Report

Getting Electrification Right

The broader challenge of induced emissions

JUNE 2025

Authors

This report was written by Adrien Assous, Chloé Barré and Duncan Woods. We would like to thank Maxime Gérardin and Simon Ferrière for their critical and consructive feedback on this research work.

About Sandbag

We are a think tank conducting data-driven and **evidence-based advocacy** to improve **EU climate policy**. We combine expertise in **decarbonisation** with **data analysis** to propose policies that drive impactful, cost-effective emissions reductions in the EU and beyond. Through our holistic approach, we make sure our recommendations are not only well-informed and effective but also inclusive, considering economic and geostrategic realities.

contact@sandbag.be

sandbag.be

LinkedIn

@sandbag-eu.bsky.social

@sandbag_eu

Table of content

1. **Renewables targets: A steep climb that will require some optimising** ... 5
   1.1. Summary of the current legislation ... 5
      1.1.1. Renewable energy targets ... 6
      1.1.2. Hydrogen targets ... 7
   1.2. Estimating demand for renewable electricity ... 9
      1.2.1. Scenarios and assumptions ... 9
      1.2.2. Modelling electricity demand ... 13
   1.3. Estimating renewable power capacity ... 16
2. **Emissions induced by production patterns** ... 18
   2.1. RFNBO hydrogen: A case study ... 18
      2.1.1. Methodology ... 20
      2.1.2. Results ... 22
   2.2. If interconnection was perfect ... 24
   2.3. If electrolysers ran 24 hours ... 26
3. **Decarbonising industry** ... 28
   3.1. How much green hydrogen can we really produce? ... 28
   3.2. When is ‘green steel’ not green steel? ... 30
   3.3. Other industrial applications ... 32
4. **Recommendations** ... 33
   4.1. Getting the renewable mix right ... 33
   4.2. Minding induced emissions ... 34
5. **Appendix** ... 35
   5.1. Appendix 1: Annex IX of RED ... 35
   5.2. Appendix 2: Assumptions used in scenarios ... 36
   5.3. Appendix 3: Load factors ... 36
   5.4. Appendix 4: Hydrogen project infrastructure ... 38
   5.5. Appendix 5: Minimum fossil content ... 38
   5.6. Appendix 6: Calculation for perfect interconnection ... 39

Executive Summary

Electrification is a cornerstone of Europe's green transition. However, until the electricity supply is fully decarbonised, the climate impact of electricity use can vary significantly depending on where and when it is consumed. New electricity demand can inadvertently lead to increased fossil fuel generation if it occurs during periods of limited renewable supply. This dynamic means that even well-intentioned climate measures can have counterproductive effects if they create demand at the wrong times. This is true for any demand for electricity, including the production of 'green' hydrogen, which we will use in this report as a representative example.

In its amended Renewable Energy Directive (RED III), the EU commanded a steep increase in the overall share of renewables in its energy mix, from 24.5% in 2023 to 42.5% in 2030, and set ambitious sectoral sub-targets. While this ambition is welcome, the way in which these targets are met could have significant consequences for the EU's energy mix. A high reliance on Renewable Fuels of Non-Biological Origin (RFNBO), including renewable hydrogen, could hinder rather than help the EU achieve its climate goals. This is due to 1) the relative inefficiency of hydrogen use over direct electrification in some sectors, and 2) the **weak additionality criteria** for renewables used to produce these fuels.

The RFNBO standard applies to hydrogen produced from electricity that is either "spare" (i.e. generated at times of excess electricity) or produced by recently built RES, with some degree of mismatch allowed between the timing of RES output out and electricity used for hydrogen. However, the standard ignores the fact that, when there is demand for thermal electricity, using RES capacity to produce hydrogen instead of feeding the grid prevents the displacement of fossil electricity. In those time intervals, **hydrogen production induces fossil electricity generation** and CO_2 emissions.

Emissions **induced** by RFNBO production depend on the amount of renewables available at the time of production, so one would expect them to fall as the share of renewables increases in Europe. But we find that, even in a scenario where RED targets are met, induced emissions would still be as high as 5.45 tCO_2 per tH_2 produced by 2030, on average across Europe. This is not much lower than emissions from the production of hydrogen from steam methane reforming (9.1 tCO_2/tH_2).

If the pace of renewable electricity build does not pick up compared to the last few years, RFNBO induced emissions may not fall below 13.4 tCO_2/tH_2. And these are **under-estimations**, ignoring the benefits achievable from increased cross-border electricity flows as alternative to hydrogen production. If power grids were perfectly interconnected, induced emissions would still be 10.2 tCO_2/tH_2 by 2030 in a RED compatible scenario, and **23.7 tCO_2/tH_2 if renewable electricity build followed the *current trend***. As a result, in some cases in the nearterm, green steel produced from RFNBO hydrogen may not be any greener than if produced from grey hydrogen (made from fossil fuels).

These findings underscore the **broader challenge of increasing demand for electricity while the electricity system is still decarbonising.** We recommend that induced emissions should be taken into account by the RFNBO methodology and hydrogen production with such emissions excluded from its scope, and renewable energy targets should better encourage energy-efficient uses such as direct electrification, over hydrogen use.

1. Renewables targets: A steep climb that will require some optimising

The EU's renewable energy targets are a decisive step for the bloc to reach its 55% emissions reduction target by 2030 and climate neutrality by mid-century. The most accessible source of renewable energy is electricity, the adoption of which, **combined with electrification** would enable entire sectors of the economy to decarbonise, such as transport and industry.

However, electrification and renewable energy deployment must take place in parallel. One without the other can undermine climate objectives. A simple example is the electrification of industrial heat, for which the EU has recently run a stakeholder survey for a €1 billion subsidy programme[1]. Electrifying industrial heat that is currently produced from natural gas will only reduce emissions if the electricity used does not create extra demand for fossil electricity. As peak open-cycle gas plants have thermal efficiencies around 40%, using for the same purpose electricity that creates demand for such fossil generation would actually emit 2.5 times more CO_2.

It is therefore critical that the supply of renewables can sustain electrification objectives. This raises the question of the amount of renewable electricity available for electrification, but also the intermittence of the electricity source. This chapter will show how the bottleneck of available renewable electricity should guide our choice in the optimal use of this energy. We will illustrate this with the example of hydrogen, as an important means of decarbonisation but whose impact on electricity use will only lead to climate gains if carefully used in specific applications.

The second chapter will explore the different climate impacts resulting from electrolytic hydrogen depending on production patterns, by introducing the concept of **induced emissions** in the example of the RFNBO standard currently used in the EU. This analysis allows us to estimate the level of decarbonisation that is effectively achievable through hydrogen use with the amount of renewable electricity expected to be available by 2030.

1.1. Summary of the current legislation

The current legislation intends to stimulate the deployment of renewable energy, including the use of hydrogen and its derivatives.

[1] See Sandbag (2025) Auction for industrial heat electrification: A positive step, but mind the induced emissions!

1.1.1. Renewable energy targets

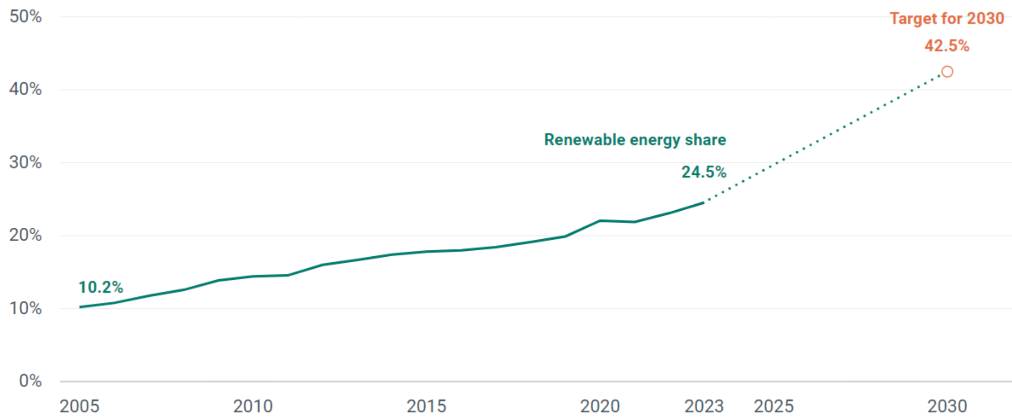

Figure 1: Share of renewable energy in gross final energy consumption (Source: EEA)

The Renewable Energy Directive, as amended in November 2023 (RED III), set an EU-wide binding target for the share of renewable energy in gross final energy consumption of 42.5% by 2030. This represents a significant increase from the 24.5% share of renewables in 2023, Figure 1.

Additionally, the recast directive includes a number of sub-targets for the use of renewables in different sectors. In terms of targets for use of renewables in **transport**, RED III (Article 25.1(a)) states that:

> *"each Member State shall set an obligation on fuel suppliers to ensure that the amount of renewable fuels and renewable electricity supplied to the transport sector leads to a share of renewable energy within the final consumption of energy in the transport sector of* ***at least 29 %*** *by 2030; or greenhouse gas intensity reduction of* ***at least 14,5 %*** *by 2030 (…);"*

The 29% target includes renewable electricity, biofuels and biogases, and renewable fuels of non-biological origin (RFNBOs). At present, all Member States fall considerably short of this target (as shown in Figure 2)

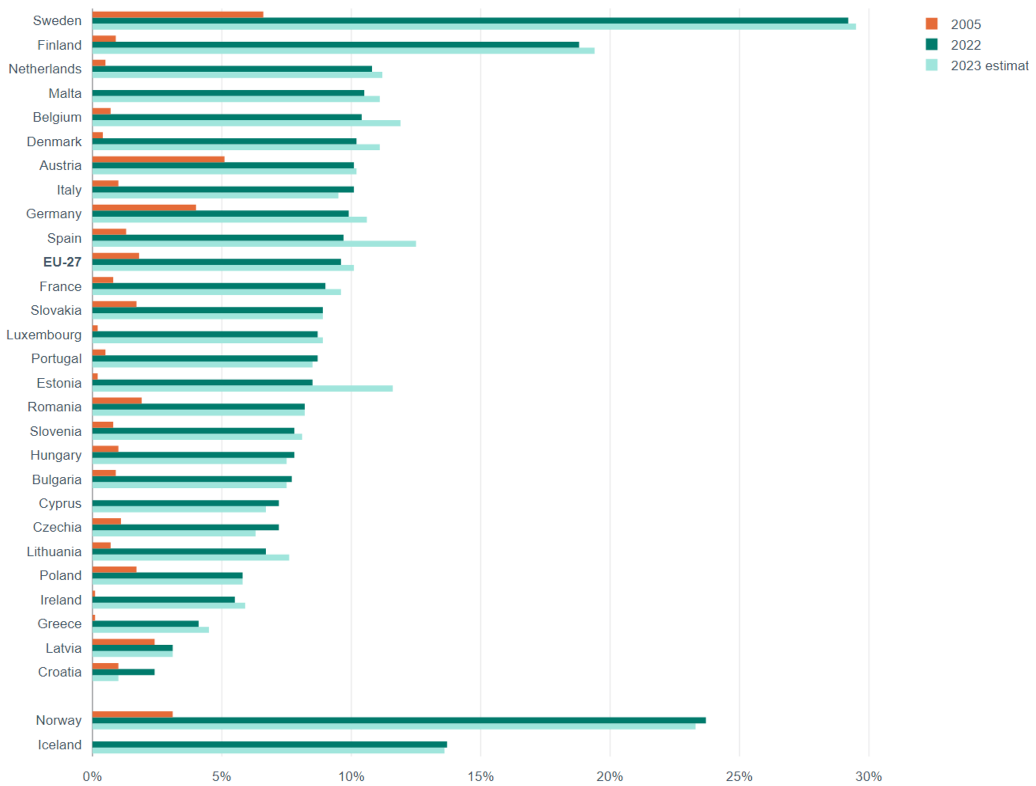

Figure 2: Share of energy from renewable sources used in transport by country. Source: EEA

1.1.2. Hydrogen targets

1.1.2.1. Industry

Article 22a of RED III mandates Member States to ensure that the contribution of renewable fuels of non-biological origin used for final energy and non-energy purposes shall be **at least 42 % of the hydrogen used for final energy and non-energy purposes in industry by 2030**, and 60 % by 2035. Oil refining is excluded from this obligation, as the use of RFNBO hydrogen in that sector counts towards the below transport target.

