HYPAT

H2 Potential

Global Atlas of H_2 Potential

Sustainable locations in the world for the green hydrogen economy of tomorrow: technical, economic and social analyses of the development of a sustainable global hydrogen atlas

HYPAT Working Paper 04/2022

Future hydrogen demand: A cross-sectoral, global meta-analysis

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Executive Summary

Hydrogen and synthesis products are considered to be of high importance in future energy systems and therefore play an increasing role in climate change mitigation strategies. This working paper provides an overview of scenarios for the future development of hydrogen demand from a global perspective. The results show the range of possible developments in total as well as for the sectors industry, buildings and transport. Next to worldwide demand, results for the EU and China are disclosed. The bandwidths of hydrogen demand have been determined based on over 40 recently published energy system and hydrogen scenarios. The focus is on scenarios with ambitious reduction targets for greenhouse gas (GHG) emissions. In the following, these scenarios are referred to as "focus scenarios". In addition, the projected hydrogen demand is compared to the bandwidth of over 300 mitigation scenarios from the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), referred to as "IPCC scenarios".

Main findings at a glance:

1 **Hydrogen is needed to reach climate neutrality.** When reaching a threshold of 80% GHG reductions compared to 1990, use of hydrogen becomes unavoidable. The main driver for climate neutrality remains a drastic decrease in final energy consumption by energy efficiency measures and direct electrification.

2 **Hydrogen will become an important but not dominant energy carrier in the future.** Globally, hydrogen reaches on average 4-11% of the final energy consumption in 2050. In Europe, the relevance of hydrogen is higher compared to the energy consumption in China or worldwide. Hydrogen will play an important role in industry and transport but a minor role in the building sector.

3 **The large range in hydrogen demand indicates a high uncertainty in the ramp of hydrogen markets, hindering investments into hydrogen production, transport, and usage.** On the one hand, hydrogen demand is reported inconsistently between studies and more optimistically in dedicated hydrogen studies. On the other hand, hydrogen partially competes with direct electrification and biomass, and a ramp up is country-specific, as it relies on national climate neutrality ambitions and already existing infrastructures. The uncertainty of projections increases over time, as hydrogen demand has the highest bandwidth in 2050 except for the building sector.

Total demand

The hydrogen demand projections vary significantly between the scenarios. **Ambition in reducing GHG emissions is identified as a key influencing factor** in this context. Hydrogen demand increases with emission reduction ambition for all regions, especially with reduction targets of more than 80% in 2050 compared to 1990. In less ambitious scenarios, hydrogen demand would stay very limited.

Compared to today's figures, a large share of focus scenarios (inner bandwidth or interquartile range) projects a relevant increase of hydrogen demand, resulting in a **global hydrogen share of 4-11% of final energy consumption in 2050** (in absolute terms, the demand ranges from 14-55 EJ or 4-15 PWh). Some scenarios predict significantly higher values of up to 23% share (79 EJ or 22 PWh). However, regional differences exist. In the EU, the inner bandwidth is larger and lies between 4% and 14% (1-4 EJ or 0.3-1 PWh). In China, on the other hand, the inner bandwidth only shows hydrogen accounting for up to 4% of final energy consumption (2-4 EJ or 0.6-4 PWh). The demand projections are influenced by the studies' sectoral coverage (in particular inclusion of refineries, reverse power generation, industry feedstocks and international transport) and inconsistent coverage of direct and indirect hydrogen demand. The latter makes it difficult to compare the allocation of demand to direct hydrogen use and derived synthetic products (e.g. ammonia or methanol). Especially in the global and European scenarios, median and mean hydrogen demand projections in 2050 in the focus studies are higher than in the IPCC scenarios. Many of the upper band hydrogen demand projections of the focus studies would be classified as outliers in the IPCC range. In China, focus and IPCC scenarios show a comparable range in total hydrogen demand in 2050.

Transport

In all regions, the transport sector has **the largest share of hydrogen in total energy demand and the largest absolute hydrogen demand**. In the EU, the median hydrogen share in transport energy is considerably higher than in the other regions in 2050 (28% compared to 14% and16% in China and World, respectively). The transport sector is also the sector with the largest interquartile range of demand. In Europe, it ranges between 13-36%. In China, it ranges between 10-19% and globally between 10%-19%.

This shows that there is **substantial uncertainty regarding the use of hydrogen in this sector**. This relates to the role of hydrogen in road-based transport. Particularly in the case of passenger cars, the projections differ greatly, but the possible use of hydrogen in trucks is also viewed controversially. Further, demand projections for the transport sector are difficult to compare between studies, as the inclusion of international aviation and shipping is handled differently across studies. However, it has been found that differences in demand projections can only partly be explained by this, as there are also studies which exclude international transport demand and yet have higher hydrogen shares than studies which explicitly cover this sector.

Industry

In the industry sector, hydrogen is often termed a **"no regret" strategy, as there are applications with no alternative decarbonisation option**, for example, in the iron and steel industry or in basic chemicals. However, the demand projections for industry are considerably lower than for transport. When interpreting these values, it should be kept in mind that many studies do not include the use of hydrogen and synthesis products as a raw material (i.e. feedstocks), for example in bulk chemistry, in their projections. "No regret" however usually targets these feedstock and reactant uses for hydrogen.

Hydrogen used **for industry heat is considered to be more uncertain**, as there are potential alternatives available, which is mirrored in the studies' projections. Regional differences are also visible in the industry sector: While the median hydrogen share in industry energy is comparable between global, EU and Chinese outlooks (2-4%), the bandwidths of demand projections vary between regions. For Europe, the interquartile range predicts a share between 3-16%, with a maximum share of 38%, in 2050. The global studies project 2-9% with the highest predictions reaching 22%. China predicts 1-4%, with the maximum value reaching 7% in 2050.

Buildings

In the building sector, the role of hydrogen is smaller than in the other sectors in all regions assessed. The median share is predicted to be less than 2% of final energy demand in buildings in 2050 in all regions, **which shows the limited importance of hydrogen in this sector**. It is the sector with the smallest interquartile range (1-2% for the world), indicating that the projections for using hydrogen in building heat are similar and therefore **relatively robust**. The maximum values, however, differ between studies, and the highest shares are found in scenarios covering the EU.

Outlook

Overall, hydrogen will thus play a significant role in climate change mitigation, but it **will not be the dominant final energy carrier**. The evaluation of scenarios also shows that increasing emission reduction ambition strongly correlates with reductions in total final energy consumption. This can be explained by energy efficiency measures and the strong increase in direct electrification, for example by electric vehicles, heat pumps, or heating networks. Energy efficiency and direct electrification are generally seen as the main emission reduction levers. **Hydrogen therefore plays a relevant role in areas of application, where other technologies are technically or economically not feasible**. While hydrogen therefore remains a theoretical option in all three demand sectors analysed, **targeted policies are necessary to trigger an efficient use across sectors.**

Zusammenfassung

Wasserstoff und Syntheseprodukten wird in der künftigen Klimapolitik weltweit eine hohe Bedeutung zugemessen, da ihnen eine strategische Rolle bei der Erreichung von Treibhausgasneutralität zugesprochen wird. Dieses Arbeitspapier gibt einen Überblick über Szenarien zur künftigen Entwicklung des Wasserstoffbedarfs aus einer globalen Perspektive. Die Ergebnisse zeigen die Bandbreite der möglichen Entwicklung insgesamt und in den Sektoren Industrie, Gebäude und Verkehr auf. Neben dem globalen Bedarf werden Ergebnisse für die Regionen EU und China gezeigt. Die Bandbreiten der Wasserstoffnachfrage wurden auf der Grundlage von mehr als 40 aktuell veröffentlichten Energiesystem- und Wasserstoffszenarien ermittelt. Der Schwerpunkt liegt dabei auf Szenarien mit ambitionierten Reduktionszielen für Treibhausgasemissionen (THG). Nachfolgend werden diese Szenarien als „Fokusszenarien" bezeichnet. Zusätzlich wurden die Wasserstoffnachfrageprojektionen mit der Bandbreite der Nachfrage aus über 300 Minderungsszenarien des 6. Sachstandberichts des Intergovernmental Panel on Climate Change (IPCC) verglichen. Diese werden als „IPCC-Szenarien" bezeichnet.

Die wichtigsten Ergebnisse auf einen Blick:

1. **Wasserstoff ist notwendig, um Klimaneutralität zu erreichen.** Bei Erreichen eines Schwellenwerts von 80 % THG-Reduktion gegenüber 1990 wird der Einsatz von Wasserstoff unumgänglich. Die wichtigste Voraussetzung für Klimaneutralität bleibt jedoch eine drastische Senkung des Endenergieverbrauchs durch Energieeffizienzmaßnahmen und direkte Elektrifizierung.

2. **Wasserstoff wird in Zukunft ein wichtiger, aber nicht dominierender Energieträger sein.** Weltweit erreicht Wasserstoff im Jahr 2050 durchschnittlich 4-11% des Endenergieverbrauchs. In Europa ist die Bedeutung von Wasserstoff im Vergleich zum globalen oder asiatischen Energieverbrauch höher. Wasserstoff wird in der Industrie und im Verkehr eine wichtige Rolle spielen, in der Gebäudeheizung jedoch nur eine untergeordnete Rolle.

3. **Die große Bandbreite der Ergebnisse zur Wasserstoffnachfrage impliziert eine große Unsicherheit bei der Entwicklung von Wasserstoffmärkten, die Investitionen in die Produktion, den Transport und die Nutzung von Wasserstoff behindert.** Zum einen wird der Wasserstoffbedarf in den verschiedenen Studien uneinheitlich und in wasserstoffspezifischen Studien sogar optimistischer eingeschätzt. Zum anderen konkurriert Wasserstoff teilweise mit direkter Elektrifizierung und Biomasse und Bedarfe sind stark regional abhängig, da ein Aufschwung, u. a. von nationalen Ambitionen zur Treibhausgasneutralität und von bereits bestehenden Infrastrukturen abhängig ist. Die Prognoseunsicherheit nimmt mit der Zeit zu, da die Wasserstoffnachfrage im Jahr 2050 die größte Bandbreite aufweist, mit Ausnahme des Gebäudesektors.

Gesamtnachfrage

Aus den ausgewerteten Szenarien geht hervor, dass die Projektionen des Wasserstoffbedarfs erheblich variieren. Als ein **wesentlicher Einflussfaktor wurde dabei die Ambition zur Minderung von Treibhausgasemissionen identifiziert.** Es zeigt sich, dass die Wasserstoffnachfrage in allen Regionen mit Zunahme des Emissionsreduktionsziels steigt, besonders deutlich bei Minderungszielen von über 80 % in 2050 gegenüber 1990. Der Vergleich mit weniger ehrgeizigen Minderungsszenarien demonstriert, dass die Wasserstoffnachfrage sehr begrenzt bleiben würde.

Im Vergleich zu den heutigen Zahlen prognostiziert ein großer Teil der Szenarien (innere Bandbreite entsprechend dem Interquartilsabstand) einen deutlichen Anstieg der Wasserstoffnachfrage. Die Bandbreite des gesamten **Wasserstoffbedarfs im Jahr 2050 liegt für die Welt zwischen 4-11 % des Endenergiebedarfs** (14-55 EJ bzw. 4-15 PWh). Einige Szenarien sehen bedeutend höhere Ausreißerwerte von bis zu 23 % Anteil (79 EJ bzw. 22PWh). Es gibt jedoch regionale Unterschiede. In der EU ist die innere Bandbreite größer und liegt zwischen 4-14 % (1-4 EJ bzw. 0.3-1 PWh). In China hingegen zeigt die innere Bandbreite nur einen Wasserstoffanteil von bis zu 4 % der Endenergienachfrage (2-4 EJ bzw. 0.6-4 PWh). Die Nachfrageprojektionen sind beeinflusst von dem in den Studien gesetzten Sektorrahmen (insbesondere Einbezug von Raffinerien, Rückverstromung, stofflichem Einsatz in der Industrie oder internationalem Transport) und die Studien unterscheiden sich darin, wie sie direkte und indirekte Wasserstoffnachfrage berichten. Letzteres erschwert einen Vergleich der Allokation in direkte Wasserstoffnutzung und abgeleitete synthetische Produkte (z. B. Ammoniak oder Methanol). Insbesondere in den globalen und europäischen Szenarien sind der Median und das arithmetische Mittel der Wasserstoffnachfragen im Jahr 2050 in den Fokusstudien höher als in den IPCC-Szenarien. Viele der oberen Bandbreiten der Wasserstoffbedarfsprojektionen der Fokus-Studien würden als Ausreißer im IPCC-Bereich eingestuft werden. Für China zeigen die Fokus- und IPCC-Szenarien eine vergleichbare Bandbreite des gesamten Wasserstoffbedarfs im Jahr 2050.

Verkehr

In allen Regionen hat der Verkehrssektor den größten Wasserstoffbedarf, anteilig am Gesamtenergiebedarf und absolut. In der EU ist der mittlere Wasserstoffanteil (Median) an der Verkehrsenergie im Jahr 2050 wesentlich höher als in den anderen Regionen (28 % gegenüber 14-16 % in China bzw. der Welt). Der Verkehrssektor weist für die Wasserstoffnachfrage unter allen Sektoren die größte innere Bandbreite auf. In Europa liegt diese zwischen 13-36 %, in China zwischen 10-19 % und weltweit zwischen 10 %-19 %.

Es zeigt sich, dass erhebliche Unsicherheiten hinsichtlich des Einsatzes von Wasserstoff in diesem Sektor bestehen. Insbesondere bei Pkw gehen die Prognosen weit auseinander, aber auch der mögliche Einsatz von Wasserstoff in Lkw wird kontrovers gesehen. Darüber hinaus sind die Nachfrageprognosen für den Verkehrssektor zwischen den Studien nur schwer vergleichbar, da die Einbeziehung des internationalen Luft- und Schiffsverkehrs in den einzelnen Studien unterschiedlich gehandhabt wird. Es hat sich jedoch gezeigt, dass sich die Unterschiede in den Nachfrageprognosen im Verkehrssektor nur zum Teil dadurch erklären lassen, dass es auch Studien gibt, welche die Nachfrage im internationalen Verkehr ausklammern und dennoch höhere Wasserstoffanteile aufweisen als Studien, die diesen Sektor ausdrücklich berücksichtigen.

Industrie

Im Industriesektor wird Wasserstoff **oft als "no regret"-Strategie bezeichnet, da es Anwendungen gibt, für die es keine alternative Dekarbonisierungsoption gibt**, z. B. in der Eisen- und Stahlindustrie oder in der Grundstoffchemie. Die Nachfrageprognosen für die Industrie sind jedoch wesentlich niedriger als für den Verkehr. Bei der Interpretation dieser Werte ist zu berücksichtigen, dass viele Studien den Einsatz von Wasserstoff und Syntheseprodukten als Rohstoff beispielsweise in der Grundstoffchemie nicht in ihre Projektionen einbezogen haben. "No regret" zielt jedoch in der Regel auf die Verwendung von Rohstoffen und Reaktanten für Wasserstoff ab.

Der **Einsatz von Wasserstoff für die industrielle Wärmeerzeugung gilt als unsicherer**, da es potenzielle Alternativen gibt, was sich auch in den Projektionen der Studien widerspiegelt. Auch in diesem Sektor sind regionale Unterschiede zu erkennen: Während der mittlere Wasserstoffanteil (Median) zwischen globalen, Europäischen und Chinesischen Prognosen vergleichbar ist (2-4 %), unterscheidet sich die Wasserstoffnachfrage zwischen den Regionen. In Europa prognostizieren die Studien eine innere Bandbreite zwischen 3-16 %, mit Maximalanteilen von bis zu 38 % in 2050. Die globalen Studien gehen von einem Wasserstoffanteil in der Industrie von 2-9 % aus, mit Maximalwerten von 22 %. China prognostiziert 1-4 % für 2050 mit Maximalwerten von 7 %.

Gebäude

Im Gebäudesektor spielt Wasserstoff in allen Regionen eine deutlich geringere Rolle als in den anderen Sektoren. Der Median wird auf weniger als 2% der Gebäudeenergie in 2050 geschätzt und misst somit **Wasserstoff in diesem Anwendungsbereich keine große Bedeutung** zu. Es handelt sich um den Sektor mit der geringsten inneren Bandbreite (1-2% weltweit), was darauf hindeutet, dass die Projektionen für die Nutzung von Wasserstoff in der Gebäudewärme in den meisten Studien ähnlich gesehen wird und daher **relativ robust** sind. Die Maximalwerte hingegen unterscheiden sich zwischen den Studien und die höchsten Wasserstoffanteile lassen sich auch hier in den Europäischen Szenarien finden.

Ausblick

Wasserstoff wird also eine wichtige Rolle in der Umsetzung der Klimapolitik spielen, aber **er wird nicht der dominierende Endenergieträger sein**. Die Szenarien zeigen, dass zunehmende Emissionsminderungsambitionen eng mit der Verringerung des gesamten Endenergieverbrauchs verknüpft sind. Dies lässt sich durch Energieeffizienzmaßnahmen und die starke Zunahme der direkten Elektrifizierung, zum Beispiel durch Wärmepumpen, Elektrofahrzeuge oder Wärmenetze erklären. Energieeffizienz und direkte Elektrifizierung werden als die wichtigsten Hebel zur Emissionsminderung angesehen. **Wasserstoff spielt daher in den Anwendungsbereichen eine relevante Rolle, in denen andere Technologien technisch oder wirtschaftlich nicht umsetzbar sind**. Während Wasserstoff also eine theoretische Option in allen Sektoren bleibt, werden Politikmaßnahmen zielgerichtet dafür sorgen müssen, dass Wasserstoff über die Sektoren hinweg effizient eingesetzt wird.

Contents

Executive Summary 3

Zusammenfassung 6

1 Introduction 11

2 State of research: metastudies on hydrogen demand 13

3 Methodological approach 15

3.1 Scenario selection 15

3.2 Focus scenarios 15

3.2.1 IPCC scenarios 17

3.3 Estimating hydrogen demand 17

3.3.1 General considerations 17

3.3.2 Direct hydrogen demand 18

3.3.3 Indirect hydrogen demand 18

3.4 Method for results visualisation 19

3.4.1 Boxplots: demand bandwidth 19

3.4.2 Scatter plots: emission changes 20

3.4.3 Regions and countries 21

4 Sectors of hydrogen demand 22

4.1 Industry 22

4.2 Buildings 22

4.3 Transport 23

5 Results 25

5.1 World 26

5.1.1 World - Total Demand 26

5.1.2 World - Industry Sector 32

5.1.3 World - Building Sector 36

5.1.4 World - Transport Sector 39

5.1.5 World - Summary of sectoral demand 43

5.2 Europe (EU28) 45

5.2.1 Europe - Total Demand 45

5.2.2 Europe - Industry Sector 51

5.2.3 Europe - Building Sector 55

5.2.4 Europe - Transport Sector 58

5.2.5 Europe - Summary of sectoral demand 62

5.3 Central Asia (China) 64

5.3.1 Central Asia - Total Demand 64
5.3.2 Central Asia - Industry Sector 70
5.3.3 Central Asia - Building Sector 74
5.3.4 Central Asia - Transport Sector 77
5.3.5 Central Asia - Summary of sectoral demand 81
5.4 Regional differences 82
5.4.1 Industry Sector 82
5.4.2 Building Sector 83
5.4.3 Transport Sector 84
5.4.4 Summary of regional differences 85

6 Discussion of hydrogen demand ranges 87
6.1 Influencing factors in energy system models 87
6.1.1 Influence of climate change mitigation ambition 87
6.1.2 Influence of total final energy consumption 87
6.1.3 Influence of the sector scope in studies 88
6.1.4 Influence of competing technologies 88
6.2 Sectoral and regional differences on hydrogen demand 89
6.3 Influence on study type 90

7 Conclusions 91

Literature 93

List of figures 94

List of tables 96

Abbreviations 97

A.1 Annex 98
A.1.1 List of focus scenarios 98
A.1.2 List of IPCC scenarios 101
A.1.3 Statistical data displayed in graphics 107

1 Introduction

The HYPAT project creates a global hydrogen potential atlas, with the aim to assess sustainable production locations based on technical, economic and social criteria. The project's findings will help understand and characterise the development of a global hydrogen market.[1]

A key question in the creation of a global hydrogen market and linked infrastructure is an assessment of the magnitude and location of hydrogen demand. The projection of this demand faces a multitude of uncertainties and difficulties. A global hydrogen market that serves a variety of end use applications does not exist today. The development of hydrogen supply depends on stable consumers on the demand side, which in turn expect affordable, secure and reliable hydrogen supplies. Furthermore, various potential hydrogen applications exist in all sectors. Their efficiency as well as ecological and economic sense must be evaluated in comparison to alternative technologies. Therefore, a sound projection of the actual global hydrogen demand is challenging. The related uncertainty, in turn, delays investment decisions and hinders hydrogen market ramp-up. The development of the hydrogen market needs to take place in parallel on the supply and demand side as the supply side needs certainty about demand quantities and the consumers' willingness to pay for it. Large bandwidths in projections need to be understood in order to develop targeted hydrogen policies.

The objective of this working paper is to study different scenarios and identify the bandwidths of hydrogen demand for different regions in the world and different sectors. These bandwidths are calculated based on over 40 recently published scenarios which assess future hydrogen demand. These are referred to below as focus studies. Moreover, the hydrogen demand of the scenarios from the IPCC's 6th Assessment report have been included as a reference bandwidth to classify the evaluated focus studies. The selected studies include global and regional studies and use a variety of energy system, techno-economic, integrated assessment, sectoral and other models. The comparison allows a robust assessment of the projected hydrogen demand, as the bandwidth points out which sectors and end-use applications face a high uncertainty in hydrogen demand. A small bandwidth can indicate a lack of decarbonisation alternatives for a certain end-use application. This limitation in turn increases the willingness to pay for hydrogen, if climate protection requirements make it necessary.

Due to the range of findings to be presented, this working paper lays its focus on the results for the geographic scopes World, Europe and China, showing the overall hydrogen demand as well as the demand for the three end-use sectors industry, transport and buildings. Sections on industry discuss feedstock use of hydrogen while international bunkers are discussed for the transport sector. Further publications on other regions or sectors are planned. The total hydrogen demand estimate includes all hydrogen uses in the energy system, including hydrogen in synthetic fuels (synfuels). Next to hydrogen demand in absolute terms, the total final energy consumption (FEC)[2] and the share of hydrogen in FEC are discussed. Furthermore, the change in FEC over the years and the share of hydrogen are compared with Greenhouse

[1] Further information about HYPAT can be found at https://HYPAT.de/HYPAT/projekt.php.

[2] "Final energy demand" and "final energy consumption" are used interchangeably in this paper.

Gas (GHG) changes. The different geographical scopes are compared in a dedicated section and selected influencing factors on the observed bandwidths discussed.

Within the project HYPAT, the results will be further used in modelling of a global hydrogen demand curve, which represents the willingness to pay for a unit of hydrogen in relation to the hydrogen price for different sectors and end use applications.

In the following Chapter 2, the paper starts with a brief overview of the state of research in hydrogen demand estimates, summarising other meta-studies. Subsequently, the methodology of hydrogen data collection, preparation and presentation is outlined in Chapter 3. Chapter 4 gives an overview on how hydrogen can potentially be used in the three end-use sectors industry, buildings and transport. Chapter 5 presents the results, separated by location (World, Europe and China) and by end-use sector (total, industry, buildings and transport). A discussion of results in view of climate change mitigation, total final energy consumption, sector scope, regional differences and other factors is presented in Chapter 6.

2 State of research: metastudies on hydrogen demand

Hydrogen demand trajectories published in various energy system modelling studies have been found to show a broad range of variability (Quarton et al. 2020; Wietschel et al. 2021).

In view of the large number of studies of future energy systems, especially in recent years, some meta-studies already exist which compare scenarios and evaluate influencing factors for the demand of different energy carriers. Hydrogen can potentially play a role in a variety of end use applications, such as in electricity supply, as well as the end-use sectors transportation, buildings and industry (DLR 2020), but it is not necessarily the most cost-effective or energy efficient solution for all applications to reach climate neutrality. Furthermore, regulatory incentives for market ramp-up must be put in place.

Differing projections on hydrogen demand can be caused by multiple reasons, which complicate the understanding of drivers behind hydrogen demand. Influencing factors are for example level of climate change mitigation ambition, assumptions of economic development, technological maturity of hydrogen technologies, production pathway and infrastructure of hydrogen, as well as the development of alternative and complementary technologies in different sectors. The number of scenario studies projecting hydrogen demand therefore often come to different conclusions. There is still no certainty about the actual size of the future hydrogen market, which creates investor uncertainty on both the supply and the demand side. Reliable demand estimations and resulting willingness to pay and price elasticities of consumers is vital information to establish supply infrastructures.

To briefly summarise the state of research on hydrogen demand, this chapter will provide a short overview of hydrogen metastudies.

Quarton et al. (2020) review the conflicting role of hydrogen in global energy scenarios. They find, in agreement with an earlier analysis of hydrogen demand by Hanley et al. (2018), that more ambitious emission reductions in scenarios increase the use of hydrogen. It is found that model result descriptions often do not provide details on assumptions behind hydrogen applications. While techno-economic data (e.g. production cost) is specified, descriptions on the value chain of hydrogen is often omitted (e.g. the electrolysis technology type, or transportation and storage of hydrogen). Most details regarding the use phase are provided for the mobility sector. Other end use applications, such as the interactions of hydrogen with the gas grid, are often qualitatively discussed but not quantified in the model results. It is also found that hydrogen from steam methane reforming with carbon capture and storage is frequently only presented in cost comparisons to renewable electrolytic hydrogen, or cited as short-term step to fully decarbonised hydrogen, but otherwise not further assessed. It is found that hydrogen has the largest potential in the transport sector, as it is modelled by most of the studied scenarios, with a contribution of total energy demand ranging from less than 2% to 25%. The contribution of hydrogen to the industry sector varies between 0.7% and 12% of final energy consumption in scenarios, and many scenarios do not include it at all. In the heat sector, hydrogen demand ranges from 0 to 12%.

The **World Energy Council (2021b)** reviews 13 scenarios on drivers and barriers of global hydrogen demand. They also find a broad range of hydrogen demand in the studied scenarios 18-72 EJ[3] (150 to 600 Mt in 2050), which they explain through differing assumptions on decarbonisation ambition and substitution technologies used (continued use of natural gas, efficiency improvements, direct electrification and CCS). Similar trends are observed for the temporal uptake of hydrogen: before 2030, hydrogen demand growths steadily but slowly due to commercial immaturity of hydrogen projects, limited electrolyser capacity, and corresponding long timeframes to set up hydrogen infrastructure.

The **Joint Research Centre** of the EU commission has published a summary study on hydrogen use in EU decarbonisation scenarios, where 11 scenarios are compared (JRC 2019). Hydrogen demand is found to make up between 10-25% of EU final energy consumption in 2050. The bandwidth of hydrogen demand varies between sectors, but also largely between studies. In the industry sector, the projected demand ranges from 0.3-2.3 EJ (69-627 TWh), in the transport sector from 0.6-6.4 EJ (165-1790 TWh) and in the building sector from 0.23-2.2 EJ (46-604 TWh). The scenarios investigated in this study are also incorporated into the dataset of the underlying meta-study.

The meta analysis conducted by **Fraunhofer ISI, ISE and IEG** in 2021 analyses energy system studies of the European Union with a focus on Germany (Wietschel et al. 2021). In 2050, the bandwidth without outliers lies between 1.4-2.9 EJ (400-800 TWh). The authors find that hydrogen and synfuel demand varies significantly between the scenarios, explained through several factors, including: level of decarbonisation effort, included demand sectors, use of CCS and sustainable biomass and technology options. It is observed that the level of emission reduction has to reach -80% before a significant hydrogen demand evolves. Consistent with the other overview studies, it is found that CCS is a competing technology for hydrogen as an option to mitigate greenhouse gases. Furthermore, biomass is identified as a substitution energy carrier. The availability of biomass and its sectoral allocation remains to be elaborated.

3 The values have been converted with the lower heating value of hydrogen (120 MJ/kg)

3 Methodological approach

3.1 Scenario selection

3.2 Focus scenarios

The scenarios analysed in detail for HYPAT and for this working paper were selected based on certain criteria, which are presented in Table 1. Although the selection includes national studies, this first working paper focuses on three larger geographic regions (World, Europe and China), with details on the selection given in section 3.4.3. In this paper, 43 scenarios were selected for review.

Table 1: Scenario selection parameters

Geographic scope	Time period	Climate mitigation pathways	Hydrogen demand available
Global, regional and national studies are evaluated. A selection of countries for which a high excess hydrogen demand is anticipated was studied in detail	The focus is on studies published between 2015 and 2022.	The focus is on ambitious climate protection scenarios. Most of the scenarios are compliant with the Paris Agreement targets (1.5-2.0°C global warming).	The focus is on studies modelling and quantifying the demand for hydrogen and synthetic fuels explicitly. However, some other relevant energy system studies were added for comparison.

Source: own illustration

The 43 scenarios selected as focus scenarios are from the 25 studies shown in Table 2. In the results section (chapter 5), the focus scenarios are referred to using a shorter designation (shorthand). The full publisher, study and scenario name for each shorthand can be found in Annex A.1.1.

Table 2: List of focus scenarios

Publisher	Study	Year	No of scenarios
Agora	No-regret hydrogen	2021	1
British Petroleum (BP)	Energy Outlook 2020	2020	2
The Economic Research Institute for ASEAN and East Asia	Energy Outlook and Energy Saving Potential in East Asia 2020	2020	1
Energy Watch Group (EWG)	GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY - Power, Heat, Transport and Desalination Sectors	2019	1
ERIA	Demand and Supply Potential of Hydrogen Energy in East Asia	2018	3
European Climate Foundation	Net Zero by 2050: From Whether to How	2018	3
European Commission	A clean planet for all - Long Term Strategic Vision	2018	2
	Policy scenarios for delivering the European Green Deal	2021	2
Greenpeace	Energy [R]Evolution	2015	2
Hydrogen Council	Net zero Hydrogen	2021	1
International Energy Agency (IEA)	Energy Technology Perspectives 2017	2017	1
	World Energy Outlook 2021	2020	2
	Net Zero by 2050	2021	1
	Global Hydrogen Review	2021	1
International Renewable Energy Agency (IRENA)	World Energy Transitions Outlook	2021	1
	A Pathway to Decarbonise the Shipping Sector by 2050	2021	1
Joint Research Centre (JRC)	Global Energy and Climate Outlook 2020	2021	2
	Global Energy and Climate Outlook 2021	2022	2
	Deployment Scenarios for Low Carbon Energy Technologies	2018	3
Navigant	Gas for Climate	2019	1
Öko-Institut	The Vision Scenario for the European Union	2015	1
Paris Agreement Compatible Scenarios for Energy Infrastructure	Building a Paris Agreement Compatible (PAC) energy scenario	2020	1
Shell	Shell Sky	2018	1
World Energy Council (WEC)	World Energy Scenarios	2019	2
	International Aspects of a power-to-x roadmap	2018	4

3.2.1 IPCC scenarios

The IPCC scenarios are included as a backdrop to the focus studies, but are not analysed in detail. For the 6th Assessment Report (AR) of the IPCC, Working Group 3 evaluates the impacts of climate change mitigation strategies with the use of climate, energy and economic systems models (e.g., integrated assessment models). The data can be downloaded from the AR6 Scenario explorer hosted by IIASA, including 188 models, 1389 scenarios, 1775 variables and 244 regions. For the comparisons in the framework of this study, a selection of scenarios has been carried out as described in Table 3. Scenarios with outliers in relevant variables that point to incorrect data transfer have been omitted from the selection. The complete list of chosen IPCC models and scenarios is provided in Annex A.1.2.

Table 3: Selection of IPCC scenarios

Geographic scope	Time frame	Climate mitigation pathway	Variables
10 World regions (R10) • Countries of centrally-planned Asia; primarily China • Eastern and Western Europe (i.e., EU28)	2020, 2030, 2040, 2050	*Category name:* C1: limit warming to 1.5°C (>50%) with no or limited overshoot C2: return warming to 1.5°C (>50%) after high overshoot C3: return warming to 2°C (>67%) C2: return warming to 2°C (>50%) *Category subset:* Excluded: "no climate assessment" and "NDCs" *IMP marker:* Excluded "CurPol" (Current policies)	Depending on availability in scenarios: • Emissions|CO_2 • Final Energy • Final Energy|Hydrogen • Final Energy|Industry • Final Energy|Industry|Hydrogen • Final Energy|Residential and Commercial • Final Energy|Residential and Commercial|Hydrogen • Final Energy|Transportation • Final Energy|Transportation|Hydrogen

Source: own illustration

3.3 Estimating hydrogen demand

3.3.1 General considerations

The total hydrogen demand includes all sectors where hydrogen demand has been modelled in the respective studies and scenarios. Not all studies model all sectoral demand, some studies only model one sector and not the overall demand. In the majority of the studies, total demand includes hydrogen used in the end-use sectors industry, buildings, transport and others (which is often not further specified) as well as in the transformation sector (e.g. for electricity production, in refineries or other indirect uses of hydrogen). The transformation sector can be one reason for differing demand estimations. Transformation sector branches such as oil refining, electricity production from seasonal storage or synfuel production are often not included in final energy consumption, as they are an intermediate step. However, when total hydrogen demand is estimated in studies, the demand for power, oil refining or synfuel production is often included. Sometimes the transformation sector subsectors are allocated to the end-use sectors. For example, oil refining is allocated to industry or transport demand. In this paper, the transformation sector demand, when reported, was included in the total hydrogen demand figure. Final energy consumption was taken as reported in the different studies.

The collected energy demand data from the selected studies and scenarios is aligned in structure with the IPCC and EUROSTAT energy balances (EUROSTAT 2019). An energy balance consists of three major parts: The energy supply, which describes the use of primary energy sources (e.g. coal, gas, bioenergy, etc.), the energy transformation (e.g. production of electricity from gas), and the total final consumption in the end-use sectors (e.g. industry, transport, buildings). In order to derive the total hydrogen demand, we distinguish direct and indirect hydrogen demand. Direct hydrogen demand is reported in end-use sector as "hydrogen". Indirect hydrogen demand is reported in end-use sectors as "synfuels". All figures and values refer to the sum of direct and indirect hydrogen demand if not noted differently.

3.3.2 Direct hydrogen demand

Hydrogen can be used directly for non-energy-purposes, electricity generation and heat generation. In the non-energy-use, hydrogen is consumed chemically for steel production in the direct reduction of iron ore or for basic chemicals production for the chemical industry (e.g. ammonia, methanol). Fuel cells at the final consumer (e.g. fuel cell vehicles) convert hydrogen into electricity. When combusted in hydrogen burners, hydrogen can be used for heating in industrial processes, service processes or heat in buildings. Especially high temperature heating in industrial processes is an interesting use case for hydrogen.

3.3.3 Indirect hydrogen demand

An indirect hydrogen demand arises from synfuels demand and from hydrogen used for reversed power generation (e.g. for seasonal storage of renewable electricity). In power generation, a fuel cell is converting hydrogen electro-chemically into electricity. This generated electricity is further distributed and used to power the final sectors industry, transport, heating. This hydrogen demand is not reported in final energy consumption, but it is part of the total hydrogen demand. In the studies collected for this report, the reported data was not always consistent in the allocation of hydrogen to direct and indirect uses. It was attempted to create comparability by determining the total demand including all indirect uses. Therefore, hydrogen used in the power sector has been included - where reported - in the total hydrogen demand estimates.

The estimated hydrogen demand for synfuels is added to the direct use of hydrogen for the studies where hydrogen and synfuels have been reported separately. For the synfuels that have not been explicitly defined in the studies, we calculate and use the mean hydrogen content of the identified hydro-carbon synfuels shown in Table 4. This estimate of hydrogen demand based on the chemical composition of the fuel does not account for additional hydrogen needed to compensate for process inefficiencies.

Table 4: Overview of different synfuel types based on reported synthetic fuels in focus studies

Specified types of Synfuels	Chemical formula	kg/per mol unit of fuel	Lower heating value (MJ/kg)	Hydrogen content in EJ/EJ synfuel
Ammonia	NH_3	0.017	18.6	1.15
PtDiesel	$C_{13}H_{23}$	0.179	41	0.38
PtKerosin	$C_{10}H_{22}$ to $C_{16}H_{34}$	0.184	41	0.44
PtGasoline	C_8H_{18}, C_7H_{16}	0.114	43.6	0.44
Methanol	CH_4O	0.048	19.9	0.51
Synthetic Methane	CH_4	0.016	50	0.6
Values used for non-specified synfuels (mean value for C_xH_x)				0.47

Source: own illustration

3.4 Method for results visualisation

3.4.1 Boxplots: demand bandwidth

The focus of this study is the final energy consumption and particularly hydrogen demand. For this reason, the collected data has been checked for inconsistencies and sector designation aligned with the IPCC and EUROSTAT energy balance structure. This allocation has then been subject to data checks (e.g. incorrect totals over sectors or energy carriers have been corrected, missing totals have been added). Note that there are often diverging sector specifications. E.g. in the Greenpeace study, agriculture demand is part of the building sector, while it is part of the industry sector in Shell_sky. When demand figures could not be separated into the three presented end-use sectors, this is indicated in the result section if the respective scenario is discussed. All presented hydrogen demand figures include direct and indirect hydrogen demand from synfuels, if the latter was reported separately from hydrogen demand in the studies. For each region, the break-down of hydrogen demand estimated from synfuels is also presented separately for total demand. Table 5 shows which variables are shown for which sectors.

Table 5: Overview of data presented in this paper for World, Europe and China

Total demand	**Industry Sector**	**Buildings Sector**	**Transport Sector**
Total energy demand	Industry energy demand	Buildings energy demand	Transport energy demand
Hydrogen demand	Hydrogen demand in industry	Hydrogen demand in buildings	Hydrogen demand in transport
Share of hydrogen in total demand	Share of hydrogen in industry	Share of hydrogen in buildings	Share of hydrogen in transport

Source: own illustration

The hydrogen demand bandwidths from the evaluated studies are presented as boxplots. Boxplots allow to illustrate the distribution of values over the bandwidth. To achieve this, several orientation points are calculated for the datasets: mean, median, lower and upper quartiles and lower and upper quartile ranges, as shown in Figure 1.

