H2 set-up in WILIAM, hydrogen economy scenarios, and results

Introduction & Overview of Activities

Within Work Package 4, under the Task 4.1, UVa and CARTIF expanded the global, multi-regional WILIAM Integrated Assessment Model (IAM) so that it can generate the greenhouse-gas, pollutant and hydrogen-emission pathways required by atmospheric chemistry and climate models. In other words, this work connects assumptions about hydrogen technologies and deployment with their wider consequences for energy, land, materials, the economy and the climate system. Figure 1 shows the simulation-based optimization process followed by WILIAM (the used version is a significantly expanded version of WILIAM 1.4: https://github.com/LOCOMOTION-h2020/WILIAM_model_VENSIM). The entire WP4 workflow involving all of the activities, tasks, interconnections between models and expected outputs are illustrated in Figure 2.

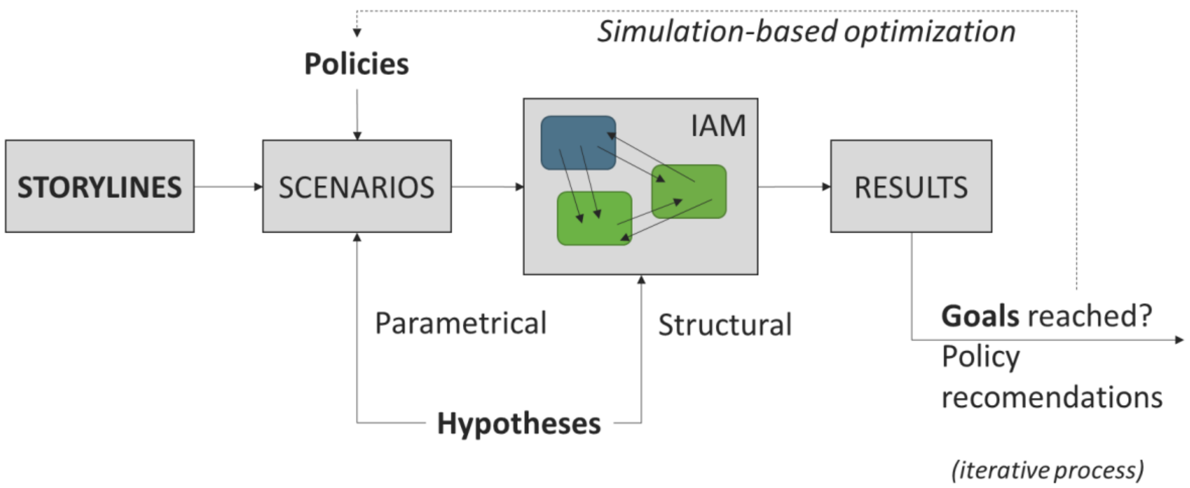

Figure 1. Operationalization of policy-simulation IAM. Source: WILIAM MOOC: https://www.locomotion-$H_2$020.eu/resources/mooc/, derived from D4.2