1.1.2.2. Transport

Regarding fuel use, RED Transport (i.e. Article 25.1(b)) states that at least 5.5% of energy use in transport in 2030 must come from advanced biofuels/biogas (produced from the feedstock listed in Part A of Annex IX, see Appendix 1) and RFNBOs combined, with at least 1% from RFNBOs.

RED Transport will be partly achieved by targets set in the RED Transport Maritime, FuelEU Maritime, and ReFuelEU Aviation. **RED Transport Maritime** puts a target of at least 1.2% RFNBOs as of 2030 within the total amount of energy supplied to the maritime transport sector by maritime ports of member states. **FuelEU Maritime** is a conditional target for 2034 that is only triggered if the share of RFNBOs in the annual energy consumption of maritime transport sector is less than 1% as of 1st January 2030[2]. Meanwhile the **ReFuelEU Aviation** sets mandates on the fuel made available to aircrafts, with a target for 6% use of Sustainable Aviation Fuels (SAF)[3] in all EU airports in 2030.

Table 1: Representation of concurrent transport targets for 2030 under RED III

<table>
<tr><td rowspan="5">RED Transport:
29% of final energy consumption in transport</td><td rowspan="5">made up of…</td><td rowspan="4">RFNBO and advanced biofuels:
5.5%</td><td rowspan="3">RFNBO:1%</td><td>REFuelEU Aviation: 6% SAF</td></tr>
<tr><td>RED Transport maritime: 1.2%</td></tr>
<tr><td>Other RFNBO</td></tr>
<tr><td colspan="2">RFNBO and advanced biofuels: 4.5%</td></tr>
<tr><td colspan="3">RFNBO, renewable electricity, biofuels, biogas: 24.5%</td></tr>
</table>

In July 2020, the Commission unveiled the **EU Hydrogen Strategy**, outlining a comprehensive plan to integrate hydrogen into the energy system. The strategy primarily emphasised the production, distribution, and utilisation of renewable and low-carbon hydrogen in multiple sectors, such as industry, transportation and heating. The blueprint also outlined non-binding electrolysing capacity targets within the EU of 6 GW by 2024 and 40 GW by 2030. According to DG ENER's communications, the European Commission is expecting that 40 GW of electrolysers would produce 15.7 Mtoe of renewable hydrogen, i.e. 5.5 Mt. This still implies relatively high efficiency and load factors, e.g. around 80% efficiency and 6000 load hours/year.

[2] While FuelEU Maritime impacts the RFNBOs consumption by EU vessels, RED Transport Maritime impacts the RFNBOs supplied by EU ports.

[3] SAFs are defined as: Synthetic aviation fuels from renewable hydrogen and captured carbon (in the meaning of Article 2(36) of RED and limited to liquid drop-in fuels only); Advanced biofuels from waste and residues notably (produced from feedstock listed in Part A of Annex IX, in the meaning of Article 2(34) of RED); Biofuels produced from oils and fats notably (such as from feedstock listed in Part B of Annex IX, in the meaning of Article 2(33) of RED); Recycled carbon aviation fuels in the meaning of Article 2(33) of RED.

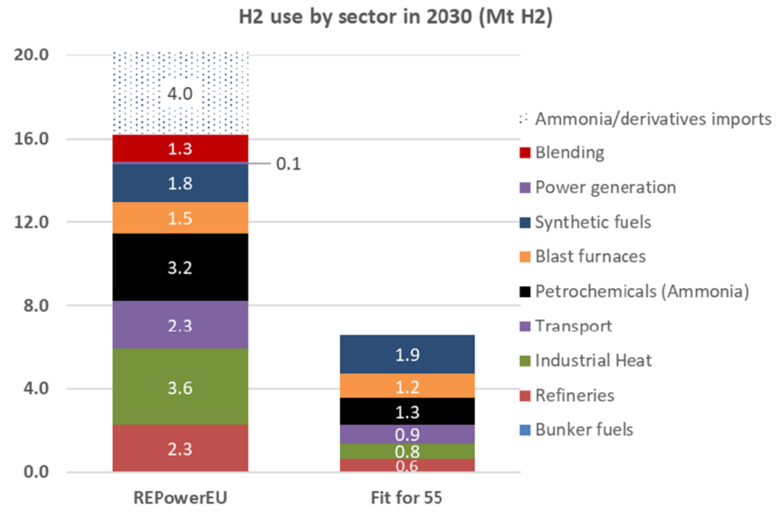

Figure 3: Comparison of hydrogen use by sector in 2030 through implementation of the REPower EU Action Plan

In May 2022, the Commission adopted the **REPowerEU Plan**, which aims for an annual domestic production of 10 million tonnes by 2030, in addition to importing another 10 million tonnes of hydrogen annually. The EC indicated that this would require "other forms of fossil-free hydrogen, notably nuclear-based".

1.2. Estimating demand for renewable electricity

Renewable energy targets are widely expressed in percentage terms and with some flexibility between different types of energy, so the corresponding amount of required renewable electricity (in megawatt-hours) depends on choices within the ranges set by those targets. One key parameter is the share of RFNBO's contribution to these targets, which will impact the overall demand for electricity.

1.2.1. Scenarios and assumptions

In its impact assessment ahead of the **Fit-For-55 package**, the European Commission estimated energy demand in 2030 under different policy scenarios, of which we found the **MIX** scenario[4] as the closest to the combination of policies currently in place. We therefore used estimates found in the impact assessment for the MIX scenario (later called FF55 MIX) as basis for this analysis.

[4] Data on the FF55 MIX scenario can be found here

Demand for hydrogen and renewable electricity in 2030 will be highly dependent on how the targets mandated by RED III are achieved. Therefore, we estimated demand under different scenarios based on the targets outlined in RED III, as detailed in Table 2.

Table 2: Overview of scenarios used to estimate hydrogen and electricity demand in 2030

Scenario	Description
Mixed	Based on shares of renewable energy in the FF55 MIX scenario[5] but adapted to achieve 29% RES-T target and overall 42% RED target[6]
Electrification	RES-T target is achieved primarily through electrification, with sub-targets for RFNBO and advanced biofuels still achieved
RePowerEU	RES-T target is achieved primarily through synthetic fuels, with some electrification of road transport and advanced biofuels
RePowerEU (no H_2 imports)	Identical to RFNBO scenario above, with only domestic production of hydrogen for use in synthetic fuel production rather than imports of renewable hydrogen above a 10 Mt threshold

The scenarios are based on the following key assumptions. Further details of specific assumptions used in these scenarios are provided in Appendix 2: Assumptions used in scenarios.

- The planned phase-out of internal combustion engine (ICE) vehicles in the EU in 2035 will happen, leading to a 2.8% increase in total electricity consumption, in line with the EC's 2021 impact assessment[7].
- EVs have an energy efficiency of 89%, compared to 20% for ICE vehicles[8], which makes electrified transport less energy intensive.
- The share of renewable electricity used in rail and other (non-road) transport in 2030 is in line with expected increase in demand in the FF55 MIX scenario and assumes an overall RES percentage of 65%
- As per a study produced for the European Parliament's TRAN committee, RFNBO use in transport will be primarily e-kerosene for aviation.
- The ReFuelEU Aviation target, will be met fully by e-kerosene as it is the best available jet fuel (and therefore no biofuels, hydrogen etc). E-kerosene demand from the ReFuelEU Aviation target on RFNBOs was estimated by applying the 1.2% target to the Aviation sector final energy consumption from the FF55 MIX scenario, multiplied by the 1.5 energy content as per RED Transport Article 27.2. This target counts towards the 5.5% target from RED Transport.

[5] European Commission (2021), Policy scenarios for delivering the European Green Deal

[6] The EU previously indicated the MIX scenario would achieve 27.7% RES-T share, so falling short of the 29% target

[7] European Commission (2021), Impact Assessment accompanying the proposal for a regulation strengthening the CO_2 emission performance standards for new passenger cars and new light commercial vehicles

[8] Ritchie (2023), Most of the energy you put into a gasoline car is wasted

- E-kerosene has a conversion rate of 42% energy content from electricity, compared to 75% for hydrogen[9].
- The RED Transport sub-target for maritime commands that 1.2% of total energy supplied to maritime transport must come from RFNBOs. This was assumed to be e-hydrocarbon and was calculated by applying the 1.2% target to the Maritime sector final energy consumption from the FF55 MIX Scenario, multiplied by the 1.5 energy content as per RED Transport Article 27.2. This counts towards the 5.5% target from RED Transport.
- We follow the rules set out in the RED Transport Article 27.2 regarding the energy content of different fuels.
    - The share of renewable electricity shall be considered to be four times its energy content when supplied to road vehicles and may be considered to be 1,5 times its energy content when supplied to rail transport
    - The biofuels and biogas produced from the feedstock listed in Annex IX and renewable fuels of non-biological origin (RFNBOs) are considered to be twice their energy content
    - The share of advanced biofuels and biogas produced from the feedstock listed in Part A of Annex IX supplied in the aviation and maritime transport modes are considered to be 1.2 times their energy content
    - The share of RFNBOs supplied in the aviation and maritime transport modes are considered to be 1.5 times their energy content
- Switching to green hydrogen for ammonia and methanol production is assumed to be 42%, in line with the 2030 RED Industry target, apart from in our *mixed* scenario where switching of 80% is assumed in line with the figures specified in the Commission's FF55 MIX scenario.

While developing the scenarios, we encountered several challenges due to overlapping – and sometimes contradictory - documents published by the European Commission, summarised in Box 1 below.

[9] Concawe (2022), e-fuels, A Techno-Economic Assessment of European domestic production and imports towards 2050

Box 1: Problems and inconsistencies

• *The increased scope and ambition of the RES-T target presents a significant challenge, the ramifications of which do not seem to have been considered in sufficient detail. As pointed out by T&E, there is a risk that the increased overall RES-T target will drive the uptake of the most unsustainable biofuel feedstocks.*

• *There is a confusing picture around the expected shares of different energy sources. For example, in the Commission's accompanying document to RePowerEU published in 2022, the share of all advanced biofuels in transport in 2030 is stated as 2.2% (single-counted) in both their Fit-for-55 and RePowerEU scenarios but in the previously published MIX scenario the share of just Annex IX Part A biofuels and biomethane (based on REDII formula) was notably higher at 8.6%. While this is assumed to include double counting (due to the 2x multiplier), it is still notably higher than the figure reported in the newer publication. A justification for this decrease was not widely publicised.*

• *In relation to the consumption of hydrogen and derivative fuels in different scenarios, Table 8 of RePowerEU's accompanying document shows that RePowerEU scenario assumes a lower consumption of synthetic fuels than the Fit-for-55 scenario whereas the consumption of hydrogen in the transport sector is higher by 1.4 Mt of hydrogen in REPowerEU, or about 2.5 times what it would be in Fit-for-55. Again a justification for this was not provided.*

• *While the application of multipliers is a well-intentioned measure intended to drive the use of renewables with higher associated efficiencies and GHG savings, it can create confusion. We note that some Member States appear to have used multipliers inconsistently (and in some instances incorrectly) when we tried to replicate calculations in the SHARES summary results.*

• *In general, mixed signals have been provided by the Commission over expected future hydrogen demand and the electrolyser capacity required to achieve this. This is also pointed out in the recent European Court of Auditors report and discussed further in Section 2.*

1.2.2. Modelling electricity demand

The electricity demand related to the achievement of RED targets depends on the contribution of RFNBO in the achieving those targets. The results of our modelling exercise, displayed in Table 3 and Figure 4 demonstrate how the way in which the 29% RES-T target is achieved significantly impacts the production of hydrogen and total energy demand of the EU.

Table 3: Expected RFNBO hydrogen production and energy demand in 2030 in our modelled scenarios

Scenario	2030			
	Mixed scenario	Electrification scenario	RePowerEU scenario	RePowerEU scenario (no H_2 imports)
RFNBO H_2 production (t)	6,579,000	1,657,663	10,000,000	14,500,779

In each scenario, the annual increase in renewable energy fills three main purposes:

- Meet existing demand by **replacing fossil-based electricity** in the grid.
- Meet new demand by **producing hydrogen**: One tonne of hydrogen requires about 48.2 MWh according to some literature sources[10, 11] on current best processes for water electrolysis (PEM or alkaline electrolysis). This is probably a conservative assumption, as other sources mention 54-55 MWh. Production volumes are taken from Table 2 for each scenario.
- Meet new demand from other activities, including **direct electrification**, e.g. in transport, heating and industry.