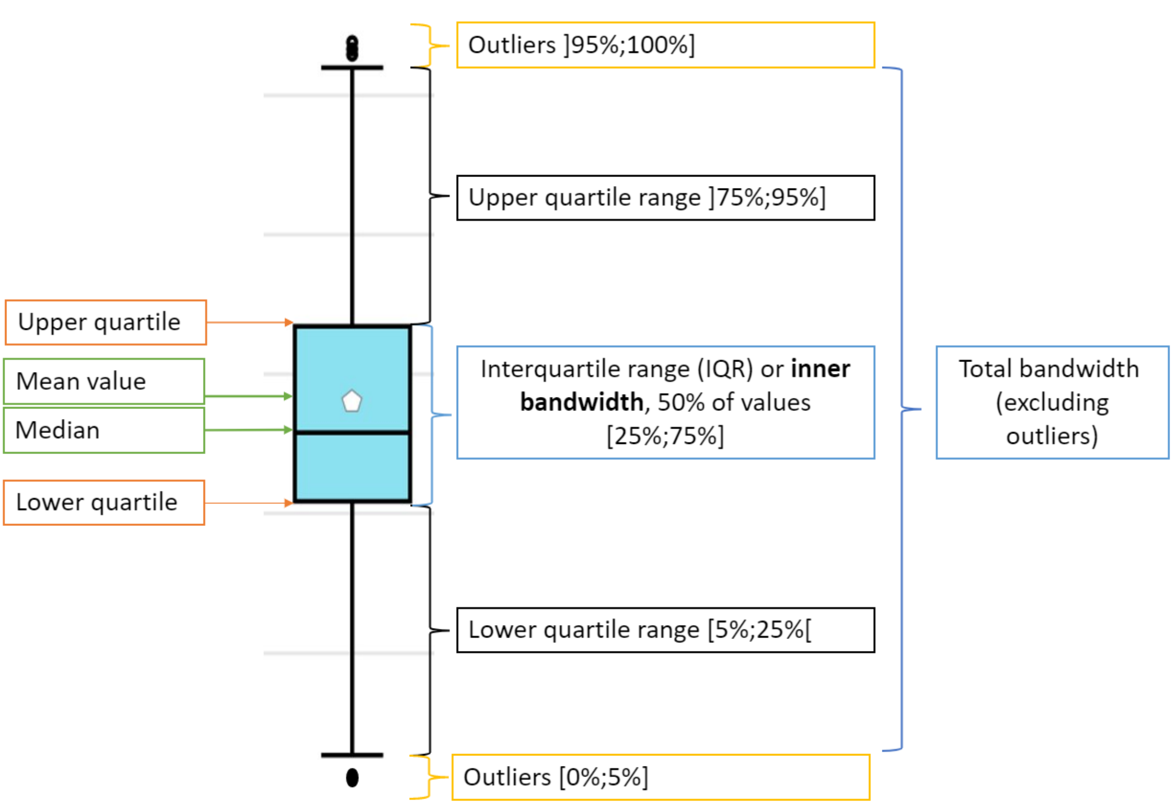

Figure 1: Structure of the boxplot to show the distribution of the data

Source: own illustration

The presentation allows to evaluate the distribution within the focus studies: the lowest and highest 5% of values are classified as outliers. The interquartile range or inner bandwidth encompasses 50% of the values around the median. The remaining 20% on each side of the interquartile range are referred to as lower and upper quartile range. In the result section, "total bandwidth" refers to all values within 5%-95% range (not including outliers). "Inner bandwidth" or "inner range" refers to the interquartile range.

Most results are compared to equivalent boxplots for the IPCC scenarios. For focus scenarios, the individual scenarios results are also indicated as scatter overlying the box.

3.4.2 Scatter plots: emission changes

In addition to box plots, two scatter plots are presented for every region. The first scatterplot shows the relationship between changes in energy demand projections and changes in end-emission levels between 2020 and 2050[4]. The second scatterplot shows the change in hydrogen demand in relation to the changes in end-emission levels. Note that not all scenarios report emission values and therefore, the scatter plots do not contain all scenarios.

4 In some studies, the start emission values were from 2018 or 2019.

3.4.3 Regions and countries

The analysis takes a global view and incorporates studies from different world regions. The distinction of world regions differs between the studies, which complicates a comparison of the values. As an orientation for this study, the IPCC R10 regions have been chosen as a basis, to which the other studies' regions have been allocated as shown in Table 6. For this working paper, the global results are presented and two regions, Europe (which often corresponds to EU28) and Central Asia (which is mainly determined and sometimes classified equal to China). Europe was chosen as a potential large demand centre with limited own production potential, where imports from other regions are very likely needed (World Energy Council 2021a). China was chosen as a region with large hydrogen demand but also a high domestic production potential.

Publications on further world regions are planned.

Table 6: Allocation of regions and countries from the focus studies to the IPCC R 10

IPCC classification	Short name	Classifications from focus studies		
Countries of centrally-planned Asia; primarily China	Central Asia (China)	China	North-East Asia	
Eastern and Western Europe (i.e., the EU28)	Europe (EU28)	EU28	EU 27	OECD Europe

Source: own illustration

4 Sectors of hydrogen demand

4.1 Industry

Hydrogen use in the industry sector is versatile. On the one hand, the industry sector already produces and uses large quantities of fossil hydrogen used as a feedstock in e.g. ammonia production (55% of hydrogen demand) for urea, hydrocracking and hydrodesulphurisation (25%) and methanol synthesis (10%) (Quarton et al. 2020). Current fossil hydrogen-based processes need to be converted into (novel) climate neutral processes. On the other hand, new potential applications for hydrogen arise for high-temperature heat or as a reactant in newly developed processes, such as in the direct reduction of iron ore for steel production (DECHEMA und FutureCamp 2020; Geres et al. 2018; Rissman et al. 2020; Navigant 2020). Many hydrogen applications in the industry sector are classified as "no regret", indicating that the potential for technologies alternative to hydrogen is technically limited or non-existent (Agora Energiewende 2021).

Although "no regret" applications create an environment of higher investor certainty for hydrogen technologies, the industry sector in itself is subject to complex transition behaviour: In many of the potential applications of hydrogen, incumbent process technology that has been used for decades has to be replaced by cost-intensive investments. At the same time, many branches in industry are competing on the world market with low profit margins and little product differentiation. As long as climate neutral hydrogen-based technologies are not cost competitive compared to the fossil or alternative novel processes, businesses are risking economic viability existent (Agora Energiewende 2021).

Long investment cycles of 30 to 40 years, however, drive the industry to invest as soon as possible, to be on track with necessary decarbonisation efforts for climate neutrality by mid-century (Agora Energiewende and Wuppertal Institute 2021).

Nonetheless, the demand for hydrogen in industry is considered to be of high magnitude, with higher certainty for feedstock uses in ammonia, ethylene, and fuel production or as a reactant in hydrogen direct reduction of iron ore, and lower certainty in industry energy provision (Wietschel et al. 2021).

Electrification is likely the main decarbonisation lever for low and medium grade heat in industry. For high grade heat, electric heating is less efficient and may require process alterations, potentially making hydrogen a more suitable option. By-product hydrogen is already used for heat provision today, e.g. being combusted in steam methane reformers for steam production and optimised energy integration (FCH 2 JU 2019).

4.2 Buildings

In the building sector, potential applications for hydrogen are its use for district heating, its blending into an existing natural gas system, as a gaseous derivative (e.g. as synthetic methane) in the natural gas system, as a liquid derivative for current oil-based boilers (e.g. synthetic diesel) in dedicated hydrogen condensing boilers as well as in local combined heat and power systems. The usefulness of hydrogen for heat provision in the building sector is highly debated in literature. It is also subject to regional differences in the available decarbonisation options. For example, in a more recent study, for Germany the building sector is decarbonized by extending the heat district network and the implementation of heat pumps. Direct electrification and use of hydrogen derivatives in gas and oil boilers remains an option for countries with currently no or a weakly established heat grid and a low innovation power (Prognos et al. 2022).

Arguments against hydrogen use in buildings are the availability of more suitable decarbonisation technologies. Hydrogen competes with direct electrification technologies (e.g. heat pumps and resistance heating) as well as other energy carriers that can be used in district heating. The hydrogen value chain in the building sector is characterised by low overall efficiencies (e.g. fuel cell heating 57%, hydrogen condensing boiler 64% compared to heat pumps with 300% or electric boilers with 95% efficiency (SRU 2021).

Arguments for hydrogen use in buildings are the complexity of using heat pumps in older existing buildings with poor insulation, where heat generation becomes very inefficient. In addition, the large electricity requirements of heat pumps, also characterised by substantial seasonal differences, pose a challenge for the electricity grid. To mitigate this shortcoming would require extensive capacity expansion with associated high investment cost. It is argued that a combination between indirect electric heating (heat pumps) and hydrogen would be the most cost-efficient approach to decarbonisation (FCH 2 JU 2019). Some of the arguments are difficult to judge, as they depend on uncertain parameters such as investment cost of refurbishment, where estimates can differ. For example, SRU (2021) estimates the financial burden of refurbishments to use hydrogen in condensing boilers to be substantial, including replacement or adjustments of natural gas grids and gas burners. FCH 2 JU (2019) on the other hand considers the investments for large-scale heat pump installations to be significantly higher. Blending of hydrogen into the natural gas grid is highly debated and is restricted by the physical properties of the pipelines (FCH 2 JU 2019). Some studies consider and discuss this option.

The building sector is complex, as each building faces individual challenges regarding the applicability of decarbonisation technologies, which make it difficult to draw general conclusions on which technology is the most suitable for decarbonisation. It may likely be a combination of different decarbonisation levers (Wietschel et al. 2021).

4.3 Transport

The use in transport has been the prevailing sector of interest for hydrogen for a long time (Quarton et al. 2020). Hydrogen can be used in a variety of transport subsectors. The effectiveness of hydrogen for decarbonisation depends also in this sector on many factors and differs for the individual transport modes.

In road transport, hydrogen can be mainly used in Fuel Cell Electric Vehicles (FCEV) or as a derivative in internal combustion engines (ICE). For passenger road transport, hydrogen competes with battery electric vehicles (BEV) and biogenic fuels. The advantages of hydrogen use are a shorter charging time of only a few minutes and longer driving ranges compared to battery charging in battery electric vehicles (BEV). The FCH 2 JU (2019) considers these criteria critical for customer acceptance of alternative vehicles.

However, considering well-to-wheel energy efficiency, the hydrogen-based drive types are substantially behind BEV due to the many conversion steps involved in the process chain: BEV achieve well-to-wheel efficiencies of 77%, FCEV of 34% and PtX based internal combustion engine vehicles 14% (SRU 2021). Furthermore, the cost of FCEV outweighs those of BEV, caused by the lack of scaling effects due to low market penetration. As of 2021, only 25,000 FCEV were globally on the roads, while BEVs and plug-in hybrid cars reached approx. 15 million vehicles in 2022 (Plötz 2022). The Hydrogen Council takes a different stance, arguing that the "sun-to-wheel" efficiency of BEV and FCEV can be on a comparable level if the FCEV is powered with imported renewable hydrogen from regions with a high solar PV potential. Higher load factors enable the production of more than double the amount of electricity compared to a German reference case for the same installed PV capacity (Hydrogen Council 2021). Hydrogen use in passenger transport can therefore be considered as one of the subbranches with a high uncertainty in demand projections and might only be considered for long distance frequent commuters (Prognos et al. 2022; Wietschel et al. 2021).

In long distance and heavy freight transport, hydrogen can potentially be a cost-efficient solution. It is argued that the added weight of increasing battery sizes and the longer charging process make battery electric freight less feasible. After a certain capacity requirement, the gravimetric and volumetric energy density of compressed or liquid hydrogen is higher than for batteries. In addition, large battery sizes would also drive up the cost of trucks to substantially outweigh those of hydrogen trucks. Arguments for hydrogen use here are furthermore that hydrogen infrastructure is faster in refuelling, allows more flexible loads, and requires less space at similar cost, compared to electric fast charging (FCH 2 JU 2019). However, technological advancements for battery electric vehicle truck charging stations as well as in overhead line networks are a competition for hydrogen (Plötz 2022), classifying this application area as uncertain as well.

For trains, electric drives are usually already prevailing, especially on highly frequented long-distance track sections. Batteries and potentially also hydrogen are discussed as options for newly developed track sections that are used less frequently and where the capacity extension of the electric grid would be cost-intensive (e.g. in rural areas) (SRU 2021).

More certainty for hydrogen demand in synthetic fuels can be found in the international aviation and maritime sectors (IRENA 2021; Wietschel et al. 2021). Liquid hydrogen and hydrogen-based synthetic fuels such as ammonia or methanol can be used in fuel cells or internal combustion engines (SRU 2021). The IEA NZ study finds that hydrogen fuel cells could play a role for flights up to 1600 km (up to 30% of aviation fuel consumption), while combustion of hydrogen-based fuels would be used in long-distance flights (up to 55% of fuel consumption), but both technologies require retrofitting aircrafts. On the contrary, the International Air Transport Association foresees hydrogen and batteries to play a negligible role in aviation (IATA 2021). In the maritime sector, the IEA NZ and IRENA NZ Shipping study see the highest potential in the use of ammonia fuel (IRENA 2021).

5 Results

In the following sections, the total and sector-specific hydrogen demand for World, Europe and China are presented for total demand and sectoral demand in industry, buildings, and transport, in this order. We also display feedstock demand in industry and international transport as well as the relationship between changes in energy demand (total and hydrogen) with changes in GHG emissions.

Next to the focus studies, the IPCC scenarios are shown. However, the corresponding boxplots for the focus and IPCC studies should not be directly compared, as the number of IPCC scenarios is much larger than the focus studies scenarios. This impacts the shape of the boxplot, as median, quartiles and arithmetic mean values are influenced by outliers. The IPCC boxplots can therefore be used as an orientation to classify the focus studies results.

A table with all statistical indicators shown in the figures is provided in Annex A.1.3.

5.1 World

5.1.1 World - Total Demand

5.1.1.1 World - Total demand - Final energy consumption

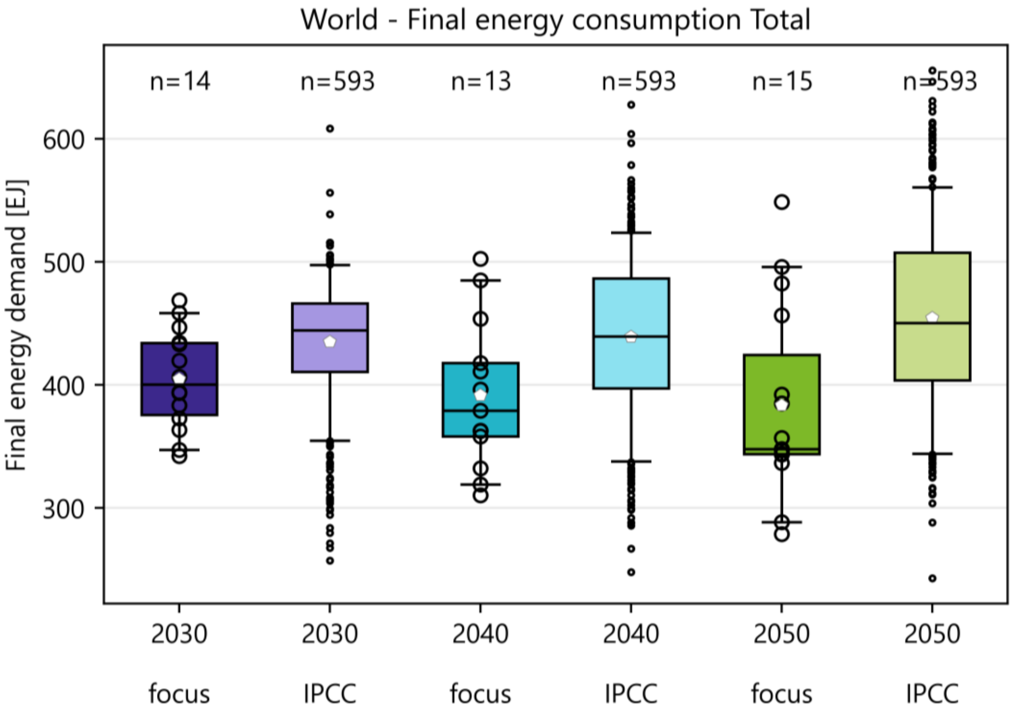

Figure 2: World - Total demand - Final energy consumption

Final energy consumption differs between the focus scenarios (Figure 2). Towards 2050, the inner bandwidth increases, indicating a higher uncertainty. The median energy consumption decreases towards 2050, indicating that the scenarios integrate energy efficiency measures. In general, the focus studies' median and mean values are lower than that of the IPCC scenarios.

Energy consumption ranges from 279 EJ to 549 EJ in 2050 (total bandwidth including outliers). The Shell_sky scenario constitutes the higher end of the bandwidth. Although this scenario is compliant with the Paris Agreement, it models 2070 to be the year where net zero is reached, while many other studies reach climate neutrality by 2050. The lowest energy demand of 279 EJ is found in the Greenpeace advanced e[r] scenario (not including non-energy uses). The interquartile range lies between 344 and 424 EJ.

5.1.1.2 World - Total demand - Final energy demand and GHG emissions

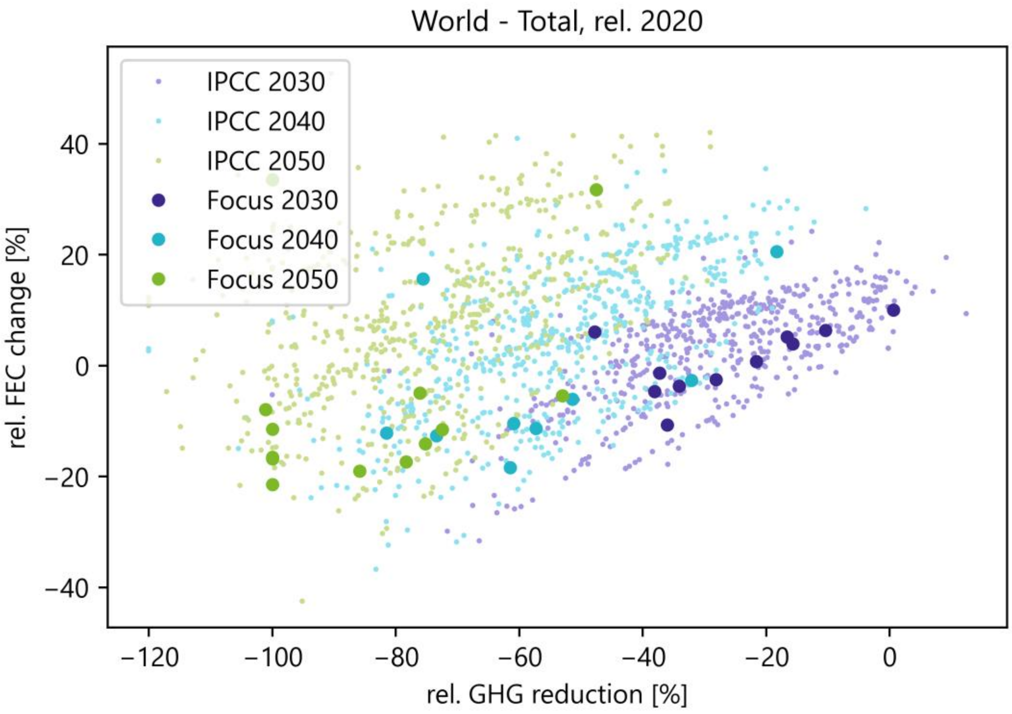

Figure 3: World - Total demand - Final energy demand and GHG emissions

Figure 3 depicts the relationship between emission reductions between 2020 and 2050 in relation to final energy consumption (FEC) changes.

For the focus studies, it can be observed that higher emission reduction efforts are linked to reduced FEC. In most scenarios, energy consumption is reduced already in the earlier 2030er years. In the IPCC scenarios, a similar trend emerges, although a fraction of 2050 values with high emission reductions can still be found to have a net increase in energy consumption. The focus studies' energy consumption reductions are ambitious compared to the majority of the IPCC scenarios. For the IPCC scenarios, the differing colour between years shows that for the collection of all scenarios and years, the changes between years are clearly distinct from the relationship with GHG reduction and dominate across years.

5.1.1.3 World - Total demand - Hydrogen demand

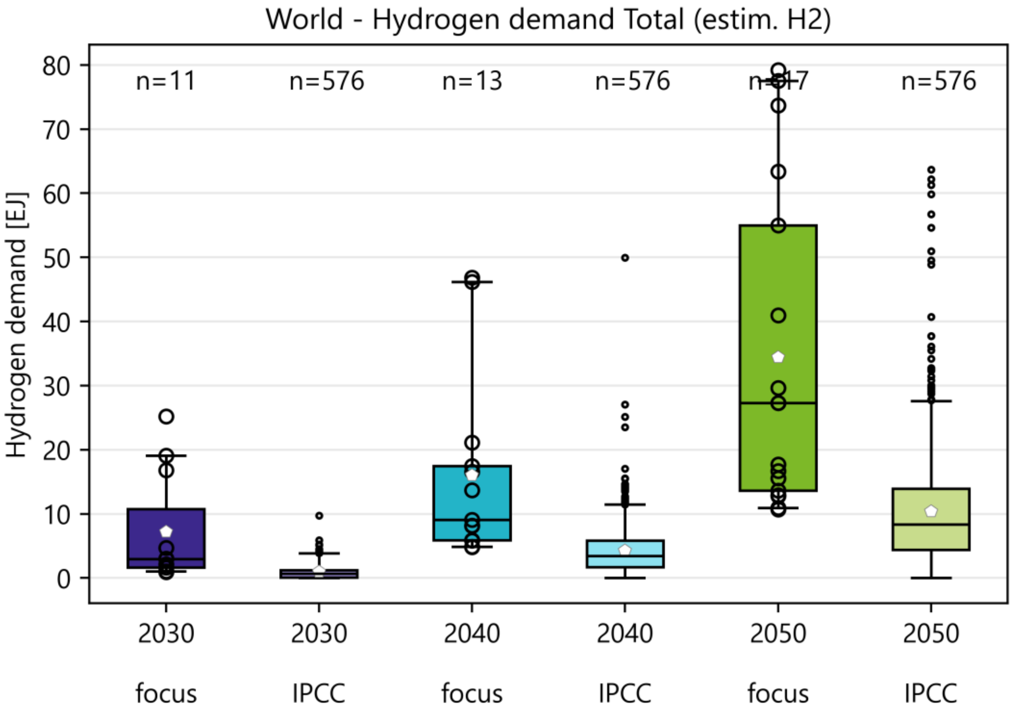

Figure 4: **World - Total demand - Hydrogen demand**

The total hydrogen demand estimate bandwidths are shown in Figure 4. Hydrogen demand increases for all studies from 2030 to 2050. The focus studies have a higher median and mean hydrogen demand than the majority of the IPCC scenarios throughout all years. In 2050, the focus studies inner bandwidth ranges between 14 - 55 EJ hydrogen demand, with a median of 27 EJ and a mean of 34 EJ. The focus scenarios maximum reported hydrogen demand is higher than all IPCC scenario values in 2050.

The highest outlier values (74-79 EJ)[5] are found in the Hydrogen Council and International Renewable Energy Agency (IRENA) 1.5 scenarios. The lowest hydrogen demand is projected by the JRC's Global Energy and Climate Outlook (GECO) 2020-2C scenario with 11 EJ.

High hydrogen demand projections can also be found in the International Energy Agency (IEA) H2 NZ scenario (63 EJ in 2050). The boxplot shows that the inner bandwidth of IPCC scenarios projects a total hydrogen demand between 4-14 EJ in 2050. This range is lower compared to the focus studies. The median for the IPCC scenarios is at 8 EJ, the mean value at 10 EJ.

5 Hydrogen demand for NH3 fuel and for synfuels has been allocated to the transport sector for this scenario.

5.1.1.4 World - Total demand - Share of hydrogen

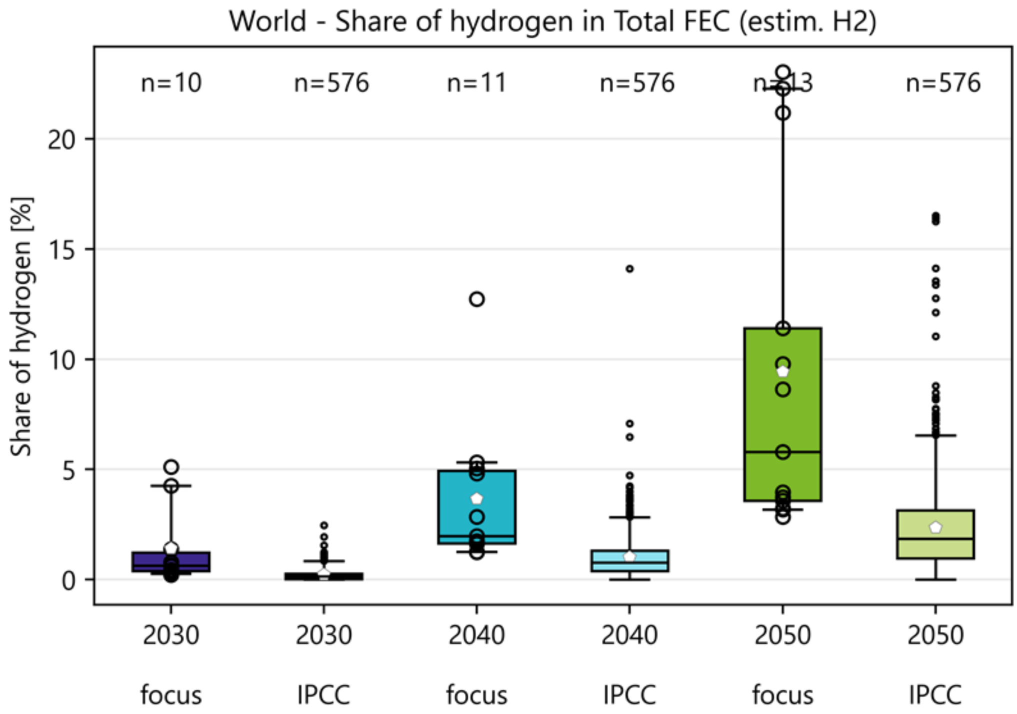

Figure 5: World - Total demand - Share of hydrogen

In the focus scenarios, the inner bandwidth of the hydrogen share in FEC ranges from approx. 4-11%, with a median share of 6% in 2050 (Figure 5). The Hydrogen Council and IRENA 1.5 project the highest relative hydrogen demand with a 22-23% share. In the Hydrogen Council study, the share is based on the IEA NZ total energy demand projections. The lowest share is reported in GECO2020-2C scenario (3%). The median and mean share of hydrogen is higher in the focus scenarios than in the IPCC scenarios throughout all years.

5.1.1.5 World - Total demand - Hydrogen demand and GHG emissions

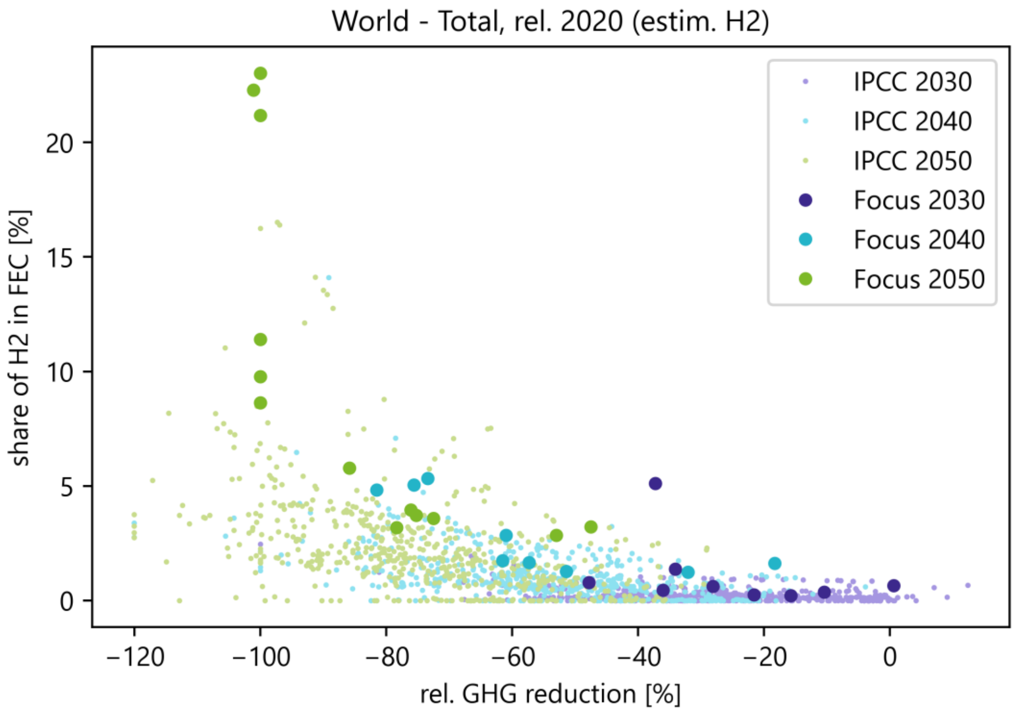

Figure 6: World - Total demand - Hydrogen demand and GHG emissions

Figure 6 shows the share of hydrogen in relation to emission changes between 2020 and 2050. For the focus studies, a trend seems to be emerging: higher mitigation efforts up to 100% relative GHG reduction between 2020 and 2050 and higher shares of hydrogen. For some studies, this trend is weaker: In the Joint Research Center's (JRC's) Global Energy and Climate Outlook (GECO) studies, hydrogen consumption only moderately increases with more ambitious emission reduction. From an emission level of 56 Gt CO_2 in the NewNormal scenario (Study from 2020) to approx. 7.6-8.1 Gt CO_2 in the 1.5°C scenarios hydrogen demand increases from approx. 8 EJ to only 13 EJ. The GECO study finds that hydrogen will play a role in the long term in the transport and industry sector, but its contribution to overall emission reduction remains limited. This figure shows that hydrogen is necessary for deep decarbonisation, but there is a large uncertainty in the quantities needed, as illustrated by the large bandwidth at 100% emission reduction.

For the IPCC scenarios, the same trend can be inferred, although even with high mitigation ambition, there is a large bandwidth in hydrogen demand.

5.1.1.6 World - Total demand - Indirect hydrogen demand

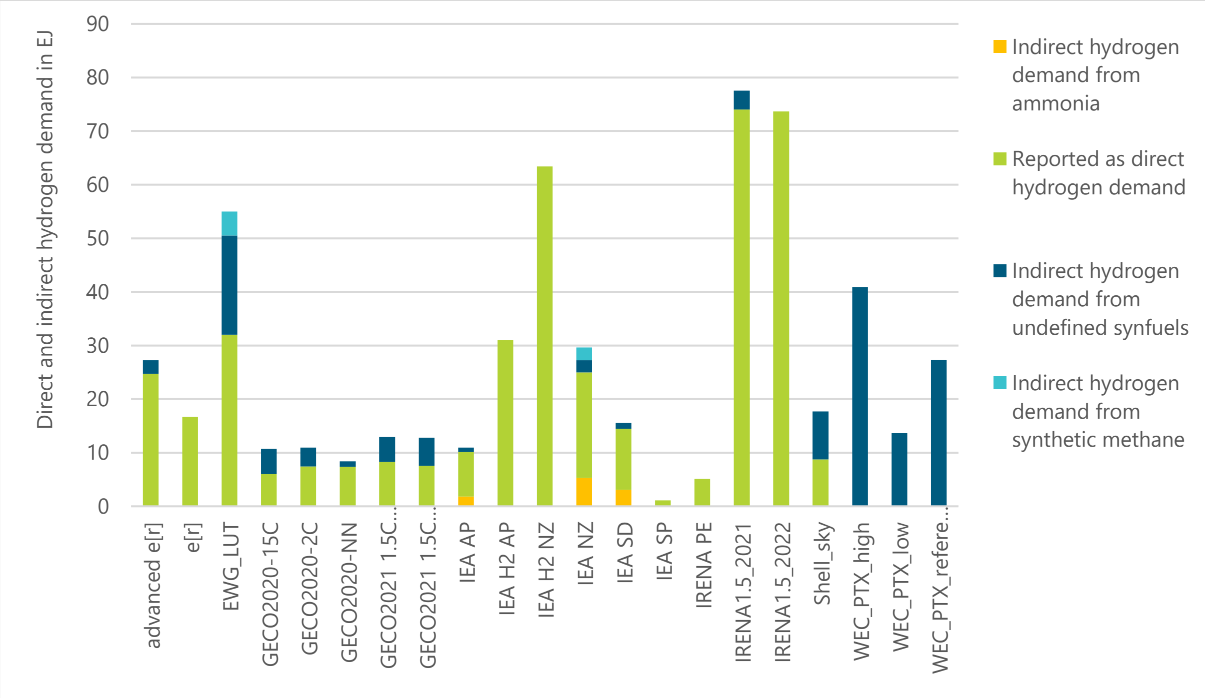

Figure 7: World - total demand - indirect hydrogen demand in 2050[6]

As explained in section 3.3, the studies handle the indirect demand for hydrogen differently. In some studies, a total hydrogen demand estimate is provided that encompasses all uses, including indirect uses in the transformation sector (e.g. for synfuel production). In other cases, the end-use sectors report demand for hydrogen and demand for synfuels. In these cases, the hydrogen demand for these synfuels has to be added to the direct use of hydrogen. Figure 7 shows the estimated indirect hydrogen demand from synfuels on top of direct hydrogen demand. In the legend, "Indirect hydrogen demand from undefined synfuels" includes all values that were not directly reported as hydrogen or another specified synfuel, but with terms such as "PtX" or "synfuels". "Reported as direct hydrogen demand" includes those values that were reported as “hydrogen” in studies, but this does not necessarily mean that this hydrogen was used directly. The different treatment of hydrogen and synfuel hydrogen complicate a comparison between the studies. Especially, because studies usually do not further specify the type of synfuel used, which make it difficult to estimate and compare the resulting hydrogen demand amongst studies. The World Energy Council (WEC) study only reports the overall PtX demand without a further split into direct hydrogen or synfuel use. In the IRENA 1.5 study, the category "hydrogen" includes all production methods of hydrogen (green and blue) as well as all types of synfuels (e-ammonia and e-methanol), but the exact fuel type quantities are not further differentiated. In the GECO study, synfuels include liquid hydrocarbon-based fuels without further breakdown. The source of hydrogen can be green or blue, the source of carbon is captured CO_2. In the IEA H_2 NZ scenarios, synfuel types are reported in more detail: ammonia, synthetic methane and synthetic oil. The hydrogen demand for the production of synfuels constitutes 20% of overall hydrogen demand in this study.

6 Estimation based on the methodology described in section 3.3.

5.1.2 World - Industry Sector

5.1.2.1 World - Industry - final energy consumption

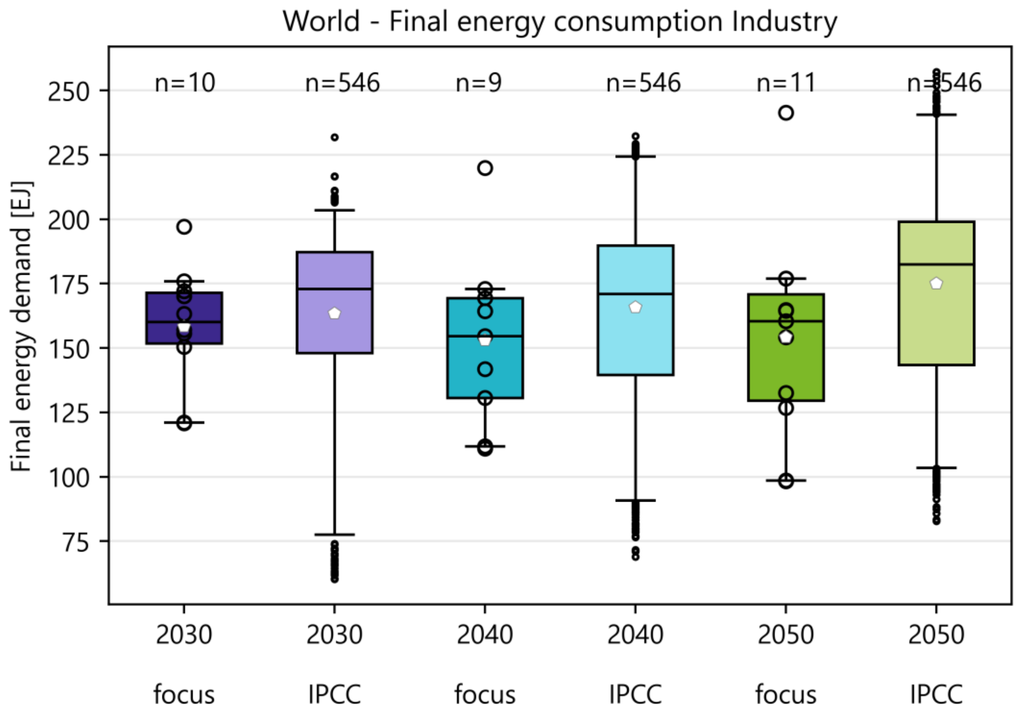

Figure 8: World - Industry - final energy consumption

Median industry energy demand remains relatively stable between 2030 and 2050 (155-160 EJ). The total bandwidth (including lower and upper quartile range) however increases through the years: in 2050, the minimum industry energy is lower than in 2030 and the maximum value is higher than in 2030. In 2050, the total bandwidth ranges from 98 EJ to 177 EJ for the focus scenarios (Figure 8), excluding outliers.[7] The Shell_sky scenario (reaching net zero only in 2070) has the highest industrial energy demand (241 EJ). Due to the allocation of energy demand in the scenario design, the industry energy includes also the data for "agriculture and other industries" and may therefore be overstated. The lowest energy demand is found in the Greenpeace e(r) scenario[8]. Many of the ambitious scenarios have energy demand projections that are lower than the current policy scenarios in the studies. The values for industry energy in the focus scenarios are lower than the IPCC predictions throughout all years, indicating that the projections for energy efficiency and sufficiency in the focus scenarios are more optimistic than the IPCC predictions.

7 Note that not all scenarios model all displayed years, which can influence the bandwidth.

8 The non-energy demand was only provided for the total energy demand figure and not on the sector or energy carrier level.

5.1.2.2 World - Industry - Hydrogen demand

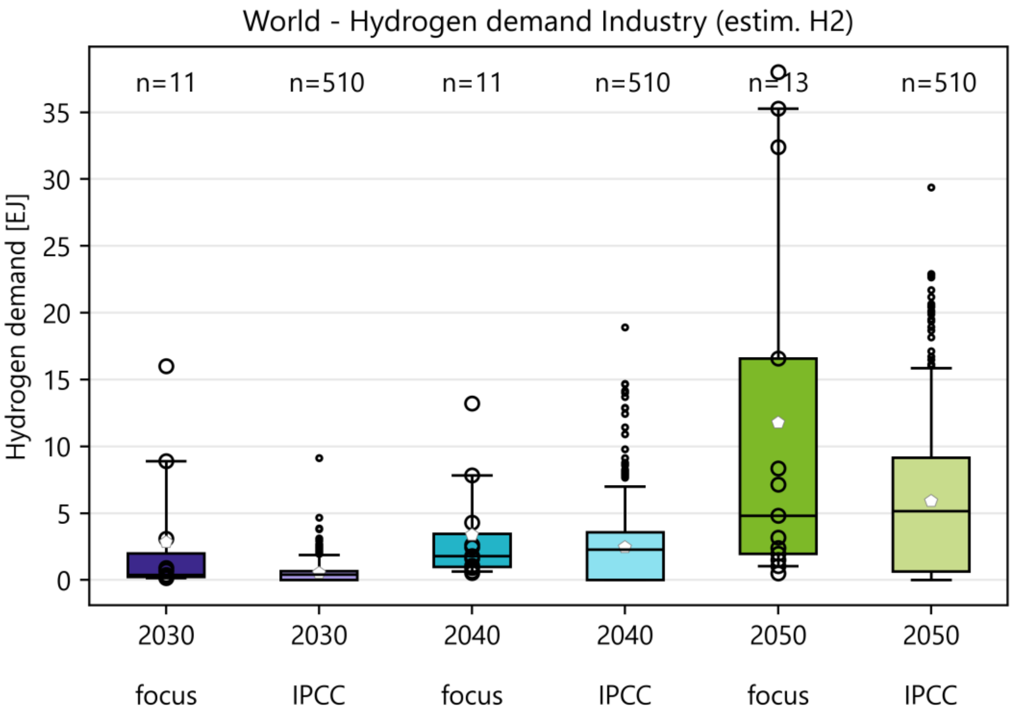

Figure 9: World - Industry - Hydrogen demand

The median hydrogen demand increases from nearly 0 EJ in 2050 to 5 EJ in 2050 (Figure 9). It can be observed that the inner bandwidth of industry hydrogen demand within the focus scenarios ranges from 2-17 EJ in 2050. On the lower end of the lower quartile range lie the values of the GECO-study which in the ambitious 1.5°C scenario assumes a hydrogen demand of only 0.5 EJ. The values projected by IRENA (35-38 EJ) are considered to be outliers compared to the remaining projections. IRENA assumes that hydrogen and derivatives will account for 12% of the FEC in the industry sector in 2050, incl. a chemical hydrogen use, which is considered the sector with the highest emission abatement needs (-11.9 Gt CO_2/yr).