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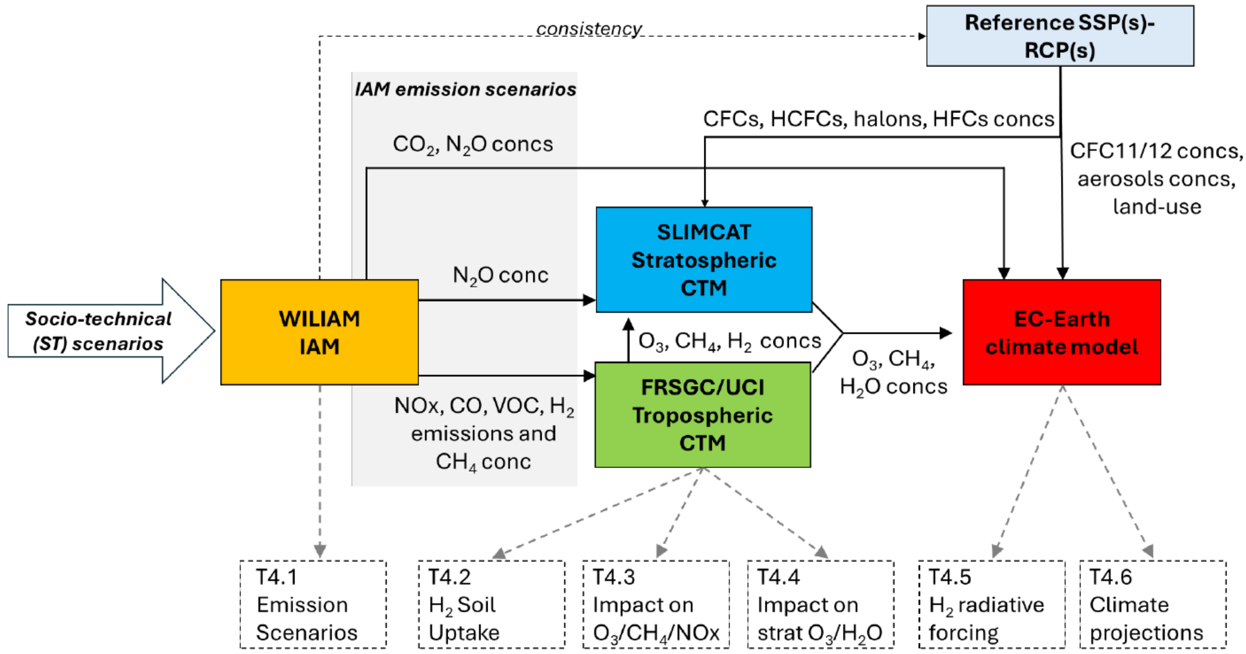

Figure 2. HYDRA Modelling Chain connecting the IAM, the CTMs and the climate model. Source: D4.2 (own work)

The HYDRA modelling developments cover the complete hydrogen value chain: on the supply side, WILIAM now represents electrolysis, fossil-based production routes, synthetic fuels, Carbon Capture and Utilisation (CCU), and Direct Air Capture (DAC), whilst also including hydrogen transport and storage; on the demand side, the model captures non-energy uses in chemicals and refining, hydrogen-based steelmaking, high-temperature industrial heat, freight and passenger transport. Additionally, a key update has been made to the modelling H_2 combustion emissions and leakages, together with the short-lived atmospheric pollutants such as CO, NO_x and VOCs.

The second major activity involved the design and parametrisation of several global socio-technical scenarios up to 2100. A Reference pathway, which continues current trends, was compared with four different Green Growth (GG) narratives based on rapid renewable deployment, electrification, efficiency improvements, carbon pricing and other decarbonisation measures. These GG scenarios span four hydrogen deployment pathways, starting with a scenario without green hydrogen and progressively increasing the levels of ambition. The combination of the five deployment narratives with four assumptions regarding H_2 emissions and leakage resulted in 20 scenarios (presented in Figure 3) and offers a wide range of solutions for Hydra's subsequent activities.

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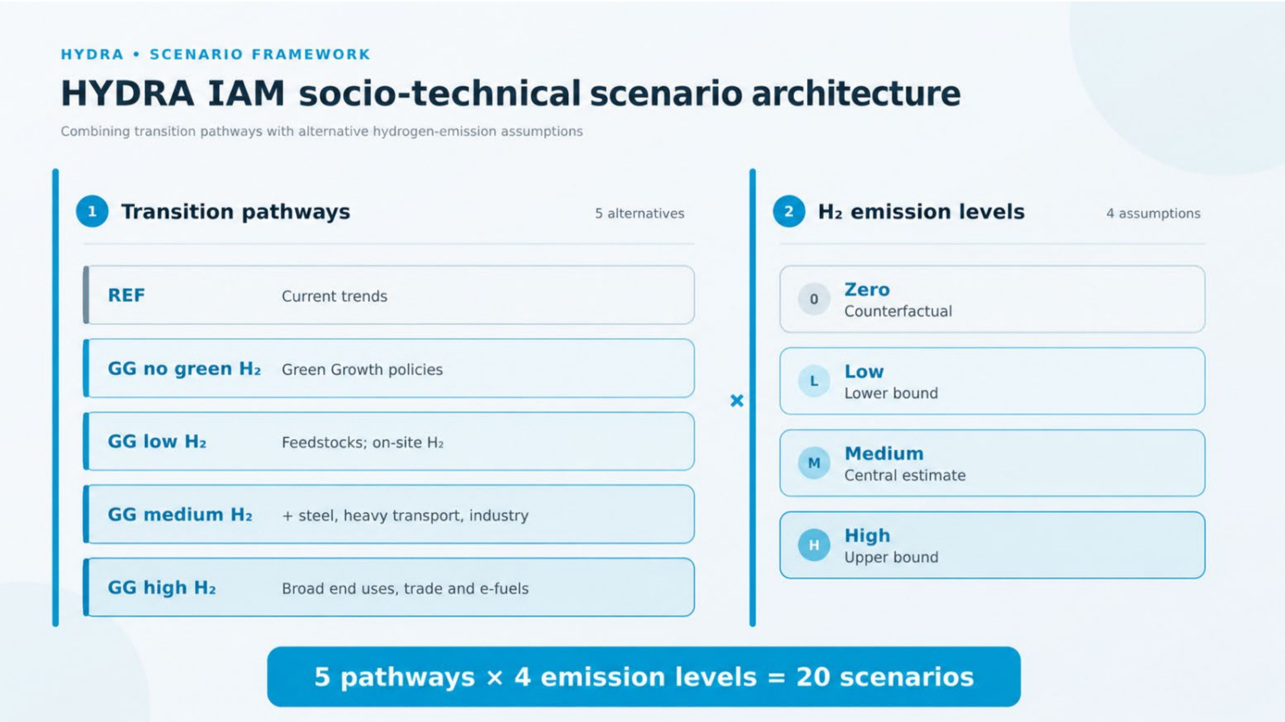