Table 4 compares the annual increase in renewable electricity production needed in each scenario, while the *current trend* scenario just continues the trend of net renewables build observed over the past five years.

Table 4: Annual increase in electricity generation

	Mixed scenario	Electrification scenario	RePowerEU scenario	Current trend scenario
Additional renewable production (TWh)	174	156	175	79
- replacing fossil electricity (TWh)	107	112	95	79
- for hydrogen (TWh)	40	10	60	0
- for other demand growth (TWh)	27	35	20	0

Source: Sandbag calculation

Predictably, the RePowerEU scenario **allocates less of the newly added renewable electricity to replace fossil fuels** in the energy mix: only 95 TWh is used to displace fossil electricity, compared to 112 TWh in the electrification scenario.

[10] Clean Hydrogen Partnership (2024), Clean Hydrogen Joint Undertaking: work programme 2024

[11] Hydrogen Tech World

The ***mixed*** scenario, which represents the most likely scenario with a mixture of renewable energy sources used in transport, will require a significant increase in renewable electricity generation from 2022 to 2030, even though overall energy demand is expected to fall[12].

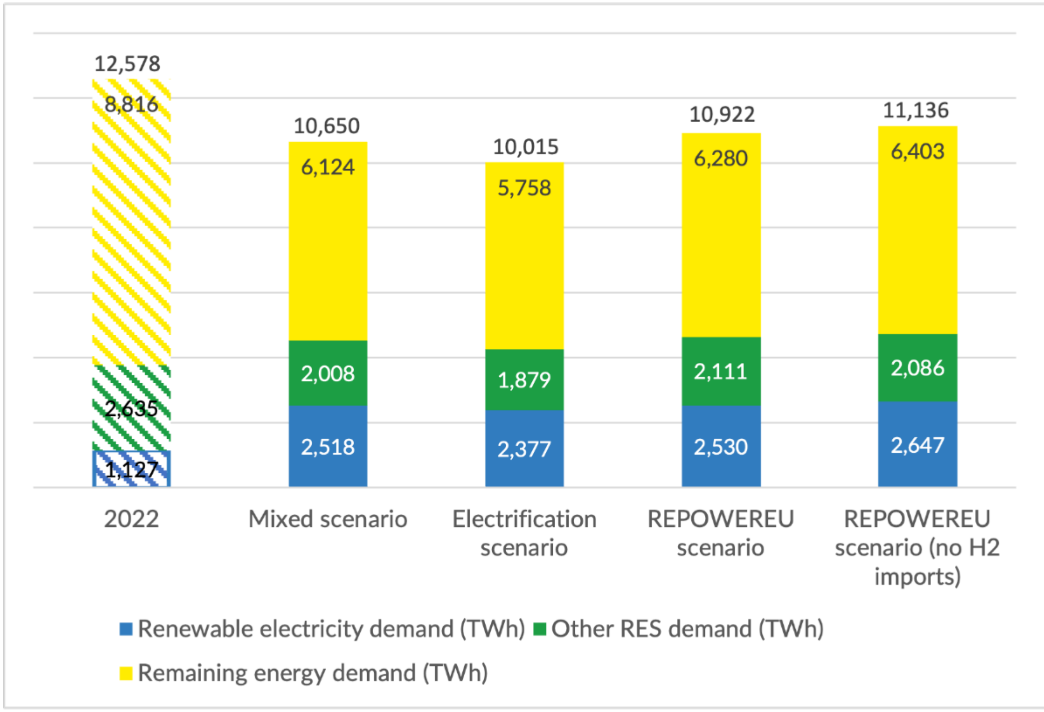

Figure 4: Total EU energy demand in each of the modelled scenarios in 2030, broken down into renewable electricity, energy from other RES sources and remaining (non-renewable) energy

Achieving RED targets through the ***electrification*** scenario would require the lowest overall energy demand of all the different scenarios. This underlines the superior efficiency of direct electrification and reinforces the argument that we should look to electrify wherever possible.

Achieving RED targets through the ***RePowerEU*** scenario would create higher demand for renewable electricity than the previously discussed scenarios. The total RES demand (renewable electricity + other RES demand) of 4,642 TWh in the *RePowerEU* scenario is perhaps not as high compared to the electrification scenario (4,256 TWh) as might be expected, considering the losses encountered in the production of green hydrogen and, subsequently, synthetic fuels. This is because the increased energy demand is masked by the fact that renewable electricity used to produce RFNBOs would itself count towards the total RES target of 42.5%. This has the knock-on effect of pushing up demand for fossil energy; 'remaining' (i.e. non-RES) energy demand increases from 5,758 TWh in the electrification scenario to 6,280 TWh in the *RePowerEU* scenario. Therefore, as well as creating additional steps, costs and bottlenecks, **a high use of RFNBOs to meet RED III would mean greater demand for fossil energy in other parts of the economy.**

[12] According to the EU FF55 Mix scenario, European Parliament (2021), Policy scenarios for delivering the European Green Deal

Importantly this scenario also relies on the use of imported H_2 above the threshold of 10 Mt. This gives a somewhat artificial picture of achieving RED targets using other countries' renewable energy to produce green hydrogen, depriving these countries of renewable electricity they could be using to decarbonise their own energy systems. Additionally, this scenario creates a reliance on imports and there remains doubt over whether importing these quantities of hydrogen is realistic, or environmentally sound. Indeed, the aspirational targets for imports of hydrogen set out in RePowerEU have already been cast into doubt, due to high costs. The Commission Staff Working Document for Europe's 2040 climate target, published in 2023 [13] , states "*the amounts of imports of hydrogen and e-fuels remain relatively small in 2040, due to still relatively high costs*". Imports appear negligible in 2040 in all the scenarios presented in the Commission's SWD, a whole decade after the timeframe of the aspirational RePowerEU targets. If renewable hydrogen demand were to be met by domestic production the energy demand would increase further. This is shown in the **RePowerEU (no H_2 imports)** scenario, which would require 14.5 Mt of hydrogen to be produced to meet the demand for synthetic fuels, increasing renewable electricity demand.

Other studies have reached similar conclusions. A 2022 report by Concawe estimated that, if current transport fuel demand of the EU was completely provided with e-fuels, this would result in demand for renewable electricity of approximately 12,000 TWh_e/a, with the transport sector alone requiring more than half of total renewable power generation potential[14]. While this scenario (and indeed the *RePowerEU* scenario without H_2 imports we have outlined) is not realistic, these scenarios clearly illustrate the potential downsides of driving hydrogen production higher without careful consideration of alternative fuel switching technologies, especially electrification.

[13] European Commission (2024), Impact assessment on 2040 target, SWD(2024) 63, Part 3, p. 28.

[14] Concawe (2022), E-fuels: a techno-economic assessment of European domestic production and imports towards 2050

1.3. Estimating renewable power capacity

Having estimated the demand for renewable power generation, in this section we try to estimate how this translates in terms of renewable capacity needed given a certain technology breakdown (photovoltaic solar, offshore and onshore wind, hydropower, biomass, and geothermal energy, among others) and their geographical location. These technologies have varying future growth potentials, so we assumed that new capacity will be added in the same proportions as foreseen in the European Commission's FF55 MIX scenario described in section 1.2.1. Using load factor figures for each technology (see Appendix 3: Load factors), we deduced the share of each technology in extra production, as illustrated in Figure 5.

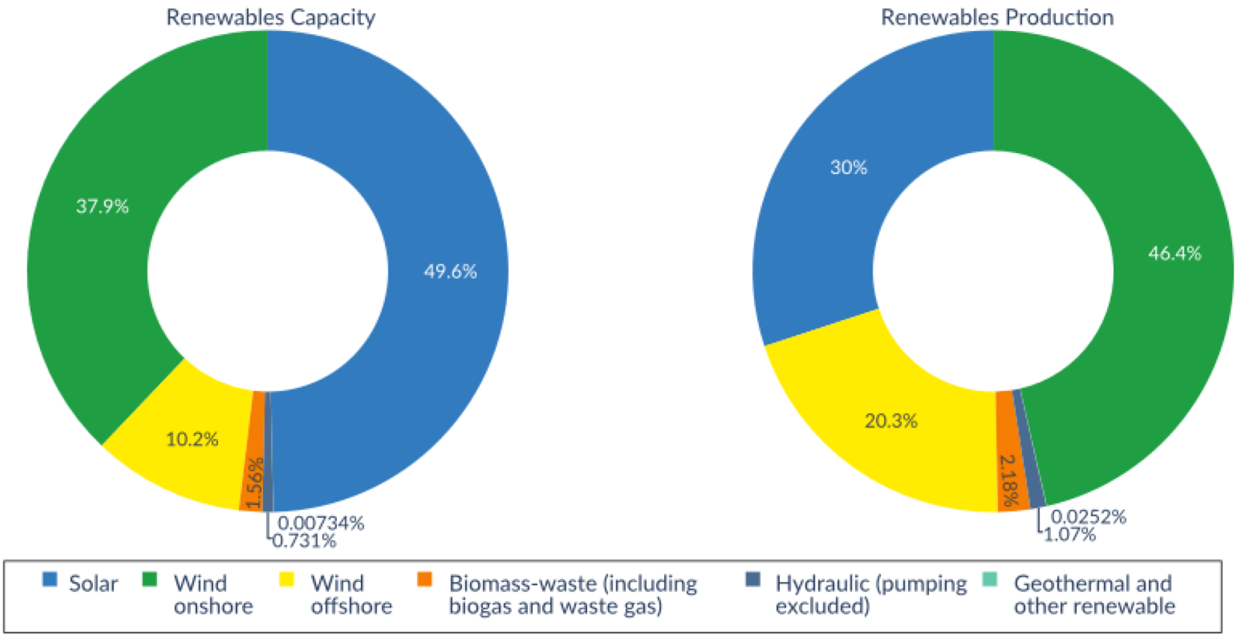

Figure 5: Left: Share of net capacity additions between 2020 and 2030 in the FF55 MIX scenario (Source: European Commission). Right: Production from added capacity in the FF55 MIX scenario (Source: European Commission).

Figure 6 shows the geographic distribution of this extra capacity between 2020 and 2030, based on the FF55 MIX scenario.

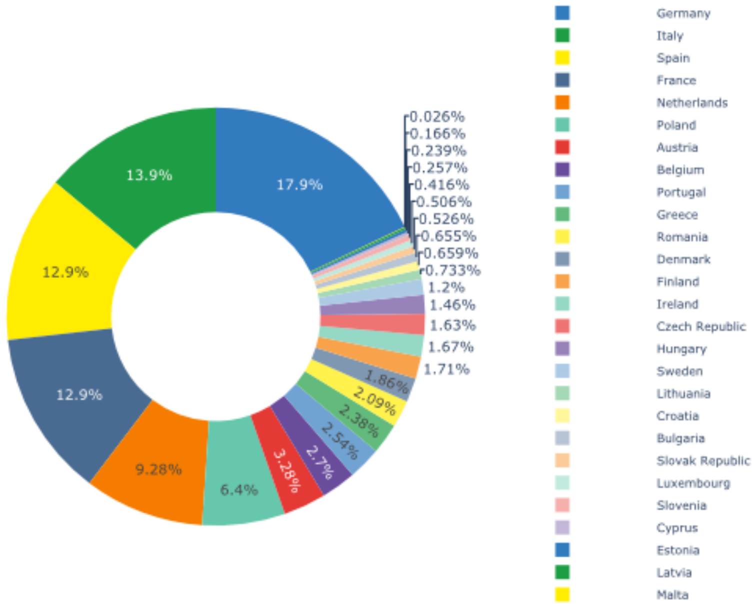

Figure 6: Share of net capacity additions between 2020 and 2030 in the FF55 MIX scenario (Source: European Commission and Sandbag).

Figure 7 illustrates the growth in renewable capacity as well as the required capacity to be achieved by 2030 under each scenario, based on data from IRENA[15].