For the IPCC, the inner range of values is only slightly different, industrial hydrogen demand is projected to lie between approx. 0.6 EJ and 9 EJ. The median hydrogen demand is comparable to the focus studies (5 EJ), the mean demand is lower than in the focus studies (6 EJ).

5.1.2.3 World - Industry - share of hydrogen

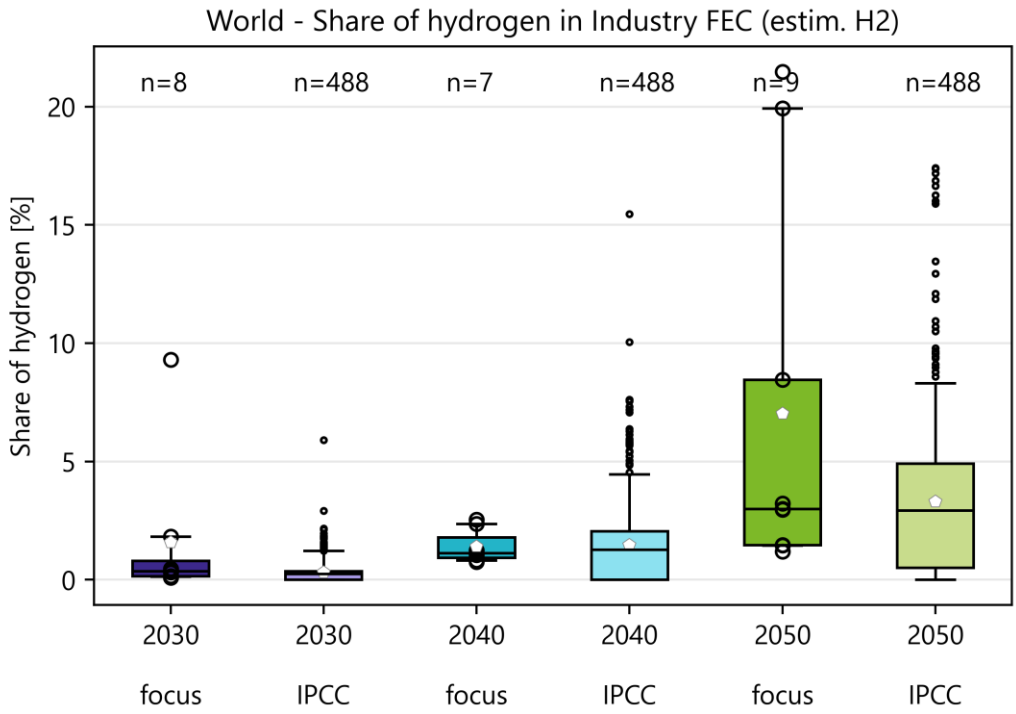

Figure 10: World - Industry - Share of hydrogen

The share of hydrogen in industry energy has an inner range between 2% to 9% in the focus studies in 2050 (Figure 10). The median is at 3%, the mean value 7%. The largest share of 22% is found in IRENA 1.5, which includes feedstock uses, and is considered an outlier compared to the other studies. The inner bandwidth of IPCC scenarios ranges between 0.8% and 5%. The median is comparable to the focus studies (3%), the mean value is lower (3%).

5.1.2.4 World - Industry - Consideration of feedstock demand

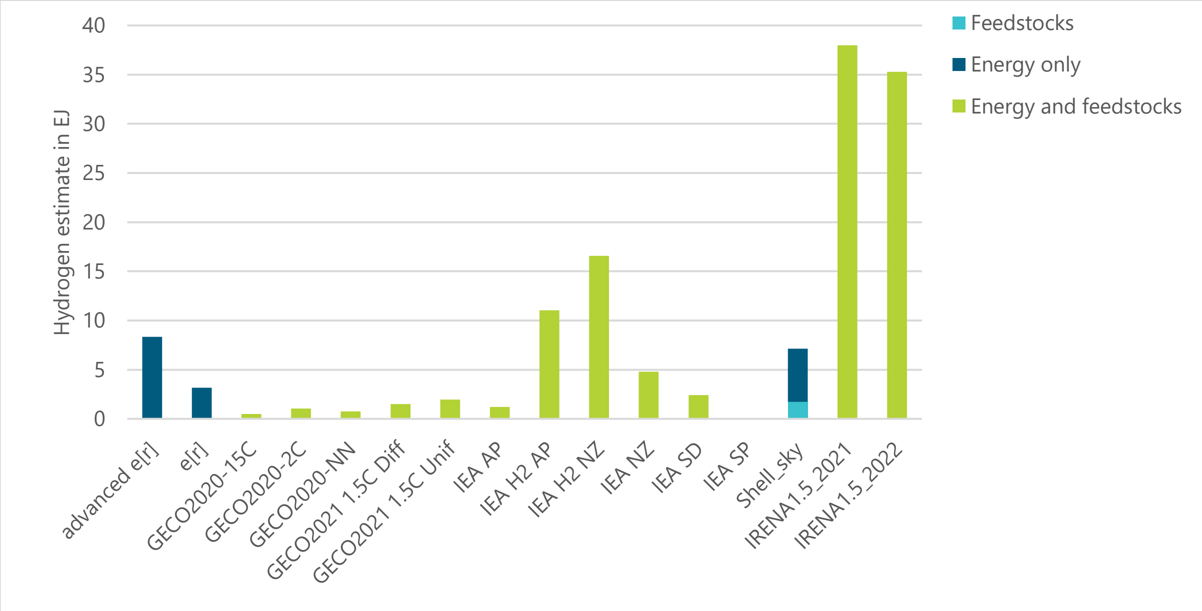

Figure 11: World - Industry - Consideration of feedstock demand in 2050

In the industry sector, the scope of the study has a large impact on the projected hydrogen quantities. Hydrogen is used chemically as a feedstock or reactant in industry (non-energy uses) and for high temperature heat generation. Interestingly, many of those studies assess the overall industrial hydrogen demand, while the distinction between non-energy and energy demand remains mostly unclear (see Figure 11). For example, IEA and IRENA consider feed-stocks in their significantly higher demand estimations. However, the results for the GECO study are considerably lower, even though they also consider feedstocks. Therefore, not all differences in demand projections can be attributed to the industry sector scope of the study.

5.1.2.5 World - Industry - Exemplary study comparison

Table 7: Assumptions influencing industry hydrogen demand in two global focus scenarios

		IRENA 1.5 2022	**GECO 1.5 2022**
Energy demand projections	Industry FEC	177 EJ	127 EJ
	Industry hydrogen demand	38 EJ (including ammonia and methanol) 21%	1.5 EJ (1.2%)
Alternatives to hydrogen	Electricity	46 EJ (26%)	56 EJ (44%)
	Biomass	36 EJ (20%)	26 EJ (20%)
	CCS	CCS industry: 2.3 Gt/yr BECCS: 1.14 Gt/yr	Total CCS: 4.3 Gt CO_2 (Not disclosed how much is used in industry)
Technological assumptions for hydrogen production		Switch from SMR to electrolysis, SMR with CCS, and bioenergy reforming with CCS (BECCS)	Switch from SMR to electrolysis and bioenergy reforming with CCS (BECCS)

Source: own illustration

Climate mitigation ambition has been found to influence hydrogen demand. In this exemplary study comparison, it can be observed that this trend is not linear and can also be influenced by model assumptions on the decarbonisation potential of hydrogen and the availability of other decarbonisation technologies and their respective mitigation cost.

The 1.5°C scenarios from the GECO and IRENA studies have a comparable level of climate mitigation ambition. In both studies, non-energy uses of hydrogen are within the sector scope, but the demand estimations differ significantly. Table 7 summarises some modelling assumptions that influence the characteristics of the industry sector. It can be seen that GECO generally assumes a significantly lower total industry energy demand. For the industry sector, hydrogen application in process heat potentially competes with biomass, electrification or the continued use of fossil fuels in combination with CCS. Comparing the two studies, it can be seen that the share of biomass as an energy carrier is on a comparable level. But the use of electricity is substantially higher in GECO.

It can be inferred that industry hydrogen demand is influenced by the studies' projected potential of energy efficiency measures as well as the technological potential of alternatives such as biomass, electrification, and CCS.

5.1.3 World - Building Sector

5.1.3.1 World - Buildings - Final energy consumption

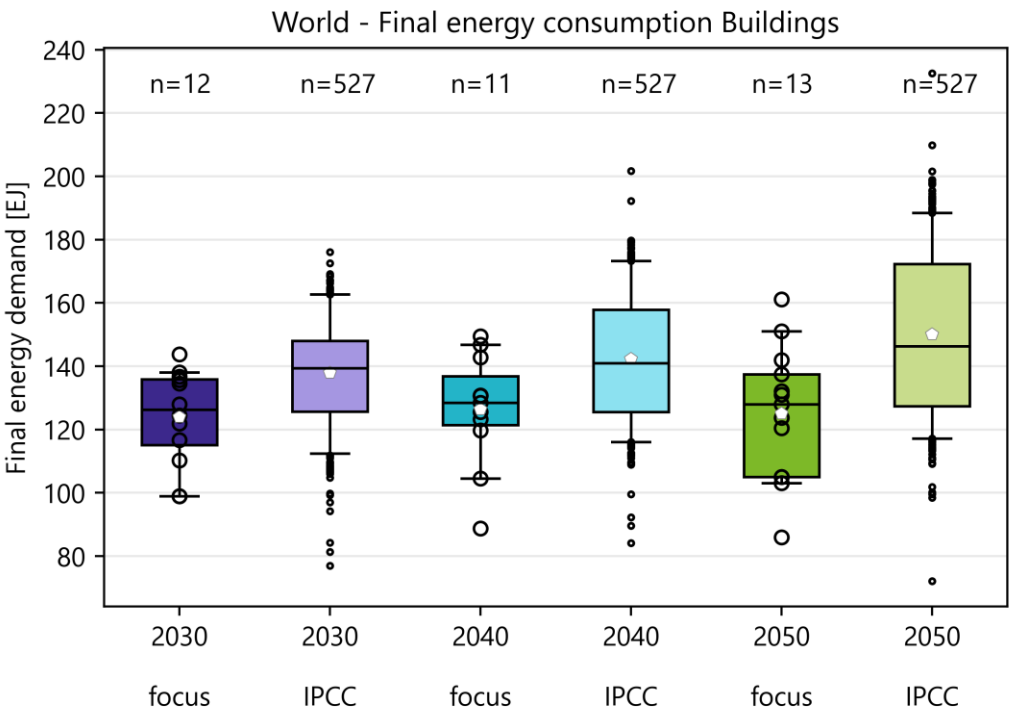

Figure 12: World - Buildings - Final energy consumption

Final energy consumption in the building sector does not show many outliers for both the focus and IPCC scenarios (see Figure 12). It can be observed that the median energy consumption does not deviate much in the studies over the years and also in comparison with the predictions from the IPCC (between approx. 124 EJ to 126 EJ). The IPCC median predictions are slightly higher than the focus studies. In 2050, the highest building energy demand is predicted by Shell_sky (161 EJ), the lowest by IEA NZ (86 EJ) (see Figure 14).

5.1.3.2 World - Buildings - Hydrogen demand

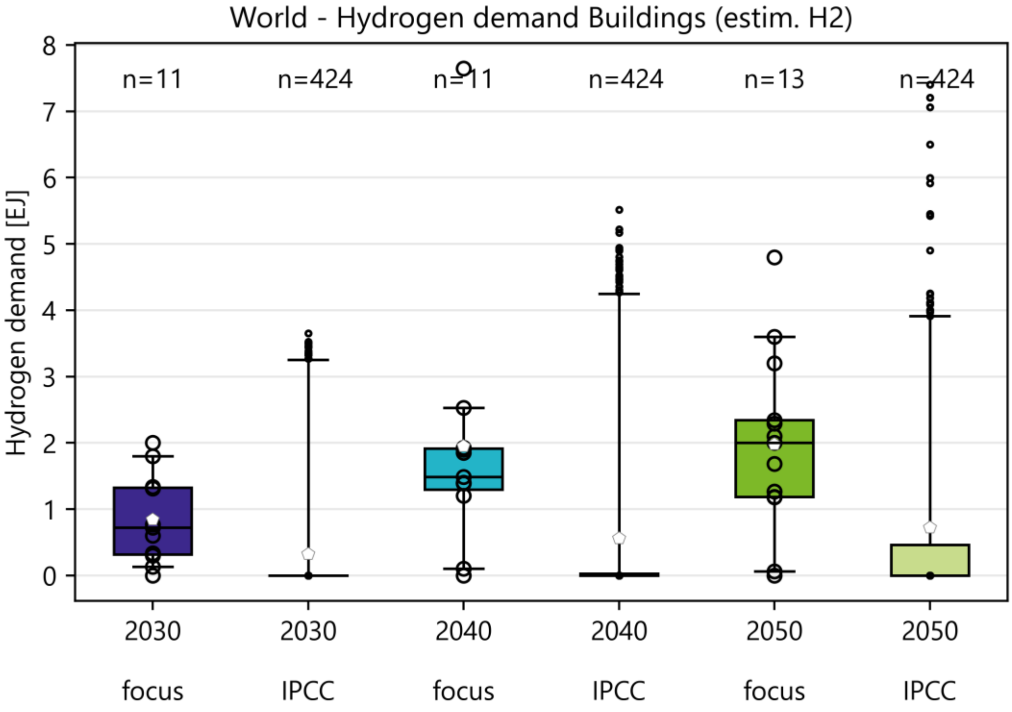

Figure 13: World - Buildings - Hydrogen demand

Hydrogen use in buildings is shown in Figure 13. The demand for hydrogen in the building sector ranges from 1 to 2 EJ in 2050 (inner bandwidth). This bandwidth is small compared to the other sectors and there are no outlier values, indicating a relative certainty about hydrogen usage in this sector. The predictions of the focus studies are all within the range of IPCC scenario outliers, such as the focus scenarios project in average a higher hydrogen demand than the average in the IPCC scenarios throughout the years.

The maximum value is reported in the Hydrogen Council study (5 EJ). Although this value is high compared to the other studies, the contribution of hydrogen to the building sector decarbonisation is considered low in this study compared to the other sectors. Similar results are found in IRENA 1.5_2022, where the hydrogen demand is 4 EJ. The IEA scenarios H_2 NZ also models high hydrogen demand. Here, hydrogen is used in the building sector through synthetic methane in the gas grid. The use of hydrogen in this sector is seen as limited due to higher efficiencies of direct electrification, resulting in a hydrogen share of a little over 5% of total heating. In the Greenpeace study, the building sector is not modelled as a separate sector. Instead, all remaining energy consumed apart from industry and transport is reported under "other". Here, the hydrogen consumed rises to 2 EJ in the advanced (r) scenario. In this study, it is assumed that hydrogen is applied in the building sector next to heat pumps and biofuels, and after 2030, hydrogen replaces the whole remaining natural gas demand in the overall energy system. In the GECO 1.5 scenarios, it is assumed that hydrogen has only a limited role in space heating (1 EJ) due to blending restrictions and heat pumps as a competitive technology.

5.1.3.3 World - Buildings - Share of hydrogen

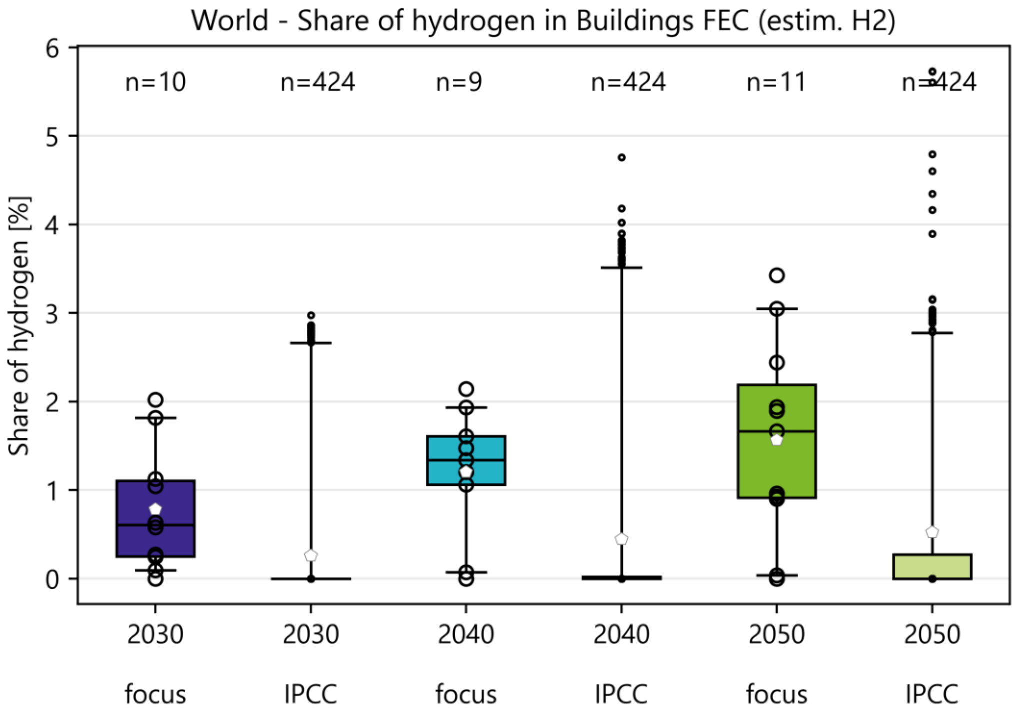

Figure 14: World - Buildings - Share of hydrogen

The observations above can also be inferred from the share of hydrogen in building energy demand (Figure 14). The total bandwidth of the relative share is low (1-2% in 2050) for the focus studies. While there are outliers, the share in IPCC scenarios is generally lower, as indicated by the quartiles.

5.1.4 World - Transport Sector

5.1.4.1 World - Transport - Final energy demand

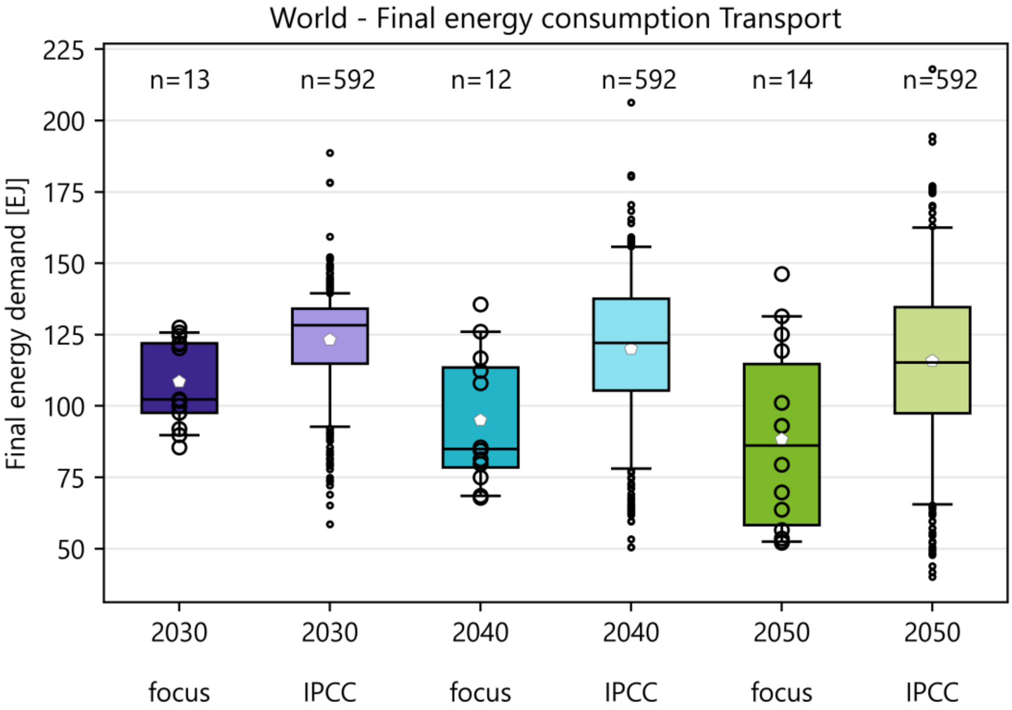

Figure 15: World - Transport - Final energy demand

The global median transport energy consumption reduces from 102 EJ in 2030 to 86 EJ in 2050 in the focus studies. It can be observed that uncertainty in total transport demand projections increases over time (see Figure 15). The focus scenarios are within the IPCC total bandwidth, but it can be seen that the median energy demand is usually lower in the focus studies. A major driver of the differences in demand projections is found to be the sector scope, as many studies do not include international bunkers, which will be further analysed in section 5.1.4.4.

5.1.4.2 World - Transport - Hydrogen demand

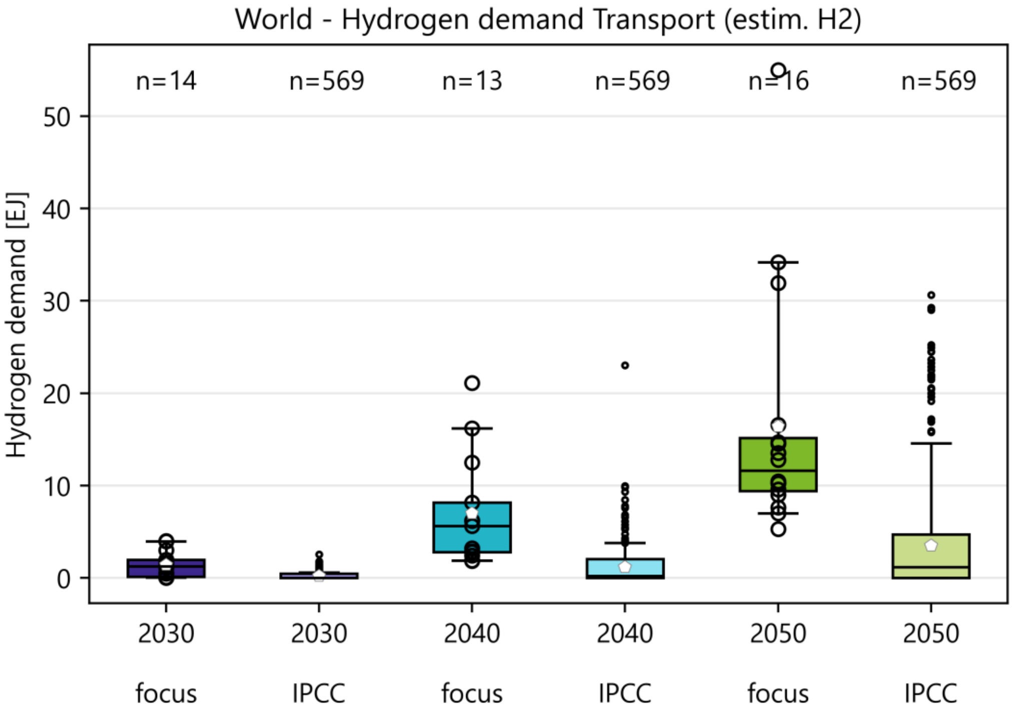

Figure 16: World - Transport - Hydrogen demand

For hydrogen use in transport, the focus studies show high variation as well (Figure 16). The median predictions from the focus studies are higher than the IPCC for all years. It can be seen that in 2050, all focus studies assume a minimum hydrogen demand above 5 EJ. The inner range of hydrogen demand spans from 9 EJ to 15 EJ in 2050. Outlier values are reported by EWG LUT (55 EJ). EWG LUT assumes that energy demand will be stable from today to 2050, as a consequence of the counteracting factors of increased transport demand and energy efficiency through electrification. Renewable electricity based liquid fuels constitute a share of 30%. The majority of this demand serves the aviation and maritime sector.

The upper quartile range is determined by the IEA H_2 NZ, Hydrogen Council and IRENA 1.5_2022 study, which all include international transport. The IEA H_2 NZ sees a substantial role for hydrogen in road transport (45% share in 2030). The availability of sustainable carbon sources for synfuels is considered to be limited and therefore, the majority of synfuels is allocated to the aviation sector where other alternatives (batteries, direct use of hydrogen) are currently not feasible for long-distance. Ammonia fuels are projected to fulfil 45% of shipping energy demand due to their technical advantages over direct hydrogen use. At least one third of fuel demand in aviation is covered by synthetic kerosene. The updated 2021 GECO study only sees a limited amount of hydrogen in transport. The study does not model international bunkers. In 2050, the share of e-fuels in the two GECO 1.5 C scenarios is approx. 22%. Interestingly, when looking at the horizon up to 2070, the share of hydrogen remains relatively constant, while biofuels substantially increase, replacing remaining oil in the mix.

5.1.4.3 World - Transport - Share of hydrogen

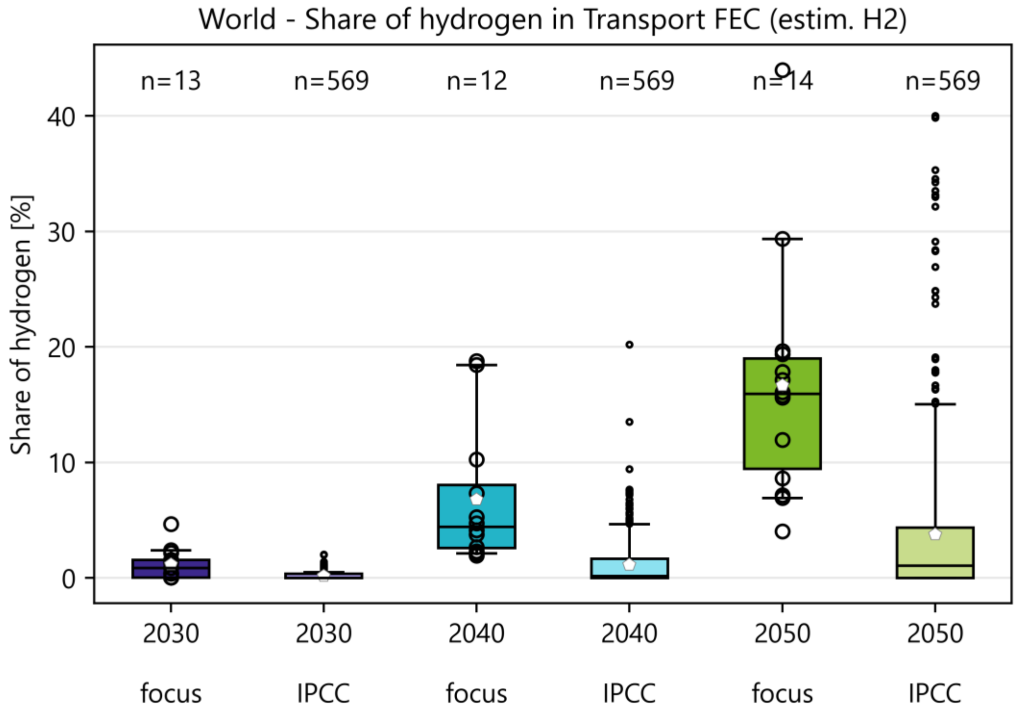

Figure 17: World - Transport - Share of hydrogen

The inner bandwidth of the share of hydrogen in transport ranges between 10% and 19% in 2050 (Figure 17). The highest share is found in the Greenpeace advanced (r) scenario. The median share differs substantially between focus and IPCC scenarios in 2050 (16% vs. 1%, respectively).

The Greenpeace study was published already in 2015 and is the oldest study evaluated in this paper. It considers the use of FCEV, arguing that the potential of biomass and battery electric vehicles is too limited. Only green hydrogen is considered. It is stated that hydrogen is not enough to completely defossilise trucks, aviation and the maritime sector, and synthetic fuels are needed. Hydrogen use in this sector is higher than biofuel use, contrary to the study's results for building heat. The study considers efficiency increases of hydrogen production from 8% in 2020 up to 75% in 2050 and for synfuel production from 37% in 2020 to 42% in 2050. In the advanced e(r) scenario, it is further assumed that the transport energy demand can be reduced through higher efficiencies in vehicles and modal shifts. The switch to renewable fuels however requires to compensate energy losses in the synfuel production with the adaption of infrastructure and mobility behaviour.

5.1.4.4 World - Transport - Consideration of international bunkers

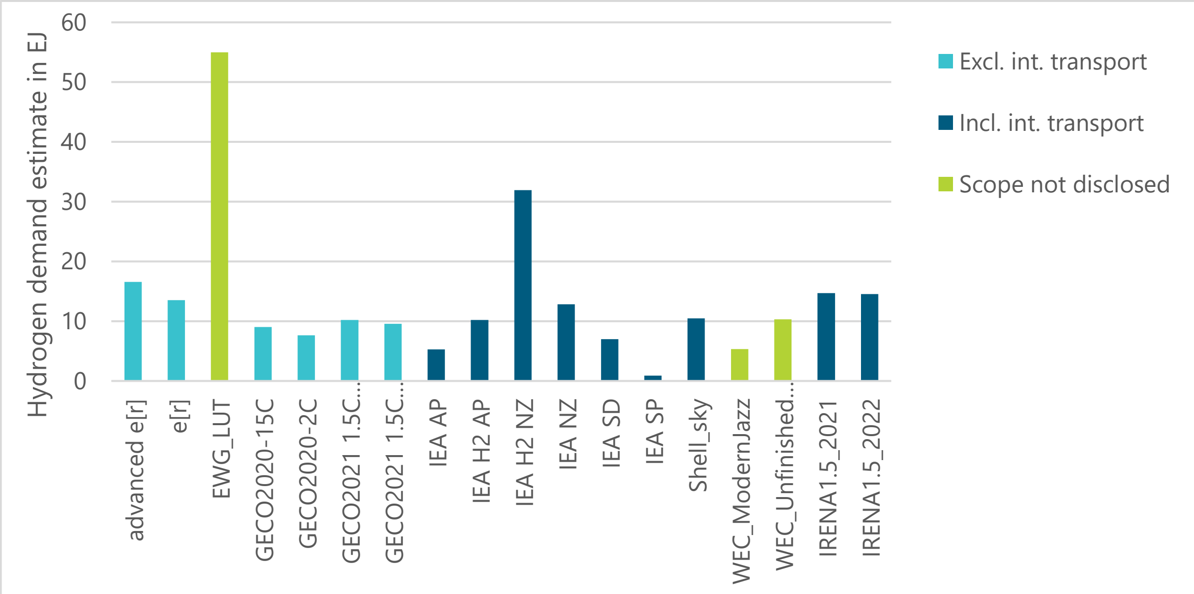

Figure 18: World - Transport - Consideration of international bunkers in 2050

As hydrogen and its derivates are one of the main decarbonisation levers for international aviation and shipping, differences in demand projections in studies are partially caused by considering and not considering international bunkers. Figure 18 shows whether the focus studies consider international transport. It can be seen that differences in demand projections can only partly be explained by the inclusion of international transport. The ambitious IEA scenarios do have a higher demand than the ambitious GECO scenarios. However, the Greenpeace scenarios advanced e(r) and e(r) do not include international transport but have higher hydrogen demand than the IEA scenarios. For the EWG and the WEC studies, it could not be determined whether international transport was included.

5.1.4.5 World - Transport - Exemplary study comparison

Table 8: Assumptions influencing transport hydrogen demand in two global focus scenarios

		Advanced e(r)	GECO2021 1.5C Diff
Energy demand projections	Transport energy demand	57 EJ	52 EJ
	Transport hydrogen demand	17 EJ	10 EJ
Alternatives to hydrogen	Electricity	29 EJ	17 EJ
	Biofuels	8 EJ	15 EJ
	Fossil fuels	0 EJ	20 EJ
	CCS	Not implemented	2.8 Gt captured through DACCS and BECCS
Technological assumptions for hydrogen production		Hydrogen from renewable electricity	Switch from SMR to electrolysis (wind, PV, nuclear, grid) during 2020-2040

Source: own illustration

Significant differences in the scope of the sector hinder a direct comparison of demand projections. To provide further insights on the demand bandwidth between studies with the same scope, Greenpeace advanced e(r) and GECO are compared. Nevertheless, the two scenarios differ in their demand projections for hydrogen. Table 8 summarises some modelling assumptions influencing hydrogen demand. It can be observed that total transport energy projections in 2050 are similar. In transport, biofuels and electrification are two potential alternatives to hydrogen, depending on the mode of transport. Comparing the employed energy carriers, it can be seen that GECO still uses significant amounts of fossil fuels in 2050, in connection with carbon removal technologies such as BECCS and DACCS. Greenpeace on the other hand, is completely decarbonised, with a high use of electrification. Furthermore, GECO uses more than double the amount of bioenergy. It was also observed that Greenpeace uses more direct hydrogen, while GECO relies more on synfuels. The comparison shows the influence of the availability of alternative technologies on hydrogen demand estimation. The quantification of sustainable biomass potential and realistic deployment and scale-up of DACCS is therefore crucial for reliable hydrogen demand projections also for the transport sector.

5.1.5 World - Summary of sectoral demand

5.1.5.1 World - Summary of sectoral demand - share of hydrogen

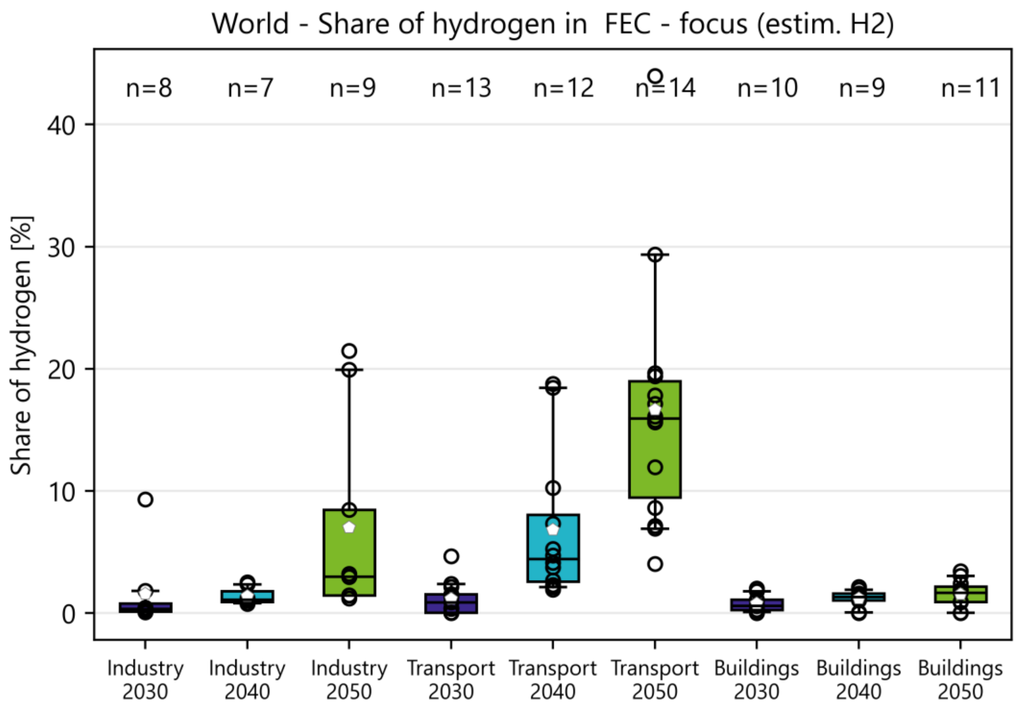

Figure 19: World - Summary of sectoral demand - share of hydrogen

Figure 19 summarises the hydrogen share over the three end use sectors in the global scenarios. The following observations can be inferred: There is an increase in the share of hydrogen across all sectors from 2030 to 2050. The transport sector has the largest median hydrogen demand in all years. From the outlier values it can be concluded that large quantities of hydrogen are used in the production of methanol and ammonia, and it is not always transparent how these are allocated to the transformation sector or to industry or transport. The building sector has the lowest overall hydrogen projections and the smallest total bandwidth, indicating that the low demand in the building sector is a relatively robust finding. The maximum values for total, industrial and hydrogen demand for buildings come from the same scenario (IRENA 1.5_2022). Only for the transport sector, the EWG LUT scenario has higher projections, but here, IRENA 1.5 2022 also models the third largest demand projection.

5.1.5.2 World - Summary of sectoral demand - absolute hydrogen demand

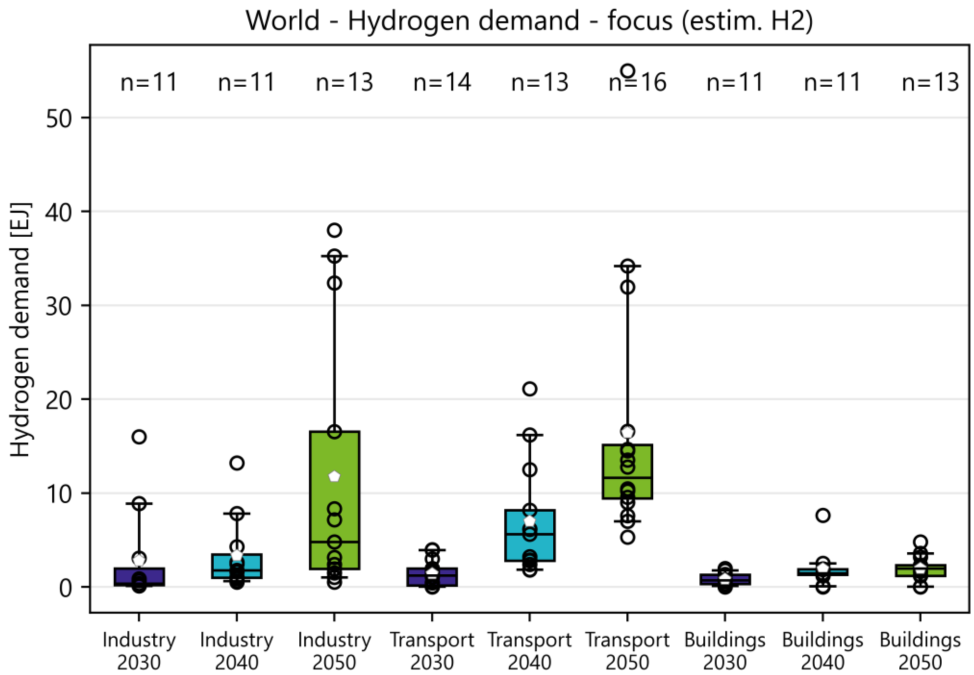

Figure 20: World - Summary of sectoral demand - absolute hydrogen demand

Figure 20 summarises the hydrogen demand in absolute numbers over the three end use sectors in the global scenarios. This figure can be read in conjunction to Figure 19, but shows the absolute values of hydrogen demand. Equally to the share of hydrogen in energy demand, absolute numbers are highest in transport, followed by the demand in industry. However, the difference between the two distributions is not strict as for the hydrogen share. Note that the number of studies is partly higher here, which influences statistical results and leads to differences studies estimating maximum values in some cases. While all others remain the same, the maximum values of absolute hydrogen demand in buildings is estimated by a different scenario (Council_NZH).