Figure 3. Hydra socio-technical scenario framework. Source: Own work (derived from D4.2)

Methodology

WILIAM was used as the core component of these first stages of WP4. Its System-Dynamics (SD) structure links demographic and economic activity with energy demand, technology deployment, resource use, land-use change and emissions across multiple world regions. The model was extended and recalibrated so that hydrogen production, conversion, distribution, storage and final uses respond consistently to the rest of the energy system rather than being imposed as an isolated demand. Scenario construction followed a common narrative-and-parameter approach:

1. The Reference and no-hydrogen-GG storylines were translated into quantitative assumptions for WILIAM's modules. Green Growth assumes continuous economic expansion and an ambitious transition towards electrification, efficiency and nearly fossil-free electricity. For the impact analysis, selected energy-availability and energy-return constraints were relaxed, and commercial deployment of large-scale H_2 technologies was assumed.

2. The three H_2-GG cases were then specified. The low-ambitious level restricts green hydrogen mainly to feedstock uses for which alternatives are limited. The medium deployment scenario adds steelmaking, heavy transport, moderate high-temperature heat, intra-regional trade and synthetic fuels. Finally, the high implementation pathway pushes hydrogen towards its technical limits, including broader transport and industrial uses, international trade and larger synthetic-fuel production. Each deployment scenario was cross combined with zero, low, medium and high estimates of anthropogenic H_2 emissions from combustion and leakage.

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3. Emission factors and sectoral activity data were harmonised to calculate CO, NO_x, VOC and H_2 emissions. Historical greenhouse-gas and pollutant outputs were validated by region and IPCC sector. Finally, the modelling outputs were assessed to understand the potential synergies and trade-offs of a future hydrogen economy, and mapped to the spatial, sectoral and temporal formats required by the chemistry-transport and climate models.

In parallel, the climate module was calibrated and validated against historical reference data for atmospheric concentrations, radiative forcing and global mean temperature, ensuring that WILIAM consistently reproduces the full chain from emissions to climate response.

Figure 4 depicts some of the key assumptions made to build the green H_2 deployment scenarios:

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HYDRA socio-technical assumptions for green-H_2 deployment scenarios