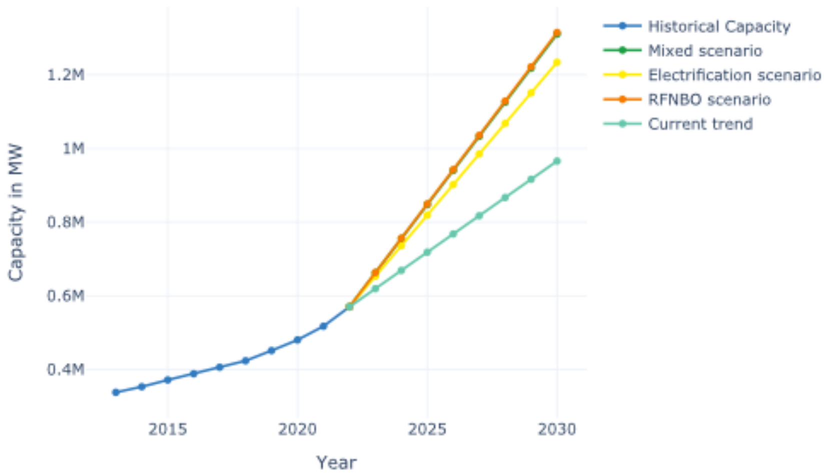

Figure 7: Capacity Projection with Different Scenarios (2013-2030)

[15] IRENA (2023), Renewable Capacity Statistics

2. Emissions induced by production patterns

Section 1 focused on total amounts of renewable energy. It showed that a large-scale recourse to RFNBO (for example in the transportation sector) would increase the overall demand for renewable but also non-renewable electricity. This explains why, in our more efficient 'electrification' scenario, a lower amount of hydrogen is used, mostly for **industrial decarbonisation** where some processes cannot be directly electrified.

This section looks more closely at hydrogen production patterns and how they impact CO_2 emissions from power generation. Although hydrogen is labelled as "zero-emission" if produced using renewable electricity sources (RES), depending on the specific timing of the electricity used, its production can have a knock-on effect on the electricity grid, resulting in **'induced' emissions**. This section aims to measure the emissions induced by different patterns of electricity use.

We consider that, at any given time, a new load of renewable electricity demand has "induced emissions" if at that same moment, fossil electricity is produced in the grid, which the new load will prevent from being displaced by renewable electricity. This approach estimates the carbon footprint of electricity use by considering its **overall impact on the grid**, rather than just tracing the source of the electricity used.

2.1. RFNBO hydrogen: A case study

The **RFNBO standard**, as defined by EU legislation, qualifies any hydrogen produced from electricity that is either "spare" (i.e. generated at times of excess electricity) or produced by "additional" (i.e. recently built) RES. There are also derogative provisions that extend eligibility to less strict conditions, allowing some degree of mismatch between the timing of RES output and electricity used for hydrogen.

However, the standard ignores the fact that, in some cases, newly built RES used to produce hydrogen could instead feed the electricity grid to displace fossil electricity, and the very use of this RES electricity for hydrogen production prevents the substitution of this fossil electricity in the power grid. In this sense, **hydrogen production can indirectly induce fossil electricity generation** and CO_2 emissions.

For any new renewable capacity, we estimated the emissions induced by RFNBO hydrogen production as follows:

i. At all times, we estimated (see Appendix 5: Minimum fossil content) a quantity of **non-displaceable fossil** electricity for technical reasons (illustrated on Figure 8 as the red area below the black horizontal line). The remaining fossil electricity (above that line) is considered displaceable.

ii. At times of **'spare' electricity**, when no displaceable fossil electricity is present in the grid**:** we considered the hydrogen produced by any new capacity as carbon-free.

iii. At times when **displaceable fossil electricity is present in the grid** (non-spare): we attributed to hydrogen the portion of this displaceable fossil electricity that is consumed by electrolysers.

To estimate emissions per tonne of hydrogen in a given year, we summed the emissions attributed to hydrogen under iii) over that year and divided that sum by the total amount of hydrogen expected to be produced in that year.

The calculation can be summarised by the following equation:

$$\text{Induced emissions of 1t } H_2 \text{ in a given year} = \frac{\sum_{t\,\in non-Spare} \min\left(displaceable\ elec(t), elec\ consumed\ by\ electrolysers(t)\right) \times \text{emission intensity of fossil electricity(t)}}{\text{Total amount of hydrogen produced over the year}}$$

Figure 8 represents the difference in the German electricity grid mix between a certain week in November 2022 and that same week in 2030, assuming additional renewables production as per the *mixed* scenario. In the figure, the striped red and black area is **fossil electricity not removed from the grid because of hydrogen production**, the emissions of which are therefore induced by hydrogen production.

The real RFNBO standard has derogations from additionality conditions, for example in countries with low-carbon grids, where hydrogen may qualify as RFNBO even without electrolysers and renewable sources operating simultaneously, but our calculations assume a slightly idealised version of the standard without derogation, so that only electricity from new renewable sources is counted.

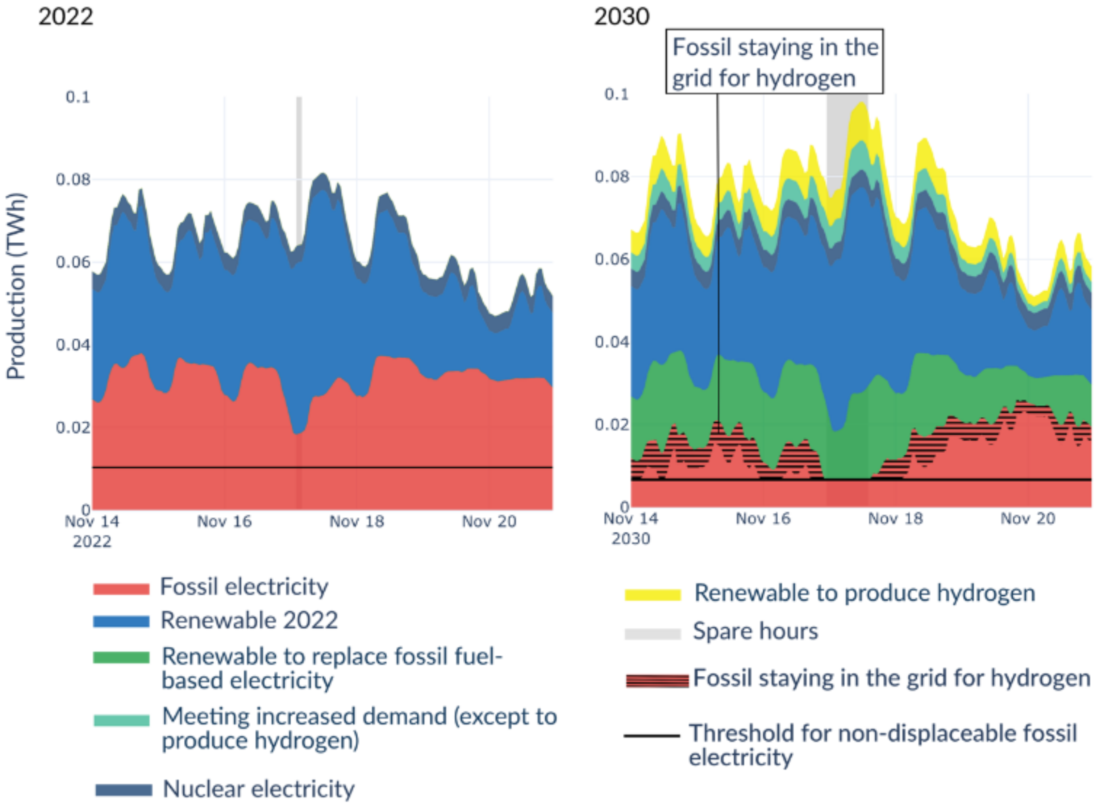

Figure 8: The grid in 2022 and the projection of the grid in Germany in 2030 in the Mixed scenario with spare hours.

2.1.1. Methodology

To calculate "spare" electricity each year (represented as the vertical grey band in Figure 8, we first identified the hours in 2022 when power prices were below €20/MWh (which is the criteria used in Article 6.3 of the Delegated Act on methodology for the production of RFNBO), shown in Table for most EU countries. For comparison, the number of hours in a year is 8,760.

Table 5: Number of hours when prices was below €20/MWh in 2022[16].

Country	Number of "spare" hours in 2022	Country	Number of "spare" hours in 2022
Austria	45	Italy	2
Belgium	209	Latvia	214
Bulgaria	88	Lithuania	212
Croatia	79	Netherlands	220
Czech Republic	110	Ireland	144
Denmark	387	Poland	8
Estonia	299	Portugal	162
Finland	1165	Romania	106
France	60	Slovakia	81
Germany-Luxembroug	209	Slovenia	58
Greece	22	Spain	162
Hungary	63	Sweden	1512

We then deduced spare electricity in 2023–2030 by superimposing each year to the load curve of the previous year the amount of electricity that would be generated by that year's additional renewables capacity assuming its load curve follows **the 2022 renewable load curve**[17] (Figure 8 left panel, blue area). Renewable generation for demand growth and fossil replacement by country follows the distribution of new renewable shares between 2022 and 2030 in the FF55 MIX scenario, Figure 6, while renewable generation for hydrogen production mirrors the distribution of hydrogen infrastructure projects (see Appendix 4: Hydrogen project infrastructure).

The resulting load curve for 2030 is shown on the right panel of Figure 8. It shows, based on the breakdown as shown in Figure 8, the amount of new renewables used to:

- Replace fossil fuel-based electricity (Figure 8, right panel, green curve)
- Meet increased demand (except for hydrogen) (Figure 8, right panel, cyan curve)
- Produce hydrogen (Figure 8, right panel, yellow curve)

Only the displaceable fossil electricity was counted in hydrogen-induced emissions. The red striped area in Figure 8 represents this portion of fossil fuel electricity that remains in the grid for hydrogen production. Hydrogen-induced emissions are from this fossil portion. The emissions intensity is assumed to be the same as the current fossil mix, on an hourly basis. Hydrogen-induced emissions are determined each year by dividing these emissions over the year by the amount of hydrogen produced that year (in tonnes).

[16] Data from Eurelectric. For countries with multiple bidding zones (Sweden, Italy, and Denmark), we compute the number of hours where the price is below €20/MWh across all bidding zones within the country. Data are missing for Malta and Cyprus.

[17] Data from Eurelectric

2.1.2. Results

Figure 9 shows the emissions induced by the production of 1 tonne of hydrogen under the *mixed* scenario and the *current trend* scenario between 2025 and 2030 while lists the emissions figures for 2030. As the grid becomes less emission intensive, emissions induced by hydrogen production decrease. However, average emissions intensity only becomes lower than that of hydrogen from steam methane reforming (9.1 tCO_2/tH_2[18]) from 2028 if the deployment of renewables follows the relatively ambitious *mixed* scenario where renewables capacity build meets all RED targets, see Figure 10. If renewables deployment continued in line with its *current trend*, emissions induced by RFNBO would remain higher than from steam methane reforming until after 2030.