5.2 Europe (EU28)

5.2.1 Europe - Total Demand

5.2.1.1 Europe - Total demand - Final energy consumption

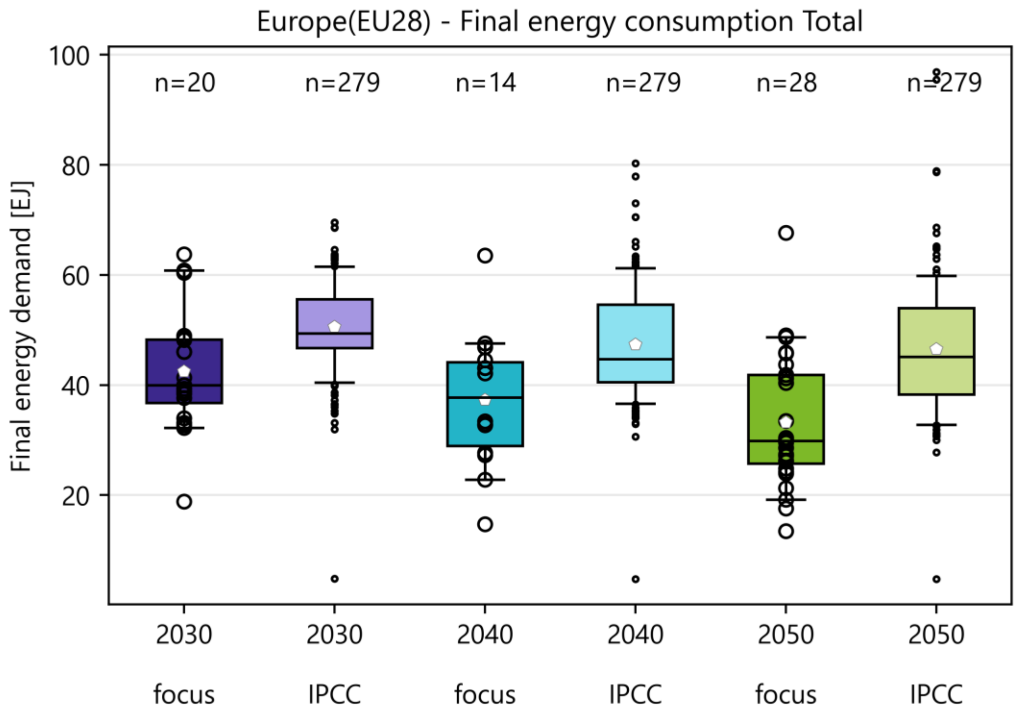

Figure 21: Europe - Total demand - Final energy consumption

Figure 21 shows the range of total energy consumption for the European studies. The median total energy consumption in the focus studies remains relatively steady between 2030 and 2040 (approx. 38-40 EJ), and reduces until 2050 (30 EJ). The IPCC scenarios predict higher median and mean energy consumption throughout the years, and some focus scenarios are lower than the IPCC range throughout the years. In 2050, the inner bandwidth of the focus studies ranges from approx. 26-42 EJ. The highest energy demand is modelled in the EWG_LUT study, which is an ambitious climate mitigation study that models an energy system with 100% renewable energy. The lowest demand in 2050 is modelled by the GECO2021 1.5C Diff scenario. Demand projections differ more between studies than they differ between scenario ambitions. For example, all BP scenarios, including their net zero emission scenario, project a FEC between 49 EJ and 53 EJ, while all European Climate Foundation (ECF) studies project a FEC between 17 EJ and 27 EJ. The JRC studies have similar characteristics, where the scenarios range between 40 and 49 EJ.

5.2.1.2 Europe - Total demand - Final energy demand and GHG emissions

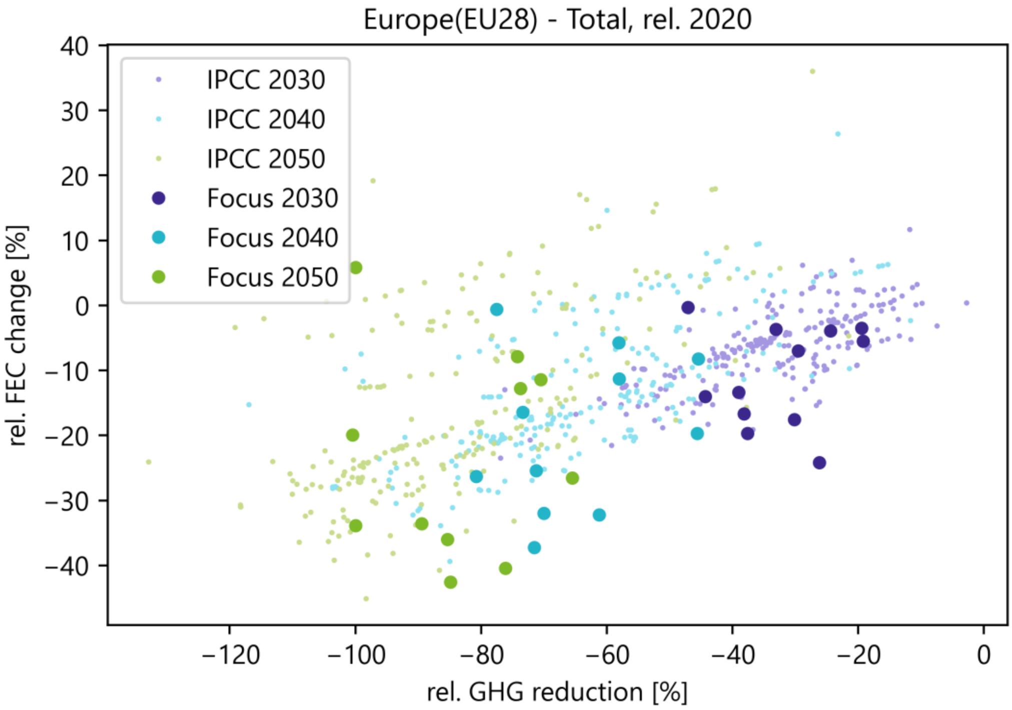

Figure 22: Europe - Total demand - Final energy demand and GHG emissions

Within a study, the more ambitious scenarios usually have the lowest energy consumption. This trend, for reduced FEC with higher GHG reduction ambitions, can be observed in the focus studies (see Figure 22). Despite this trend, a large bandwidth in FEC changes can be seen for the same level of GHG reduction amongst the different studies. In the focus studies, for example, where GHG are reduced by ca. 70%, the FEC decreases by roughly 7-40%. For the IPCC scenarios, a similar trend can be observed, although a few outlier values show a net energy consumption increase for higher GHG reduction ambitions.

5.2.1.3 Europe - Total demand - Hydrogen demand

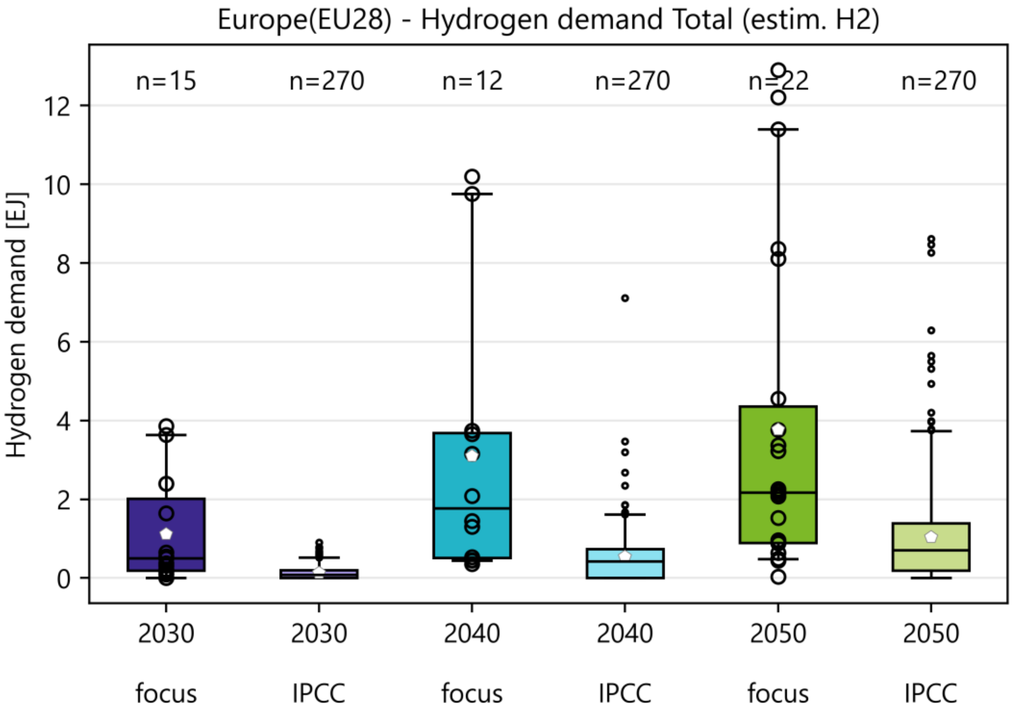

Figure 23: Europe - Total demand - Hydrogen demand

In Europe, median hydrogen demand increases to approx. 2 EJ in 2050. The demand is projected to range between approx. 1 EJ and 4 EJ in the interquartile range (see Figure 23).

The IPCC inner ranges are significantly lower than in the focus studies, indicating that many of the high projections in the focus studies are above the median hydrogen demand in the included 270 IPCC scenarios. However, the outlier values of the IPCC scenarios reach hydrogen demand levels comparable to the focus studies.

Outlier values in the focus studies with substantially higher demand are modelled by the two Hydrogen for Europe scenarios H24_RP (12.9 EJ) and H24_TD (12.1 EJ), which can be considered very optimistic on hydrogen projections. This study aims for carbon neutrality by 2050 and considers green (electrolysis and biogenic), blue and turquoise hydrogen, including imports from the Middle East, North Africa, Russia and Ukraine. Natural gas still plays a vital role in 2050 in both scenarios, ranging from a share in primary energy demand of 26-32%, especially combined with CCUS, e.g. for blue hydrogen. Another outlier value is modelled by the FCHJU hydrogen roadmap (FCH-H_2Road) for Europe with 8 EJ. This roadmap models all sectors, including feedstocks for industry.

On the lower bound of hydrogen demand, the GECO 1.5-2.0°C scenarios (<1 EJ) and the IEA B2DS (Beyond 2°C) scenario can be found. Differences in hydrogen demand could be caused by general differences in FEC demand projections. Nevertheless, for studies with comparable climate ambitions and energy projections, hydrogen demand differs. E.g. the European Commission (EC), GECO, Fuel Cell and Hydrogen Joint Undertaking (FCHJU) or Greenpeace studies model a FEC of 25-30 EJ, but hydrogen demand projections differ more widely between 1-8 EJ.

5.2.1.4 Europe - Total demand - Share of hydrogen

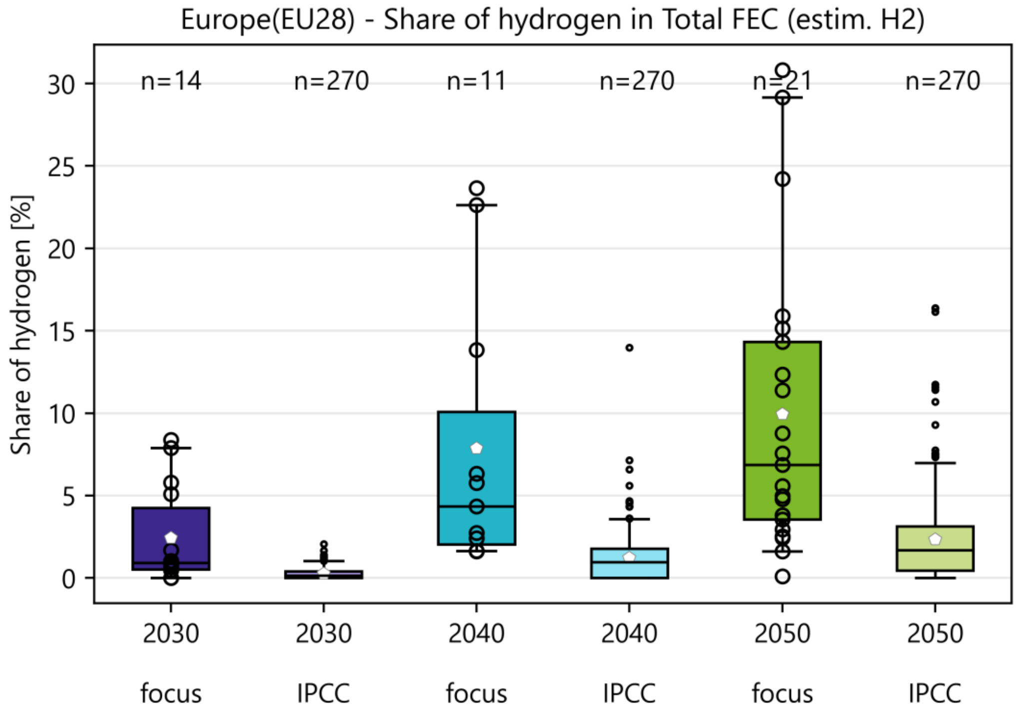

Figure 24: Europe - Total demand - Share of hydrogen

Consistently with the previous findings, the median share of hydrogen in the FEC is higher in the focus studies than in the IPCC scenarios throughout the years (see Figure 24). In 2050, the focus studies reach 7%, while the IPCC reach only a 2% hydrogen share in the FEC. The highest value of nearly 31% hydrogen share in final energy consumption is projected by the H24_RP scenario in 2050. For the focus studies, almost half of the values are being in range of the IPCC outlier values.

The focus studies predict a large bandwidth, which indicates a high uncertainty in hydrogen demand projections. The total bandwidth ranges from nearly 0% share (IEA B2DS) to 31% (H24_RP).

5.2.1.5 Europe - Total demand - Hydrogen demand and GHG emissions

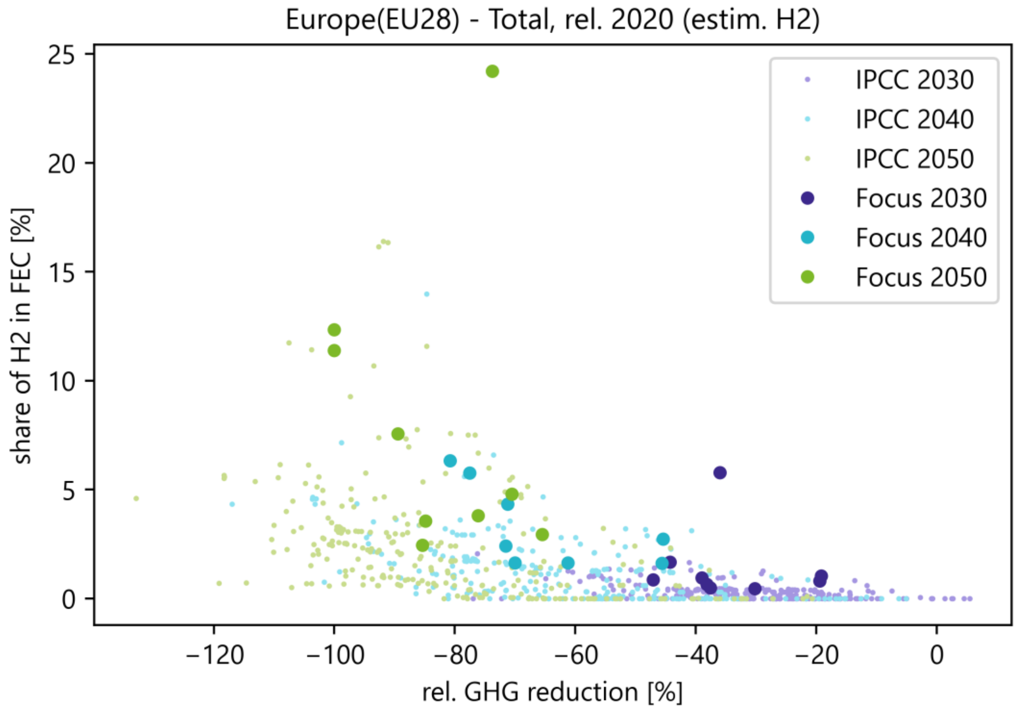

Figure 25: Europe - Total demand - Hydrogen demand and GHG emissions

Figure 25 shows that a higher hydrogen demand share in TEC is linked to a higher emission reduction ambition in the focus scenarios and IPCC scenarios, although the trend is weaker in the IPCC scenarios, due to the high variation in hydrogen shares. It can, however, be observed that for all emission reductions beyond 80%, the hydrogen share is non-zero in the IPCC scenarios.

5.2.1.6 Europe - Total demand - Indirect hydrogen demand

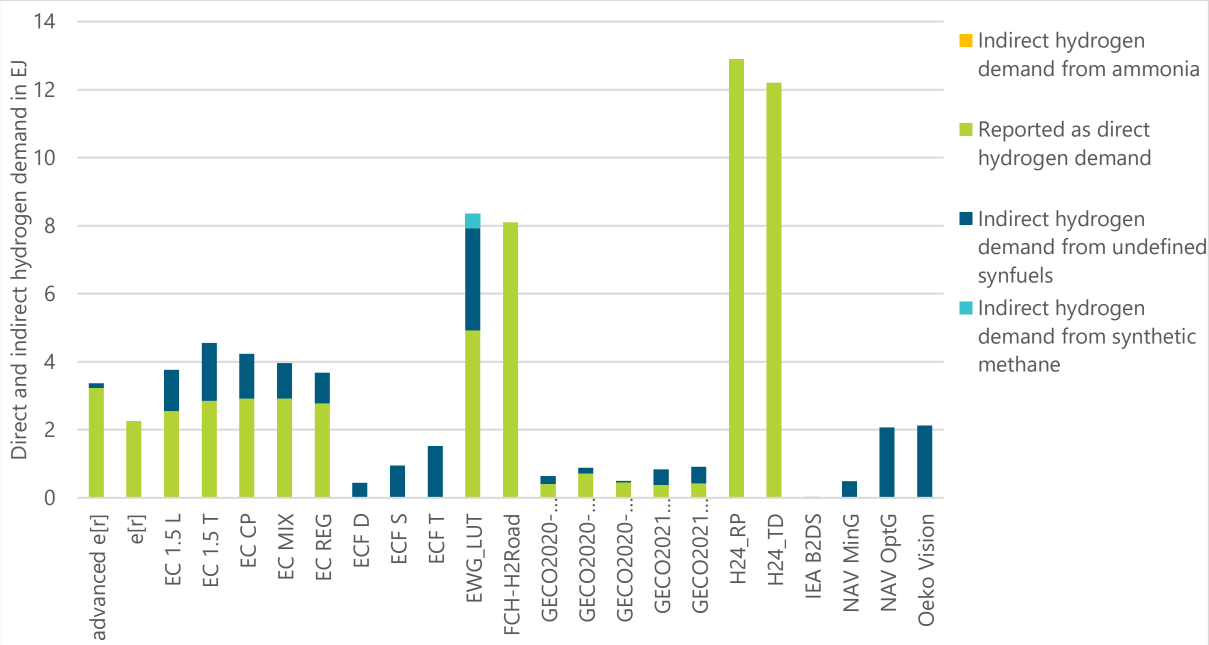

Figure 26: Europe - Total demand - Indirect hydrogen demand in 2050

According to section 3.3.3, the indirect hydrogen demand is calculated from synfuels and added to the reported direct hydrogen demand in the studies. To show how synfuel demand relates to hydrogen demand in the studies, that report the two separately, Figure 26 shows the resulting indirect hydrogen demand from synfuels in comparison to directly used hydrogen.

5.2.2 Europe - Industry Sector

5.2.2.1 Europe - Industry - Final energy consumption

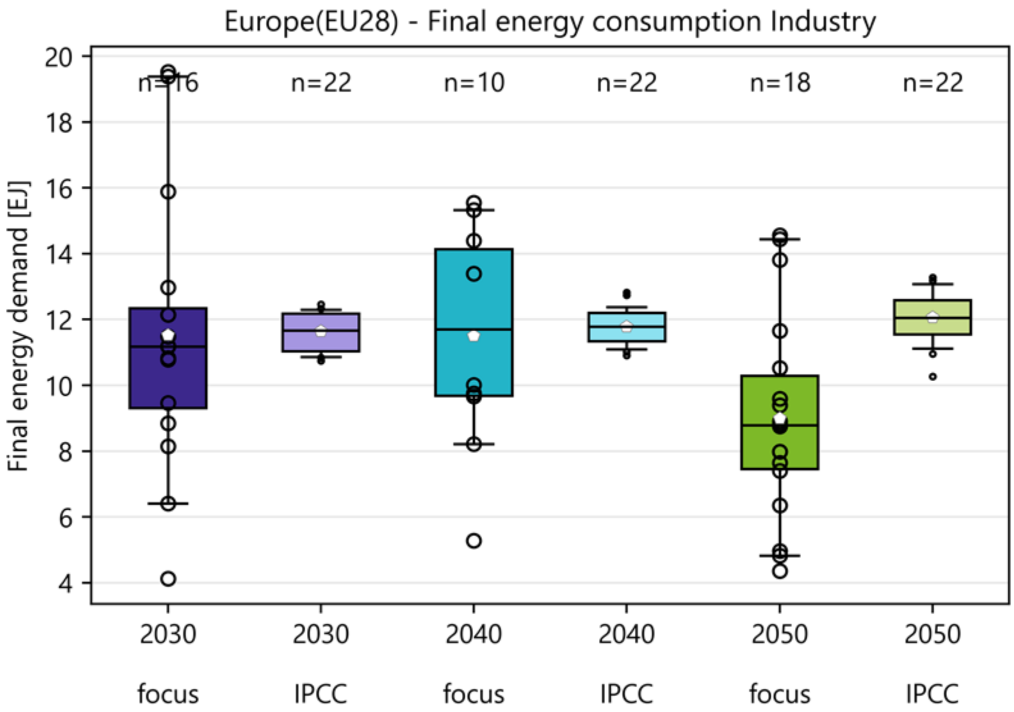

Figure 27: Europe - Industry - Final energy consumption

Figure 27 shows that the median industry energy demand remains relatively constant between 2030 and 2040 for the focus studies (11-12 EJ). In 2050, the median reduces slightly to 9 EJ. In the focus studies, industry energy demand varies substantially throughout the years, the total bandwidth excluding outliers becomes smaller in 2050, but is still substantial (4-15 EJ). The highest energy demand is projected in the Shell_sky scenario (15 EJ), the lowest in the ECF D (Demand Focus) scenario (4 EJ). Comparably low demand figures can also be found in GECO2021 1.5C Diff (5 EJ).

In the IPCC scenarios, there is a substantially lower deviation in demand throughout the years, although the number of scenarios is higher than in the focus studies. The IPCC median value is constant throughout the years (12 EJ), no demand reductions are predicted for the future. The FEC is higher than in the focus studies through all years, and the median FEC difference between the focus and IPCC scenarios increases towards 2050.

5.2.2.2 Europe - Industry - Hydrogen demand

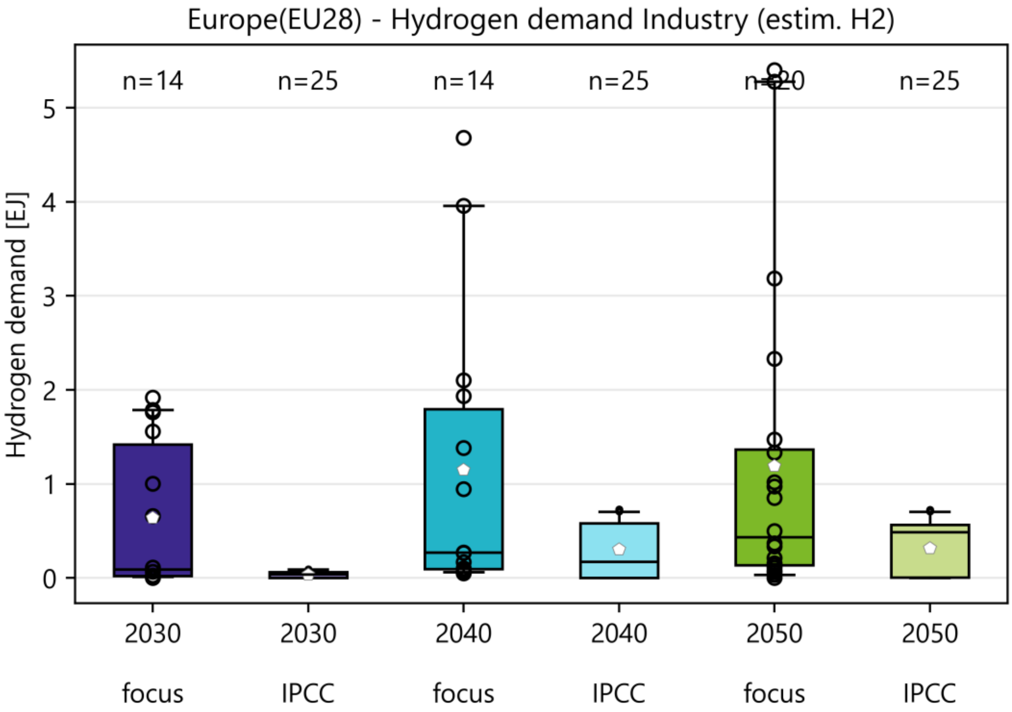

Figure 28: Europe - Industry - Hydrogen demand

The median hydrogen demand in industry remains low through the years (< 1 EJ) in the focus and IPCC scenarios (see Figure 28). In the focus scenarios the bandwidth of hydrogen demand is substantially higher than in the IPCC scenarios. In 2050, the inner bandwidth of focus scenarios shows that industrial hydrogen demand ranges between approx. 0.1 and 1.4 EJ. The highest demand (5 EJ) is found in the Hydrogen Europe's study (H24_RP and H24_TD). In this study, the industry sector is the second largest hydrogen application sector after transport. It is assumed that hydrogen is primarily used for the production of process heat and steam, mostly in steel production and chemical sectors. Hydrogen constitutes the main energy carrier in the industry (40% of total energy demand). Strikingly, despite the high estimates, the study does not include an assessment of the potential of hydrogen in non-energy uses. Another high value for hydrogen demand in industry is seen in the FCHJU hydrogen roadmap (3.2 EJ). This study includes both hydrogen for energy and for feedstock use in industry.

Values on the lower side of the bandwidth come from IEA B2DS, that assumes no hydrogen use in industry, followed by the GECO scenarios with low projections of less than 0.2 EJ. The IPCC projections are slightly more consistent than the focus studies. For 2050, the total bandwidth ranges between 0-0.8 EJ. The median values for the IPCC are on a comparable level to the focus studies. The large bandwidth for the hydrogen share in the industrial energy demand might be, amongst others, due to the following reasons: A high uncertainty for this sector and an inconsistent data structure for hydrogen demand in refineries, either displayed in the industry section, under transformation or not at all.

5.2.2.3 Europe - Industry - Share of hydrogen

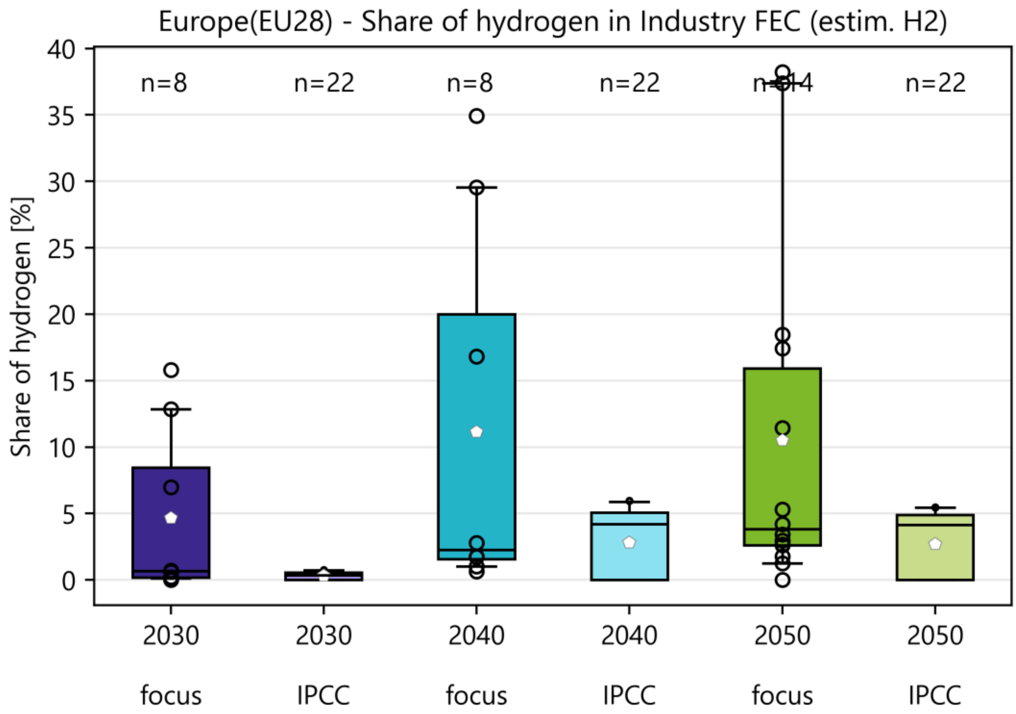

Figure 29: Europe - Industry - Share of hydrogen

The hydrogen demand shares in the industrial sector grow over time in the focus scenarios, while they stagnate from 2040 in the IPCC scenarios (see Figure 29). In the focus scenarios, shares can be as high as 38%, but the median of the studies is at approx. 4% in 2050. While the inner bandwidth of the focus studies ranges between 3-16% hydrogen share in 2050, the IPCC scenarios range between 0-5%. The highest share of hydrogen can be found in the focus studies in the Hydrogen Europe scenarios (38%), the lowest in the IEA B2DS scenario (0%).

5.2.2.4 Europe - Industry - Consideration of feedstock demand

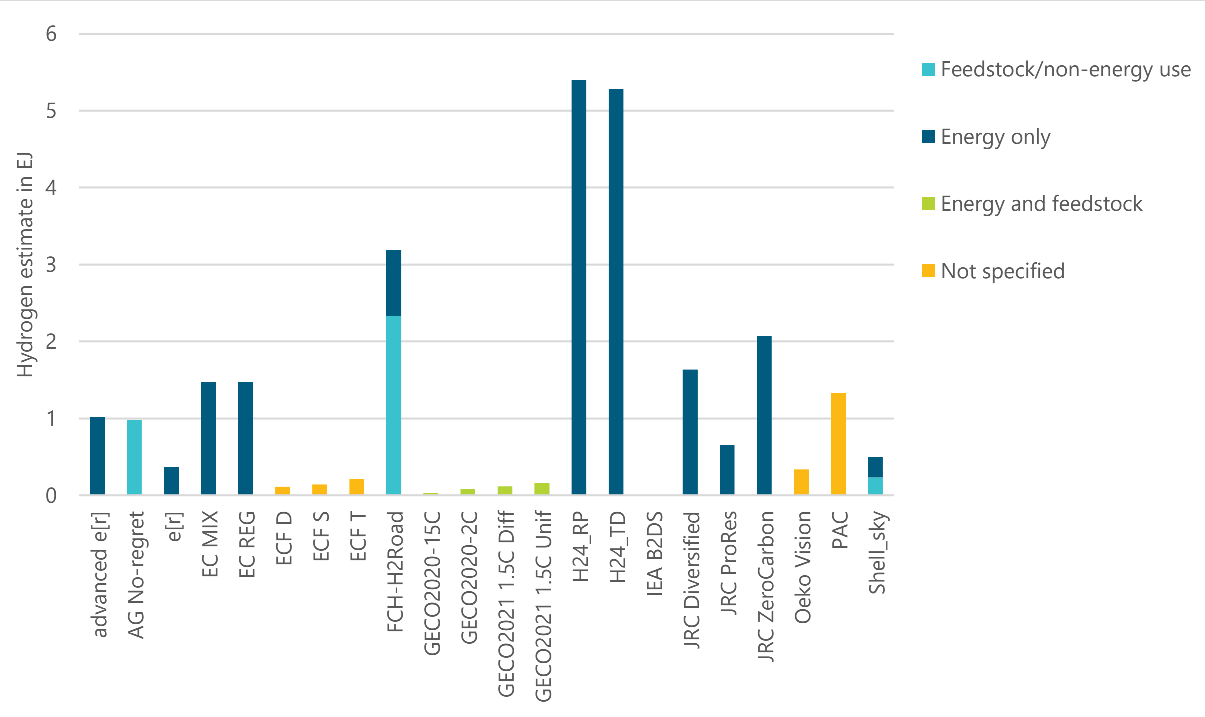

Figure 30: Europe - Industry - Consideration of feedstock demand in 2050

As discussed in the global results, industrial hydrogen demand can vary due to different sector scope (energy and non-energy hydrogen demand, direct and indirect hydrogen demand). From Figure 30 it can be observed that most studies do not include feedstocks in their projections, except for the GECO study and the FCHJU study. Nevertheless, the GECO study reports very low hydrogen demand compared to the other studies. The high outlier values of the Hydrogen for Europe study do not consider non-energy uses, yet are still significantly above the results from the FCHJU roadmap.

The different scopes complicate an analysis of the bandwidth. It can, however, be observed that the two substantially higher demand projections came from two hydrogen dedicated studies (FCHJU hydrogen roadmap and Hydrogen for Europe study). The projections from the EU institutions European Commission (EC) and JRC are on a comparable level, and the Greenpeace, Agora and the Paris Agreement Compatible (PAC) scenarios are within in a similar range. Significantly lower are the GECO and ECF projections.

5.2.3 Europe - Building Sector

5.2.3.1 Europe - Buildings - Final energy consumption

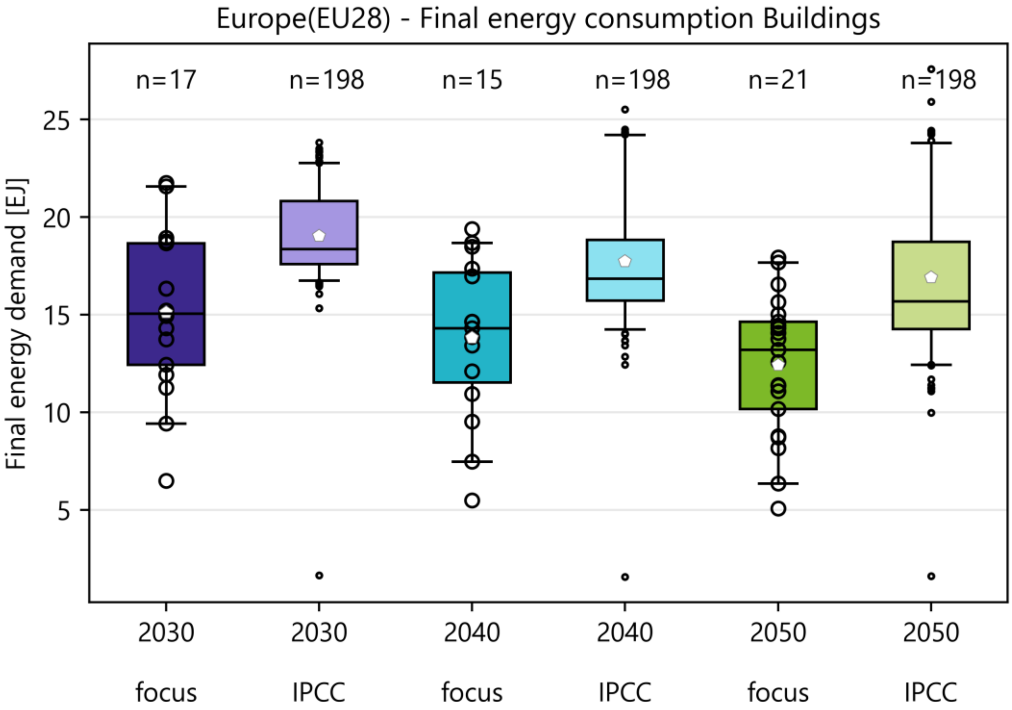

Figure 31: Europe - Buildings - Final energy consumption

Figure 31 shows the bandwidth of FEC in the building sector of the European studies. Building energy consumption has a median of 15 EJ in 2030 and only reduces to 13 EJ in 2050 in the focus scenarios, indicating that energy efficiency is limited in the scenarios. The total bandwidth (excluding outliers) is similarly high throughout the years, ranging between 5 and 21 EJ in 2050. This is a substantial bandwidth. The highest value is reported in the BP Net Zero scenario. The lowest is again reported in the GECO2021 1.5C Diff scenario (5 EJ). The IPCC scenarios assume a higher median energy consumption for all years compared to the focus studies. The range of estimates is comparable to the focus scenarios, however calculated from a significantly higher number of scenarios. There is also only a small decrease in median energy consumption over the years.

5.2.3.2 Europe - Buildings - Hydrogen demand

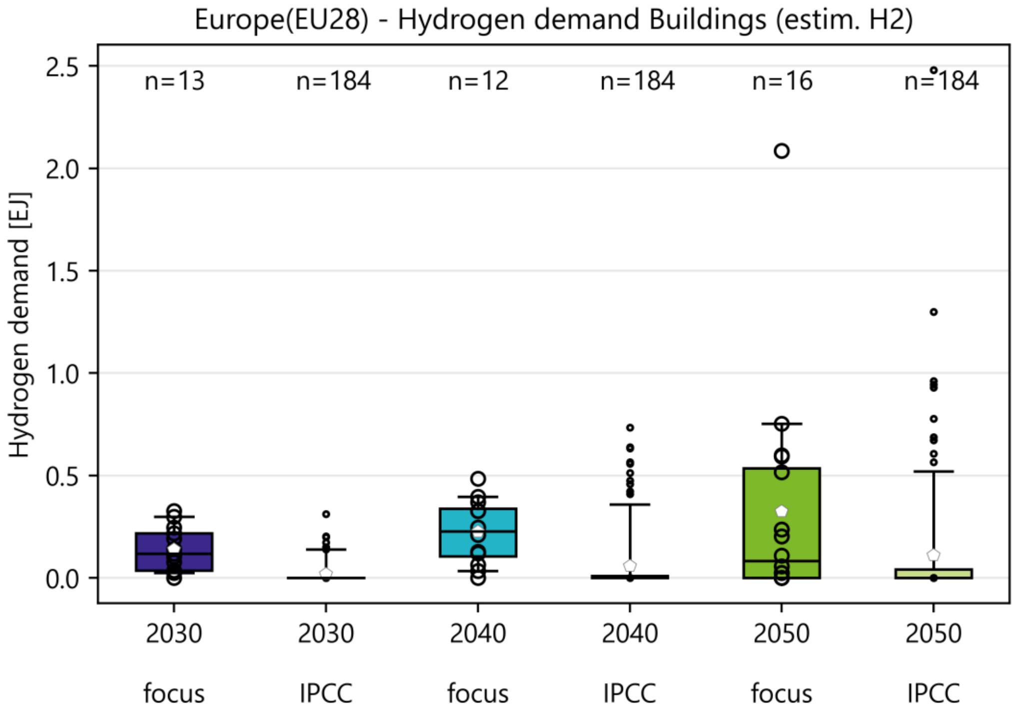

Figure 32: Europe - Buildings - Hydrogen demand

The building hydrogen demand in the European studies is shown in Figure 32.

Median hydrogen demand in the building sector remains on a very low level throughout the years (<0.2 EJ). The inner bandwidth for the building sector is small for the focus studies, ranging between approx. 0 EJ to 0.5 EJ in 2050. The outlier value comes from the FCH hydrogen roadmap (2 EJ). The study assumes that hydrogen plays a vital role in this sector, due to its complementarity with electrification of building heat.

In the H24_TD and H24_RP scenarios, hydrogen delivers only a small contribution to the building sector (0.2 and 0.5 EJ, respectively), under the assumption that competing technologies such as biogas, direct renewables, heat pumps and natural gas will be more successful. Higher use in the RP scenario can be explained through the synergy effects of hydrogen use with high renewable uptake. This finding is interesting considering that this study, with an exclusive focus on hydrogen, models significantly higher overall hydrogen demand than all other scenarios. But herein, hydrogen is mostly allocated to the industry and transport sectors.

The lower end of the bandwidth is created by the ECF D (demand focus) scenario (nearly 0 EJ).

In the IPCC scenarios, the majority are homogenous in their assumptions that hydrogen will play a negligible role in the building sector, if at all. Outlier values, however, reach as high as 2.5 EJ in 2050. The level of the focus scenarios estimates is higher than the IPCC and they would all be considered outlier values by the IPCC.

