW benefit be always communicated for the whole system and not at the sectoral level, independently of the regional granularity choice. By doing so, a stronger and more relevant signal is provided for market participants but also, the projects across the difference sector are all assessed in a fairer manner considering their impact on the system as a whole.

8.2 **Recommendation 2:** Use of Model

The observation from ILM2024 is that the system integration can bring clear benefit at multiple levels due to the co-optimisation of systems and the underlying cross-sectoral impact. On the other side, it is recognised that integrated models come with further complexities. It is therefore recommended that integrated models be used whenever possible and relevant for the CBA project assessments in the TYNDPs, especially when clear cross-sectoral impact is expected.

8.3 **Recommendation 3:** Consistency of modelling

It is recommended that the Integrated models are always based on a modification of the scenario model, keeping the key concepts as consistent as possible. Once the model has been built, any single sector modifications should be implemented in that model; This could include topologies, demand profiles, simplifications etc. to ensure that there is always a common baseline set when using the Integrated models while allowing updates based on actual projects submitted to the respective TYNDPs and in line with relevant CBA methodologies.

8.4 Price structure for hydrogen market

It is recommended that a varied supply source price structure is used for the hydrogen market. Some methods to vary the price structure could be to add a seasonal variability in the hydrogen prices which will in turn impact the storage usage and prices. A regional variation of hydrogen prices could also add a good level of variation to the model. Another method of variation is changing prices through import sources and import means e. g. shipped imports vs pipeline imports. The SMR could also be separated from ATR which are different technologies and will therefore have different technical parameters such as CO_2 capture rates and Variable and Operational Costs.

A real curtailment price is not used in the model. The current method works as long as there are no hydrogen supply sources cheaper than it would cost to produce hydrogen from CCGTs. This is unlikely to always be the case. A new methodology should be developed to evaluate the cost of hydrogen shortages. This could include valuing curtailed hydrogen not as energy unserved, but as a failure to achieve fuel switching from the original fuel (oil, coal, natural gas) to hydrogen. This would mean that the original fuel would still be operational and producing CO_2 emissions which could be considered in the model.

8.5 Modelling of shared RES

The modelling of shared RES must be aligned with how they have been developed in the scenarios. If the scenario expansion model builds RES where a significant amount flows to the electricity sector, the sector will rely on this RES and its removal will impact the electricity dispatch. It may be the case that shared RES options should be retired from the scenario modelling until it can be ensured to prioritise the hydrogen system rather than the electricity system.

9 CONCLUSIONS AND FUTURE PERSPECTIVES //

9.1 Conclusions

The ILM2024 has taken great strides since the last publication. The key developments have been:

- **Development of a single Interlinked Model**
- **Proof of concept of Interlinked Model**
  - **Electricity Grid Projects**
  - **Hydrogen Pipeline Projects**
  - **Electrolyser Projects**
- **Proof of concept of SEW decomposition method.**

9.2 Future opportunities

For each TYNDP cycle, innovations in the applied models are important to keep up with trends in the energy system. Innovation typically starts in the Scenario Building Innovation process, where some can be pushed into the ILM process and others rejected, always ensuring that it the model fits the purpose of the TYNDP .

9.2.1 Working Group Scenario Building Developments

The ILM2024 has room for further improvements. The Working Group Scenario Building Innovation Team has made headway in improving the way sectors are modelled. These innovations, all mapped on the scenario building model topology in Figure 33 include:

- **Offshore Wind Hub Modelling**
- **Hybrid Heat Pump Modelling**
- **Synthetic Fuel Modelling (SNG, e-Kerosene, e-Diesel)**
- **EV Modelling**

The first 3 innovations are based on cross sectoral links. They all consider a link between hydrogen and electricity. The “Synthetic Fuel Modelling” also include a link between the methane and hydrogen systems.

The EV modelling does not contain such links and therefore can be omitted from the ILM2024.

9.2.2 Offshore Wind Hub Modelling

Offshore hubs have been included in the 2024 scenario development process. The Offshore Hubs serve as production facility providing electricity and hydrogen to the mainland. The offshore hubs form a parallel offshore electricity and hydrogen grid which is interconnected into the mainland grid. The development of the offshore hubs is a result of the expansion modelling in the scenario development process.