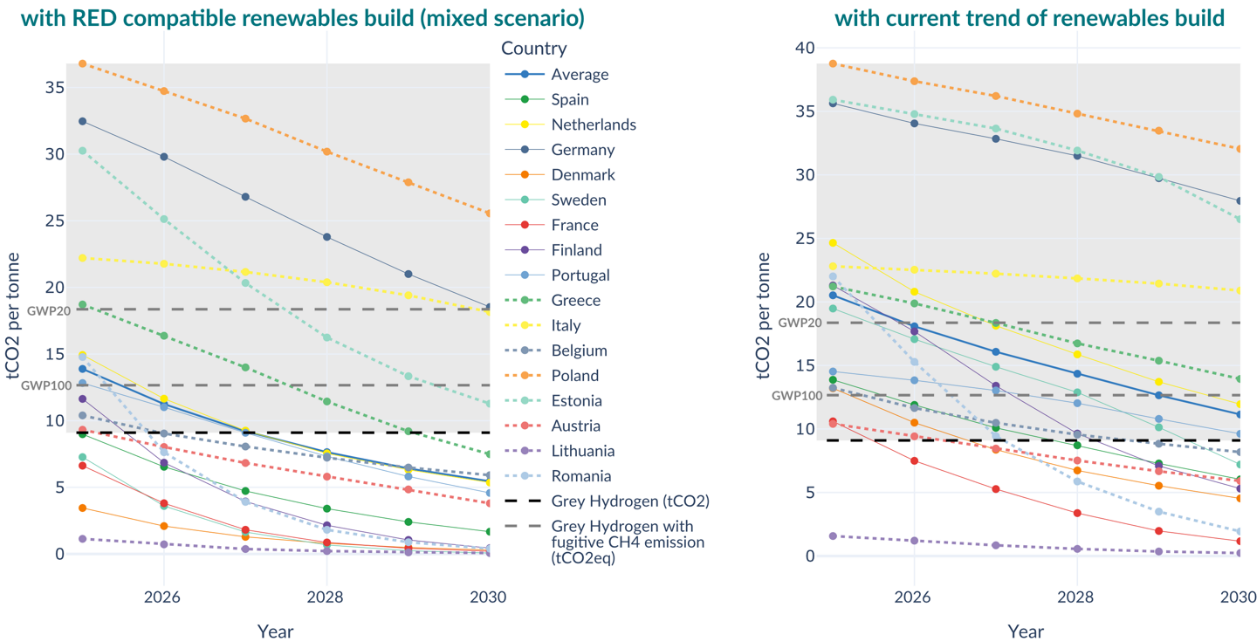

Figure 9: Emissions induced by the production of 1 tonne of RFNBO hydrogen under the Mixed scenario and the Current trend scenario between 2025 and 2030

Table 6: Emissions induced by the production of 1 tonne of hydrogen in 2030 for each country hosting hydrogen projects.

Country	Mixed scenario (tCO_2/tH_2)	Current trend (tCO_2/tH_2)	Country	Mixed scenario (tCO_2/tH_2)	Current trend (tCO_2/tH_2)
Wtd average	**5.45**	**11.14**	**Greece**	7.48	13.94
Spain	1.67	6.03	**Italy**	18.15	20.89
Netherlands	5.36	11.9	**Belgium**	5.91	8.18
Germany	18.53	27.95	**Poland**	25.56	32.04
Denmark	0.30	4.53	**Estonia**	11.28	26.5

[18] The carbon footprint of grey hydrogen is taken from Robert W. Howarth and Mark Z. Jacobson, *How Green is Blue Hydrogen?*. This value includes both direct CO_2 emissions and indirect upstream CO_2 emissions associated with the production and transport of natural gas.

Sweden	0.07	7.2	**Austria**	3.80	5.90
France	0.20	1.16	**Lithuania**	0.07	0.23
Finland	0.44	5.3	**Romania**	0.40	1.93
Portugal	4.58	9.62	**Slovakia**	11.44	19.27

It is also clear that induced emissions are highly dependent on the country, as we did not consider possible changes in electricity flows between power grids. In other words, we assume that any increment in renewable electricity generation could only be consumed in the country where it is produced, whereas in reality, part of it could be exported to neighbouring countries. This simplification tends to over-estimate the amount of 'spare' electricity and, in turn, **under-estimate hydrogen-induced emissions**. Under those assumptions, in Member States with low-emission grids, induced emissions could be as low as 0.20 tCO_2/tH_2, as seen in France. Conversely, in countries more reliant on fossil electricity, such as Poland, they can be as high as 25 tCO_2/tH_2.

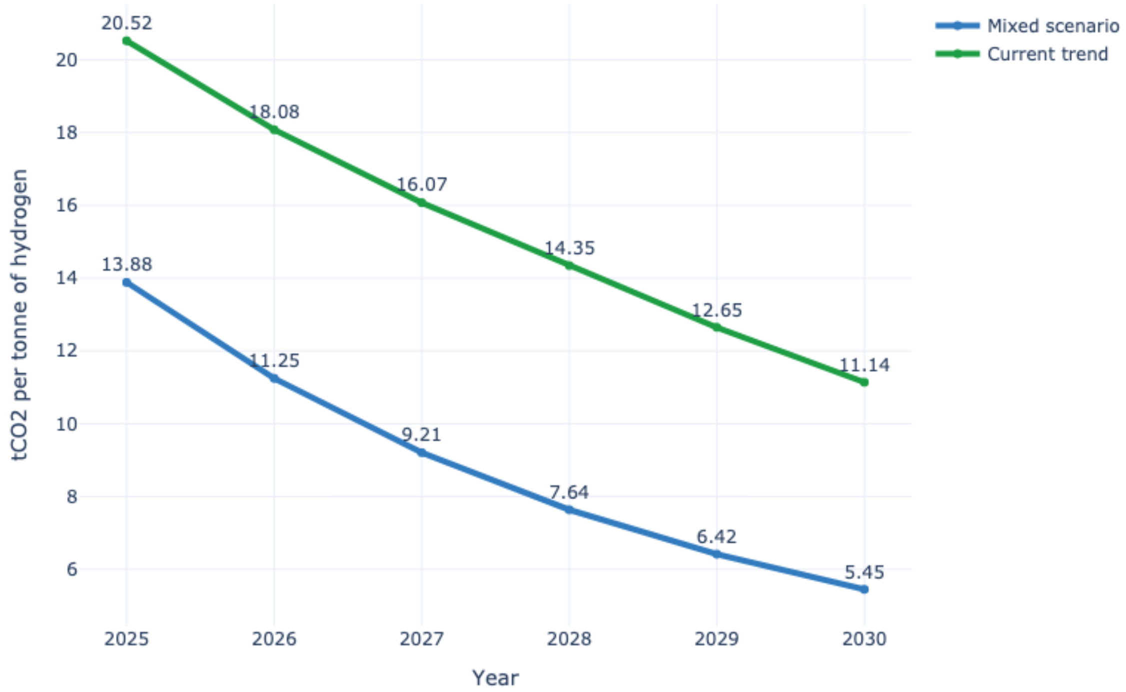

Figure 10: Emissions induced by RFNBO hydrogen production (tCO2/tH2) between 2025 and 2030

2.2. If interconnection was perfect

The previous section ignored possible changes in electricity flows between power grids, which creates differences in induced emissions between countries and under-estimates hydrogen-induced emissions. In reality, electricity flows can vary between countries to let some of the added renewable power surplus generated in a given country displace fossil power in its neighbouring countries through existing interconnectors. Moreover, it is likely that interconnection capacity will increase over time, allowing even more electricity to flow between Member States. So, in this section we make the opposite assumption; that power grids are perfectly connected, so that any excess power supply in one country flows through borders to meet the demand in any neighbouring country. If that was the case, there would be no difference in availability of renewables capacity between Member States.

Under such circumstances, there would be less time when renewable capacity is in excess, because excess in the grid of one country would more likely be used by neighbouring countries. Conversely, the carbon intensity of the European grid is likely to be lower, because less renewables capacity would be left unused, displacing more fossil electricity. This is reflected by shows a slightly larger share of renewables in the overall European mix in November 2022 under a simulated "perfectly connected" grid, Figure 11.

Achieving such interconnection is not feasible by 2030, as interconnection project timeframes are an average of nine years in Europe[19]. While this makes hydrogen production more relevant in the meantime, it also adds to the urgency of prioritising interconnection.

The need to better connect EU regions is already recognised by the European Commission. In its proposed Clean Industrial Deal, the Commission announced a forthcoming **Action Plan for Affordable Energy** which is supposed

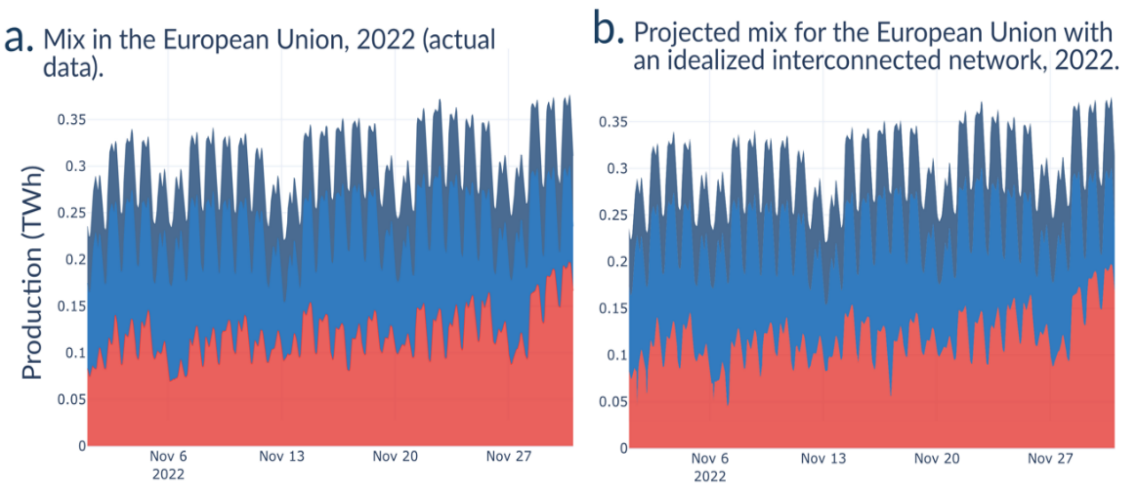

Figure 11: European mix actual data and simulation with perfectly interconnected network in 2022

[19] EEB and Ember (2023), Power in Unity

to address "interconnections and grids". The document promises a **European Grid Package** by Q1 2026 “to, among others, simplify Trans-European Networks for Energy, ensure cross-border integrated planning and delivery of projects, especially on interconnectors…”. We can only approve this initiative, except for its delayed timing.

With perfectly connected grids, emissions induced by hydrogen production would be about double the amount under the “current flow” assumption (see Figure 12), ending at 10.24 tCO_2 compared to 5.45 tCO_2 per tH_2 in 2030 in the *mixed* scenario. The difference between “perfect” and “current” flows is even wider if renewables build only follows the *current trend*, with nearly 23.75 tCO_2 vs. 11.14 tCO_2 per tH_2, respectively. These two assumptions (current vs. perfect flows) are gross simplifications, neither of which match reality, but it is certain that the former under-estimates induced emissions whereas the latter over-estimates them. A more accurate value would therefore sit somewhere between the two curves, whatever the scenario.

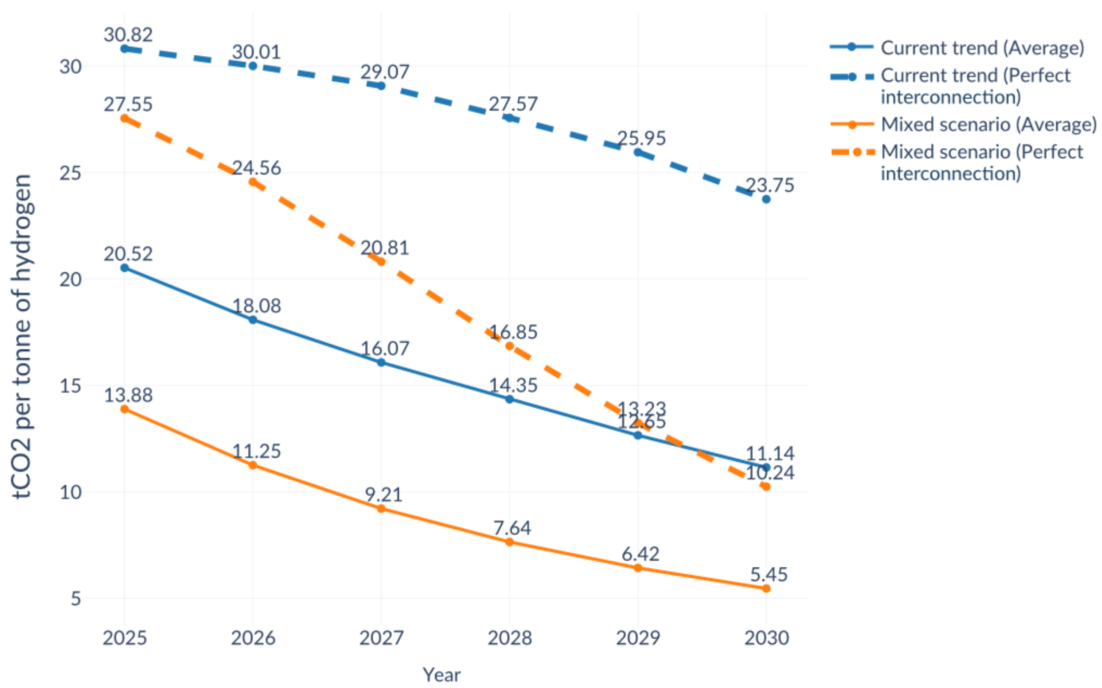

Figure 12: Emissions induced by RFNBO hydrogen production, either in weighted average between countries, or with a perfectly connected grid in the Mixed scenario.