Explicit scenario parameters used in WILIAM

Scenario	Freight transport	High-temperature industry	Passenger transport	Non-energy use	Merchant vs in situ production	International trade	Synthetic fuels
Low green-H_2 deployment	—	—	—	100% replacement of fossil H_2 for methanol, ammonia and refining by 2050 Steel: 100% DRI by 2100	100% in situ	—	—
Medium green-H_2 deployment	Electric and hybrid road transport 90% of rail transport electric 5–15% hydrogen-powered vehicles (depending on transport mode)	≥50% fossil-fuel replacement with solid biofuels and electric arc Up to 10% merchant H_2 and 5% on-site electrolysis H_2	Public transport: 35% FCEV in heavy public road transport (buses)	100% replacement of fossil H_2 for methanol, ammonia and refining by 2050 Steel: 50% HDRI by 2100	22% of non-energy uses supplied by merchant H_2	—	e-gas: 61% of final-energy gases in 2050 e-liquid: 11% of final-energy liquids in 2050
High green-H_2 deployment	Electric and hybrid road transport 90% of rail transport electric 10–60% hydrogen-powered vehicles (depending on transport mode)	≥50% fossil-fuel replacement with solid biofuels and electric arc Up to 20% merchant H_2 and 10% on-site electrolysis H_2	Public: 35% FCEV in heavy road transport; 5% aviation; 3.5% maritime Private: 25% of LDV passenger-km	100% replacement of fossil H_2 for methanol, ammonia and refining by 2050 Steel: 100% HDRI by 2050	22% of non-energy uses supplied by merchant H_2	Net importers in 2050: EU 30%, UK 46%, EASOC 66% Net exporters: China 47%, India 15%, USMCA 38%	e-gas: 61% of final-energy gases in 2050 e-liquid: 11% of final-energy liquids in 2050

Figure 4. Sectorial H_2 implementation by scenario. Source: own work

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Preliminary Results

Before starting to present and analyse the results, it is essential to point out that the reported outcomes in D4.2 were preliminary and are constantly being updated in WP4 in order to achieve the most reliable emissions and concentrations for the climate and atmospheric chemistry models. Table 1 and Figure 5 show main emission results until 2050 and 2100.

The first result is the modelling capability itself as WILIAM can now reproduce hydrogen penetration levels at the upper end of the integrated-assessment literature while tracing consequences across energy, economy, materials, land and emissions. The 20 simulations provide a sufficiently broad range for the atmospheric chemistry and climate models to identify the most informative cases for deeper analysis.

Across the scenarios, the Green Growth narrative is the dominant driver of lower emissions. Compared with the Reference pathway, all Green Growth scenarios follow substantially lower greenhouse-gas and pollutant trajectories, with differences becoming increasingly visible towards 2050. These improvements are mainly driven by renewable deployment, electrification, energy-efficiency measures and the progressive replacement of fossil fuels.

Differences among the Green Growth scenarios are more gradual and do not follow a simple linear relationship with hydrogen deployment. During the transition to 2050, scenarios with greater green-H_2 penetration may show slightly higher emissions for some indicators than Green Growth without green H_2. This reflects the additional electricity, infrastructure and upstream energy required to expand the hydrogen value chain. The climate benefits of greater H_2 deployment become more apparent later, as the energy system adapts and hydrogen increasingly replaces carbon-intensive options in hard-to-abate sectors.

Air pollutants generally follow the same pattern. Green Growth produces clear reductions relative to the Reference pathway, particularly in road transport, where electrification and alternative fuels progressively displace conventional vehicles. However, reductions are less pronounced in industrial processes, refining, solvent use and other activities that remain linked to economic growth. Consequently, differences between hydrogen scenarios vary by pollutant and sector rather than following a uniform ranking.

Hydrogen-related emissions follow a different trajectory, since they remain comparatively limited in scenarios without a deep green-H_2 deployment but increase as hydrogen production, transport, storage and use expand. This divergence is already visible by 2050 and becomes stronger thereafter. Value-chain leakages progressively become the main source of anthropogenic H_2 emissions, highlighting leakage control as a critical condition for ensuring the overall climate performance of a hydrogen-based transition.

In the three scenarios with H_2 deployment, the demand increases gradually to 2050 and accelerates thereafter, with clear differences in both scale and end-use composition (shown in Figure 6). The low-deployment remains largely concentrated in existing non-energy uses, while the medium narrative expands H_2 consumption into high-temperature industry, freight

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transport and synthetic-fuels. These uses grow much more strongly in the high-deployment narrative, particularly after 2050, making synthetic fuels and hard-to-electrify sectors the main drivers of demand. Passenger transport plays a comparatively limited role.