5.2.3.3 Europe - Buildings - Share of hydrogen

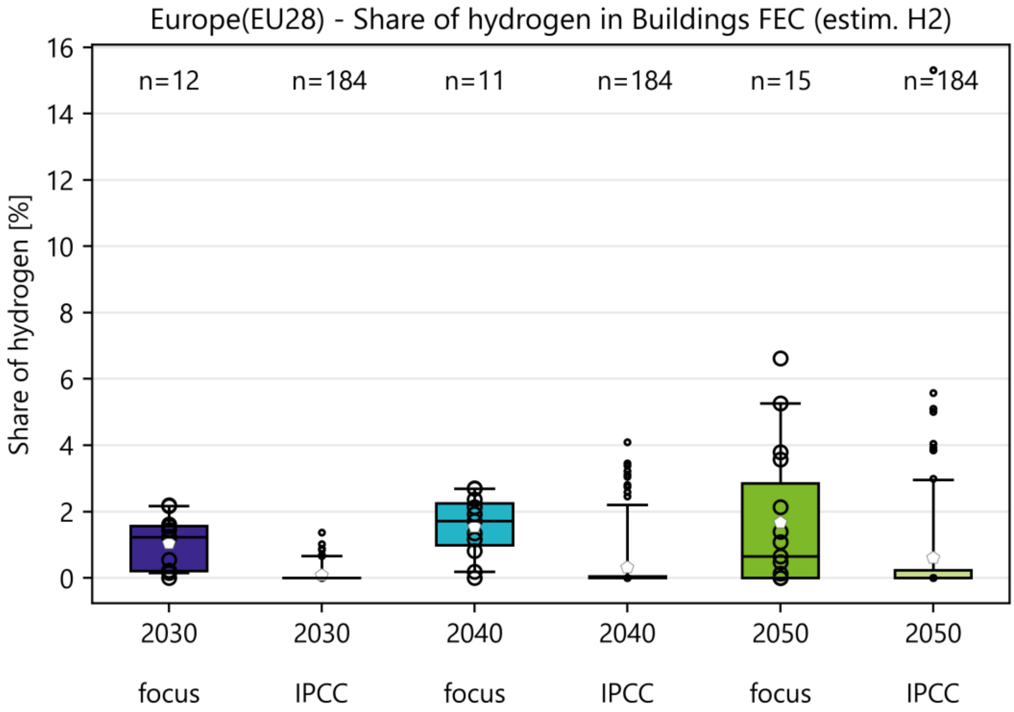

Figure 33: Europe - Buildings - Share of hydrogen

Consistently, the share of hydrogen in the building sector is very low for the IPCC scenarios (see Figure 33). The hydrogen demand shares in the building sector grow slowly over time in the focus and IPCC scenarios. In the focus scenarios, shares reach up to 7% in 2050 (EC MIX scenario), whereas the median of the studies is at 1%. While the inner bandwidth of the focus studies lies between 0-3% hydrogen share in 2050, it ranges between 0-0.5% for the IPCC scenarios. The IPCC scenarios show that hydrogen plays almost no role in the building sector (mean value: 0.5%). Likewise, in the focus studies a mean of 2% is projected.

5.2.4 Europe - Transport Sector

5.2.4.1 Europe - Transport - Final energy consumption

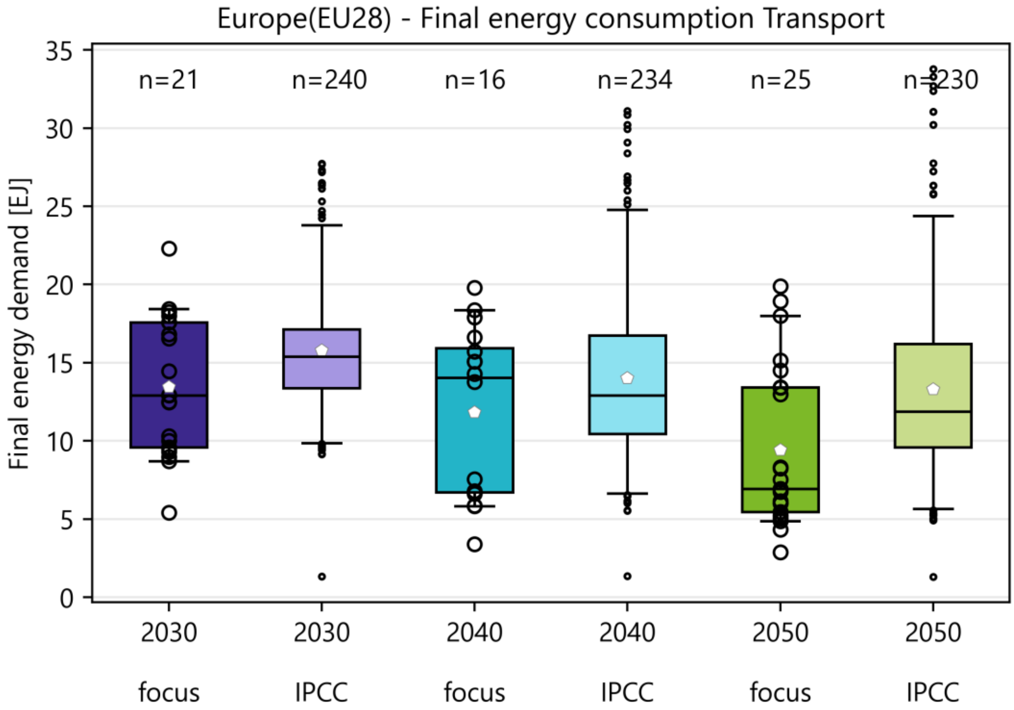

Figure 34: Europe - Transport - Final energy consumption

Transport energy varies substantially between studies and over the years (Figure 34). Median energy consumption reduces from 13 EJ in 2030 to 7 EJ in 2050 in the focus studies, indicating energy efficiency and demand reduction measures are employed. In 2050, the highest value is projected by BP_Netzero (20 EJ). The lowest value is projected by GECO2021 1.5C Diff with 3 EJ (without international transport). As in the global scenarios, energy predictions are difficult to compare between studies due to different sector scopes. This will be further analysed in the next section.

It can be observed that the IPCC scenarios predict a generally higher transport demand than the focus studies, with a median of approx. 12 EJ in 2050. The bandwidth increases over the years, indicating growing uncertainty.

5.2.4.2 Europe - Transport - Hydrogen demand

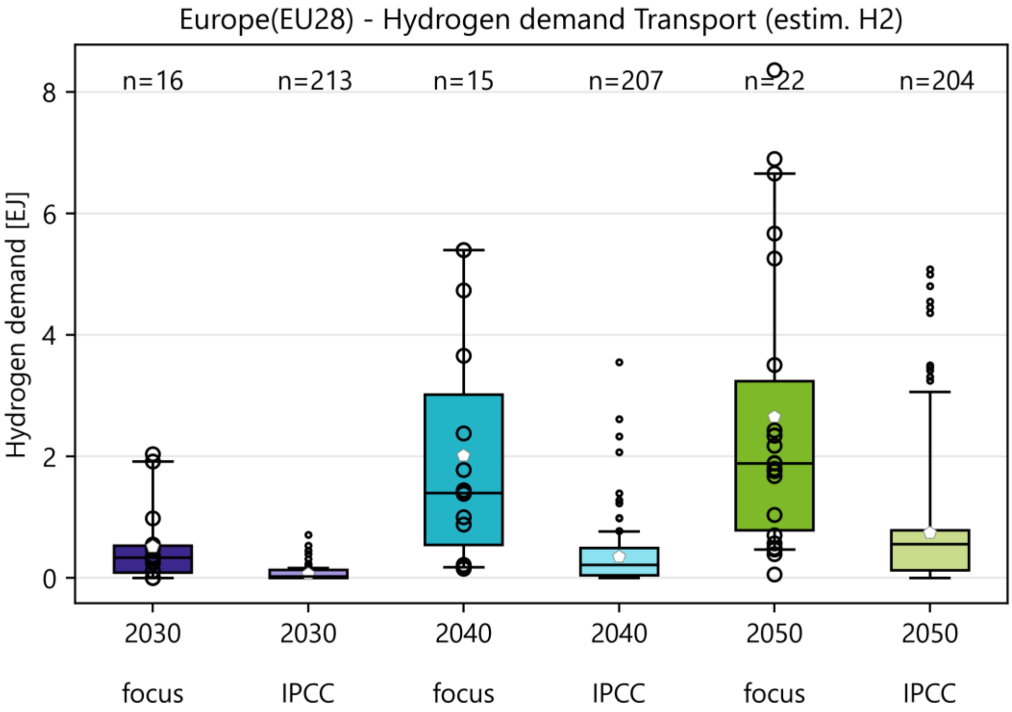

Figure 35: Europe - Transport - Hydrogen demand

For hydrogen demand, there is more certainty in the IPCC projections (Figure 35). The median hydrogen demand is less than 1 EJ even in 2050, although a number of outlier values exists. The interquartile range for the focus studies are significantly larger (1-3 EJ in 2050). Outlier values exceed the IPCC range in 2050 (8 EJ). Median hydrogen demand increases from 0.3 EJ in 2030 to 2 EJ in 2050

The highest hydrogen demand of 8 EJ is projected in the EWG_LUT scenario, driven by both hydrogen and liquid electricity-based renewable fuels. Further high predictions can be found it the H24_RP and H24_E scenarios. It is assumed that more than half of hydrogen demand is used in the transport sector, e.g. in fuel cells, as an intermediary feedstock for synfuels, or biorefineries. The demand for synfuel production is primarily for the aviation sector. Hydrogen is also applied in long-distance and heavy road transport. The hydrogen demand of refineries is also allocated to this sector. Other scenarios on the higher end of the bandwidth include the ambitious JRC scenarios (ZeroCarbon, ProRes and Diversified) and the FCHJU hydrogen roadmap. The FCHJU hydrogen roadmap considers hydrogen as the most promising decarbonisation option for trucks, buses, ships, trains, large and commercial vehicles, due to its higher energy density for long distances and heavy loads. Furthermore, hydrogen infrastructure is considered to be superior to fast charging electricity in the long run.

Lower values of hydrogen are found in IEA B2DS and the GECO scenarios (<0.1 EJ-0.4 EJ).

5.2.4.3 Europe - Transport - Share of hydrogen demand

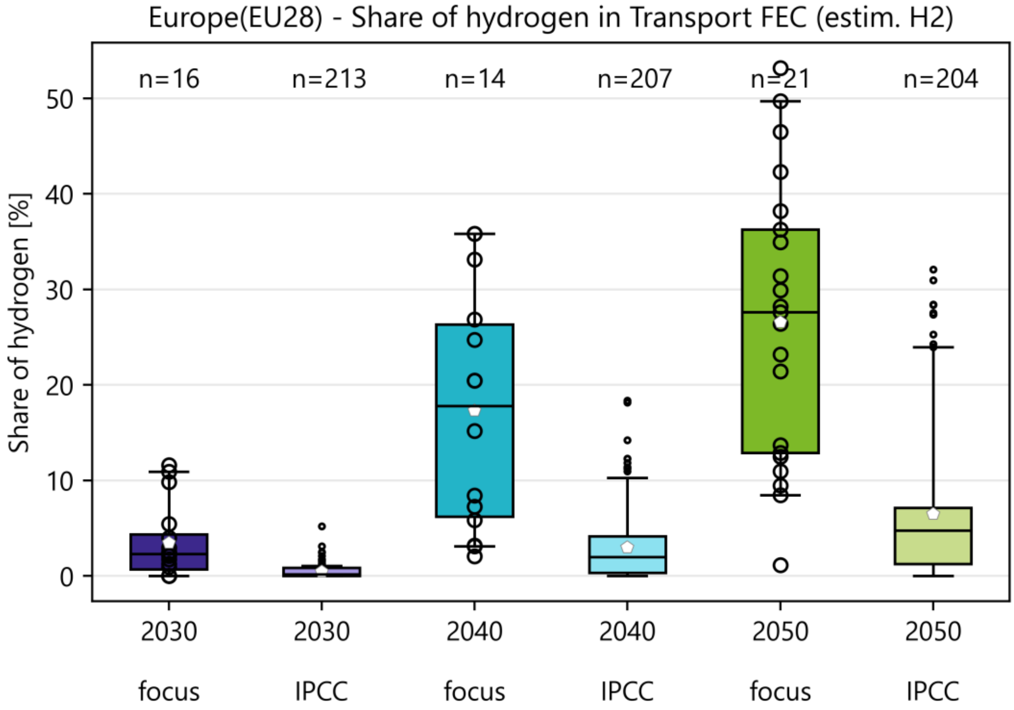

Figure 36: Europe - Transport - Share of hydrogen demand

The share of hydrogen in transport grows substantially over the years in the focus studies (Figure 36). From a median of close to 0% in 2030, it reaches 28% in 2050. The bandwidth and therefore uncertainty of predictions also increases over the years, resulting in a total range of 1-53% in 2050. The highest share is found in H24_RP scenario. On the lower bound, IEA B2DS can be found. Likewise, the hydrogen share grows in the IPCC scenarios from a median value of nearly 0% in 2030 to 5% in 2050. The inner bandwidth of the IPCC scenario reports a hydrogen share in transport between 1-7% and therefore see a substantially lower hydrogen share compared to the focus scenarios.

5.2.4.4 Europe - Transport - Consideration of international bunkers

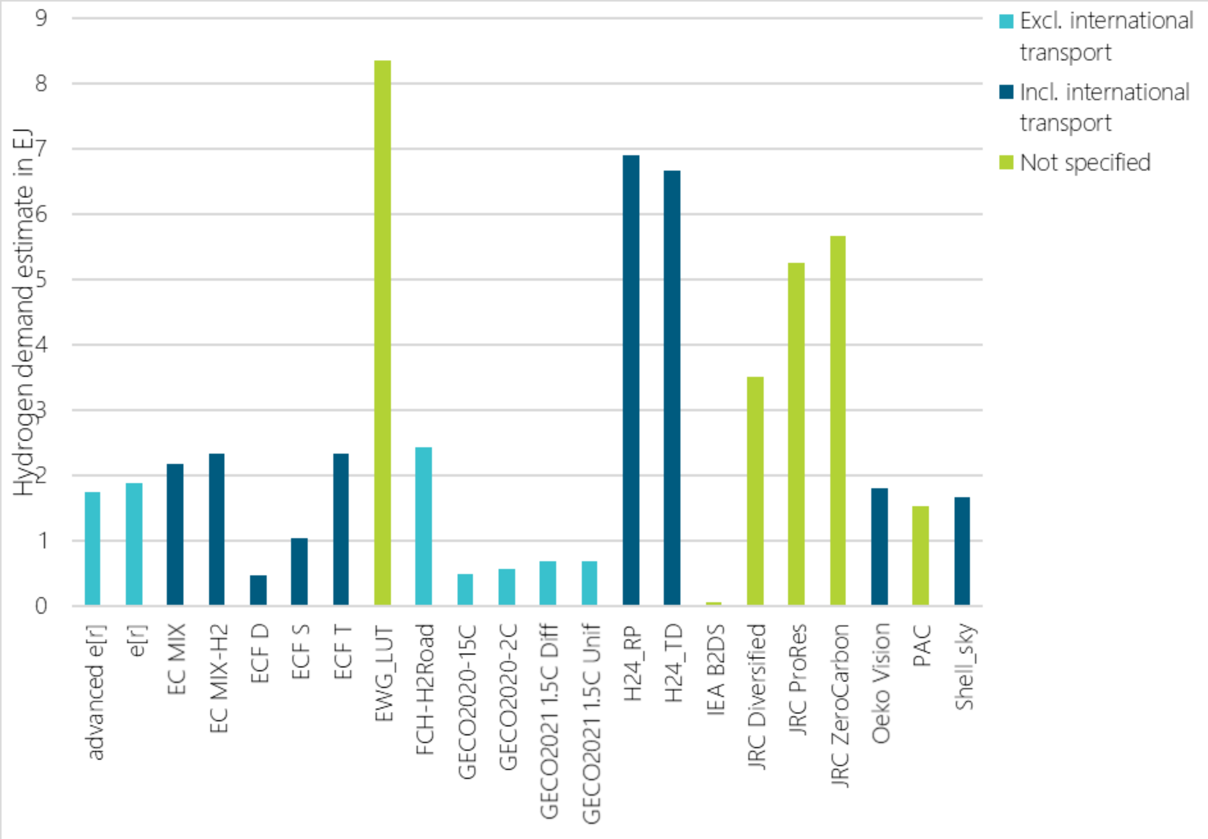

Figure 37: Europe - Transport - Consideration of international bunkers in 2050

Figure 37 shows which studies included international transport (aviation and/or shipping) in the modelling of the transport sector. In general, it can be inferred that the lower demand estimates in the GECO study are partly due to not considering international transport. However, it can also be seen that the two Greenpeace scenarios advanced (r) and e(r) reach similar hydrogen demand levels without considering international transport. On the other hand, the extremely high values from the H24 scenarios are not caused by the inclusion of international transport. A lot of scenarios do not disclose whether international transport is included.

5.2.5 Europe - Summary of sectoral demand

5.2.5.1 Europe - Summary of sectoral demand - share of hydrogen

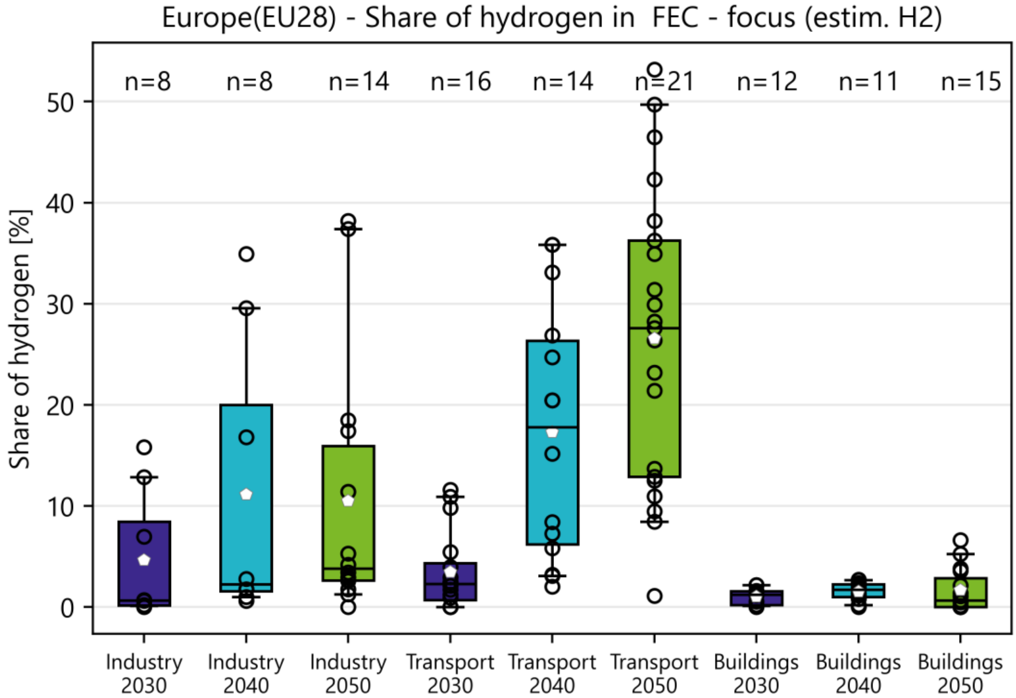

Figure 38: Europe - Summary of sectoral demand - share of hydrogen

Figure 38 compares hydrogen demand across sectors. Similar to the global results, the highest median hydrogen demand in 2050 is found in the transport sector. The transport sector also has the largest inner and total bandwidth, indicating a higher level of uncertainty. The industry sector shows values in the higher quartile that are on a comparable level to the transport hydrogen share, but the median and mean industry hydrogen demand is substantially lower than in transport. The building sector is considerably smaller than for the other two sector and more certain, indicated by the small range of values.

5.2.5.2 Europe - Summary of sectoral demand - absolute hydrogen demand

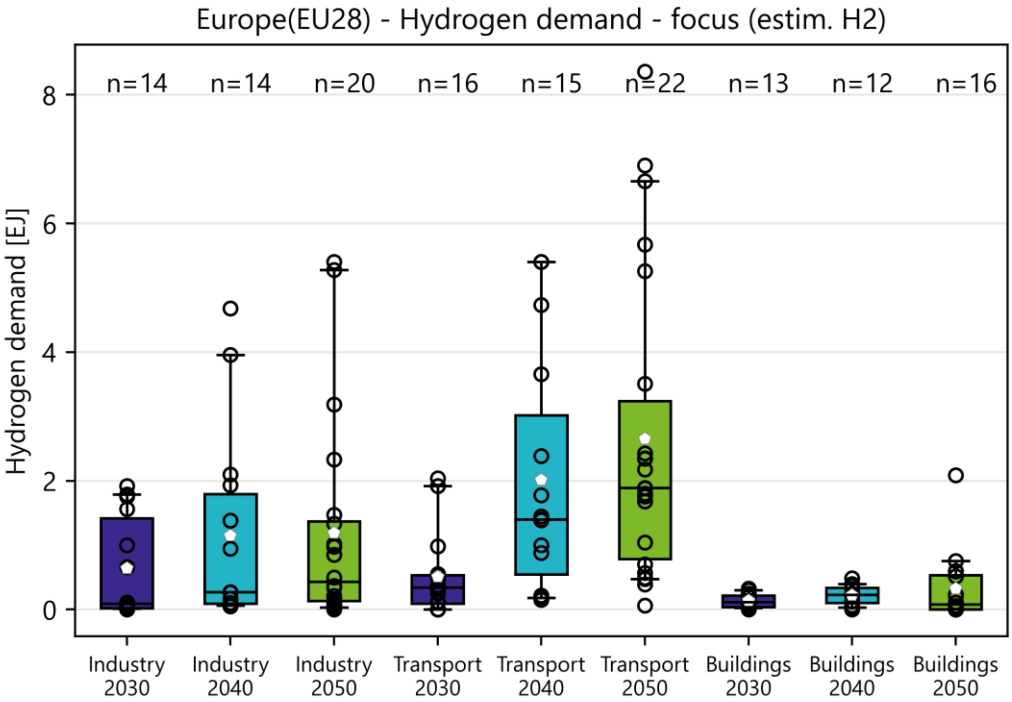

Figure 39: Europe - Summary of sectoral demand - absolute hydrogen demand

Figure 39 compares hydrogen demand across sectors in terms of absolute numbers. This figure can be read in conjunction with Figure 36, but shows the absolute values of hydrogen demand. Equally to the share of hydrogen in energy demand, absolute numbers are highest in transport, followed by the demand in industry. The building sector is considerably smaller than for the other two sector and more certain, indicated by the small range of values. The outlying maximum value is estimated by the scenario FCH-H_2Road.

5.3 Central Asia (China)

5.3.1 Central Asia - Total Demand

5.3.1.1 Central Asia - Total demand - Final energy consumption

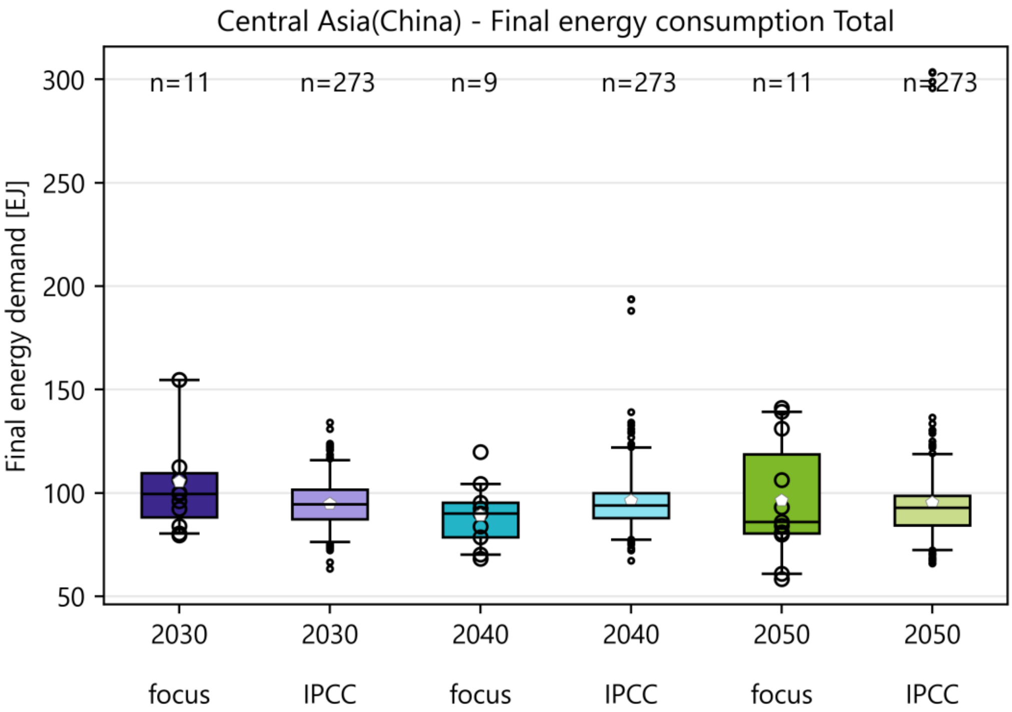

Figure 40: Central Asia - Total demand - Final energy consumption

For Central Asia (China), the inner bandwidth of the focus scenarios illustrate a decreasing FEC from 2030 to 2040, and a nearly constant median value between 2040 and 2050, which is coming with a high insecurity seen by the large FEC inner bandwidth in 2050 (from 80 EJ to 119 EJ) (Figure 40). This wide bandwidth is explained by two contradictory assumptions in the scenarios: A series of energy efficiency measures leading to an FEC decline, and an increasing population and economy (GDP) growth inducing a rising FEC.

Unlike most studies, the British Petroleum (BP) study (2020) discloses limited information regarding the FEC. Therefore, the primary energy demand of the BP scenarios is presented in the Figure 40 above and in the following sectoral analysis. As a result, both BP scenarios (BP Netzero and BP Rapid) end up with the highest projects of 155 EJ in 2030. For the projections of FEC in 2050, 4 IPCC scenarios aiming at a 2°C climate target result highest FEC between 256 EJ and 304 EJ, followed by the two BP focus scenarios with a projected primary energy demand of around 140 EJ. The lowest FEC of around 60 EJ in 2050 is seen in the e[r] and advanced e[r] scenarios by Greenpeace (2015), even though economic growth and an increased living standard are considered next to ambitious energy efficiency measures in all sectors.

5.3.1.2 Central Asia - Total demand - Final energy demand and GHG emissions

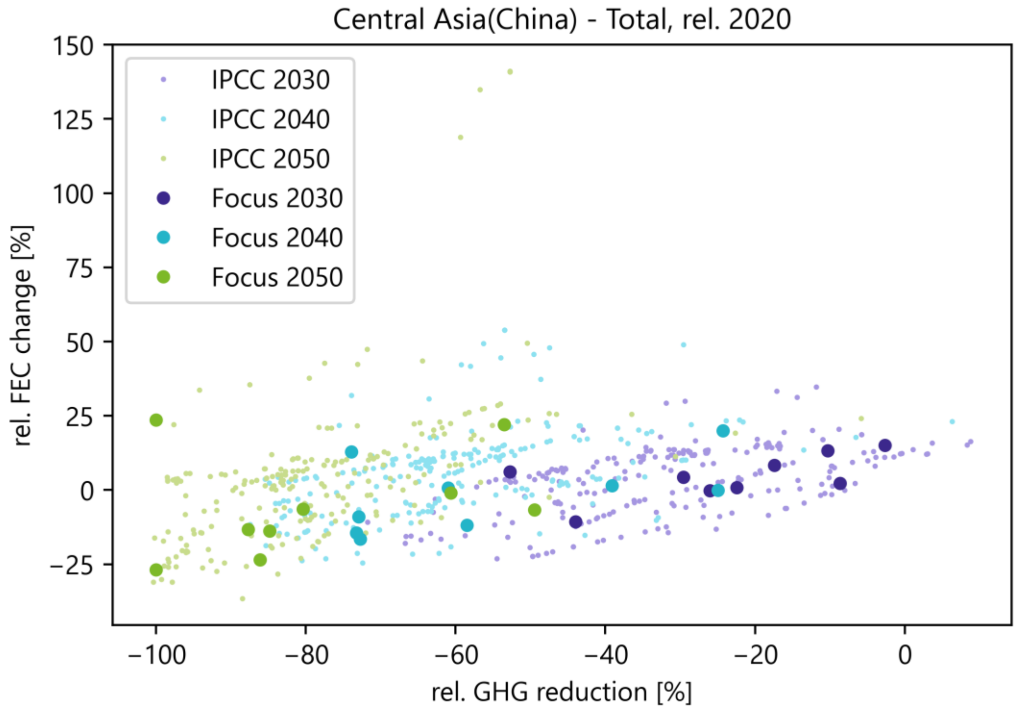

Figure 41: Central Asia - Total demand - Final energy demand and GHG emissions

China is the country with the highest GHG emissions, therefore it has the highest decarbonisation potential but the rapid economic growth and steady energy demand increase make decarbonisation challenging (Liu et al. 2022). Figure 41 shows a negative correlation between FEC and the ambitious level of GHG reduction in most of the scenarios. Although most scenarios assume continued economic growth in China, energy efficiency measures appear to outweigh the energy needs for a growing population and per capita energy consumption. Therefore, most scenarios expect the Chinese final energy consumption to decrease along the path of decarbonisation. Interestingly, some of the IPCC scenarios show that a complete GHG reduction by 100% is achieved, while FEC remains constant or even increases.

5.3.1.3 Central Asia - Total demand - Hydrogen demand

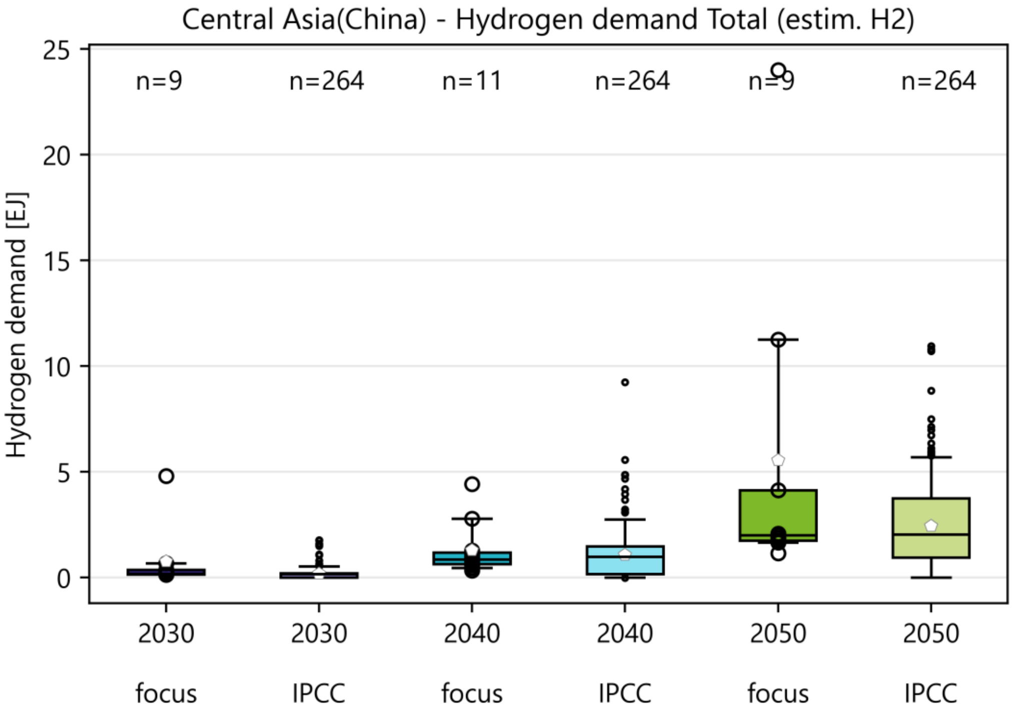

Figure 42: Central Asia - Total demand - Hydrogen demand

For hydrogen demand, all scenarios in Figure 42 show an increasing trend until 2050. As a result, China's total hydrogen demand in 2050 is projected to range between 2 EJ and 4 EJ in inner bandwidth. For most of the IPCC scenarios, the inner bandwidth is on a comparable level between 1 EJ and 4 EJ. Considering also the total bandwidth and outlier values, the range differs largely between focus and IPCC scenarios, but the median values are similar (2 EJ).

Beyond the range of hydrogen demand projections from most of the focus scenarios, the Greenpeace advanced e[r] scenario expects a relatively high hydrogen demand of 3.5 EJ in 2050. This high hydrogen demand comes mainly from the industry sector (1.8 EJ) and the transport sector (1.4 EJ), while only a very small to no hydrogen demand is foreseen in the building sector. An outlier value with a total hydrogen demand of 24 EJ in 2050 is reported in the Hydrogen Council study, which expects China to be the largest hydrogen consumer in the future. Several IPCC scenarios project relatively high hydrogen demand of up to 10.9 EJ.

The lowest hydrogen demand of 1.1 EJ in 2050 is projected by the scenario GECO2020 1.5C, of which 85% results from the transport sector, 12% from industry.

5.3.1.4 Central Asia - Total demand - Share of hydrogen

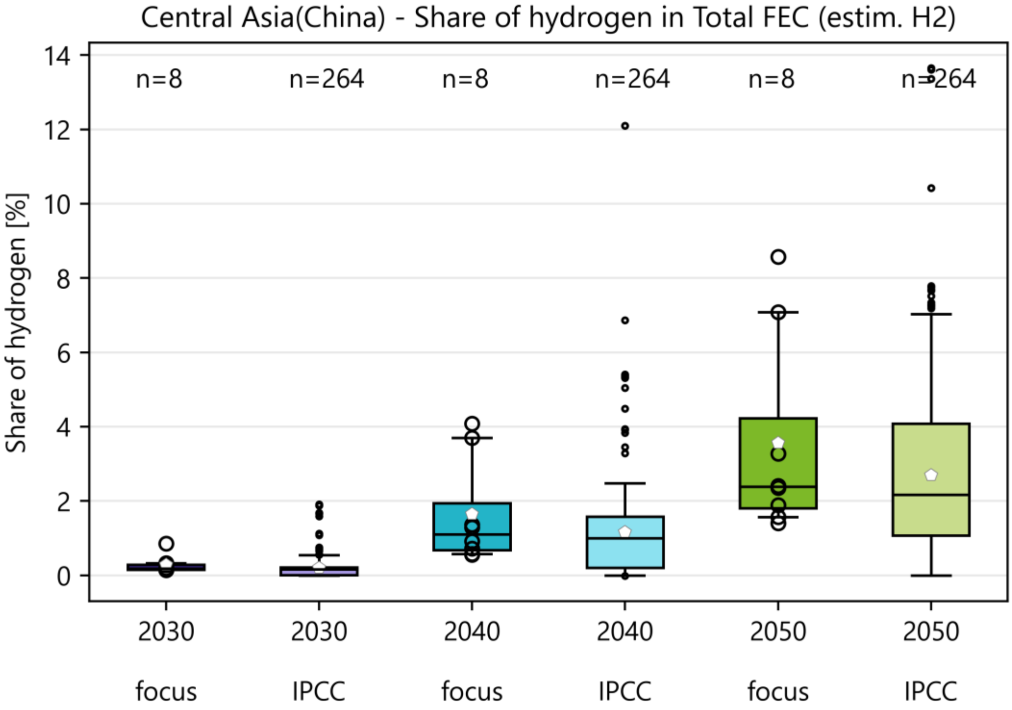

Figure 43: Central Asia - Total demand - Share of hydrogen

Figure 43 presents a clearly increasing trend of hydrogen shares in FEC in all scenarios in China, increasing from <1% in 2030 to 14% in 2050. Without consideration of outliers, in 2030, the hydrogen share ranges between 0.2-0.3% in the focus scenarios and 0 – 0.2% in the IPCC scenarios, and in 2050, 2-4% in the focus scenarios and 1.1 - 4.1% in the IPCC scenarios. The projection uncertainty for the hydrogen share increases over time in the IPCC scenarios, shown by an increasing total bandwidth. Despite the different ranges between focus scenarios and IPCC scenarios, they have similar median values in 2030 (0.2%), 2040 (1%) and in 2050 (2%).

Among all focus scenarios, the EWG_LUT scenario models the highest share of hydrogen in total energy (9%). Other high values are projected by the Greenpeace study (2015), due to its low FEC and high hydrogen demand in absolute terms.

Among the focus scenarios, the GECO2021 1.5°C Undif scenario and the GECO2020 1.5°C scenario represent the lowest hydrogen shares in 2030 and 2050, respectively. The GECO studies (2020, 2021) expect a relatively low hydrogen demand in absolute term. Within the focus scenarios, the GECO2020 1.5°C scenario shows the slowest increase of hydrogen demand, and therefore reports the lowest total hydrogen demand and lowest share of hydrogen in FEC in 2050. The limited hydrogen demand in the GECO2020 1.5°C scenario comes mostly from the building sector in 2030 and shifts gradually to the transport sector (as fuel for heavy duty vehicles and maritime transport) in 2050.

5.3.1.5 Central Asia - Total demand - Hydrogen demand and GHG emissions

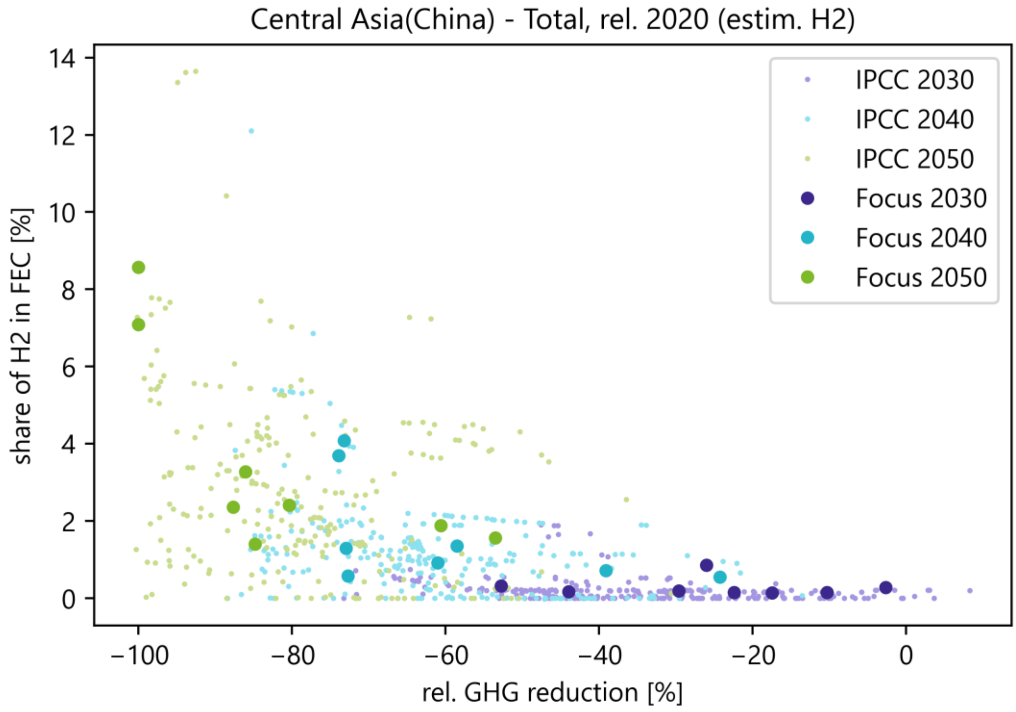

Figure 44: Central Asia - Total demand - Hydrogen demand and GHG emissions

The majority of the scenarios in Figure 44 show a positive correlation between the share of hydrogen demand in final energy consumption and the ambitious level of GHG emission reductions.