2.3. If electrolysers ran 24 hours

The RFNBO standard allows some flexibility in the attribution of "additional" renewable electricity generation to hydrogen production. For example, before 2030, it only requires that the timing of renewable electricity generation matches electricity use for hydrogen on a monthly[20] —rather than hourly[21]— basis; the temporal correlation criteria does not even apply in low-carbon[22] or high-RES Member States[23]; and until 2028, the "additionality" requirement is waived altogether, making eligible any existing RES and grid connections for hydrogen production.

We have not precisely modelled these derogations, but we have modelled the slightly more extreme case where electrolysers ran 24 hours a day. Whenever electricity is lacking in the grid, the shortfall is then met by natural gas OCGT plants, with emission intensity of 0.5 tCO_2 per MWh.

Figure 13 illustrates this: allocated renewable electricity is intermittent, while electrolyser demand is constant (black line), the new renewable energy allocated to hydrogen is shown in yellow, while the shortfall is shown in orange. When demand exceeds allocated renewables, the shortfall is met by grid electricity, typically from gas OCGT plants (0.5 tCO_2/MWh).

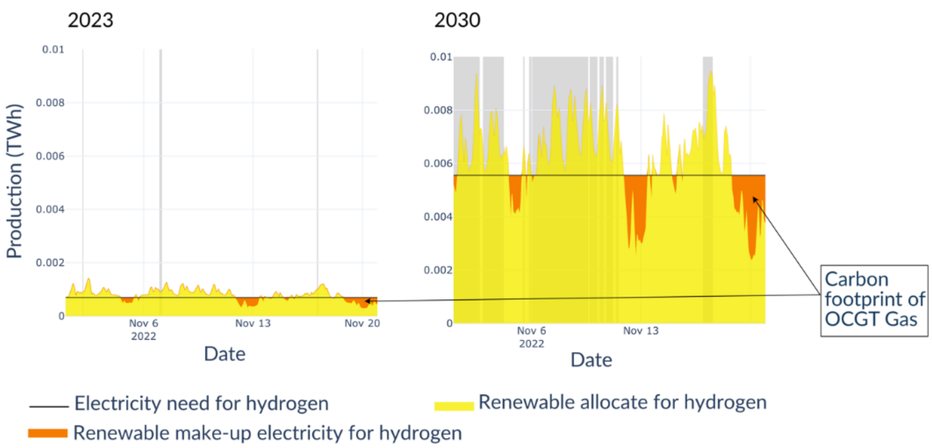

Figure 13: Electricity produced allocated to hydrogen in Germany in November 2023 and 2030, and the electricity demanded by electrolysers without the time correlation.

[20] Article 6, paragraph 1 of the Delegated Regulation on RFNBO production rules

[21] Article 5 of Delegated Regulation on RFNBO production rules

[22] Renewable generation ≥ 90% or a carbon intensity <18 gCO_2eq/MJ on average over the previous calendar year, as per Art 4.1 and 4.2 of the Delegated Regulation on RFNBO production rules

[23] For low-carbon grids, a power purchase agreement with existing RES is sufficient - Article 4(2)(a) of Delegated Regulation on RFNBO production rules

Figure 14 compares the emissions induced by hydrogen produced either under the RFNBO assumptions described in 2.1.1 or under no constraint to match electricity use with any renewable power generation, i.e. 24h a day. Predictably, induced emissions are higher in the “24h” mode (at 9.02 tCO_2/tH_2 in 2030) than in the RFNBO mode (5.45 tCO_2/tH_2) in the *mixed* scenario. Given that the RFNBO assumptions used in the chart are stricter than reality (ignoring all derogations from additionality or correlation criteria), they likely **underestimate induced emissions** whereas the “24h” case likely overestimates emissions, as it assumes no low-carbon electricity is imported from neighbouring countries. As discussed in Section 2.2, a more accurate estimate of induced emissions would likely fall between the two curves.

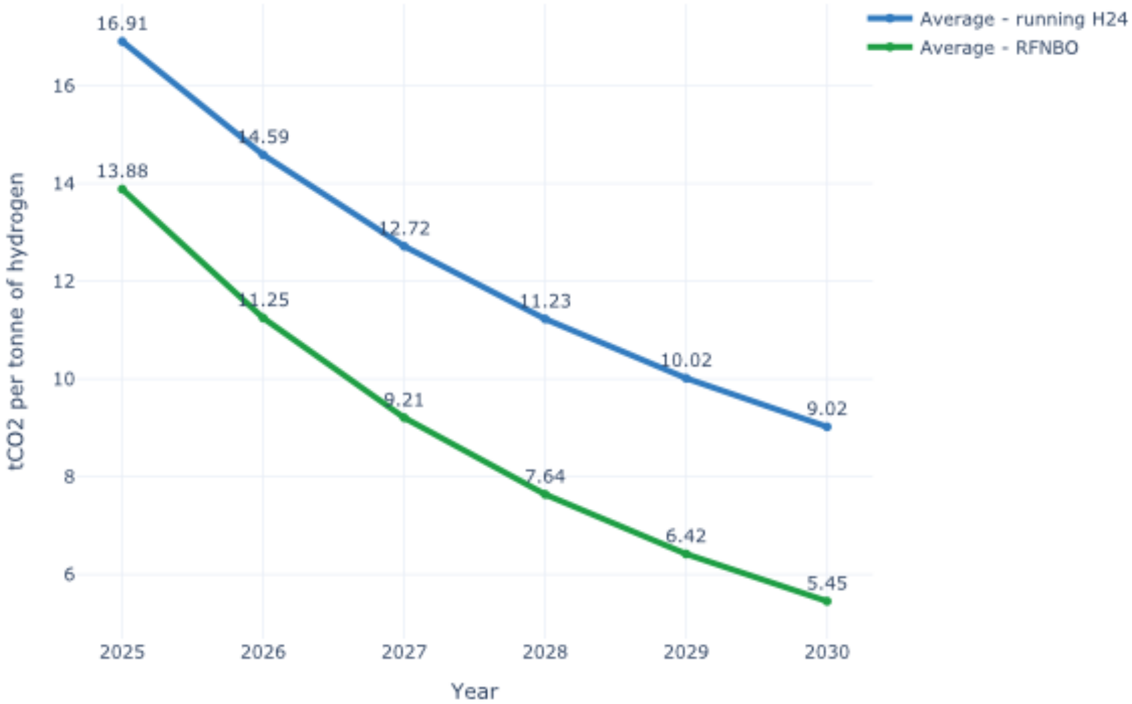

Figure 14: Carbon footprint of hydrogen production in the mixed scenario, based on the model described earlier. This model assumes that electrolyser is turned on without time constraints.

3. Decarbonising industry

3.1. How much green hydrogen can we really produce?

The previous sections showed that, when renewable electricity capacity is not in excess, it is better to use it to decarbonise the grid than to power electrolysers while keeping thermal electricity in the grid. However, when electrolysers operate using surplus renewable electricity that would otherwise be curtailed or wasted, as described in section 2.1, hydrogen production does not induce additional emissions. We therefore estimated the amount of such 'induced emissions-free' hydrogen that can be produced in each scenario.

By 2030, if renewables capacity has been developed in line with our *mixed* scenario compatible with RED targets, about 5.5 million tonnes of truly green hydrogen could be produced in Europe, whereas another 1.1 million under the RFNBO standard would induce emissions (see Figure 15). Although induced emissions are caused by a relatively small proportion of the hydrogen produced (17%), the induced emission intensity of this small proportion is very high, at about 30 tCO_2/tH_2 on average, with differences between countries depending on their fossil electricity mix. Figure 16 breaks down those quantities for different countries under the assumption of constant electricity flows through borders. Under those assumptions, nearly all RFNBO hydrogen have no induced emissions in countries like Sweden, France and Finland, whereas the proportion of hydrogen without induced emissions falls to only 55% in Germany.

It's important to note that the amount of hydrogen calculated without induced emissions is likely to be **overestimated** due to 1) the relatively **stricter assumptions used than in the actual RFNBO standard** and 2) the assumption of **constant electricity flows between countries**. It also assumes that new renewables capacity will be built in line with the *mixed* scenario, which means reaching all RED targets. Under more conservative assumptions, the amount of induced emissions-free hydrogen could be as much as six times lower, as suggested by Figure 15.

With these elements in mind, producing hydrogen without induced emissions will only be possible by running electrolysers at lower load factors than the RFNBO standard otherwise allows. This makes the economic case of electrolytic hydrogen less interesting if capital costs need to be amortised over fewer operating hours. A more thorough study would have involved only considering the production potential in countries where emission-free load factors can be higher than, say, 4000 hours per year, which would have further reduced the volumes achievable.

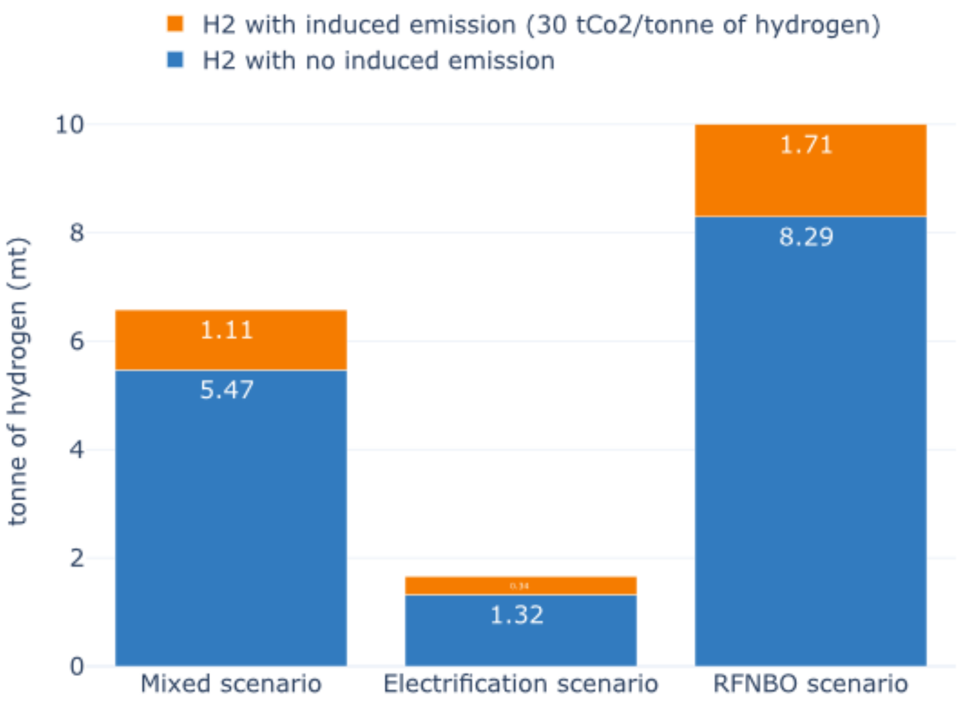

Figure 15: Hydrogen produced with and without induced emissions in 2030 under the RFNBO standard

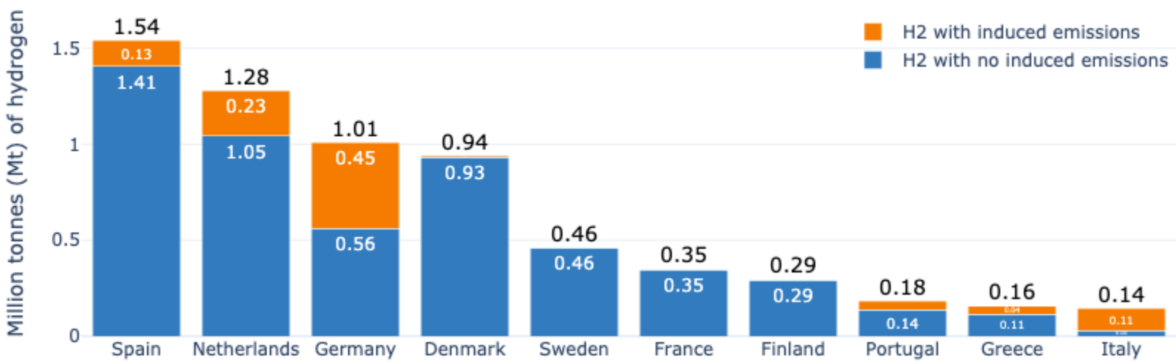

Figure 16: RFNBO hydrogen with and without induced emissions in 2030 (under the mixed scenario)

3.2. When is ‘green steel’ not green steel?

Section 3.1 showed that an amount lower than 5.5m tonnes of hydrogen per year could be produced without induced emissions by 2030. Under these conditions, green steel made from hydrogen induces no emissions. In contrast, steel that would be produced using RFNBO hydrogen produced at times that induce grid emissions, would have a much higher carbon footprint.