9.2.3 Hybrid Heat Pump Modelling

As an innovation in heating, hybrid heat pumps have been modelled in the 2024 scenario development process. This is because there is market competition between hydrogen boilers and heat pumps when both are available in a dwelling. The optimisation of the asset used will depend on market prices, efficiencies, and COPs.

9.2.4 Synthetic Fuel Modelling (SNG, e-Kerosene, e-Diesel)

Synthetic fuels can be produced using Biogenic CO_2 in scenario model. This will trigger an additional demand in both the electricity and hydrogen systems and therefore should be modelled to see these impacts. The EC CBA guidelines for Electrolysers include an indicator for production of synthetic fuels, therefore this addition can be useful for the calculation of this indicator if requested.

9.2.5 Methane Modelling

There are important links between Methane and both electricity and hydrogen systems. Natural Gas supplies gas to CCGTs in the electricity system and to SMRs in the hydrogen system. Natural Gas peak cases and reduction of infrastructure could have significant impacts on the total energy system. Natural gas infrastructure is furthermore part of the definition of the ILM in in the TEN-E.

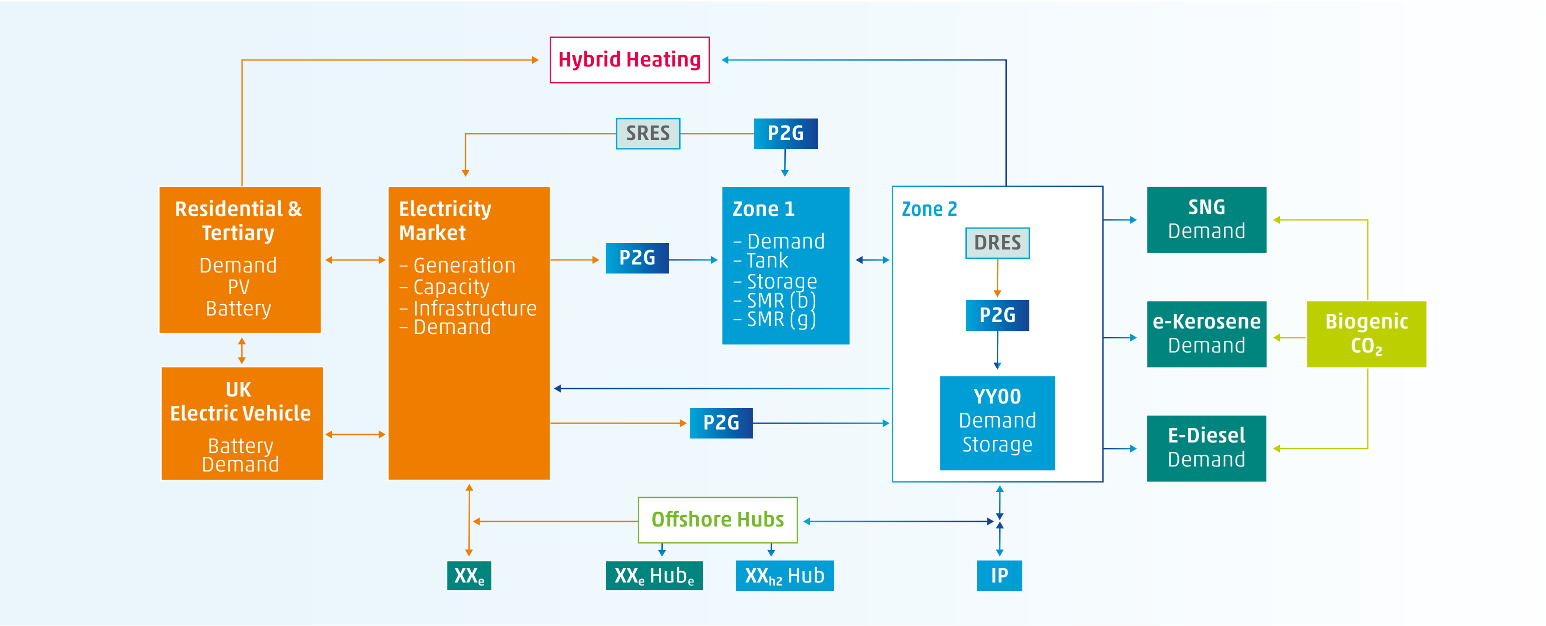

Figure 33: Potential future ILM model

ANNEX 1

Key Input data

Below are some keys inputs to the ILM2024 which are taken from the scenarios. Table 12 shows the Input and which sector they belong to.