The focus scenario (advanced [e]r) with the highest shares of hydrogen in FEC (0.8%, 4% and 7%, in 2030, 2040 and 2050, respectively), achieves 100% CO_2 emissions reduction in 2050. In the IPCC scenarios, 13.65% is the highest hydrogen share while GHG emissions are reduced by 93% between until 2050.

As for the lowest share and lowest hydrogen demand, 28 IPCC scenarios foresee no hydrogen demand at all in the future. Among the focus scenarios, the lowest share of hydrogen in 2030 and 2040 is shown by the Shell_sky scenario, which has the lowest absolute hydrogen demand in 2030. The 1.5°C scenario from the GECO study (2021) results with the lowest share of hydrogen as well as the lowest absolute hydrogen demand in 2050.Generally speaking, for the same level of GHG emission reduction, the hydrogen shares in FEC for China are lower compared to the world and much lower in comparison to Europe.

5.3.1.6 Central Asia - Total demand - Indirect hydrogen demand

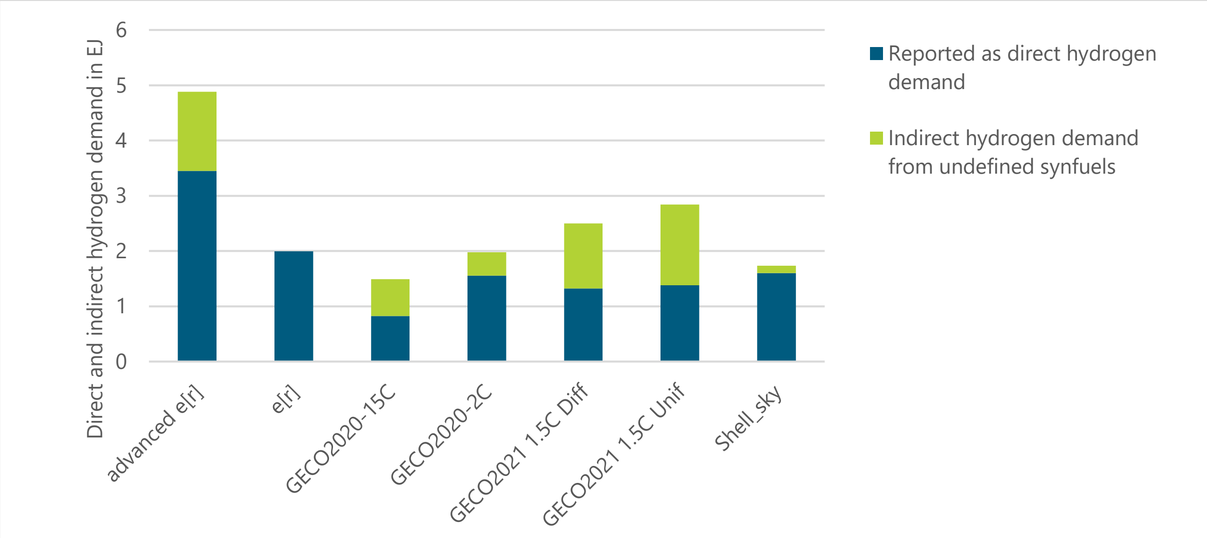

Figure 45: Central Asia - Total demand - Indirect hydrogen demand in 2050

As shown in Figure 45, most of the scenarios expect a contribution of hydrogen in synfuels comparable to direct hydrogen demand in 2050. Two scenarios (e(r) from Greenpeace and Shell_sky) foresee no or only a small contribution from synfuels. All scenarios expect the synfuel demand in China mainly or even completely for the transport sector.

5.3.2 Central Asia - Industry Sector

5.3.2.1 Central Asia - Industry - Final energy consumption

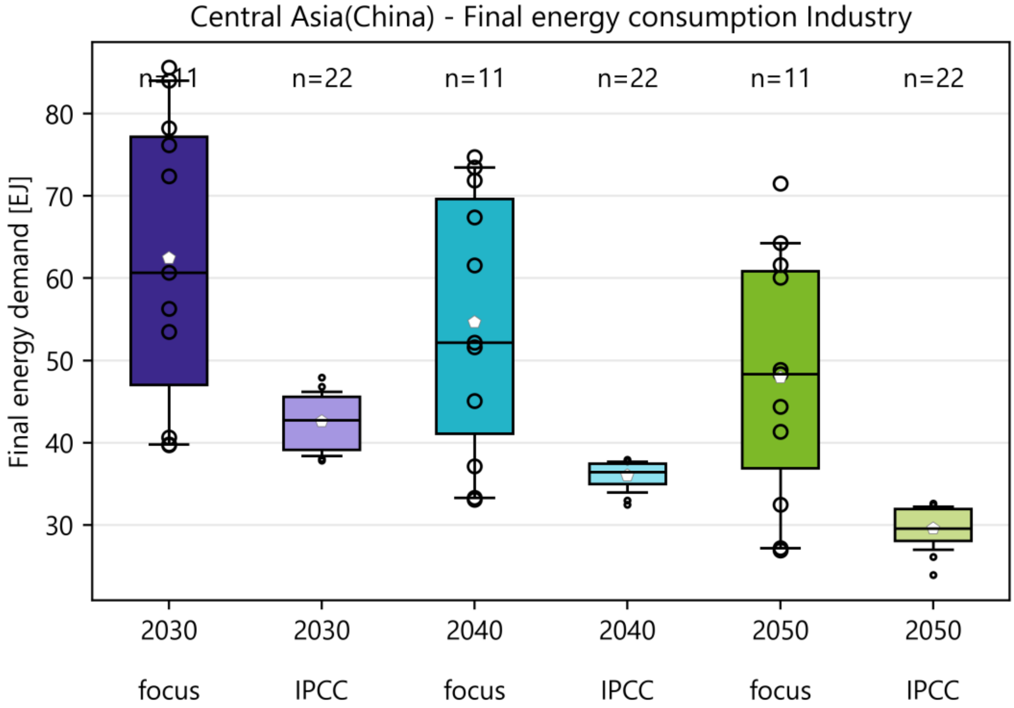

Figure 46: Central Asia - Industry - Final energy consumption

The interquartile range of the IPCC scenarios projects a future FEC in the Chinese industry of 39–46 EJ in 2030 and 28–32 EJ in 2050. In comparison, the interquartile range of the focus scenarios projects substantially higher industrial FEC between 37 EJ and 61 EJ in 2050. Both focus scenarios and IPCC scenarios show a decreasing mean FEC in the industry sector in China (Figure 46), while the focus scenarios have a four to six times larger bandwidth compared to the IPCC scenarios. The final energy consumption in the industry sector projected in the focus scenarios converges gradually to a smaller bandwidth from 2030 to 2050. On the contrary, in the IPCC scenarios the bandwidth for FEC decreases from 2030 to 2040, followed by an incline between 2040 and 2050. Furthermore, most IPCC scenarios result an industrial energy demand that is mostly lower than in the focus scenarios, seen in the FEC mean, median, and bandwidth. For instance, the median FEC in the focus scenarios is 10 to 20 EJ higher in 2030, 2040, 2050 compared to the IPCC scenarios.

Beyond this range, amongst the focus scenarios, in 2050, the Policy Scenario by Tsinghua University (2022) projects the highest industrial energy demand (72 EJ). On the contrary, the two Greenpeace scenarios (advanced [e]r and [e]r) (2015) result the lowest FEC in the industry (27 EJ). The high value seen in the Tsinghua University Policy scenario is due to the relatively high baseline energy demand and conservative energy reduction measures in industry. Additionally, the Tsinghua University assumes that, except for the 1.5°C scenario, the industrial energy demand will peak in 2030 and subsequently continuously reduce the energy demand. Most other scenarios expect the reduction to start already from 2020.

5.3.2.2 Central Asia - Industry - Hydrogen demand

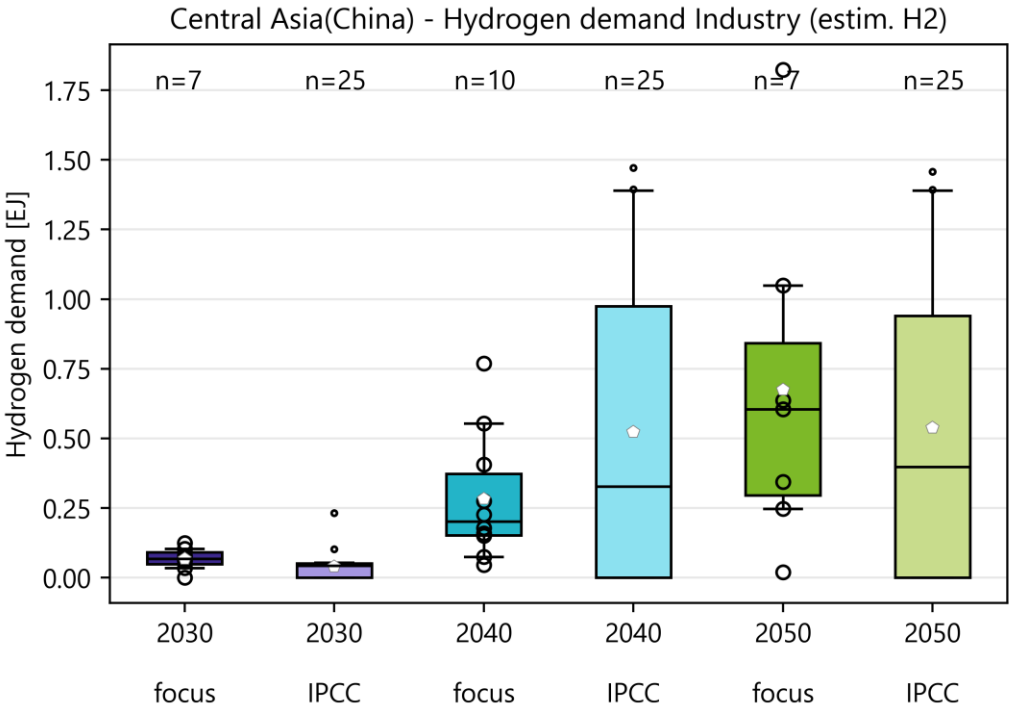

Figure 47: Central Asia - Industry - Hydrogen demand

Unlike the development of the industrial FEC, the industrial mean hydrogen demand increases in the future (Figure 47). Overall, the IPCC scenarios show a larger bandwidth than the focus scenarios, especially the projections in 2040 and 2050. All scenarios expect no or a very limited hydrogen demand in the Chinese industry in 2030 of up to 0.2 EJ. In 2040, the hydrogen demand in the industry is expected to increase to 0.2-0.4 EJ in the focus scenarios (inner bandwidth), and to 1 EJ in the IPCC scenarios. This bandwidth increases to 0.3-0.8 EJ in 2050 for the focus studies, while it stays stable for the IPCC scenarios.

Among all focus scenarios, the maximum hydrogen demand (0.1 EJ, 0.8 EJ and 1.8 EJ, in 2030, 2040, and 2050 respectively) is found in the advanced e[r] scenario from the Greenpeace study (2015). Together with other renewable energies (e.g. solar collectors, geothermal energy with the help of heat pumps, electricity), renewable hydrogen is used to cover the heating demand in the industry and substitute fossil fuel-based fire system. Furthermore, the Greenpeace study (2015) does not consider hydrogen to replace fossil-based feedstock, as biomass is used for feedstock purposes.

For the lowest hydrogen demand in the industry in 2050, the GECO2020 1.5C° scenario reports a hydrogen demand of 0.02 EJ, followed by the GECO2020 2°C scenario with 0.2 EJ. Furthermore, seven IPCC scenarios do not foresee any hydrogen demand in the industry, which are all from the same model IMAGE 3.2.

5.3.2.3 Central Asia - Industry - Share of hydrogen

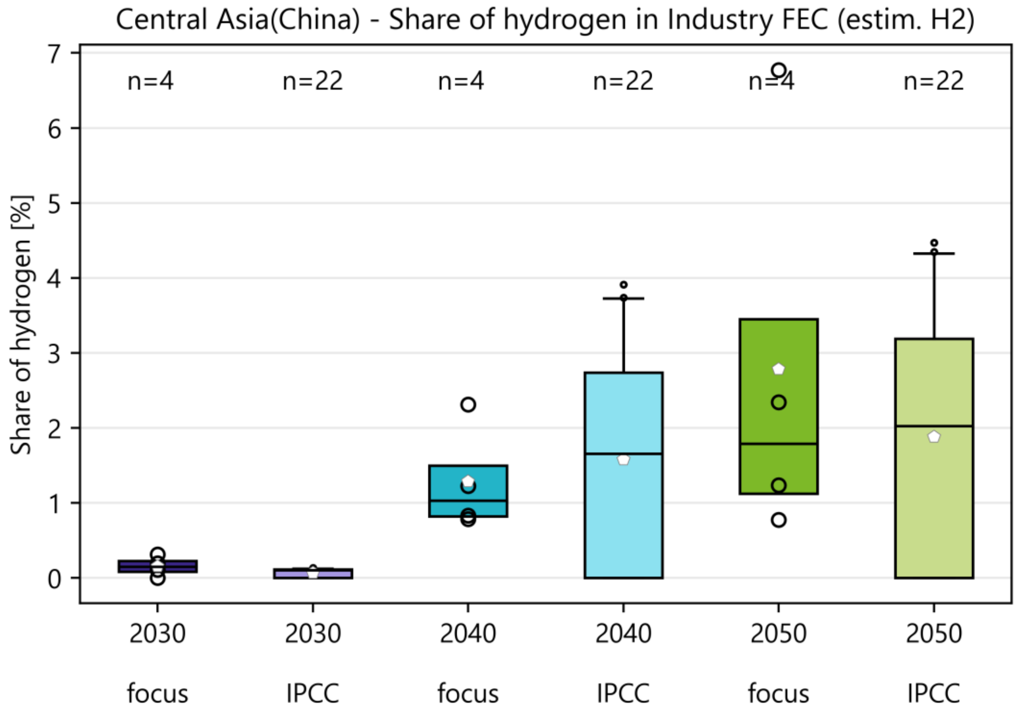

Figure 48: Central Asia - Industry - Share of hydrogen

Similar to the absolute industrial hydrogen demand, the share of hydrogen demand in the FEC in industry increases after time and the demand range in the IPCC scenarios is generally larger than in the focus scenarios (Figure 48). The inner bandwidth of scenarios in the focus studies presents a share of hydrogen in the industry between 0.1% and 0.2% in 2030 and between 1% and 3% in 2050, while the most IPCC scenarios present a range between 0% and 0.1% in 2030 and between 0% and 3% in 2050.

The highest share of hydrogen in the industry in 2050 of 7% is shown by the advanced [e]r scenario, which also reports the highest hydrogen demand in the industry in absolute term. The lowest share among the focus scenarios is represented by the GECO2021 1.5 scenario with 1%, while among the IPCC scenarios 0% is the lowest due to the seven scenarios expect no hydrogen demand in the industry.

5.3.2.4 Central Asia - Industry - Consideration of feedstocks

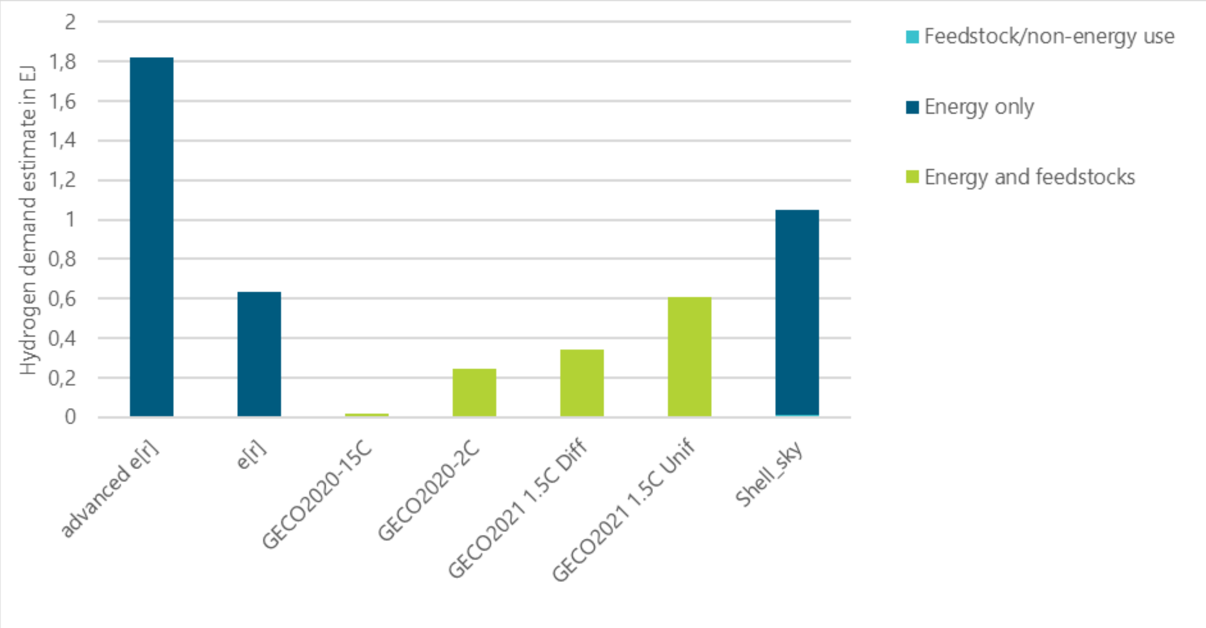

Figure 49: Central Asia - Industry - Consideration of feedstocks in 2050

Figure 49 shows a large range of hydrogen demand in the industry among the focus scenarios. The Greenpeace study (2015) reports the highest hydrogen demand, although hydrogen is only expected to contribute to the decarbonisation of industrial energy use. In the earlier GECO study (2020), electricity and biomass play the most important roles in the decarbonisation of the Chinese industry, with no specification between energy use and non-energy use (feedstocks). Therefore, the role of hydrogen in the industry is very limited. In the latest GECO study (2021), biomass plays a much smaller role in the decarbonisation of the Chinese industry and in exchange the demand of hydrogen has increased. Overall, the hydrogen contribution in the Chinese industry is considered conservative in comparison to its contribution in the European industry.

5.3.3 Central Asia - Building Sector

5.3.3.1 Central Asia - Buildings - Final energy consumption

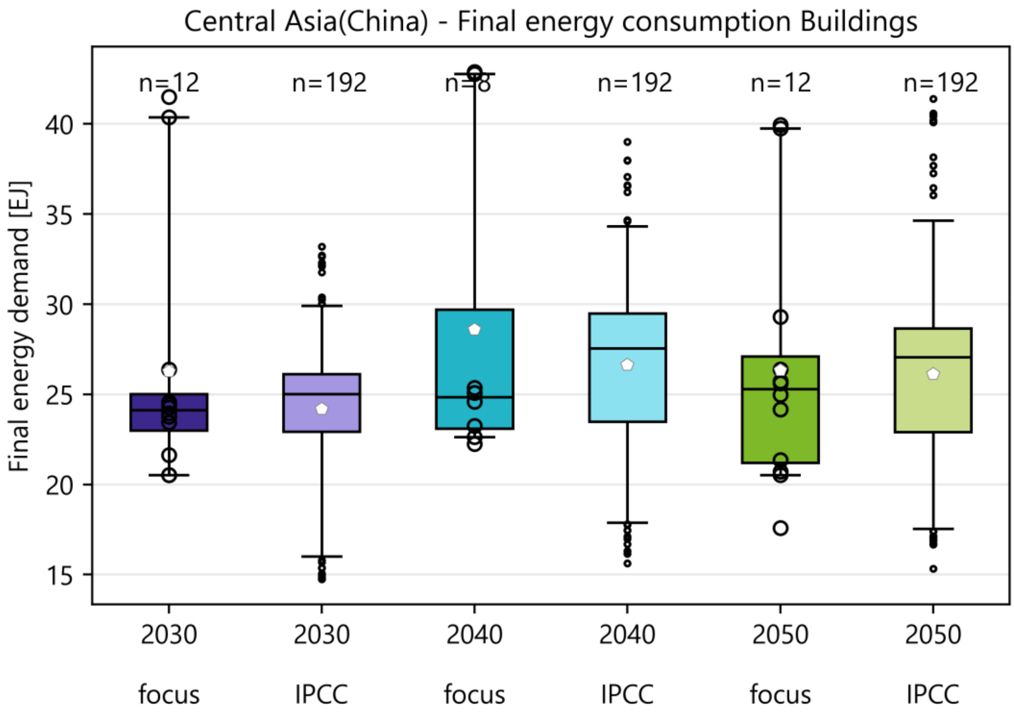

Figure 50: Central Asia - Buildings - Final energy consumption

Unlike the FEC in the other sectors, the FEC in the building sector does not show a decreasing trend over the years. In fact, there is even a slight increase from 2030 to 2040 and it stays at a similar level until 2050 (Figure 50). As a result, the inner bandwidth of FEC in the building sector ranges from 23 EJ to 26 EJ in 2030, and from 21 EJ to 29 EJ in 2050 according to most focus and IPCC scenarios. In general, the IPCC scenarios report slightly higher FEC in the building sector than the focus scenarios. The highest FEC in the building sector are observed in 2040, with an inner range variation between 23 EJ to 30 EJ according to most of the focus scenarios and IPCC scenarios.

Beyond the upper quartile of most focus scenarios, the outliers (around 40-43 EJ from 2030 to 2050) from the two scenarios (BP Netzero, BP Rapid) are reported by BP (2020) due to the applied baseline FEC in the building sector in the study, that is almost twice as high compared to in the other studies.

Among the focus scenarios, the Tsinghua University (2022) reports the lowest FEC in the building sector in 2030 (21 EJ) and 2050 (18 EJ) in their 1.5°C scenario, which also shows the most FEC decrease from 2030 to 2050.

5.3.3.2 Central Asia - Buildings - Hydrogen demand

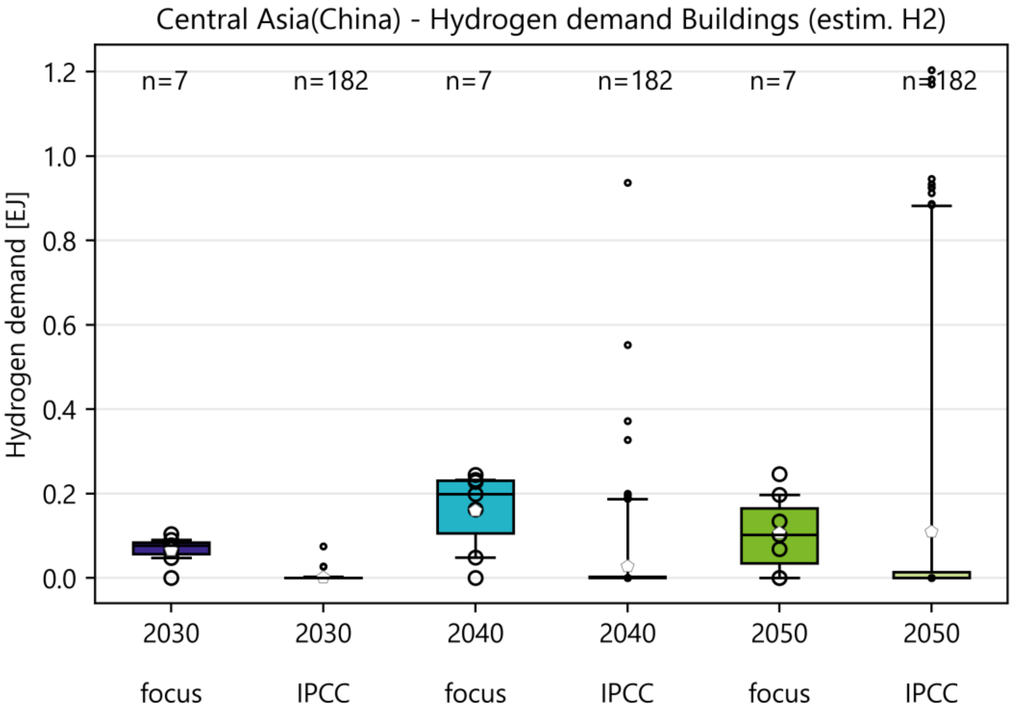

Figure 51: Central Asia - Buildings - Hydrogen demand

As shown in Figure 51, hydrogen plays a very limited role (up to 1.2 EJ) in the building sector in the future. For the focus scenarios, the median increases from 0.1 EJ in 2030 to 0.2 EJ in 2040, and decreases to 0.1 EJ in 2050. Hydrogen demand in most IPCC scenarios is 0 even in 2050

Among the focus scenarios, several scenarios from the GECO study (2020, 2021) report the highest hydrogen demand in the building sector in 2030 and 2040. In 2050, Greenpeace (2015) reports the highest hydrogen demand in the building sector with its advanced e[r] scenario, which achieves a complete substitution of the remaining gas consumption with the help of hydrogen generated from renewable electricity. It is to be noted that the Greenpeace study (2015) aggregates agriculture and building sectors together and it is unable to differentiate the energy demand between these sectors. On the other hand, another scenario e[r] from Greenpeace (2015) expects no hydrogen demand at all throughout the years.

Most IPCC scenarios assume hydrogen to play a negligible role in the building sector. 43 IPCC scenarios expect no hydrogen demand at all for the building sector in 2050. On the other hand, the highest outlier comes also from the IPCC study and reaches 1.2 EJ in 2050.

5.3.3.3 Central Asia - Buildings - Share of hydrogen

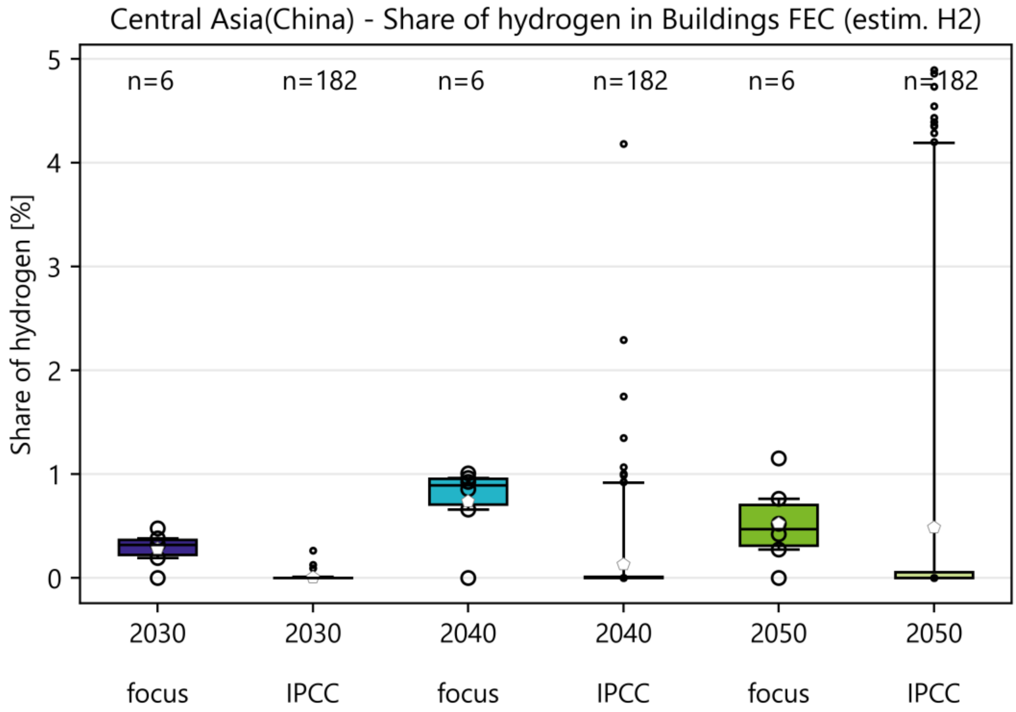

Figure 52: Central Asia - Buildings - Share of hydrogen

Due to the rising FEC and limited contribution of hydrogen demand in the future, the median share of hydrogen in FEC in the building sector is still only 0.5% in in 2050 for the focus studies (Figure 52). Overall, the interquartile range of hydrogen shares from most focus scenarios increase from 0.2–0.4% in 2030 to 0.7-1% in 2040, and decrease to 0.3–0.7% in 2050. In the inner bandwidth of the IPCC scenarios, the hydrogen shares in FEC are much lower compared to the focus scenarios, and reach 0-0.1% in 2050. On the other hand, the highest shares of 4% in 2040, and 5% in 2050 also come from IPCC scenarios.

5.3.4 Central Asia - Transport Sector

5.3.4.1 Central Asia - Transport - Final energy consumption

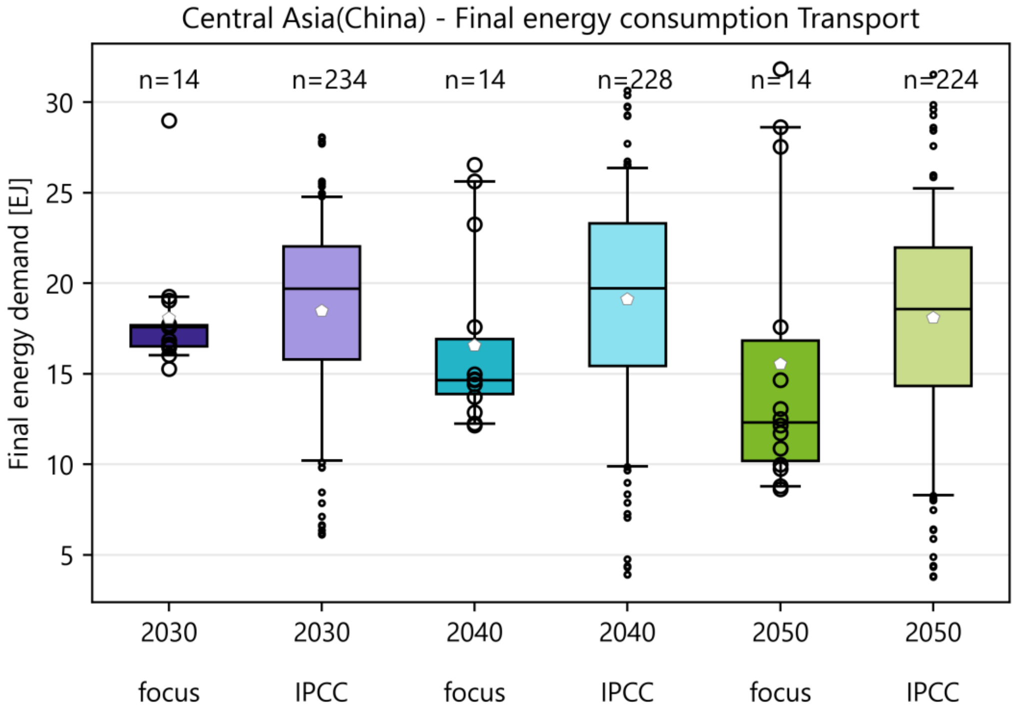

Figure 53: Central Asia - Transport - Final energy consumption

Figure 53 shows that the FEC in the transport sector remains relatively stable from 2030 till 2050 in the IPCC scenarios. In the focus the bandwidth increases over time. Generally speaking, the IPCC scenarios show a higher FEC in the transport sector than the focus scenarios for all years. In the focus scenarios the FEC in the transport sector decreases from 17-18 EJ in 2030 to 10-17 EJ in 2050. The consumption is reduced through more efficient vehicles (e.g. highly efficient hybrid, plug-in hybrid and battery-electric power trains) and higher use of public transport like rail, light rail and buses, especially in the expanding large metropolitan areas. Most IPCC scenarios show less fluctuation than the focus scenarios and result 14 - 22 EJ in 2050.

Besides the average focus scenarios, the BP Netzero reports the highest FEC in transport sector of 32 EJ, while the lowest FEC of 7 EJ is predicted in the GECO2021 1.5C Diff scenario. An even lower FEC of 4 EJ is foreseen within the IPCC scenarios.

5.3.4.2 Central Asia - Transport - Hydrogen demand

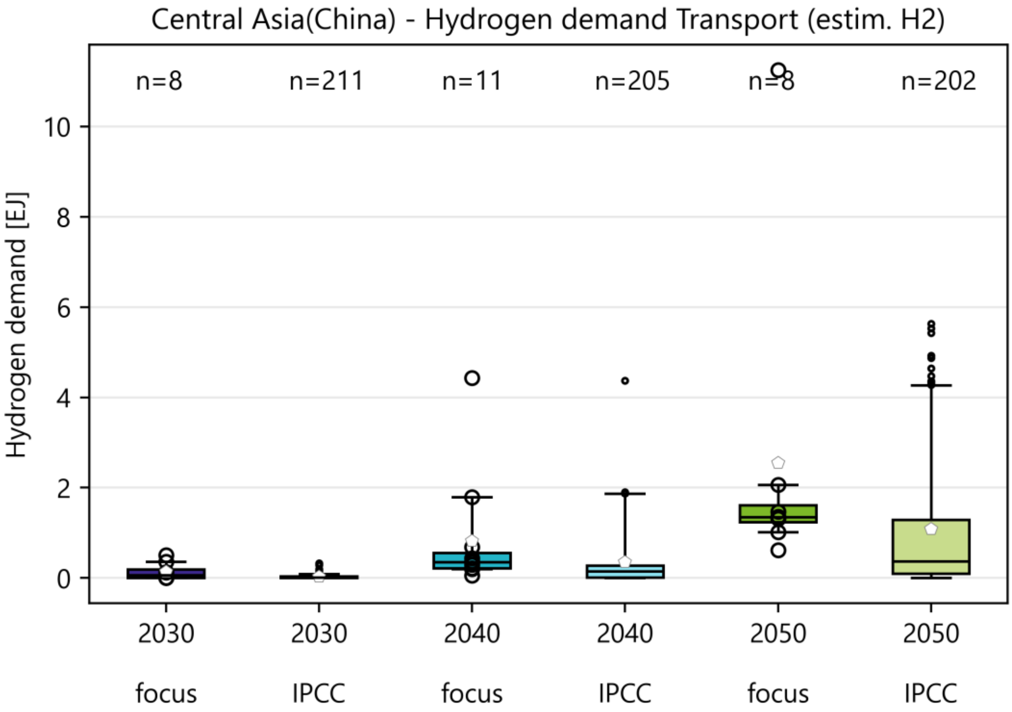

Figure 54: Central Asia - Transport - Hydrogen demand

Hydrogen demand in the transport sector increases the most and shows the smallest range in comparison to the other sectors in China. As shown in Figure 54, most of the IPCC scenarios show a lower hydrogen demand than most of the focus scenarios. In 2030, the hydrogen demand in the transport sector ranges from 0.003 EJ to 0.2 EJ according to most focus scenarios, increases to 1.2-1.6 EJ in 2050. Many studies expect renewable hydrogen and other renewable synthetic fuels to be complementary options to further increase the renewable share in the transport sector.

The EWG LUT scenario by the Energy Watch Group and the LUT University (2019) reports a hydrogen demand in transport sector in 2050 of 11 EJ, which is much higher than the reported range over most scenarios. The EWG LUT scenario considers a different geographical coverage in comparison to other studies and models the decarbonisation in Northeast Asia instead of China. Although hydrogen is expected to play an important role in the transport sector in China, 15 IPCC scenarios do not expect any hydrogen demand in this sector.

5.3.4.3 Central Asia - Transport - Share of hydrogen

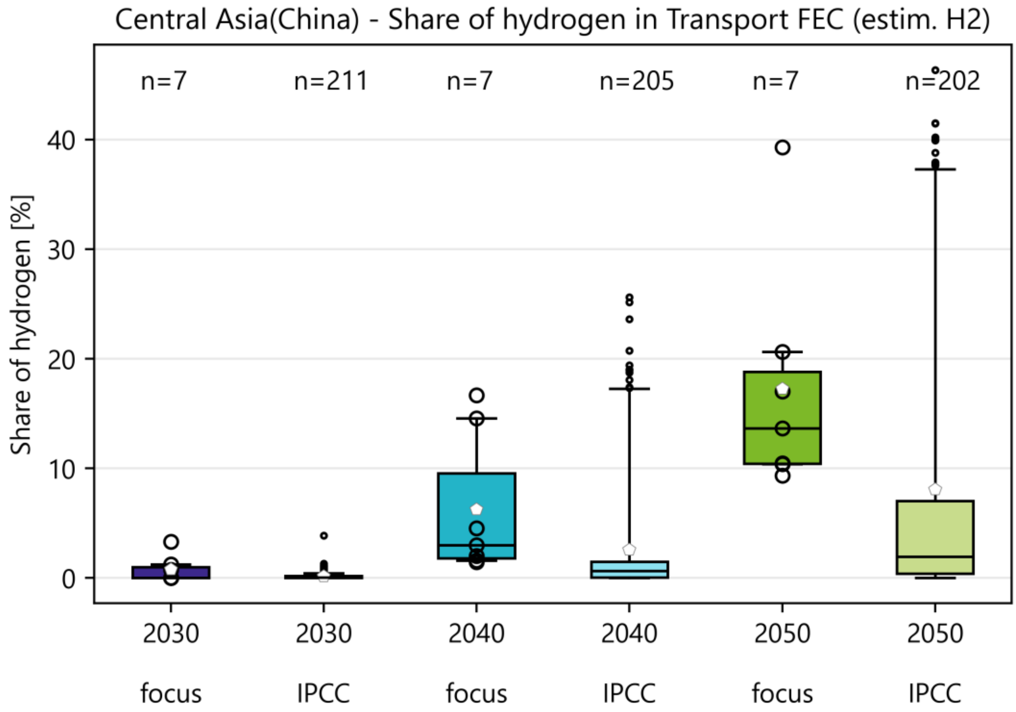

Figure 55: Central Asia - Transport - Share of hydrogen

Because of the decreasing FEC and the increasing hydrogen demand in the transport sector in China, the share of hydrogen in the transport sector increases over the analysed period and shows a very small bandwidth (Figure 55). In comparison to the other sectors, the share of hydrogen in the transport sector is relatively high. The inner bandwidth of the focus scenarios shows a share of hydrogen between 0.02% and 1% in 2030, and between 10% and 19% in 2050. The hydrogen share in the IPCC scenarios is mostly lower than in the focus scenarios and ranges from 0.4% to 7% in 2050.

In 2050, the highest share among focus scenarios of 39% is predicted by the EWG LUT scenario, which also reports the highest absolute hydrogen demand. Among the IPCC scenarios, the highest share goes up to 46%. On the contrary, the lowest shares of 9% and 0% in 2050 are projected by the GECO2020 1.5°C scenario, and the 15 IPCC scenarios, respectively, which do not foresee any hydrogen demand in the transport sector.