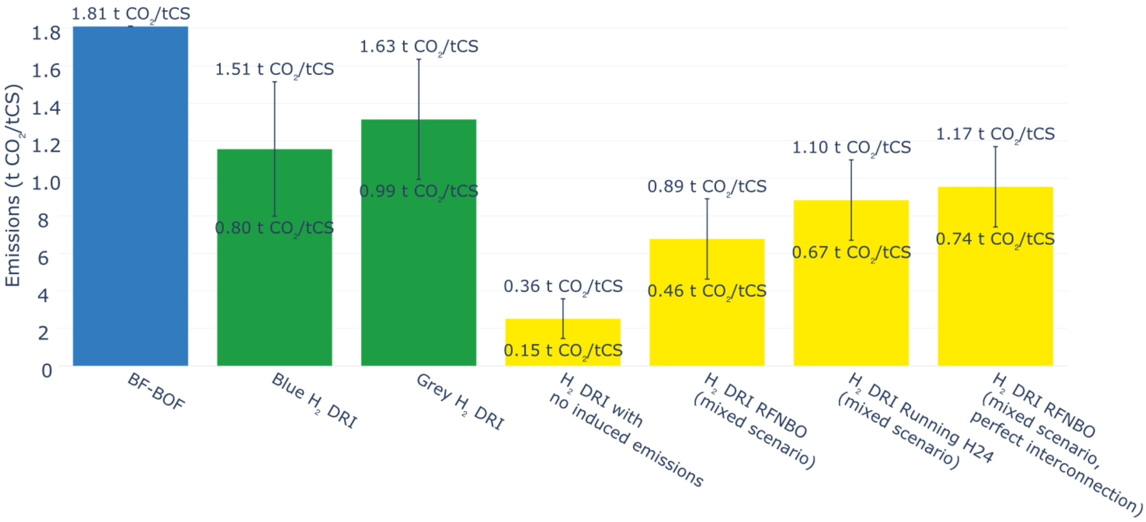

Figure 17: CO_2 emissions per tonne of finished steel in Europe, in 2030

Figure 17 compares the carbon footprint of steel production using different technologies, including hydrogen produced in different ways. Figures for hydrogen DRI steel are based on the assumption of 58kg of hydrogen[24] and 1 tonne of DRI per tonne of steel[25]. The figure for BF-BOF steel represent “scope 1 & upstream + scope 2” emissions (as labelled by JRC[26]) covered by the EU ETS.

[24] Millner, R. et al. (2021), MIDREX H_2 – The Road to CO_2-free Direct Reduction

[25] Other inputs include electricity (1.062 MWh/tCS), fuel for carburisation (high value with natural gas: 73.4 $kgCO_2$/tDRI, low value with biofuel: 0), lime and electrodes (53 $kgCO_2$/tCS), ferro-alloy (11 kg/tCS), pelletisation are taken between 0.163 tCO_2/t pellet (high value, which corresponds to the EU’s 10% least emission-intensive sintering plants) and 0.03 tCO2/t pellet (low value). These numbers take into account both direct (Scope 1) and indirect (Scope 2) emissions, with variations due to electricity intensity and the choice of high/low values for inputs. The emission intensity of hydrogen includes fugitive emissions (How green is blue hydrogen, Robert W. Howarth at al.), low and high values correspond to the GWP100 and GWP20 assumptions, respectively. For grey, blue and RFNBO hydrogen, the low value assumes no emissions for electricity used other than for hydrogen production, while the high value reflects the carbon intensity projected in 2030 for electricity in Germany in the mixed scenario (0.204 tCO_2/MWh). For green hydrogen with no induced emissions, only zero-emission electricity is assumed.

[26] JRC (2022), Greenhouse gas intensities of the EU steel industry and its trading partners

Steel produced through the BF-BOF route has the highest emission intensity, at 1.81 tCO_2 per tonne of steel. As for steel produced using electrolytic hydrogen, its carbon footprint could range from 0.15 tCO_2 in the best case (use of biofuels and zero emissions electricity in the arc furnace etc.) if DRI production does not induce emissions, up to 1.17 tCO_2 in the worst case (furnace using natural gas and electricity at average German emissions intensity etc.) if it does. Steel from electrolytic hydrogen has a higher climate impact when electrolysers operate continuously (24/7). Induced emissions from hydrogen production would appear higher if cross-border electricity flows were better estimated. In perfectly interconnected countries, they would look even higher, reflecting the relatively better climate impact in increasing cross-border flows.

These figures are all given for 2030 in the *mixed* scenario, which assumes that RED targets are all met, including a large amount of new renewable electricity capacity. Carbon footprints (for H_2-DRI steel) would be higher if renewable electricity generation misses the RED target.

Figure 18 shows how RFNBO hydrogen steel production compares between countries in 2030, assuming renewables capacity in line with the mixed scenario. It shows large differences between countries due to different availability levels of low-carbon electricity, but these differences are exaggerated because the potential benefits of increased cross-border electricity flows are ignored.

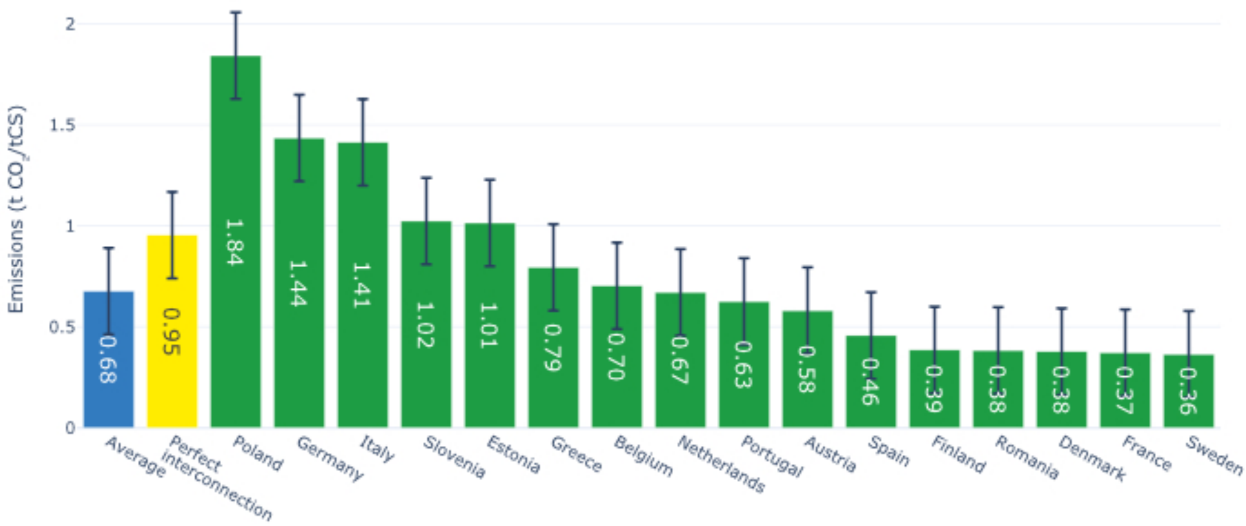

Figure 18: CO_2 emissions per tonne of steel per country with RFNBO H_2 DRI process under the Mixed scenario

3.3. Other industrial applications

Amongst other industrial application where green hydrogen could be considered as a decarbonisation pathway, the most likely candidates are applications already using hydrogen produced from fossil fuels: refining, ammonia, methanol and other chemicals production. For all these applications, the comparison of carbon footprints boils down to comparing the footprint of 1t RFNBO and 1t hydrogen from steam methane reforming. This is what we have shown in Section 2.

4. Recommendations

In this report we have shown how the climate impact of electricity use depends not only on *how* electricity is generated, but also *when and where* it is consumed. As Europe ramps up renewable energy deployment to meet RED III targets, the way new electricity demand is introduced can either support or undermine decarbonisation goals. Misaligned electricity use, particularly during periods of fossil-based grid generation, risks increasing emissions even when the electricity is nominally renewable. While green hydrogen served as a case study in our analysis, the core insights apply more broadly: efficient, well-timed electricity use is essential to avoid induced emissions, minimise energy system inefficiencies, and make the most of limited renewable capacity in the critical years before electricity supply is fully decarbonised.

4.1. Getting the renewable mix right

The increased ambition of the overall RED III target means renewable electricity generation needs to expand significantly by 2030 regardless of how sectoral RED III sub-targets are achieved. In particular, the increased scope and ambition of the RES-T target represent a significant challenge. While this increased ambition is welcome, it is crucial to ensure that this target is achieved in the most energy efficient and sustainable way possible.

Electrification wherever possible is the most energy-efficient means of reaching the RED III transport target. Our modelling shows that meeting the RED targets with an increase in the use of RFNBOs, as targeted by the RePowerEU plan, would increase demand for renewable electricity and push up overall energy demand. The inefficiency is masked by the fact that renewable electricity used to produce green hydrogen counts towards the overall RES target. Incentivising the use of RFNBOs in transport, beyond niche applications to which it is most suited, creates a vicious cycle of inefficiency, pushing energy demand higher and higher. Additional challenges associated with RFNBOs (high costs, complex supply chains, need for imports etc) also present a risk that RED III targets may not be achieved.

Of course, other renewable fuels are not without their drawbacks. Most notably, there is a risk that the target will be met by the least sustainable biofuels which must be avoided. Instead, transport should be electrified wherever possible to avoid competition for the use of renewable hydrogen in industry and to **minimise the amount of renewable capacity that needs to be installed by 2030**.

4.2. Minding induced emissions

The climate impact of electricity use is very sensitive to the emission intensity of marginal power production at the time of production. Any extra electricity demand load at times of fossil marginal generation creates a net increase in CO_2 emissions unless the overall energy conversion rate from fossil fuel to power to end use is higher than 100%. This is the case of some advanced heat pumps which, due to their high coefficients of performance (COP), are still more energy efficient than burning fossil fuels even after the energy losses in the conversion of gas to power. But for any other electrification technology, extreme caution should be given to the timing of electricity use.

When calculating the carbon footprint of used electricity, we included broader impact on electricity grids, which the EU's RFNBO standard ignores, for now. In this report, we calculated the negative consequences of this omission under different scenarios and assumptions, and the **resulting emissions can vary dramatically** within a range as wide as 5-30 tCO_2 per tonne of hydrogen produced, on average across Member States. As for differences between Member States, they are very high (between 0.3 and 25 tCO_2 in our *mixed* scenario), but the constant border flow assumption undoubtably underestimates the lower end of this range.

While it is possible to **use electricity without inducing emissions**, that would involve running equipment at lower load factors than in a business-as-usual case or even, in the case of hydrogen, than allowed by the RFNBO standard. The electrification of industry will require some degree of adaptation to the variable nature of renewable electricity. Luckily, **RFNBO hydrogen production** is a relatively flexible process which allows for successive switching on and off. It should therefore be encouraged in areas and only at times when it would not create undesirable induced emissions but strongly discouraged outside those times and places. We recommend that the **RFNBO standard should be restricted to the condition set in Article 6.3 of the Delegated Act on the methodology for the production of RFNBO, on power prices below €20/MWh.**

Running equipment at lower load factors comes at **higher cost**, as capex is amortised over fewer operating hours. The overall benefits brought by electrification projects should therefore be carefully compared to those of alternatives such as **improved grid interconnection**, which also provide valuable emission savings thanks to the displacement of fossil electricity in countries connected to neighbours with high renewables production.