Table 1. Key results in 2015, 2050 and 2100, broken down by scenario (medium emission level). Source: own work

	Reference			*No H_2 GG*			*Low H_2 GG*			*Med H_2 GG*			*High H_2 GG*		
	2015	*2050*	*2100*	*2015*	*2050*	*2100*	*2015*	*2050*	*2100*	*2015*	*2050*	*2100*	*2015*	*2050*	*2100*
CO_2 eq. emiss (Gt/yr)	*55.3*	*74.7*	*105.2*	*55.3*	*27.3*	*53.7*	*55.3*	*26.6*	*52.0*	*55.3*	*52.0*	*40.8*	*55.3*	*32.3*	*37.5*
CO_2 conc (ppm)	*406*	*512*	*772*	*406*	*444*	*529*	*406*	*443*	*527*	*406*	*451*	*512*	*406*	*453*	*506*
CO emis (Gt/yr)	*0.58*	*0.76*	*0.87*	*0.58*	*0.51*	*0.72*	*0.58*	*0.52*	*0.75*	*0.58*	*0.49*	*0.67*	*0.58*	*0.46*	*0.62*
NO_x emiss (Gt/yr)	*0.08*	*0.11*	*0.15*	*0.08*	*0.08*	*0.19*	*0.08*	*0.08*	*0.28*	*0.08*	*0.12*	*0.17*	*0.08*	*0.11*	*0.14*
VOC emiss (Gt/yr)	*0.15*	*0.23*	*0.34*	*0.15*	*0.17*	*0.34*	*0.15*	*0.17*	*0.34*	*0.15*	*0.17*	*0.28*	*0.15*	*0.15*	*0.27*
H_2 emiss (Gt/yr)	*0.01*	*0.02*	*0.02*	*0.01*	*0.02*	*0.04*	*0.01*	*0.02*	*0.04*	*0.01*	*0.07*	*0.14*	*0.01*	*0.1*	*0.19*
T Change preind. (ºC)	*1.07*	*2.14*	*3.83*	*1.07*	*1.75*	*2.20*	*1.07*	*1.74*	*2.15*	*1.07*	*1.75*	*2.09*	*1.07*	*1.78*	*1.98*

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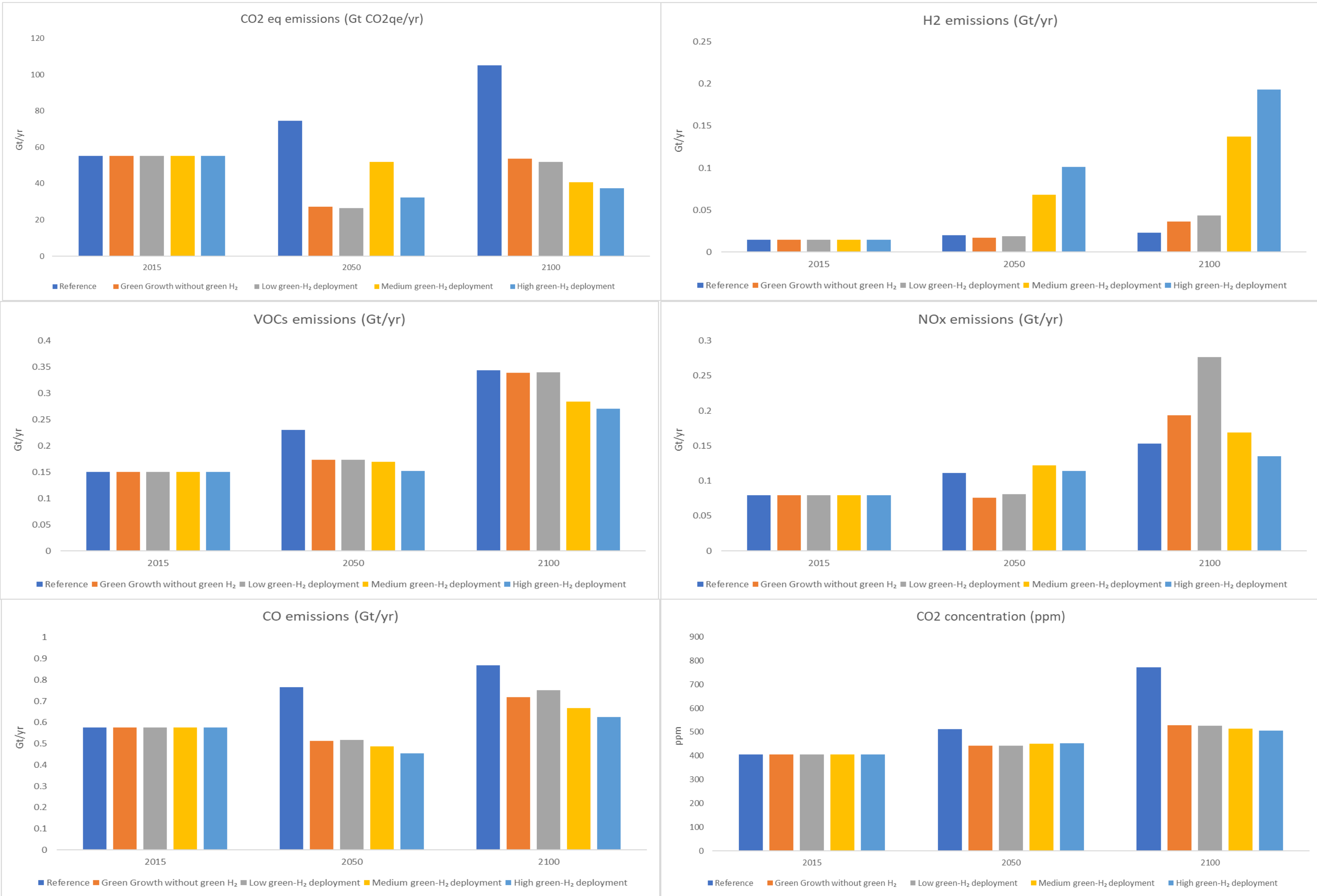