5.3.4.4 Central Asia - Transport - Consideration of international bunkers

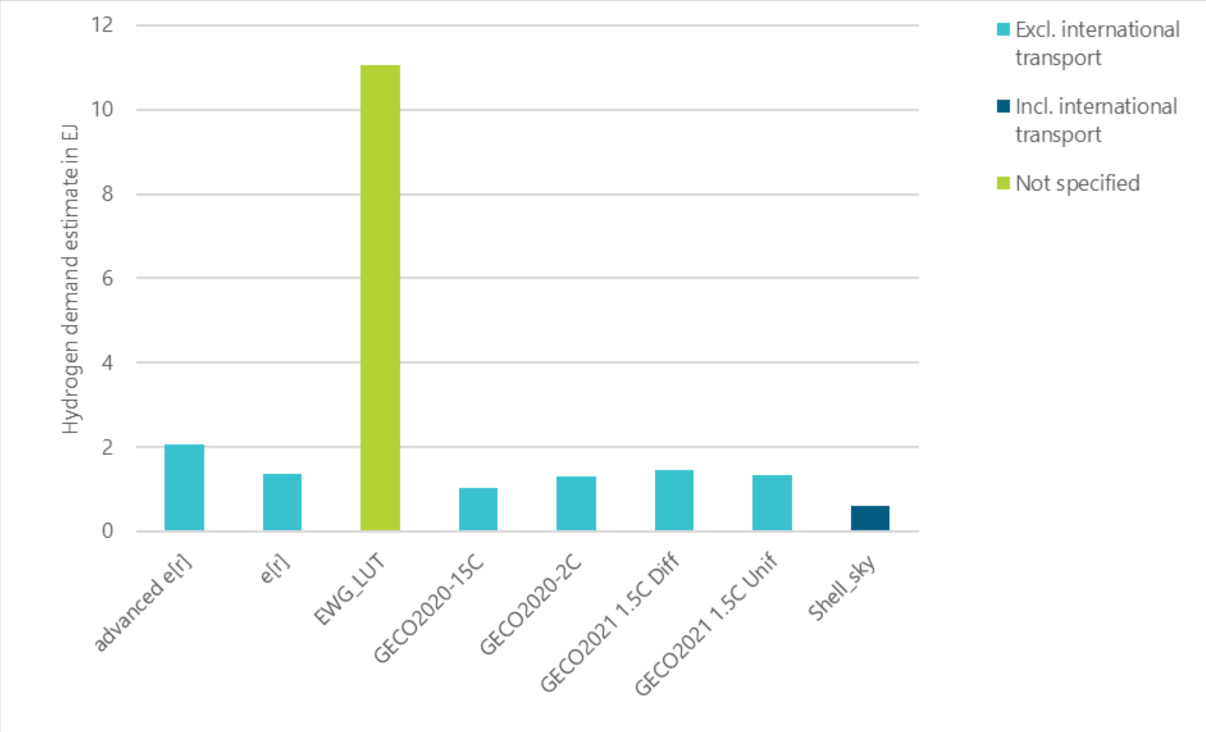

Figure 56: Central Asia - Transport - Consideration of international bunkers in 2050

Figure 56 shows an overview of hydrogen demand in the transport sector in China. Most of the focus studies on China do not consider international transport, while EWG LUT and Shell_sky scenarios distinguish the demand between passenger and freight transport without specifying if international transport is considered. Furthermore, the EWG LUT scenario covers a larger geographical scope than the other scenarios. Therefore, the EWG LUT scenario results the highest hydrogen demand of all, while the other scenarios expect a hydrogen demand in a similar range.

5.3.5 Central Asia - Summary of sectoral demand

5.3.5.1 Central Asia - Summary of sectoral demand - share of hydrogen

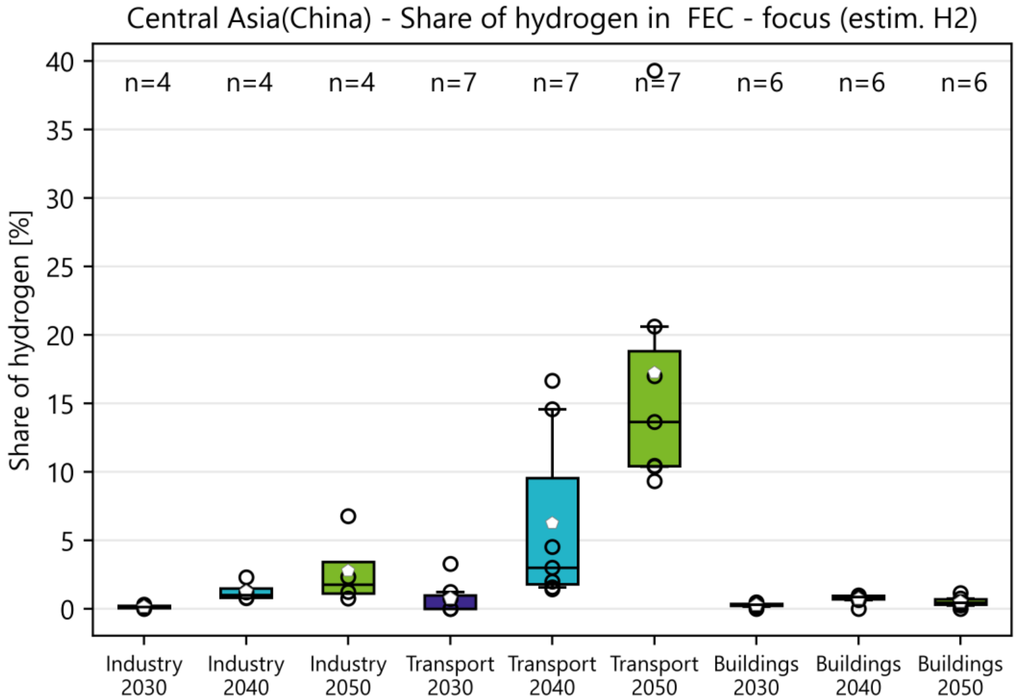

Figure 57: Central Asia - Summary of sectoral demand - share of hydrogen

The sectoral shares of hydrogen in China are shown in Figure 57, which highlights a clear priority of hydrogen applications in the transport sector. The transport sector has by far the highest projections of hydrogen demand, greatly outweighing the building and industry sector, with shares ranging from 9% to 39% of FEC. The sector is also characterised by a large range between median and outlier values. In the industry sector, which has the second highest hydrogen share, the maximum share in 2050 reaches 7%. In the building sector, hydrogen hardly plays a role and reaches less than 1%.

5.3.5.2 Central Asia - Summary of sectoral demand - absolute hydrogen demand

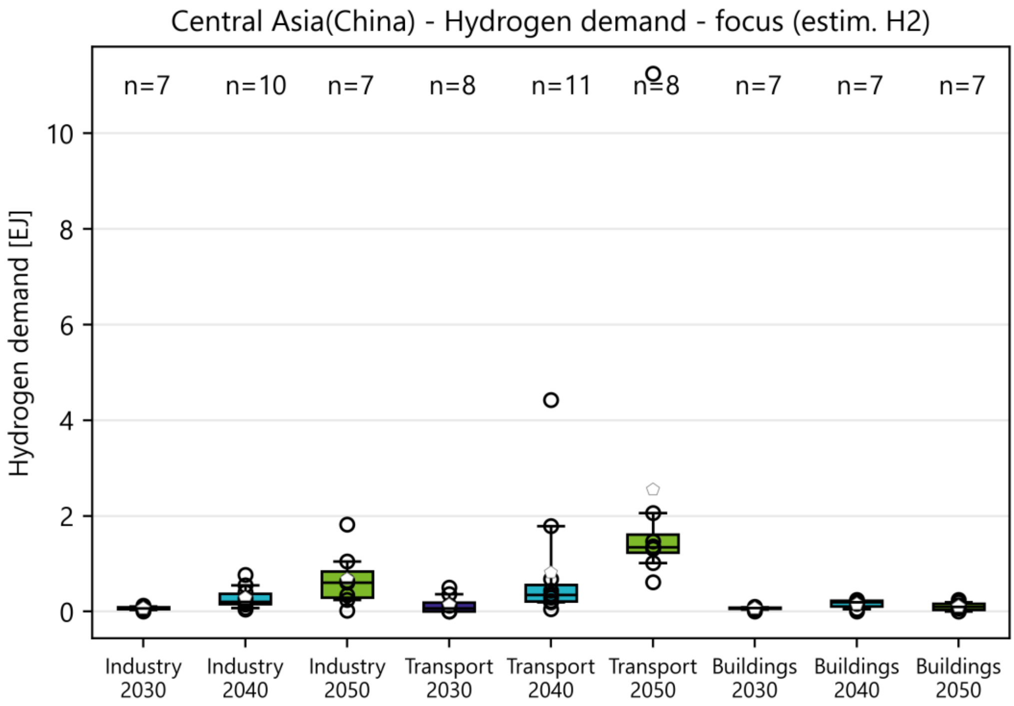

Figure 58: Central Asia - Summary of sectoral demand - absolute hydrogen demand

The sectoral demand of hydrogen in China is shown in Figure 58. This figure can be read in conjunction with Figure 57, but shows the absolute values of hydrogen demand. Equally to the share of hydrogen in energy demand, absolute numbers are highest in transport, followed by the demand in industry. The building sector is considerably smaller than for the other two sector and more certain, indicated by the small range of values. The maximum values are given by the same scenarios as for the share of hydrogen.

5.4 Regional differences

In the following, the regional differences amongst the sectors are highlighted by comparing the mean, median, lower and upper quartile of the hydrogen share in the sectoral FEC in 2050. Apart from that, those values are compared between the focus and IPCC scenarios.

5.4.1 Industry Sector

Table 9 shows the hydrogen shares in industry FEC in 2050 among the World, Europe (EU28) and Central Asia (China) in the focus and IPCC scenarios. In the focus scenarios, the inner bandwidths of the hydrogen shares vary between 1.5-8.5% globally, 2.6-15.9% for the EU28, and 1.1-3.5% for China. The inner bandwidths of hydrogen shares from the IPCC scenarios range between 0.5-4.9% globally, 0-4.9% for the EU28, and 0-3.2 % for China. According to the mean values, the focus scenarios show that the hydrogen shares for the EU28 are higher than for the global and Chinese average. This finding needs to be viewed critically, since the hydrogen share in the focus studies for the EU28 shows a large bandwidth, which can be interpreted as a relatively high insecurity. On the contrary, the median values are on a comparable level for all three regions across all scenarios (1.8-4.1%) and Europe taking the higher median in the focus (3.8%) and IPCC scenarios (4.1%). Likewise, the region-specific mean and median values are close together in the IPCC scenarios, meaning that few outliers are generated, while median and mean values differentiate more in the focus scenarios and especially for Europe. To sum up, all scenarios show higher hydrogen shares for EU28 (2.7-10.5% mean, 3.8-4.1% median) and lower shares for China (1.9-2.8% mean, 1.8-2.0% median) in comparison to the global average (3.3-7.0% mean, 2.9%-3.0 median), while overall projection certainty is higher in the IPCC scenarios then in the focus scenarios, and a high projection uncertainty is seen in EU28 in the focus scenarios.

Table 9: Hydrogen share in industry FEC in 2050, for World, EU28, and China within the focus and IPCC scenarios

	Focus scenarios			IPCC scenarios		
In %	Central Asia (China)	Europe (EU28)	World	Central Asia (China)	Europe (EU28)	World
Mean	2.8	10.5	7.0	1.9	2.7	3.3
Median	1.8	3.8	3.0	2.0	4.1	2.9
Lower quartile	1.1	2.6	1.5	0.0	0.0	0.5
Upper quartile	3.5	15.9	8.5	3.2	4.9	4.9

5.4.2 Building Sector

The findings for hydrogen shares in the building sector for the global, EU28 and Chinese assessment are at a very low level within the focus and IPCC scenarios (0.5–1.7% mean value, see Table 10).

The mean hydrogen share in the building sector in the EU28 is slightly higher compared to the global or Chinese mean value for the focus and IPCC scenarios. The median, on the other hand, is in the IPCC scenarios (0%) for all three regions lower than in the focus scenarios (0.5-1.7%). The mean and median value are very close within China (0.5% mean, 0.5% median) and World (1.6% mean, 1.7% median) in the focus scenarios, resulting in a low number of outliers and high consistency amongst the focus studies. For the IPCC scenarios, mean (0.5-0.6%) and median (0%) deviate for all three regions by 0.5-0.6%, resulting in a noticeable amount of outliers. In summary, all three selected regions show a rather low hydrogen share in buildings with a low bandwidth, indicating a relatively high consistency among the studies, and therefore, a limited contribution of hydrogen in the building sector.

Table 10: Hydrogen share in building FEC in 2050, for World, EU28, and China within the focus and IPCC scenarios

	Focus scenarios			IPCC scenarios		
In %	**Central Asia (China)**	**Europe (EU28)**	**World**	**Central Asia (China)**	**Europe (EU28)**	**World**
Mean	0.5	1.7	1.6	0.5	0.6	0.5
Median	0.5	0.6	1.7	0.0	0.0	0.0
Lower quartile	0.3	0.0	0.9	0.0	0.0	0.0
Upper quartile	0.7	2.9	2.2	0.1	0.2	0.3

5.4.3 Transport Sector

Transportation demands the highest hydrogen shares across all sectors. In all regions, hydrogen demand shares in transport are substantially lower in the IPCC scenarios than in the focus scenarios (see Table 11). While China and World are on a comparable median share and inner bandwidth in the focus studies, Europe projects a substantially larger role for hydrogen in transport, which is also characterised by a higher uncertainty. In comparison, the differences between regions are less pronounced in the IPCC scenarios. Here, China and Europe are on a more comparable level for median and inner bandwidth, while the global assessment predicts lower values. While EU28 shows the highest median value in the IPCC scenarios, the mean value is highest for China. The Chinese and global assessment show a mediocre bandwidth, depicting a hydrogen application uncertainty in the transport sector that is not negligible. All in all, the IPCC scenarios show generally lower hydrogen shares and a higher prediction uncertainty compared to the focus scenarios.

Table 11: Hydrogen share in transport FEC in 2050, for World, EU28, and China within the focus and IPCC scenarios

	Focus scenarios			IPCC scenarios		
In %	**Central Asia (China)**	**Europe (EU28)**	**World**	**Central Asia (China)**	**Europe (EU28)**	**World**
Mean	17.3	26.6	16.7	8.1	6.5	3.8
Median	13.7	27.6	15.9	1.9	4.8	1.1
Lower quartile	10.4	12.9	9.5	0.4	1.2	0.0
Upper quartile	18.8	36.3	19.0	7.0	7.1	4.4

5.4.4 Summary of regional differences

For the regions China, EU28 and World, most scenarios show a positive correlation between the share of hydrogen demand in final energy consumption and the GHG emission reductions.

Overall

Overall, Europe has a higher mean hydrogen share than the global and Chinese results, and the larger interquartile range indicates higher uncertainty of demand projections in 2050. The range for China is substantially smaller. Overall, the study sample for China is smaller (approx. 11 scenarios) than for Europe (approx. 21 scenarios). The median share for Europe and the World is on a comparable level, and smaller for China.

Transport

In all regions, the transport sector has the largest share of hydrogen in total energy demand and the largest absolute hydrogen demand. In Europe, the median hydrogen share in transport energy is considerably higher than in the other studies in 2050. The transport sector is also the sector with the largest inner bandwidth of hydrogen demand, which is again the largest in Europe. This shows that there is a substantial uncertainty regarding the use of hydrogen in this sector. On the other hand, in China and World, there is a minimum share projected for 2050 that lies above the median use in other sectors.

Across all regions and all scenarios, the transport sector shows the highest hydrogen demand shares in FEC but underlying the highest projection uncertainties:

- 8.1-17.3%[9] mean for China,
- 6.5-26.5% for EU28, and
- 3.8-16.7% for World.

The IPCC scenarios show generally lower hydrogen shares and a higher prediction uncertainty compared to the focus scenarios.

Buildings

In the building sector, the role of hydrogen is considerably smaller than in the other sectors across regions. It is the sector with the smallest bandwidth, indicating that the projections for using hydrogen in building heat are similar between studies and therefore relatively robust.

Fewest hydrogen application potential and highest projection certainty is seen in the building sector:

- 0.5% mean for China,
- 0.6-1.7% for EU28, and
- 0.5-1.6% for World.

9 Range depicts the mean comparison within a sector between the focus and IPCC scenarios.

All three selected regions show a rather low hydrogen share in buildings with a low bandwidth, indicating a relatively high consistency among the studies, and therefore, a limited contribution of hydrogen in the building sector.

Industry

In the industry sector, hydrogen is often termed a "no regret" strategy, as there are applications with no alternative decarbonisation options. However, the demand projections for industry are lower than for transport. "No regret" however usually targets the non-energy uses for hydrogen. Hydrogen used for industry heat is considered to be more uncertain, as there are potential alternatives for high-temperature heat available, which is mirrored in the studies projections. On top of that, the data structure in the industry sector is inconsistent between studies, since some studies consider refineries under the industrial sector, while others group it under the transformation sector. Regional differences are also visible in this sector: While the median hydrogen share in industry energy is comparable between global, European and Chinese outlooks, the bandwidths of demand projections is again the highest for Europe.

Industry has the second biggest demand shares and high projection certainty for China:

- 1.9-2.8% mean for China,
- 2.7-10.5% for EU28, and
- 3.3-7.0% for World.

All scenarios show higher hydrogen shares for EU28 (2.7-10.5% mean, 3.8-4.1% median) and lower shares for China (1.9-2.8% mean, 1.8-2.0% median) in comparison to the global average (3.3-7.0% mean, 2.9%-3.0 median), while overall projection certainty is higher in the IPCC scenarios than in the focus scenarios, and a high projection uncertainty is seen in EU28 in the focus scenarios.

All in all, the IPCC scenarios show a higher uncertainty in the hydrogen demand projections for buildings and transport, while the focus studies show the highest uncertainty for the industry sector, when comparing the mean to the median value.

6 Discussion of hydrogen demand ranges

A high number of energy system scenarios modelling hydrogen demand in the future have been published recently. The various and often deviating projections lead to uncertainty about the size and characteristics of a future hydrogen market, which in turn hinders hydrogen investments on the supply side, transport infrastructure, and demand side applications. This working paper provides an overview of the bandwidth of hydrogen demand found in different scenarios and conducts a first analysis of the underlying differences in the studies. In this section, conclusions will be summarised and briefly discussed to provide a foundation for future in-depth analyses of hydrogen demand drivers and barriers.

6.1 Influencing factors in energy system models

6.1.1 Influence of climate change mitigation ambition

Our observations show that increasing emission reduction ambitions correlate with lower total energy consumption. This trend is strong for the European and Chinese studies. From the global perspective, the trend is still visible but weaker. Furthermore, it can be concluded that an increased hydrogen demand correlates with increased emission reduction ambitions for all regions. The IPCC scenarios have a high variation in hydrogen shares in the final energy consumption, but it can nevertheless be observed that for nearly all emission reductions beyond 80%, the hydrogen share is non-zero. Hydrogen demand therefore strongly depends on climate policy ambition.

6.1.2 Influence of total final energy consumption

The total projected energy demand varies substantially between studies. Mostly, these variations are caused by differences in climate change mitigation ambition, such as energy efficiency (also including circular economy assumptions) or sufficiency measures, which are used as decarbonisation levers or not. Therefore, this working paper focuses on scenarios with high mitigation ambition. But even among these comparable scenarios, a large bandwidth in total energy demand projections has been found (e.g. EWG LUT is a very ambitious scenario with high total energy consumption). These differences in total energy demand projections can be caused by differing assumptions on GDP, population, or mobility trends, and national differences on already existing infrastructure.

If a model optimises the energy system based on cost efficiencies, the assumed hydrogen price influences how hydrogen can compete against other decarbonisation options. The hydrogen price itself is linked to electricity or fossil fuel prices (e.g. natural gas) and indirectly to the CO_2-price, depending on the hydrogen production process. In addition, assumptions on capital expenditure cost reduction, e.g. for electrolysers, are an influencing factor for hydrogen uptake. Not all of the assumptions are reported transparently, which makes a more precise comparison on this level complex.

The inner bandwidth of focus scenarios is more optimistic on energy demand reductions compared to the IPCC scenarios. While differences in total energy demand can be the cause of the bandwidth in hydrogen demand, it has been observed that this is not true for all studies. For example, studies with comparable levels of total energy demand have been found to have high variations in hydrogen estimates (e.g. FCH-H_2Road compared to the GECO scenarios). The relationship of hydrogen demand and total final energy consumption is worth a more detailed analysis.

6.1.3 Influence of the sector scope in studies

A key difference between studies with a potentially high influence on hydrogen demand projections is the sector scope. This concerns particularly the modelling of the transport sector with or without international aviation and shipping, consideration of refineries, or the transformation sector in general, and the industry sector with or without non-energy demand. For both the transport and the industry sector, however, it has been observed that not all differences in demand can be explained through the sector scope, as also studies without international transport demand can have larger hydrogen projections then studies with it. Likewise, studies not modelling feedstocks can project higher hydrogen demand than studies which model energy and non-energy demand.

Another difference is the modelling of the transformation sector demand. For example, some studies model the demand for hydrogen in refineries or synfuel production separately in the transformation sector demand, while other studies allocate this demand either to the transport sector (e.g. when ammonia or methanol are used as transport fuels) or the industry sector. These different approaches can have an influence on the magnitude of hydrogen demand in the respective sectors.

6.1.4 Influence of competing technologies

Hanley et al. (2018) review hydrogen use in integrated energy system models and found that barriers to hydrogen use can be substitution technologies such as large biomass potential and direct electrification measures. This observation has also been made in a first evaluation in this working paper. Direct comparison of studies with a similar scope revealed that the results usually differed in this regard: lower hydrogen demand is usually compensated by higher use of bioenergy and electricity. Where electrification reaches its limits (e.g. in long-distance aviation or shipping), hydrogen competes mostly with biofuels, but also with fossil fuels, if negative emission technologies (e.g. direct air capture (DAC) or bioenergy + CCS (BECCS)) enable to share emission burdens between sectors. Hydrogen is often used when bioenergy potentials reach their limit (e.g. Greenpeace), and these limits depend on the applied sustainability criteria in the study. For example, the Hydrogen for Europe study performs a sensitivity study where the biofuel potential is increased, which leads to greater use of oil due to negative emissions coming from the increase of BECCs. Bioenergy then also plays a greater role in hydrogen production, but it is observed that the uptake of hydrogen is slower with higher use of BECCS.

However, the relationship between hydrogen and these substitutional technologies can be ambivalent. Availability of CCS can replace the need for hydrogen, while it can also enable the use of blue hydrogen. Bioenergy can likewise replace hydrogen, e.g. as a fuel in the transport sector, while its availability also enables the production of renewable hydrogen from biogenic sources. High renewable electricity availability can trigger direct electrification, while it can also push green hydrogen production. Competing technologies are hence also linked to available hydrogen production pathways, which can also differ between studies. Depending on which production methods are considered eligible in decarbonised energy systems, the hydrogen demand varies.

6.2 Sectoral and regional differences on hydrogen demand

Energy system transformation is specific for every country. To save investment costs, relying on already existing infrastructure (e.g. extended power grid, pipelines heat grid, natural gas grid for repurposement) can be a viable option. This has an influence on the chosen decarbonisation options and thereby on the role of hydrogen. On the other hand, national or regional ambitions in taking the technological lead in hydrogen technology can influence the speed of hydrogen infrastructure development and hence the role of hydrogen in the energy system. To summarise how Europe and China compare to each other and the global results, this section discusses how the share of hydrogen in the overall, European and Chinese energy demand differs overall and for the three end-use sectors.

Across all regions and all scenarios, the **transport sector** shows the highest hydrogen demand shares in FEC but underlying the highest projection uncertainties:

- 8.1-17.3%[10] mean for China,
- 6.5-26.5% for EU28, and
- 3.8-16.7% for World.

Industry has the second biggest demand shares and high projection certainty for China:

- 1.9-2.8% mean for China,
- 2.7-10.5% for EU28, and
- 3.3-7.0% for World.

Fewest hydrogen application potential and highest projection certainty is seen in the **building sector**:

- 0.5% mean for China,
- 0.6-1.7% for EU28, and
- 0.5-1.6% for World.

Interestingly, the IPCC scenarios show a higher uncertainty in the hydrogen demand projections for buildings and transport, while the focus studies show the highest uncertainty for the industry sector, when comparing the mean to the median value.

An in-depth assessment on drivers behind the hydrogen demand and the underlying assumptions has not been within the scope of this study. The range of results, especially for the transport and industry sector, show how important it is to assess every region individually, as even municipalities within a country might show completely different ambitions, characteristics and existing infrastructures. Hence, it is necessary to study the assumptions that

[10] Range depicts the mean comparison within a sector between the focus and IPCC scenarios.

have been made for each scenario individually, to understand hydrogen demand calculations and the resulting hydrogen demand share range.

6.3 Influence on study type

It has been found that the maximum hydrogen demand projections across sectors are usually caused by the same studies. E.g., for Europe, the Hydrogen Roadmap from the Fuel Cell and Hydrogen Joint Undertaking (FCHJU) and the Hydrogen for Europe study showed the highest hydrogen demand. For the global studies, the Hydrogen for Net Zero study by the Hydrogen Council and IRENA 1.5 leads the sector predictions.

Generally, the maximum demand projections for all sectors are driven by dedicated hydrogen studies. These studies focus on the role of hydrogen. They tend to include hydrogen for refineries and for reverse power generation, and do not necessarily model the energy system as a whole. However, especially for hydrogen, system-interactions between technologies and sectors are vital. Compared to other focus and IPCC scenarios, it can be inferred that some of these very high predictions are potentially overestimating the demand for hydrogen.

For example, when comparing the focus study results to the IPCC, it can be observed that for most regions and sectors in 2050, the focus studies have a higher mean hydrogen demand and a larger interquartile range. Many of the upper band hydrogen demand projections of the focus studies would be classified as outliers in the IPCC range.

In any case, hydrogen demand estimations should be interpreted with a consideration of the studies' assumptions on alternative decarbonisation measures, such as energy efficiency, electrification, bioenergy and CCS.

7 Conclusions

The following conclusions can be drawn from the analysis of the various scenarios for the development of hydrogen and synthesis product demand.

1 **Hydrogen is needed to reach climate neutrality.** When reaching a threshold of 80% GHG reductions compared to 1990, use of hydrogen becomes unavoidable. The main driver for climate neutrality remains a drastic decrease in final energy consumption by energy efficiency measures and direct electrification.

- Hydrogen and derived synthesis products will become significantly more relevant in the future.
- This is especially seen in scenarios where very ambitious climate protection targets must be achieved (over 80% in 2050 compared to 1990).

2 **Hydrogen will become an important but not dominant energy carrier in the future.** Globally, hydrogen reaches in average 4-11% of the final energy consumption in 2050. In Europe, the relevance of hydrogen is higher compared to the energy consumption in China or worldwide. Hydrogen will play an important role in industry and transport but a minor role in the buildings sector.

- Based on the interquartile range, hydrogen will be able to reach between 4 and 11% of the final energy consumption worldwide in 2050.
- Hydrogen will thus become an important energy carrier, but it will not be the dominant one. Electrification and energy efficiency measures are usually the dominant emission mitigation levers.
- There are regional differences. Greater importance is attached to the use of hydrogen in the EU than in China.
- In the transport sector, most studies show the highest demand for hydrogen in absolute and relative terms.
- In almost all studies, the hydrogen use in buildings is limited.

3

The large range in hydrogen demand indicates a high uncertainty in the ramp of hydrogen markets, hindering investments into hydrogen production, transport, and usage. On the one hand, hydrogen demand is reported inconsistently between studies and more optimistically in dedicated hydrogen studies. On the other hand, hydrogen partially competes with direct electrification and biomass, and a ramp up is country-specific, as it relies on national climate neutrality ambitions and already existing infrastructures. The uncertainty of projections increases over time, as hydrogen demand has the highest bandwidth in 2050 except for the building sector.

- The high range of results further shows that there are still considerable uncertainties.
- These are partly due to the fact that some of the scenarios do not include material (non-energy) use of hydrogen and synthetic fuels, and international aviation and shipping.
- There are also some significant differences in the potential application areas for hydrogen, where substitution technologies exist, such as biomass and CCS potentials or electrification of heating and heavy-duty transport.
- The range of results is highest in the transport sector, since the potential role of hydrogen in cars and trucks is assessed very differently.
- The use of hydrogen as a feedstock in industry, if included, has great potential and is relevant in nearly all studies. The energetic use in industry especially for high temperature applications is evaluated inconsistently, indicated by the larger bandwidth.
- Hydrogen therefore plays a relevant role in areas of application, where other technologies are technically or economically not feasible.
- Targeted policies will be necessary to trigger an efficient use of hydrogen across sectors.

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The sources for all evaluated scenarios are provided in Annex A.1.1 and A.1.2.

List of figures

Figure 1: Structure of the boxplot to show the distribution of the data 20
Figure 2: World - Total demand - Final energy consumption 26
Figure 3: World - Total demand - Final energy demand and GHG emissions 27
Figure 4: World - Total demand - Hydrogen demand 28
Figure 5: World - Total demand - Share of hydrogen 29
Figure 6: World - Total demand - Hydrogen demand and GHG emissions 30
Figure 7: World - total demand - indirect hydrogen demand in 2050 31
Figure 8: World - Industry - final energy consumption 32
Figure 9: World - Industry - Hydrogen demand 33
Figure 10: World - Industry - Share of hydrogen 34
Figure 11: World - Industry - Consideration of feedstock demand in 2050 35
Figure 12: World - Buildings - Final energy consumption 36
Figure 13: World - Buildings - Hydrogen demand 37
Figure 14: World - Buildings - Share of hydrogen 38
Figure 15: World - Transport - Final energy demand 39
Figure 16: World - Transport - Hydrogen demand 40
Figure 17: World - Transport - Share of hydrogen 41
Figure 18: World - Transport - Consideration of international bunkers in 2050 42
Figure 19: World - Summary of sectoral demand - share of hydrogen 43
Figure 20: World - Summary of sectoral demand - absolute hydrogen demand 44
Figure 21: Europe - Total demand - Final energy consumption 45
Figure 22: Europe - Total demand - Final energy demand and GHG emissions 46
Figure 23: Europe - Total demand - Hydrogen demand 47
Figure 24: Europe - Total demand - Share of hydrogen 48
Figure 25: Europe - Total demand - Hydrogen demand and GHG emissions 49
Figure 26: Europe - Total demand - Indirect hydrogen demand in 2050 50
Figure 27: Europe - Industry - Final energy consumption 51
Figure 28: Europe - Industry - Hydrogen demand 52
Figure 29: Europe - Industry - Share of hydrogen 53
Figure 30: Europe - Industry - Consideration of feedstock demand in 2050 54
Figure 31: Europe - Buildings - Final energy consumption 55
Figure 32: Europe - Buildings - Hydrogen demand 56
Figure 33: Europe - Buildings - Share of hydrogen 57
Figure 34: Europe - Transport - Final energy consumption 58
Figure 35: Europe - Transport - Hydrogen demand 59
Figure 36: Europe - Transport - Share of hydrogen demand 60

Figure 37: Europe - Transport - Consideration of international bunkers in 2050 ... 61
Figure 38: Europe - Summary of sectoral demand - share of hydrogen ... 62
Figure 39: Europe - Summary of sectoral demand - absolute hydrogen demand ... 63
Figure 40: Central Asia - Total demand - Final energy consumption ... 64
Figure 41: Central Asia - Total demand - Final energy demand and GHG emissions ... 65
Figure 42: Central Asia - Total demand - Hydrogen demand ... 66
Figure 43: Central Asia - Total demand - Share of hydrogen ... 67
Figure 44: Central Asia - Total demand - Hydrogen demand and GHG emissions ... 68
Figure 45: Central Asia - Total demand - Indirect hydrogen demand in 2050 ... 69
Figure 46: Central Asia - Industry - Final energy consumption ... 70
Figure 47: Central Asia - Industry - Hydrogen demand ... 71
Figure 48: Central Asia - Industry - Share of hydrogen ... 72
Figure 49: Central Asia - Industry - Consideration of feedstocks in 2050 ... 73
Figure 50: Central Asia - Buildings - Final energy consumption ... 74
Figure 51: Central Asia - Buildings - Hydrogen demand ... 75
Figure 52: Central Asia - Buildings - Share of hydrogen ... 76
Figure 53: Central Asia - Transport - Final energy consumption ... 77
Figure 54: Central Asia - Transport - Hydrogen demand ... 78
Figure 55: Central Asia - Transport - Share of hydrogen ... 79
Figure 56: Central Asia - Transport - Consideration of international bunkers in 2050 ... 80
Figure 57: Central Asia - Summary of sectoral demand - share of hydrogen ... 81
Figure 58: Central Asia - Summary of sectoral demand - absolute hydrogen demand ... 82

List of tables

Table 1: Scenario selection parameters ... 15
Table 2: List of focus scenarios ... 16
Table 3: Selection of IPCC scenarios ... 17
Table 4: Overview of different synfuel types based on reported synthetic fuels in focus studies ... 19
Table 5: Overview of data presented in this paper for World, Europe and China ... 19
Table 6: Allocation of regions and countries from the focus studies to the IPCC R 10 ... 21
Table 7: Assumptions influencing industry hydrogen demand in two global focus scenarios ... 35
Table 8: Assumptions influencing transport hydrogen demand in two global focus scenarios ... 42
Table 9: Hydrogen share in industry FEC in 2050, for World, EU28, and China within the focus and IPCC scenarios ... 83
Table 10: Hydrogen share in building FEC in 2050, for World, EU28, and China within the focus and IPCC scenarios ... 84
Table 11: Hydrogen share in transport FEC in 2050, for World, EU28, and China within the focus and IPCC scenarios ... 84
Table 12: Analysed scenarios and their sources. All scenarios for which the publisher is not IPCC are focus studies in the sense of this study ... 98
Table 13: IPCC scenarios used in this analysis ... 101

Abbreviations

BECC	Bioenergy with Carbon Capture
BEV	Battery electric vehicles
CCS	Carbon Capture and Storage
CCUS	Carbon capture, utilisation and storage
DACC	Direct Air Carbon Capture
EJ	Exajoule
ECF	European Climate Foundation
FEC	Final energy consumption
FCEV	Fuel Cell Electric Vehicles
GECO	Global Energy and Climate Outlook
GHG	Greenhouse gas
Gt	Gigaton
FCHJU	Fuel Cell and Hydrogen Joint Undertaking
ICE	Internal combustion engines
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center
kg	Kilogram
MJ	Megajoule
NDC	Nationally Determined Contributions
PV	Photovoltaics
PWh	Petawatt hour
SMR	Steam Methane Reforming
THG	Treibhausgas
TWh	Terawatt hour
WEC	World Energy Council

A.1 Annex

A.1.1 List of focus scenarios

Table 12: Analysed scenarios and their sources. All scenarios for which the publisher is not IPCC are focus studies in the sense of this study

	Publisher	Study	Year	Scenario	Scenario shorthand	Link
1	Agora	No-regret hydrogen	2021	Blue-Green	AG No-regret	A-EW_203_No-regret-hydrogen_WEB.pdf (agora-energiewende.de)
2	British Petroleum (BP)	Energy Outlook 2020	2020	Rapid	BP_Rapid	https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2020.pdf
3				Net Zero	BP_Netzero	
4	The Economic Research Institute for ASEAN and East Asia	Energy Outlook and Energy Saving Potential in East Asia 2020	2020	Alternative policy scenario	EastAsia_EO_APS	https://www.eria.org/publications/energy-outlook-and-energy-saving-potential-in-east-asia-2020/
5	Energy Watch Group (EWG)	GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY - Power, Heat, Transport and Desalination Sectors	2019	Best Policy Scenario	EWG_LUT	https://www.researchgate.net/publication/320934766_Global_Energy_System_based_on_100_Renewable_Energy_-_Power_Sector
6	ERIA	Demand and Supply Potential of Hydrogen Energy in East Asia	2018	Scenario 1	ERIA_Sc_1	https://www.researchgate.net/publication/335202604_Demand_and_Supply_Potential_of_Hydrogen_Energy_in_East_Asia
7				Scenario 2	ERIA_Sc_2	
8				Scenario 3	ERIA_Sc_3	
9	European Climate Foundation	Net Zero by 2050: From Whether to How	2018	Technology	ECF T	https://europeanclimate.org/wp-content/uploads/2018/09/NZ2050-from-whether-to-how.pdf
10				Demand-focus	ECF D	
11				Shared effort	ECF S	
12	European Commission	A clean planet for all. Long Term Strategic Vision	2018	1.5 C Technical	EC 1.5 T	https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en
13				1.5 C Lifestyles	EC 1.5 L	
14		Policy scenarios for delivering the European Green Deal	2021	MIX	EC MIX	https://ec.europa.eu/energy/data-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en
15				MIX-H_2	EC MIX-H_2	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0557

	Publisher	Study	Year	Scenario	Scenario shorthand	Link
16	Greenpeace	Energy [R]Evolution	2015	Energy [r]evolution	e[r]	https://www.greenpeace.de/presse/publikationen/energy-revolution
17				Advanced energy [r]evolution	advanced e[r]	
18	Hydrogen Council	Net zero Hydrogen	2021		Council_NZH	https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf
19	International Energy Agency (IEA)	Energy Technology Perspectives 2017	2017	B2DS	IEA B2DS	https://iea.blob.core.windows.net/assets/a6587f9f-e56c-4b1d-96e4-5a4da78f12fa/Energy_Technology_Perspectives_2017-PDF.pdf
20		World Energy Outlook 2021	2020	Sustainable Development	IEA SD	https://www.iea.org/reports/world-energy-outlook-2021
21				Net Zero Emissions by 2050	IEA NZ	
22		Net Zero by 2050	2021	Net Zero by 2050	IEA NZ	https://www.iea.org/reports/net-zero-by-2050
23		Global Hydrogen Review	2021	Net Zero Emissions	IEA H_2 NZ	https://www.iea.org/reports/global-hydrogen-review-2021
24	International Renewable Energy Agency (IRENA)	World Energy Transitions Outlook	2021	1.5°C Scenario	IRENA 1.5_2022	https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_World_Energy_Transitions_Outlook_2022.pdf
25		A Pathway to Decarbonise the Shipping Sector by 2050	2021	IRENA 1.5°C Scenario (1.5-S)	IRENA 1.5	https://www.irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050
26	Joint Research Centre (JRC)	Global Energy and Climate Outlook 2020	2021	2°C	GECO2020-2C	https://publications.jrc.ec.europa.eu/repository/handle/JRC123203
27				1.5°C	GECO2020-15C	
28		Global Energy and Climate Outlook 2021	2022	Differentiated carbon price 1.5°C	GECO2021 1.5C Diff	https://data.jrc.ec.europa.eu/dataset/067e2ab2-d086-4f19-972e-5c46473f5efb#dataaccess
29				Undifferentiated carbon price 1.5°C	GECO2021 1.5C Unif	
30		Deployment Scenarios for Low Carbon Energy Technologies? Low Carbon Energy Observatory	2018	Diversified	JRC Diversified	https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112915/jrc112915_lceo_d4.7.pdf
31				ProRes	JRC ProRes	
32				Zero Carbon	JRC ZeroCarbon	
33	Navigant	Gas for Climate	2019	Minimal gas	NAV MinG	https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf
34				Optimised gas	NAV OptG	https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

	Publisher	Study	Year	Scenario	Scenario shorthand	Link
35	Öko-Institut	The Vision Scenario for the European Union	2015	Vision	Oeko Vision	https://www.oeko.de/publikationen/p-details/the-vision-scenario-for-the-european-union
36	Paris Agreement Compatible Scenarios for Energy Infra-structure	Building a Paris Agreement Compatible (PAC) energy scenario	2020	PAC Scenario	PAC	https://www.pac-scenarios.eu/scenario-development.html
37	Shell	Sky Scenario	2018	Sky Scenario	Shell_sky	https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html
38	World Energy Council (WEC)	World Energy Scenarios	2019	Modern Jazz	Modern Jazz	https://www.worldenergy.org/assets/downloads/2019_Scenarios_Full_Report.pdf Database: https://iiasa.ac.at/web/home/research/researchPrograms/Energy/IPCC_AR5_Database.html
39				Unfinished Symphony	Unfinished Symphony	
40		International Aspects of a power-to-x roadmap	2018	-	WEO_new_policies	https://www.weltenergierat.de/wp-content/uploads/2018/10/20181018_WEC_Germany_PTXroadmap_Full-study-englisch.pdf
41				Low	WEC_PTX_low	
42				Reference	WEC_PTX_reference	
43				High	WEC_PTX_high	

A.1.2 List of IPCC scenarios

For IPCC scenarios used in this analysis, the following table contains model name and scenario name.