5. Appendix

5.1. Appendix 1: Annex IX of RED

Part A

Feedstocks for the production of biogas for transport and advanced biofuels, the contribution of which towards the minimum shares referred to in the first and fourth subparagraphs of Article 25(1) may be considered to be twice their energy content:

(a) Algae if cultivated on land in ponds or photobioreactors;

(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC;

(c) Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive;

(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex;

(e) Straw;

(f) Animal manure and sewage sludge;

(g) Palm oil mill effluent and empty palm fruit bunches;

(h) Tall oil pitch;

(i) Crude glycerine;

(j) Bagasse;

(k) Grape marcs and wine lees;

(l) Nut shells;

(m) Husks;

(n) Cobs cleaned of kernels of corn;

(o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, precommercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignite and tall oil;

(p) Other non-food cellulosic material;

(q) Other ligno-cellulosic material except saw logs and veneer logs.

Part B

Feedstocks for the production of biofuels and biogas for transport, the contribution of which towards the minimum share established in the first subparagraph of Article 25(1) shall be limited and may be considered to be twice their energy content:

(a) Used cooking oil;

(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009.

5.2. Appendix 2: Assumptions used in scenarios

Scenario	Assumptions
Mixed	Amounts of hydrogen used in refineries, iron and steel, other industry, transport and synthetic fuel production and as set out in recent Commission publication.[27] Annex IX Part A biofuels based on EU fit for 55 mix % of annex ix part a as a total of transport[28] Annex IX Part B reaches its maximum of 1.7% of transport energy demand in 2030 Biofuels from food and crops and other compliant biofuels are assumed to remain constant from 2022. Extra electrification of road transport to meet RED targets
Electrification	Sub-targets for RFNBOs and advanced biofuel use are met through minimum amount of RFNBO (e-hydrocarbons and remainder of 5.5% target met through (assuming ratio of Annex IX part A to part B is the same as in 2022), Biofuels from food and crops and other compliant biofuels are assumed to remain constant from 2022. The remaining energy required to meet the RES-T target of 29% is met through electrification of road transport.
RePowerEU	Renewable hydrogen up to the 10 Mt threshold is produced domestically. Beyond this threshold, renewable hydrogen is imported. Electrification of road transport in line with the expected impact of the 2035 ICE ban All biofuels are assumed to remain constant from 2022. Assuming an energy content of 44 MJ/kg e-kerosene[29], 0.367 tH_2 / t e-kerosene is required Assuming an energy content of 40.9 MJ/kg maritime e-fuel[30], 0.341 tH_2 / t e-fuel is required
RePowerEU (no H_2 imports)	Assumptions same as in RFNBO scenario above but with all renewable hydrogen produced domestically.

5.3. Appendix 3: Load factors

Load factors are defined as the average load divided by the peak load in a specified time period.

[27] "2022.05.18 RePowerEU Accompanying document" Table 8

[28] https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en

[29] RED Industry; p.72

[30] Heavy fuel oil RED Industry; p.72

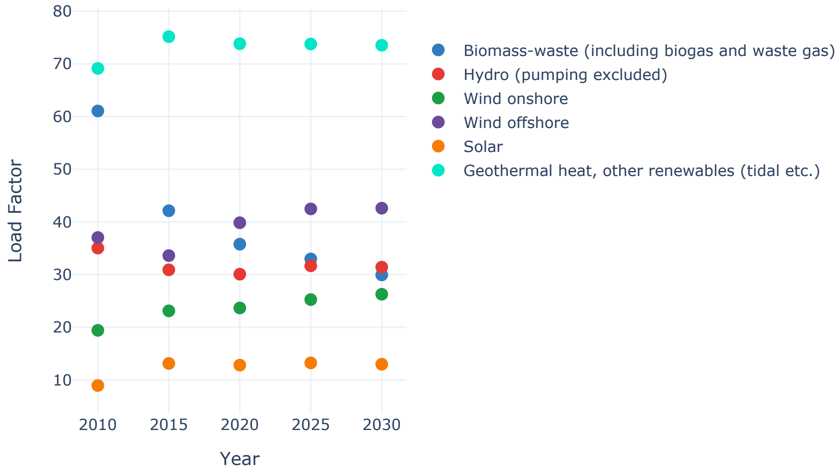

Figure 19: Load factor per year per type of fuel, under the FF55 MIX scenario[31]

The load factor is defined as: $f_{Load} = \frac{\left(\frac{E_{GWh}}{\text{time eriod}}\right)}{C_{GW}}$ where$E_{GWh}$is the electricity produced, and $C_{\{GW\}}$is the capacity.

The load factor changes over time, notably increasing for solar and wind energy. Figure 19 shows the evolution of the load factor between 2010 and 2030 based on data from the MIX scenario. For our analysis, we used the 2030 load factor as a reference (Table 2). From this load factor and the production curve, we can calculate the required capacity.

Table 2: Projection of the load factor of renewable power source in 2030

	Hydroelectric	Wind onshore	Wind offshore	Solar	Biomass waste	Other
Load Factor %	31.42	26.28	42.61	12.98	29.94	73.55

Conversely, fossil electricity production is reduced by the amount displaced by the portion of renewable electricity allocate to it. Each year, hours of spare electricity are deduced from the previous year by adding periods when fossil fuel production falls down to the minimum. These "spare" hours in 2030 for Germany are illustrated in Figure 8.

[31] Data on the MIX scenario can be found here

5.4. Appendix 4: Hydrogen project infrastructure

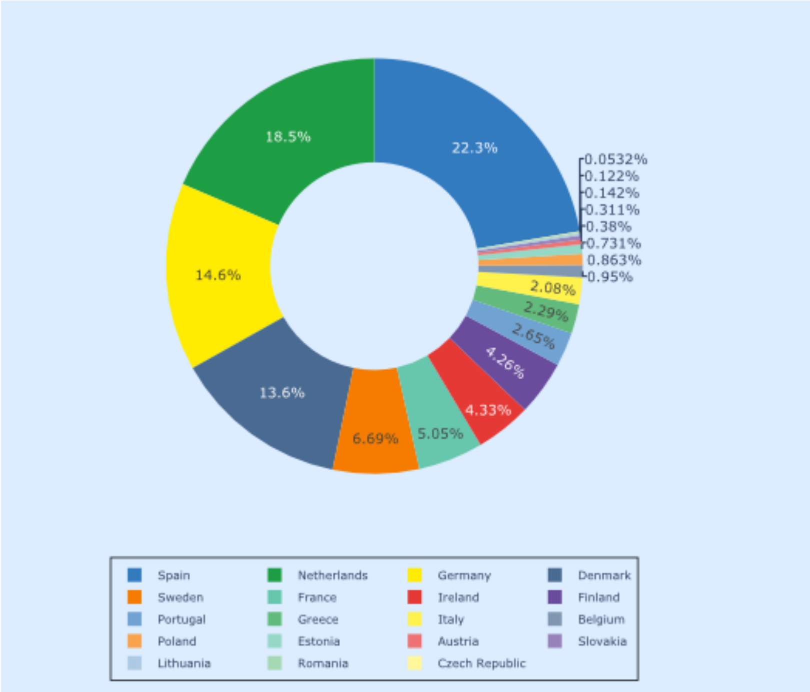

Figure 20: Hydrogen Project infrastructure 2024 proportion: the share of hydrogen production per Member State is derived from the Global Hydrogen Review 2024[1] report by the International Energy Agency. [32]

5.5. Appendix 5: Minimum fossil content

How renewables displace fossil electricity: It is assumed that renewables will displace fossil electricity in such a way that the share of each fossil fuel type remains unchanged. However, no fossil fuel type can be reduced below its baseline value.

Minimum fossil content of the grid: As power prices fall, fossil production in a country drops down to a minimum level which is usually not zero. This is due to operational constraints on power stations as well as connection issues. We estimated this minimum level over 2023-30 for each country and fuel type by calculating the median fossil electricity consumption during "spare hours" (i.e. hours with prices below €20/MWh) in 2020, 2021, 2022, and 2023, from which we derived an exponential regression over 2020 to 2030, as illustrated on the Figure 21 for Spain Netherlands and Germany for the three types of fossil fuel.

[32] IEA (2024) Global hydrogen review

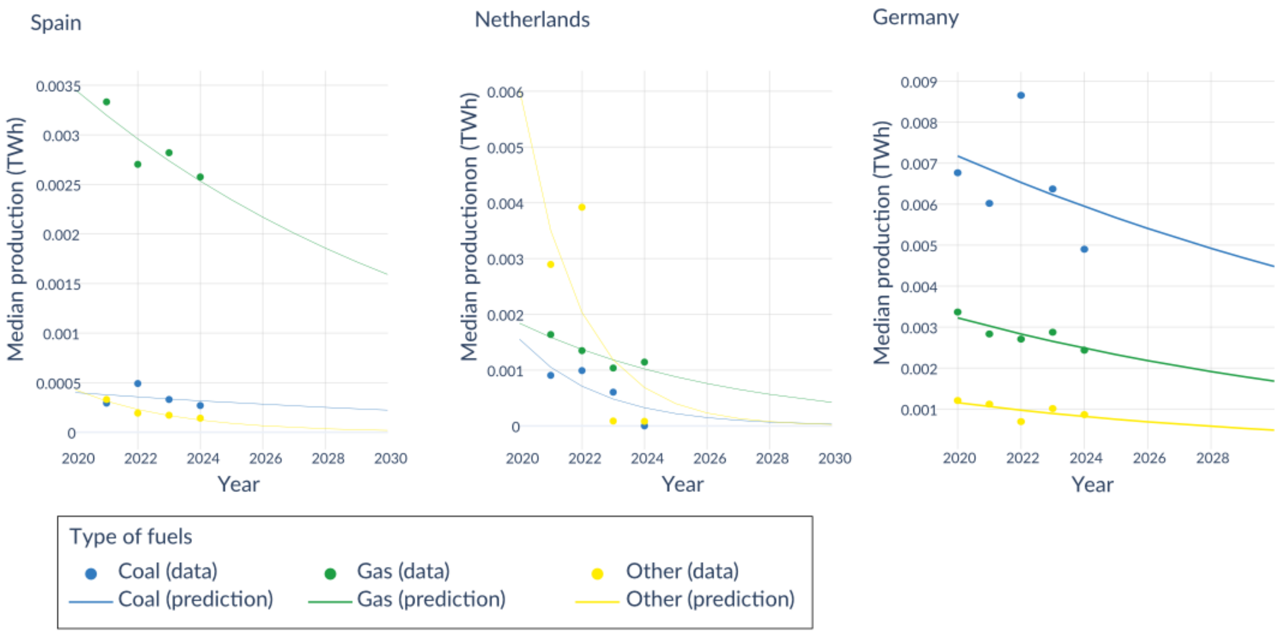

Figure 21: Median of the fossil fuel during Spare hour, data and projection for Germany, Spain and Netherlands between 2022 and 2030

5.6. Appendix 6: Calculation for perfect interconnection

Here, we estimate the renewable electricity that was in excess and could not be used in each country's grid in 2022. This unused potential is then considered as reinjected into the grid under the "perfect network" assumption — where electricity can freely flow across borders — to support demand elsewhere in the EU.

Using the load factors for solar and wind energy, represented in the figures below, we can calculate the total electricity that renewable sources could produce during spare hours in 2022. During the spare hours, we assume that the load factor is the maximum load factor for each season.

This calculation supports the existing production within the energy mix and provides an estimate of the additional low-carbon (zero-carbon) electricity that could be added for each EU country [33]. The total renewable electricity that can be produced at any hour h for each source i is: $E_{\text{renewable},i}(h) = \text{Capacity}_{\text{installed},i} \times \text{Load Factor}_i(h)$.

To estimate the additional renewable electricity that could be used to support the energy mix, we subtract the already existing renewable production: $E_{\text{available},i}(h) = E_{\text{renewable},i}(h) - E_{\text{existing}}(h)$.

The total available renewable electricity for each country is the sum of all renewable sources over the hours in a year is $E_{\text{available, total}} = \sum_{h=1}^{8760} \sum_{i=1}^{n} E_{\text{available},i}(h)$, where n is the number of renewable sources in the country, and 8760 is the total number of hours in a year.

[33] excluding Luxembourg, Malta, and Cyprus

sandbag

smarter climate policy