Figure 5. Key results in 2015, 2050 and 2100, broken down by scenario. Source: own work

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Discussion & Interpretation

The results indicate that implementing H_2 policies within a conventional Green Growth narrative (including relaxing energy-availability and net-energy return restrictions, as well as assuming full commercial availability of hydrogen technologies) can contribute to long-term decarbonisation, particularly in applications that are difficult to electrify directly. However, the comparison also shows that most of the climate benefits of the scenarios come from the wider GG policies (e.g., renewables, efficiency, electrification, afforestation, etc.) rather than from hydrogen alone. Differences in the main GHG concentrations among the Green Growth pathways are comparatively modest. Hydrogen should therefore be interpreted as one component of a broader transition, not as a standalone solution, and an option which introduces significant pressure in the energy system and has also significant trade-offs.

It is also worth noting that the timing of the assessment matters. During the first half of the century, a larger roll-out of H_2 may yield slightly worse outcomes than a Green Growth scenario without green H_2 on some indicators, particularly CO_2 emissions. This is because new infrastructure and processes require a faster expansion of the energy system, which cannot be achieved in a low-carbon manner if electrification relies solely on renewable sources. In the longer term, the more ambitious H_2 pathways tend to improve as the system adapts and hydrogen displaces more carbon-intensive end uses.

The analysis also reveals resource and atmospheric trade-offs. High H_2 deployment increases electricity demand and pressure on land through additional renewable capacity (bioenergy and solar), while hydrogen leakages grow rapidly with production and handling. Persistent industrial-process, waste and solvent emissions also limit the depth of decarbonisation, particularly under continued high economic growth.

Another important point to note is that the finding are subject to various limitations and non-ideal conditions. For example, the scenarios are global in scope and assume a broadly uniform policy adoption, while real transitions will differ markedly by region. Also, the exercise assumes that large-scale H_2 technologies will be commercially available and temporarily relaxes certain biophysical feedback. Obviously, WILIAM does not cover the entire hydrogen value chain due to its complexity and scale (e.g., the incomplete representation of Carbon Capture and Storage (CCS), residual emissions in some sectors and the bottom-up building dynamics).

The outputs of this activity are crucial for the further development of HYDRA project, as the emissions obtained are used as input data for atmospheric chemistry and climate models, in which the interactions between H_2 and OH, and the half-lives of methane and ozone, can be quantified in greater detail.

Future work within the project will refine these emission scenarios in iteration with the climate and atmospheric chemistry partners, analyse the implications for hydrogen economy of introducing energy-availability and net energy returns constraints, as well as analysing the potential of mitigation strategies to mitigate the trade-offs of hydrogen large-scale deployment.

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