CATEGORY	PARAMETER	SECTOR
SUPPLY CAPACITIES	Thermal Plants	Power
	Renewable Plants	Power
	Demand Side Response	Power
	Electrolyser Plants	Both
	Hydrogen imports	Hydrogen
	Steam Methane Reformers	Hydrogen
RENEWABLE PROFILES	Onshore Wind	Power
	Offshore Wind	Power
	Solar PV	Power
	Solar CSP	Power
	Other RES	Power
STORAGE	Underground hydrogen	Hydrogen
	Steel tanks hydrogen	Hydrogen
	Hydro Storage	Power
	Battery	Power
FUEL PRICES	Nuclear	Power
	Hard Coal	Power
	Lignite	Power
	Methane	Power
	Oil	Power
CO_2 PRICES	CO_2 prices	Both
SHORTAGE COST	Electricity Value of Lost Load	Power
	Hydrogen Shortage	Hydrogen

Table 12: Scenario input parameters

GLOSSARY

ACER: European Union Agency for the Cooperation of Energy Regulators

ATR: Autothermal Reforming

Biomethane: Gaseous renewable energy source derived from agricultural biomass (dedicated crops, by-products and agricultural waste and animal waste), agro-industrial (waste from the food processing chain) and the Organic Fraction Municipal Solid Waste (OFMSW).

CAES: Compressed air storage

Carbon budget: This is the amount of carbon dioxide the world can emit while still having a likely chance of limiting average global temperature rise to 1.5°C above pre-industrial levels, an internationally agreed-upon target.

CBA: Cost Benefit Analysis

CCGT: Combined Cycle Gas Turbine

CCS: Carbon Capture and Storage

CH_4: Methane

CSR: Cross-Sectoral Rent

CO_2: Carbon dioxide

DE: Distributed Energy

DGM: Dual Gas Model

DMIN: Minimal Duration time (in hours)

DRES: Dedicated Renewable Energy Source

EC: European Commission

ENNOH: European Network of Network Operators for Hydrogen

ENS: Energy Not Served

ENTSO-E: European Network of Transmission Operators for Electricity

ENTSOG: European Network of Transmission Operators for Gas

EU27: 27 members of the European Union

EV: Electric Vehicle

GA: Global Ambition

GHG: Greenhouse gas.

H_2: Hydrogen

Hybrid Heat Pump: Heating system that combines an electric heat pump with a gas condensing boiler to optimise energy efficiency.

ILM: Interlinked Model

JRC: Joint Research Centre

LCOE: Levelised Cost of Electricity

LNG: Liquified Natural Gas

MT: Megaton

NTC: Net Transfer Capacities

NT: National Trends

NT+: A version of the National Trends scenario which has been adapted to meet the latest EU targets

P2G: Power to Gas

PECD: Pan European Climate Database

PCI: Project of Common Interest.

PINT: Put IN one at the Time

PMIN: Minimal Stable Power level [MW]

PPA: Power Purchase Agreement

PS-CBA: Project Specific Cost Benefit Analysis

PV: Photovoltaic

RES: Renewable Energy Source

SRES: Shared Renewable Energy Source

SEW: Social Economic Welfare

SMR: Steam Methane Reformer

SNG: Synthetic Natural Gas

Synthetic fuel: Fuel (gas or liquid) that is produces from renewable or low carbon electrical energy.

TC: Total Costs

TEN-E: Trans-European Networks for Energy, EU policy focused on linking the energy infrastructure of EU countries.

TEN-E Regulation: Regulation (EU) 2022/869 on guidelines for trans-European energy infrastructure

TOOT: Take Out One at a Time

TPP: Thermal Power Plant

TS: Total Surplus

TSO: Transmission System Operator.

TST: TYNDP Study Team (ENTSO-E)

TYNDP: Ten Year Network Development Plan

TWh: Terawatt hour

V2G: Vehicle to Grid

VoLL: Value of Lost Load

VO&M: Variable, Operational and Maintenance costs

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