Source:

Edward Byers, Volker Krey, Elmar Kriegler, Keywan Riahi, Roberto Schaeffer, Jarmo Kikstra, Robin Lamboll, Zebedee Nicholls, Marit Sanstad, Chris Smith, Kaj-Ivar van der Wijst, Franck Lecocq, Joana Portugal-Pereira, Yamina Saheb, Anders Strømann, Harald Winkler, Cornelia Auer, Elina Brutschin, Claire Lepault, Eduardo Müller-Casseres, Matthew Gidden, Daniel Huppmann, Peter Kolp, Giacomo Marangoni, Michaela Werning, Katherine Calvin, Celine Guivarch, Tomoko Hasegawa, Glen Peters, Julia Steinberger, Massimo Tavoni, Detlef von Vuuren, Piers Forster, Jared Lewis, Malte Meinshausen, Joeri Rogelj, Bjorn Samset, Ragnhild Skeie, Alaa Al Khourdajie.

AR6 Scenarios Database hosted by IIASA

International Institute for Applied Systems Analysis, 2022.

doi: 10.5281/zenodo.5886912 | url: data.ene.iiasa.ac.at/ar6/

Table 13: IPCC scenarios used in this analysis

Model_scenario
GCAM 5.3_SSP_SSP1
GCAM 5.3_SSP_SSP2
GCAM 5.3_SSP_SSP3
GCAM 5.3_SSP_SSP4
GCAM 5.3_SSP_SSP5
GEM-E3_V2021_EN_NPi2020_400f
GEM-E3_V2021_EN_NPi2020_500
GEM-E3_V2021_EN_NPi2020_500f
GEM-E3_V2021_EN_NPi2020_600
GEM-E3_V2021_EN_NPi2020_600_COV
GEM-E3_V2021_EN_NPi2020_600f
GEM-E3_V2021_EN_NPi2020_600f_COV
GEM-E3_V2021_EN_NPi2020_800
GMM-17_Hard_Rock
GMM-17_Modern_Jazz
GMM-17_Symphony_1.5C
GMM-17_Unfinished_Symphony
IMAGE 3.0_ADVANCE_WP2_TRA-450-FullTech

Model_scenario
IMAGE 3.0_ADVANCE_WP2_TRA-Ctax-FullTech
IMAGE 3.0_CO_2Deg2020
IMAGE 3.0_EN_NPi2020_1000
IMAGE 3.0_EN_NPi2020_1000f
IMAGE 3.0_EN_NPi2020_1200
IMAGE 3.0_EN_NPi2020_1200f
IMAGE 3.0_EN_NPi2020_1400
IMAGE 3.0_EN_NPi2020_1400f
IMAGE 3.0_EN_NPi2020_600f
IMAGE 3.0_EN_NPi2020_800
IMAGE 3.0_EN_NPi2020_800f
IMAGE 3.2_SSP1_SPA1_19I_D
IMAGE 3.2_SSP1_SPA1_19I_D_LB
IMAGE 3.2_SSP1_SPA1_19I_LI
IMAGE 3.2_SSP1_SPA1_19I_LIRE
IMAGE 3.2_SSP1_SPA1_19I_LIRE_LB
IMAGE 3.2_SSP1_SPA1_19I_RE
IMAGE 3.2_SSP1_SPA1_19I_RE_LB
IMAGE 3.2_SSP1_SPA1_26I_D
IMAGE 3.2_SSP1_SPA1_26I_LI
IMAGE 3.2_SSP1_SPA1_26I_LIRE
IMAGE 3.2_SSP1_SPA1_26I_RE
IMAGE 3.2_SSP2_SPA0_26I_D
IMAGE 3.2_SSP2_SPA1_19I_D_LB
IMAGE 3.2_SSP2_SPA1_19I_LIRE_LB
IMAGE 3.2_SSP2_SPA1_19I_RE_LB
IMAGE 3.2_SSP2_SPA2_19I_D
IMAGE 3.2_SSP2_SPA2_19I_LI
IMAGE 3.2_SSP2_SPA2_19I_LIRE
IMAGE 3.2_SSP2_SPA2_19I_RE
IMAGE 3.2_SSP2_SPA2_26I_D
IMAGE 3.2_SSP2_SPA2_26I_LI
IMAGE 3.2_SSP2_SPA2_26I_LIRE
IMAGE 3.2_SSP2_SPA2_26I_RE
IPCC_AIM/CGE 2.2_EN_NPi2020_900f
IPCC_MESSAGEix-GLOBIOM_GEI 1.0

Model_scenario
IPCC_REMIND-MAgPIE 2.1-4.2
IPCC_REMIND-MAgPIE 2.1-4.3
IPCC_WITCH_5.0_CO_Bridge
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_200f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_300f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_400f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_450
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_450f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_500
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_500f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_600
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_600_COV
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_600f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_600f_COV
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_700
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_700_COV
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_700f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_700f_COV
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_800
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_800_COV
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_800f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_800f_COV
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_900
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_900_COV
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_900f
MESSAGEix-GLOBIOM_1.1_EN_NPi2020_900f_COV
MESSAGEix-GLOBIOM_1.1_NGFS2_Below 2°C
MESSAGEix-GLOBIOM_1.1_NGFS2_Divergent Net Zero Policies
MESSAGEix-GLOBIOM_1.1_NGFS2_Net-Zero 2050
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_int_lc_50
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_int_mc_50
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_noint_lc_50
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_noint_mc_50
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_100
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_120
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_50

Model_scenario
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_80
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_CB400
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_CB450
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_CB500
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_CB550
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_lc_CB600
MESSAGEix-GLOBIOM_GEI 1.0_SSP2_openres_mc_50
MESSAGE-Transport V.5_ADVANCE_WP2_TRA-450-FullTech
MESSAGE-Transport V.5_ADVANCE_WP2_TRA-Ctax-FullTech
PROMETHEUS 1.0_CO_2Deg2020
PROMETHEUS 1.0_CO_GPP
REMIND-MAgPIE 1.7-3.0_CD-LINKS_NPi2020_1000
REMIND-MAgPIE 1.7-3.0_CD-LINKS_NPi2020_1600
REMIND-MAgPIE 1.7-3.0_CD-LINKS_NPi2020_400
REMIND-MAgPIE 1.7-3.0_CO_2Deg2020
REMIND-MAgPIE 1.7-3.0_PEP_1p5C_full_eff
REMIND-MAgPIE 1.7-3.0_PEP_1p5C_red_eff
REMIND-MAgPIE 1.7-3.0_PEP_2C_full_eff
REMIND-MAgPIE 1.7-3.0_PEP_2C_red_eff
REMIND-MAgPIE 2.0-4.1_Diff_1300Gt_hybrid_def
REMIND-MAgPIE 2.0-4.1_Diff_1300Gt_no-transfer_def
REMIND-MAgPIE 2.0-4.1_Diff_1300Gt_uniform-pricing_def
REMIND-MAgPIE 2.1-4.2_CEMICS_SSP1-1p5C-fullCDR
REMIND-MAgPIE 2.1-4.2_CEMICS_SSP1-1p5C-minCDR
REMIND-MAgPIE 2.1-4.2_CEMICS_SSP2-1p5C-fullCDR
REMIND-MAgPIE 2.1-4.2_CEMICS_SSP2-1p5C-minCDR
REMIND-MAgPIE 2.1-4.2_CEMICS_SSP2-2C-fullCDR
REMIND-MAgPIE 2.1-4.2_CEMICS_SSP2-2C-minCDR
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1000
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1000_COV
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1000f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1000f_COV
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1200
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1200f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1400
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1400f

Model_scenario
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REMIND-MAgPIE 2.1-4.2_EN_NPi2020_1600f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_200f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_300f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_400
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_400f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_500
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_500f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_600
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_600_COV
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_600f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_600f_COV
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_700
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_700f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_800
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_800f
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_900
REMIND-MAgPIE 2.1-4.2_EN_NPi2020_900f
REMIND-MAgPIE 2.1-4.2_NGFS2_Below 2°C
REMIND-MAgPIE 2.1-4.2_NGFS2_Below 2°C - IPD-95th
REMIND-MAgPIE 2.1-4.2_NGFS2_Below 2°C - IPD-median
REMIND-MAgPIE 2.1-4.2_NGFS2_Divergent Net Zero Policies
REMIND-MAgPIE 2.1-4.2_NGFS2_Net-Zero 2050
REMIND-MAgPIE 2.1-4.2_NGFS2_Net-Zero 2050 - IPD-95th
REMIND-MAgPIE 2.1-4.2_NGFS2_Net-Zero 2050 - IPD-median
REMIND-MAgPIE 2.1-4.2_SusDev_SDP-PkBudg1000
REMIND-MAgPIE 2.1-4.2_SusDev_SSP1-PkBudg900
REMIND-MAgPIE 2.1-4.2_SusDev_SSP2-PkBudg900
REMIND-MAgPIE 2.1-4.3_DeepElec_SSP2_ HighRE_Budg1100
REMIND-MAgPIE 2.1-4.3_DeepElec_SSP2_ HighRE_Budg1300
REMIND-MAgPIE 2.1-4.3_DeepElec_SSP2_ HighRE_Budg900
REMIND-MAgPIE 2.1-4.3_DeepElec_SSP2_def_Budg1100
REMIND-MAgPIE 2.1-4.3_DeepElec_SSP2_def_Budg1300
REMIND-MAgPIE 2.1-4.3_DeepElec_SSP2_def_Budg900
REMIND-Transport 2.1_Transport_Budg1100_Conv
REMIND-Transport 2.1_Transport_Budg1100_Conv-LowD

Model_scenario
REMIND-Transport 2.1_Transport_Budg1100_ConvSyn
REMIND-Transport 2.1_Transport_Budg1100_ElecPush
REMIND-Transport 2.1_Transport_Budg1100_ElecPush-LowD
REMIND-Transport 2.1_Transport_Budg1100_H_2Push
TIAM-ECN 1.1_EN_NPi2020_1000
TIAM-ECN 1.1_EN_NPi2020_1000_COV
TIAM-ECN 1.1_EN_NPi2020_1000f
TIAM-ECN 1.1_EN_NPi2020_1000f_COV
TIAM-ECN 1.1_EN_NPi2020_1200
TIAM-ECN 1.1_EN_NPi2020_1200f
TIAM-ECN 1.1_EN_NPi2020_1400
TIAM-ECN 1.1_EN_NPi2020_1400f
TIAM-ECN 1.1_EN_NPi2020_1600
TIAM-ECN 1.1_EN_NPi2020_800
TIAM-ECN 1.1_EN_NPi2020_800f
TIAM-ECN 1.1_EN_NPi2020_900
TIAM-ECN 1.1_EN_NPi2020_900f
TIAM-Grantham 3.2_CO_2Deg2020
TIAM-Grantham 3.2_CO_GPP
WEM 2020_SDS
WITCH 5.0_EN_NPi2020_1000
WITCH 5.0_EN_NPi2020_800
WITCH 5.0_EN_NPi2020_900

A.1.3 Statistical data displayed in graphics

Variable refers to the three variables analysed: "H2" = hydrogen in EJ, "FEC" = final energy consumption in EJ and "H2share" = hydrogen share in sectoral final energy consumption in percent.

[percentage] q.] refers to the corresponding quantile values, which are equivalent to the box boundaries and whiskers shown in the respective figures.

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
0	Central Asia(China)	Total	H2	2030	0	9	0.1	4.8	0.8	0.2	0.1	0.4	-0.2	0.7
1	Central Asia(China)	Total	H2	2030	1	264	0.0	1.8	0.2	0.2	0.0	0.2	-0.3	0.5
2	Central Asia(China)	Total	H2	2040	0	11	0.3	4.4	1.3	0.8	0.6	1.2	-0.2	2.0
3	Central Asia(China)	Total	H2	2040	1	264	0.0	9.2	1.1	1.0	0.2	1.5	-1.8	3.5
4	Central Asia(China)	Total	H2	2050	0	9	1.1	24.0	5.5	2.0	1.8	4.1	-1.8	7.7
5	Central Asia(China)	Total	H2	2050	1	264	0.0	10.9	2.4	2.0	0.9	3.7	-3.3	8.0
6	Central Asia(China)	Total	FEC	2030	0	11	79.5	154.7	105.5	99.6	88.1	109.6	56.0	141.7
7	Central Asia(China)	Total	FEC	2030	1	273	63.3	134.0	94.7	94.6	87.2	101.5	65.8	123.0
8	Central Asia(China)	Total	FEC	2040	0	9	68.2	119.8	89.2	90.2	78.5	95.3	53.2	120.6
9	Central Asia(China)	Total	FEC	2040	1	273	67.2	193.7	96.2	93.9	87.8	99.9	69.7	118.0
10	Central Asia(China)	Total	FEC	2050	0	11	58.3	141.1	96.5	86.1	80.4	118.7	23.0	176.1
11	Central Asia(China)	Total	FEC	2050	1	273	66.0	303.5	95.2	92.9	84.4	98.5	63.2	119.8
12	Central Asia(China)	Total	H2share	2030	0	8	0.1	0.9	0.3	0.2	0.2	0.3	0.0	0.5
13	Central Asia(China)	Total	H2share	2030	1	264	0.0	1.9	0.2	0.2	0.0	0.2	-0.3	0.5
14	Central Asia(China)	Total	H2share	2040	0	8	0.6	4.1	1.6	1.1	0.7	1.9	-1.2	3.8
15	Central Asia(China)	Total	H2share	2040	1	264	0.0	12.1	1.2	1.0	0.2	1.6	-1.9	3.6
16	Central Asia(China)	Total	H2share	2050	0	8	1.4	8.6	3.6	2.4	1.8	4.2	-1.8	7.9
17	Central Asia(China)	Total	H2share	2050	1	264	0.0	13.6	2.7	2.2	1.1	4.1	-3.5	8.6
18	Central Asia(China)	Industry	H2	2030	0	7	0.0	0.1	0.1	0.1	0.0	0.1	0.0	0.2

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
19	Central Asia(China)	Industry	H2	2030	1	25	0.0	0.2	0.0	0.0	0.0	0.1	-0.1	0.1
20	Central Asia(China)	Industry	H2	2040	0	10	0.0	0.8	0.3	0.2	0.2	0.4	-0.2	0.7
21	Central Asia(China)	Industry	H2	2040	1	25	0.0	1.5	0.5	0.3	0.0	1.0	-1.5	2.4
22	Central Asia(China)	Industry	H2	2050	0	7	0.0	1.8	0.7	0.6	0.3	0.8	-0.5	1.7
23	Central Asia(China)	Industry	H2	2050	1	25	0.0	1.5	0.5	0.4	0.0	0.9	-1.4	2.4
24	Central Asia(China)	Industry	FEC	2030	0	11	39.7	85.6	62.5	60.7	47.1	77.2	1.8	122.5
25	Central Asia(China)	Industry	FEC	2030	1	22	37.9	47.9	42.6	42.7	39.2	45.6	29.5	55.3
26	Central Asia(China)	Industry	FEC	2040	0	11	33.1	74.7	54.7	52.2	41.1	69.6	-1.7	112.5
27	Central Asia(China)	Industry	FEC	2040	1	22	32.5	37.9	36.0	36.5	35.0	37.5	31.2	41.2
28	Central Asia(China)	Industry	FEC	2050	0	11	26.9	71.5	47.9	48.4	36.9	60.9	1.0	96.8
29	Central Asia(China)	Industry	FEC	2050	1	22	23.9	32.6	29.6	29.6	28.1	31.9	22.3	37.7
30	Central Asia(China)	Industry	H2share	2030	0	4	0.0	0.3	0.2	0.2	0.1	0.2	-0.1	0.4
31	Central Asia(China)	Industry	H2share	2030	1	22	0.0	0.1	0.1	0.1	0.0	0.1	-0.2	0.3
32	Central Asia(China)	Industry	H2share	2040	0	4	0.8	2.3	1.3	1.0	0.8	1.5	-0.2	2.5
33	Central Asia(China)	Industry	H2share	2040	1	22	0.0	3.9	1.6	1.7	0.0	2.7	-4.1	6.8
34	Central Asia(China)	Industry	H2share	2050	0	4	0.8	6.8	2.8	1.8	1.1	3.5	-2.4	6.9
35	Central Asia(China)	Industry	H2share	2050	1	22	0.0	4.5	1.9	2.0	0.0	3.2	-4.8	8.0
36	Central Asia(China)	Transport	H2	2030	0	8	0.0	0.5	0.1	0.1	0.0	0.2	-0.3	0.5
37	Central Asia(China)	Transport	H2	2030	1	211	0.0	0.3	0.0	0.0	0.0	0.0	-0.1	0.1
38	Central Asia(China)	Transport	H2	2040	0	11	0.1	4.4	0.8	0.4	0.2	0.6	-0.3	1.1
39	Central Asia(China)	Transport	H2	2040	1	205	0.0	4.4	0.4	0.1	0.0	0.3	-0.4	0.7
40	Central Asia(China)	Transport	H2	2050	0	8	0.6	11.2	2.6	1.3	1.2	1.6	0.7	2.2
41	Central Asia(China)	Transport	H2	2050	1	202	0.0	5.6	1.1	0.4	0.1	1.3	-1.7	3.1
42	Central Asia(China)	Transport	FEC	2030	0	14	15.3	29.0	18.1	17.6	16.5	17.7	14.8	19.5

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
43	Central Asia(China)	Transport	FEC	2030	1	234	6.1	28.1	18.5	19.7	15.8	22.1	6.5	31.4
44	Central Asia(China)	Transport	FEC	2040	0	14	12.2	26.6	16.6	14.7	13.9	16.9	9.3	21.5
45	Central Asia(China)	Transport	FEC	2040	1	228	3.9	30.6	19.1	19.7	15.4	23.3	3.6	35.2
46	Central Asia(China)	Transport	FEC	2050	0	14	8.6	31.8	15.6	12.3	10.2	16.9	0.2	26.8
47	Central Asia(China)	Transport	FEC	2050	1	224	3.8	31.5	18.1	18.6	14.3	22.0	2.9	33.4
48	Central Asia(China)	Transport	H2share	2030	0	7	0.0	3.3	0.8	0.0	0.0	1.0	-1.5	2.5
49	Central Asia(China)	Transport	H2share	2030	1	211	0.0	3.9	0.1	0.1	0.0	0.2	-0.3	0.5
50	Central Asia(China)	Transport	H2share	2040	0	7	1.4	16.7	6.3	3.0	1.8	9.6	-9.8	21.2
51	Central Asia(China)	Transport	H2share	2040	1	205	0.0	25.6	2.6	0.6	0.0	1.5	-2.1	3.7
52	Central Asia(China)	Transport	H2share	2050	0	7	9.3	39.3	17.3	13.7	10.4	18.8	-2.1	31.4
53	Central Asia(China)	Transport	H2share	2050	1	202	0.0	46.3	8.1	1.9	0.4	7.0	-9.6	17.0
54	Central Asia(China)	Buildings	H2	2030	0	7	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.1
55	Central Asia(China)	Buildings	H2	2030	1	182	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
56	Central Asia(China)	Buildings	H2	2040	0	7	0.0	0.2	0.2	0.2	0.1	0.2	-0.1	0.4
57	Central Asia(China)	Buildings	H2	2040	1	182	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0
58	Central Asia(China)	Buildings	H2	2050	0	7	0.0	0.2	0.1	0.1	0.0	0.2	-0.2	0.4
59	Central Asia(China)	Buildings	H2	2050	1	182	0.0	1.2	0.1	0.0	0.0	0.0	0.0	0.0
60	Central Asia(China)	Buildings	FEC	2030	0	12	20.5	41.5	26.3	24.1	23.0	25.0	20.0	28.1
61	Central Asia(China)	Buildings	FEC	2030	1	192	14.7	33.2	24.2	25.0	22.9	26.1	18.1	30.9
62	Central Asia(China)	Buildings	FEC	2040	0	8	22.2	42.9	28.6	24.8	23.1	29.7	13.2	39.6
63	Central Asia(China)	Buildings	FEC	2040	1	192	15.6	39.0	26.6	27.5	23.5	29.5	14.4	38.5
64	Central Asia(China)	Buildings	FEC	2050	0	12	17.6	40.0	26.3	25.3	21.2	27.1	12.3	36.0
65	Central Asia(China)	Buildings	FEC	2050	1	192	15.3	41.4	26.1	27.1	22.9	28.7	14.3	37.3
66	Central Asia(China)	Buildings	H2share	2030	0	6	0.0	0.5	0.3	0.3	0.2	0.4	0.0	0.6

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
67	Central Asia(China)	Buildings	H2share	2030	1	182	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
68	Central Asia(China)	Buildings	H2share	2040	0	6	0.0	1.0	0.7	0.9	0.7	1.0	0.3	1.3
69	Central Asia(China)	Buildings	H2share	2040	1	182	0.0	4.2	0.1	0.0	0.0	0.0	0.0	0.0
70	Central Asia(China)	Buildings	H2share	2050	0	6	0.0	1.2	0.5	0.5	0.3	0.7	-0.3	1.3
71	Central Asia(China)	Buildings	H2share	2050	1	182	0.0	4.9	0.5	0.0	0.0	0.1	-0.1	0.1
72	Europe(EU28)	Total	H2	2030	0	15	0.0	3.9	1.1	0.5	0.2	2.0	-2.6	4.8
73	Europe(EU28)	Total	H2	2030	1	270	0.0	0.9	0.1	0.1	0.0	0.2	-0.3	0.5
74	Europe(EU28)	Total	H2	2040	0	12	0.4	10.2	3.1	1.8	0.5	3.7	-4.2	8.4
75	Europe(EU28)	Total	H2	2040	1	270	0.0	7.1	0.5	0.4	0.0	0.7	-1.1	1.8
76	Europe(EU28)	Total	H2	2050	0	22	0.0	12.9	3.8	2.2	0.9	4.4	-4.3	9.6
77	Europe(EU28)	Total	H2	2050	1	270	0.0	8.6	1.0	0.7	0.2	1.4	-1.6	3.2
78	Europe(EU28)	Total	FEC	2030	0	20	18.8	63.7	42.5	39.9	36.8	48.3	19.4	65.6
79	Europe(EU28)	Total	FEC	2030	1	279	4.8	69.5	50.6	49.4	46.7	55.6	33.4	68.9
80	Europe(EU28)	Total	FEC	2040	0	14	14.7	63.5	37.3	37.8	29.0	44.2	6.2	66.9
81	Europe(EU28)	Total	FEC	2040	1	279	4.7	80.3	47.4	44.7	40.5	54.6	19.4	75.7
82	Europe(EU28)	Total	FEC	2050	0	28	13.5	67.7	33.2	29.9	25.8	41.9	1.6	66.0
83	Europe(EU28)	Total	FEC	2050	1	279	4.8	96.9	46.5	45.1	38.3	54.0	14.8	77.5
84	Europe(EU28)	Total	H2share	2030	0	14	0.0	8.4	2.4	0.9	0.5	4.2	-5.1	9.8
85	Europe(EU28)	Total	H2share	2030	1	270	0.0	2.1	0.3	0.2	0.0	0.4	-0.6	1.0
86	Europe(EU28)	Total	H2share	2040	0	11	1.6	23.7	7.9	4.3	2.0	10.1	-10.1	22.2
87	Europe(EU28)	Total	H2share	2040	1	270	0.0	14.0	1.2	1.0	0.0	1.8	-2.7	4.4
88	Europe(EU28)	Total	H2share	2050	0	21	0.1	30.8	9.9	6.9	3.6	14.3	-12.6	30.5
89	Europe(EU28)	Total	H2share	2050	1	270	0.0	16.4	2.3	1.7	0.5	3.1	-3.6	7.2
90	Europe(EU28)	Industry	H2	2030	0	14	0.0	1.9	0.6	0.1	0.0	1.4	-2.1	3.5

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
91	Europe(EU28)	Industry	H2	2030	1	25	0.0	0.1	0.0	0.0	0.0	0.1	-0.1	0.2
92	Europe(EU28)	Industry	H2	2040	0	14	0.1	4.7	1.1	0.3	0.1	1.8	-2.5	4.3
93	Europe(EU28)	Industry	H2	2040	1	25	0.0	0.7	0.3	0.2	0.0	0.6	-0.9	1.5
94	Europe(EU28)	Industry	H2	2050	0	20	0.0	5.4	1.2	0.4	0.1	1.4	-1.7	3.2
95	Europe(EU28)	Industry	H2	2050	1	25	0.0	0.7	0.3	0.5	0.0	0.6	-0.8	1.4
96	Europe(EU28)	Industry	FEC	2030	0	16	4.1	19.5	11.5	11.2	9.3	12.3	4.7	16.9
97	Europe(EU28)	Industry	FEC	2030	1	22	10.7	12.5	11.6	11.7	11.0	12.2	9.3	13.9
98	Europe(EU28)	Industry	FEC	2040	0	10	5.3	15.6	11.5	11.7	9.7	14.1	3.0	20.8
99	Europe(EU28)	Industry	FEC	2040	1	22	10.9	12.8	11.8	11.8	11.3	12.2	10.0	13.5
100	Europe(EU28)	Industry	FEC	2050	0	18	4.4	14.6	9.0	8.8	7.5	10.3	3.2	14.5
101	Europe(EU28)	Industry	FEC	2050	1	22	10.3	13.3	12.1	12.0	11.5	12.6	10.0	14.1
102	Europe(EU28)	Industry	H2share	2030	0	8	0.0	15.8	4.7	0.7	0.2	8.5	-12.2	20.9
103	Europe(EU28)	Industry	H2share	2030	1	22	0.0	0.8	0.3	0.4	0.0	0.6	-0.8	1.4
104	Europe(EU28)	Industry	H2share	2040	0	8	0.6	34.9	11.2	2.3	1.6	20.0	-26.1	47.6
105	Europe(EU28)	Industry	H2share	2040	1	22	0.0	6.0	2.8	4.2	0.0	5.1	-7.6	12.7
106	Europe(EU28)	Industry	H2share	2050	0	14	0.0	38.2	10.5	3.8	2.6	15.9	-17.3	35.9
107	Europe(EU28)	Industry	H2share	2050	1	22	0.0	5.5	2.7	4.1	0.0	4.9	-7.3	12.2
108	Europe(EU28)	Transport	H2	2030	0	16	0.0	2.0	0.5	0.3	0.1	0.5	-0.6	1.2
109	Europe(EU28)	Transport	H2	2030	1	213	0.0	0.7	0.1	0.0	0.0	0.1	-0.2	0.3
110	Europe(EU28)	Transport	H2	2040	0	15	0.2	5.4	2.0	1.4	0.5	3.0	-3.2	6.7
111	Europe(EU28)	Transport	H2	2040	1	207	0.0	3.6	0.3	0.2	0.0	0.5	-0.6	1.2
112	Europe(EU28)	Transport	H2	2050	0	22	0.1	8.4	2.7	1.9	0.8	3.2	-2.9	6.9
113	Europe(EU28)	Transport	H2	2050	1	204	0.0	5.1	0.7	0.6	0.1	0.8	-0.9	1.8
114	Europe(EU28)	Transport	FEC	2030	0	21	5.4	22.3	13.5	12.9	9.6	17.6	-2.4	29.6

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
115	Europe(EU28)	Transport	FEC	2030	1	240	1.3	27.7	15.8	15.4	13.4	17.1	7.7	22.7
116	Europe(EU28)	Transport	FEC	2040	0	16	3.4	19.8	11.8	14.0	6.7	15.9	-7.1	29.8
117	Europe(EU28)	Transport	FEC	2040	1	234	1.4	31.1	14.0	12.9	10.5	16.8	1.0	26.2
118	Europe(EU28)	Transport	FEC	2050	0	25	2.9	19.9	9.4	6.9	5.5	13.4	-6.5	25.4
119	Europe(EU28)	Transport	FEC	2050	1	230	1.3	33.8	13.3	11.9	9.6	16.2	-0.3	26.1
120	Europe(EU28)	Transport	H2share	2030	0	16	0.0	11.6	3.5	2.3	0.7	4.4	-4.8	9.8
121	Europe(EU28)	Transport	H2share	2030	1	213	0.0	5.2	0.4	0.2	0.0	0.8	-1.3	2.1
122	Europe(EU28)	Transport	H2share	2040	0	14	2.0	35.8	17.3	17.8	6.2	26.3	-24.0	56.5
123	Europe(EU28)	Transport	H2share	2040	1	207	0.0	18.3	3.0	2.0	0.3	4.2	-5.4	9.9
124	Europe(EU28)	Transport	H2share	2050	0	21	1.1	53.2	26.6	27.6	12.9	36.3	-22.1	71.3
125	Europe(EU28)	Transport	H2share	2050	1	204	0.0	32.1	6.5	4.8	1.2	7.1	-7.6	16.0
126	Europe(EU28)	Buildings	H2	2030	0	13	0.0	0.3	0.1	0.1	0.0	0.2	-0.2	0.5
127	Europe(EU28)	Buildings	H2	2030	1	184	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
128	Europe(EU28)	Buildings	H2	2040	0	12	0.0	0.5	0.2	0.2	0.1	0.3	-0.2	0.7
129	Europe(EU28)	Buildings	H2	2040	1	184	0.0	0.7	0.1	0.0	0.0	0.0	0.0	0.0
130	Europe(EU28)	Buildings	H2	2050	0	16	0.0	2.1	0.3	0.1	0.0	0.5	-0.8	1.3
131	Europe(EU28)	Buildings	H2	2050	1	184	0.0	2.5	0.1	0.0	0.0	0.0	-0.1	0.1
132	Europe(EU28)	Buildings	FEC	2030	0	17	6.5	21.8	15.1	15.1	12.4	18.7	3.1	28.0
133	Europe(EU28)	Buildings	FEC	2030	1	198	1.7	23.8	19.0	18.4	17.6	20.8	12.8	25.7
134	Europe(EU28)	Buildings	FEC	2040	0	15	5.5	19.4	13.8	14.3	11.5	17.2	3.1	25.6
135	Europe(EU28)	Buildings	FEC	2040	1	198	1.6	25.5	17.7	16.8	15.7	18.8	11.1	23.5
136	Europe(EU28)	Buildings	FEC	2050	0	21	5.1	17.9	12.4	13.2	10.2	14.7	3.5	21.4
137	Europe(EU28)	Buildings	FEC	2050	1	198	1.6	27.6	16.9	15.7	14.3	18.7	7.6	25.4
138	Europe(EU28)	Buildings	H2share	2030	0	12	0.0	2.2	1.0	1.2	0.2	1.6	-1.8	3.6

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
139	Europe(EU28)	Buildings	H2share	2030	1	184	0.0	1.4	0.1	0.0	0.0	0.0	0.0	0.0
140	Europe(EU28)	Buildings	H2share	2040	0	11	0.0	2.7	1.5	1.7	1.0	2.2	-0.9	4.1
141	Europe(EU28)	Buildings	H2share	2040	1	184	0.0	4.1	0.3	0.0	0.0	0.1	-0.1	0.1
142	Europe(EU28)	Buildings	H2share	2050	0	15	0.0	6.6	1.7	0.6	0.0	2.9	-4.3	7.1
143	Europe(EU28)	Buildings	H2share	2050	1	184	0.0	15.3	0.6	0.0	0.0	0.2	-0.3	0.6
144	World	Total	H2	2030	0	11	0.9	25.2	7.2	3.0	1.6	10.8	-12.1	24.5
145	World	Total	H2	2030	1	576	0.0	9.7	1.0	0.7	0.1	1.2	-1.6	2.9
146	World	Total	H2	2040	0	13	4.8	46.8	16.1	9.1	5.9	17.5	-11.4	34.8
147	World	Total	H2	2040	1	576	0.0	49.9	4.3	3.5	1.7	5.9	-4.5	12.1
148	World	Total	H2	2050	0	17	10.7	79.2	34.4	27.3	13.7	55.0	-48.3	117.0
149	World	Total	H2	2050	1	576	0.0	63.7	10.4	8.4	4.4	13.9	-9.9	28.2
150	World	Total	FEC	2030	0	14	342.2	468.9	404.7	400.4	375.6	434.0	288.0	521.6
151	World	Total	FEC	2030	1	593	257.4	608.5	435.2	444.5	410.8	466.4	327.5	549.7
152	World	Total	FEC	2040	0	13	310.4	502.4	391.6	379.2	358.1	417.8	268.5	507.4
153	World	Total	FEC	2040	1	593	247.9	627.8	439.2	439.3	397.3	486.4	263.5	620.2
154	World	Total	FEC	2050	0	15	279.0	548.8	383.5	348.0	343.8	424.5	222.8	545.4
155	World	Total	FEC	2050	1	593	242.8	655.5	454.3	450.3	403.8	507.5	248.4	662.9
156	World	Total	H2share	2030	0	10	0.2	5.1	1.4	0.6	0.4	1.2	-0.9	2.5
157	World	Total	H2share	2030	1	576	0.0	2.5	0.2	0.1	0.0	0.3	-0.4	0.6
158	World	Total	H2share	2040	0	11	1.2	12.7	3.7	2.0	1.6	4.9	-3.3	9.9
159	World	Total	H2share	2040	1	576	0.0	14.1	1.0	0.8	0.4	1.3	-1.0	2.7
160	World	Total	H2share	2050	0	13	2.8	23.0	9.4	5.8	3.6	11.4	-8.1	23.1
161	World	Total	H2share	2050	1	576	0.0	16.5	2.4	1.8	1.0	3.1	-2.3	6.4
162	World	Industry	H2	2030	0	11	0.1	16.0	2.8	0.4	0.2	2.0	-2.4	4.6

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
163	World	Industry	H2	2030	1	510	0.0	9.1	0.5	0.4	0.0	0.7	-1.0	1.7
164	World	Industry	H2	2040	0	11	0.5	13.2	3.4	1.8	1.0	3.5	-2.7	7.2
165	World	Industry	H2	2040	1	510	0.0	18.9	2.5	2.3	0.0	3.6	-5.3	8.9
166	World	Industry	H2	2050	0	13	0.5	38.0	11.8	4.8	2.0	16.6	-20.0	38.5
167	World	Industry	H2	2050	1	510	0.0	29.4	5.9	5.2	0.6	9.1	-12.1	21.9
168	World	Industry	FEC	2030	0	10	120.8	197.1	158.3	160.1	151.8	171.5	122.1	201.2
169	World	Industry	FEC	2030	1	546	60.2	231.8	163.5	172.9	148.1	187.3	89.3	246.1
170	World	Industry	FEC	2040	0	9	110.9	220.0	152.9	154.6	130.7	169.4	72.6	227.5
171	World	Industry	FEC	2040	1	546	69.0	232.3	165.8	171.0	139.6	189.8	64.4	265.0
172	World	Industry	FEC	2050	0	11	98.3	241.4	154.1	160.4	129.7	170.9	67.9	232.7
173	World	Industry	FEC	2050	1	546	82.7	257.1	175.0	182.4	143.5	199.0	60.1	282.3
174	World	Industry	H2share	2030	0	8	0.1	9.3	1.6	0.4	0.1	0.8	-0.8	1.8
175	World	Industry	H2share	2030	1	488	0.0	5.9	0.3	0.3	0.0	0.4	-0.5	0.9
176	World	Industry	H2share	2040	0	7	0.8	2.5	1.4	1.1	0.9	1.8	-0.4	3.1
177	World	Industry	H2share	2040	1	488	0.0	15.5	1.5	1.3	0.0	2.0	-3.0	5.1
178	World	Industry	H2share	2050	0	9	1.2	21.5	7.0	3.0	1.5	8.5	-9.0	18.9
179	World	Industry	H2share	2050	1	488	0.0	17.4	3.3	2.9	0.5	4.9	-6.1	11.5
180	World	Transport	H2	2030	0	14	0.0	4.0	1.4	1.2	0.2	2.0	-2.6	4.7
181	World	Transport	H2	2030	1	569	0.0	2.5	0.2	0.0	0.0	0.5	-0.7	1.2
182	World	Transport	H2	2040	0	13	1.8	21.1	7.0	5.6	2.8	8.2	-5.2	16.2
183	World	Transport	H2	2040	1	569	0.0	23.0	1.2	0.2	0.0	2.0	-3.1	5.1
184	World	Transport	H2	2050	0	16	5.3	55.0	16.4	11.6	9.4	15.2	0.8	23.8
185	World	Transport	H2	2050	1	569	0.0	30.7	3.5	1.2	0.0	4.7	-7.0	11.8
186	World	Transport	FEC	2030	0	13	85.5	127.6	108.5	102.4	97.6	122.0	61.0	158.6

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
187	World	Transport	FEC	2030	1	592	58.6	188.7	123.3	128.4	114.8	134.2	85.8	163.1
188	World	Transport	FEC	2040	0	12	67.8	135.7	95.1	85.0	78.6	113.5	26.2	165.9
189	World	Transport	FEC	2040	1	592	50.5	206.3	120.0	122.1	105.5	137.6	57.3	185.8
190	World	Transport	FEC	2050	0	14	52.1	146.3	88.4	86.3	58.3	114.8	-26.3	199.4
191	World	Transport	FEC	2050	1	592	40.1	218.0	115.8	115.2	97.6	134.6	42.0	190.2
192	World	Transport	H2share	2030	0	13	0.0	4.7	1.2	0.9	0.1	1.6	-2.2	3.8
193	World	Transport	H2share	2030	1	569	0.0	2.1	0.2	0.0	0.0	0.4	-0.6	1.0
194	World	Transport	H2share	2040	0	12	1.9	18.8	6.8	4.4	2.6	8.1	-5.6	16.3
195	World	Transport	H2share	2040	1	569	0.0	20.2	1.2	0.2	0.0	1.7	-2.5	4.2
196	World	Transport	H2share	2050	0	14	4.0	44.0	16.7	15.9	9.5	19.0	-4.8	33.3
197	World	Transport	H2share	2050	1	569	0.0	40.0	3.8	1.1	0.0	4.4	-6.5	10.9
198	World	Buildings	H2	2030	0	11	0.0	2.0	0.8	0.7	0.3	1.3	-1.2	2.8
199	World	Buildings	H2	2030	1	424	0.0	3.7	0.3	0.0	0.0	0.0	0.0	0.0
200	World	Buildings	H2	2040	0	11	0.0	7.6	1.9	1.5	1.3	1.9	0.4	2.8
201	World	Buildings	H2	2040	1	424	0.0	5.5	0.6	0.0	0.0	0.0	0.0	0.1
202	World	Buildings	H2	2050	0	13	0.0	4.8	2.0	2.0	1.2	2.3	-0.6	4.1
203	World	Buildings	H2	2050	1	424	0.0	7.4	0.7	0.0	0.0	0.5	-0.7	1.2
204	World	Buildings	FEC	2030	0	12	99.0	143.7	124.0	126.3	115.1	135.9	83.9	167.1
205	World	Buildings	FEC	2030	1	527	77.0	176.1	138.0	139.4	125.6	148.1	92.0	181.7
206	World	Buildings	FEC	2040	0	11	88.7	149.4	126.4	128.4	121.4	136.8	98.4	159.9
207	World	Buildings	FEC	2040	1	527	84.1	201.8	142.4	141.0	125.6	157.9	77.2	206.3
208	World	Buildings	FEC	2050	0	13	86.0	161.1	125.1	128.0	105.0	137.5	56.2	186.3
209	World	Buildings	FEC	2050	1	527	72.1	232.5	150.0	146.4	127.3	172.3	59.9	239.7
210	World	Buildings	H2share	2030	0	10	0.0	2.0	0.8	0.6	0.3	1.1	-1.0	2.4

	Region	Sector	Variable	Year	IPCC	n	min	max	mean	median	25% q.	75% q.	5% q.	95% q.
211	World	Buildings	H2share	2030	1	424	0.0	3.0	0.3	0.0	0.0	0.0	0.0	0.0
212	World	Buildings	H2share	2040	0	9	0.0	2.1	1.2	1.3	1.1	1.6	0.2	2.4
213	World	Buildings	H2share	2040	1	424	0.0	4.8	0.4	0.0	0.0	0.0	0.0	0.1
214	World	Buildings	H2share	2050	0	11	0.0	3.4	1.6	1.7	0.9	2.2	-1.0	4.1
215	World	Buildings	H2share	2050	1	424	0.0	5.7	0.5	0.0	0.0	0.3	-0.4	0.7