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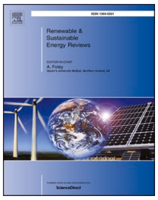

Expanding scenario diversity in prospective LCA: Coupling the TIAM-UCL integrated assessment model with Premise and ecoinvent

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ABSTRACT

Prospective life cycle assessment (pLCA) using scenarios from integrated assessment models (IAMs) can explore future environmental impacts. However, results are sensitive to the IAM used and only scenarios from two IAMs – REMIND and IMAGE – have been soft-coupled with pLCA using Premise. Here, we establish a new linkage to a third IAM - TIAM-UCL - which diversifies available IAM scenarios and strengthens potential conclusions from pLCA. Over 200 variables across 16 global regions were linked to over 300 LCA processes, representing future technological changes across seven major sectors, including electricity, fuels, and steel. We analyse the future life-cycle impacts of the global electricity mix per kWh delivered to low-voltage consumers using TIAM-UCL scenarios, ecoinvent v3.9.1, and the EF 3.1 impact assessment method. In 1.5–2.0 °C futures, projected reductions in climate change impact from fossil-fuel phase-out have substantial co-benefits in ten categories, such as acidification reducing over 90 % by 2050. Trade-offs are found in five categories, such as critical material shortages. Comparing pLCA results based on all three IAM models showed consistent reductions in climate change impact to meet 1.5–2.0 °C futures. However, differences in other impact category results arose due to variations in low-carbon technologies deployed, such as IMAGE showing smaller environmental co-benefits due to preferences for CCS-fitted fossil generation, while REMIND had increased land use from greater solar uptake. Therefore, it is essential to consider the influence of IAM choice when interpreting pLCA outcomes. The addition of TIAM-UCL, now available in Premise, will enable more robust modelling of prospective environmental impacts.

1. Introduction

Anthropogenic greenhouse gas emissions (GHG) have increased global temperatures by around 1.1 °C since pre-industrial times, leading to more extreme weather and ecological harm [1]. In order to limit climate change to a temperature rise below 1.5–2.0 °C, we must significantly reduce GHG emissions [1]. Energy systems are responsible for over 70 % of global GHG emissions and require an unprecedented shift from high-carbon fossil fuels to low-carbon renewable technologies [2]. Successfully navigating this transition requires understanding mitigation pathways, cost-effectiveness, and policy options of technologies to inform decision-makers [3].

Integrated Assessment Models (IAMs) are valuable tools to help explore energy transition scenarios [4] and are widely utilised in IPCC Assessment Reports [1]. They contain data-rich representations of global economies, energy technologies, and environmental dynamics, and can explore future trajectories *via* "Shared Socioeconomic Pathways" (SSPs) that derive socioeconomic assumptions like population, economic growth rates, and environmental attitudes [5,6]. Under an SSP, IAMs can explore cost-optimal futures under constraints such as “How should the global energy system look by 2050 to limit global warming to

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List of Abbreviations

BECCS -	Bioenergy with Carbon Capture and Storage
CCS -	Carbon Capture and Storage
DAC -	Direct Air Capture
DACCS -	Direct Air Carbon Capture and Storage
EF 3.1 -	Environmental Footprint 3.1 (Impact Assessment Method)
EFOM -	Energy Flow Optimization Model
GWP -	Global Warming Potential
IAM -	Integrated Assessment Model
IMAGE -	Integrated Model to Assess the Global Environment
LCA -	Life Cycle Assessment
LCI -	Life Cycle Inventory
LCIA -	Life Cycle Impact Assessment
LFP -	Lithium Iron Phosphate (Battery)
MARKAL -	Market Allocation (Energy-environmental model)
NDC -	Nationally Determined Contributions
pLCA -	Prospective Life Cycle Assessment
PV -	Photovoltaic
REMIND -	Regional Model of Investments and Development
RCP -	Representative Concentration Pathway
SSP -	Shared Socioeconomic Pathway
SSP2-RCP1.9 -	SSP2 Scenario with 1.9 W/m^2 radiative forcing by 2100
SSP2-RCP2.6 -	SSP2 Scenario with 2.6 W/m^2 radiative forcing by 2100
SSP2-RCP4.5 -	SSP2 Scenario with 4.5 W/m^2 radiative forcing by 2100
SSP2-RCP6.0 -	SSP2 Scenario with 6.0 W/m^2 radiative forcing by 2100
TIAM-UCL -	TIMES Integrated Assessment Model from University College London
TIMES -	The Integrated MARKAL-EFOM System

1.5 °C?".

The resulting SSP scenarios are highly dependent on IAM architecture and assumptions, and the global results should be contextualised and complemented with other models and analytical approaches [7]. For instance, IAMs cannot calculate indirect, consumption-based, and "life-cycle" GHG emissions of technologies [6,8]. For example, on-site GHG emissions are eliminated when a coal power plant is replaced with a wind farm. However, wind farms will have indirect GHG emissions due to raw material and manufacturing requirements, which, when considered, are reported under different sectors (i.e., steel production), thereby losing the supply chain perspective on emissions. Additionally, IAMs do not consider non-climate related impacts such as acidification, so it is not possible to identify co-benefits nor identify risks of increasing other environmental impacts when focusing on climate change mitigation.

Life cycle assessment (LCA) is a standardised methodology that can quantify the whole-life environmental benefits and trade-offs of technologies [9,10]. Product decision-makers have widely used LCA [11], which has been incorporated into policy, such as the recent carbon footprinting of batteries in the European Union (EU) battery directive [12]. However, scenario analysis in LCA could be improved with systematic approaches that consider system-wide changes, which is where IAMs excel [6].

As such, there is growing interest in "prospective" LCA (pLCA) that models product systems' at a future point in time [13]. One approach is by integrating energy scenarios such as from IAMs into life cycle inventories (LCI) [13,14]. This offers a systematic approach for future-orientated LCA to consider climate-aligned scenarios with cross-sector dependencies [6,8,13]. Hertwich et al. [15] were among the first to present an integrated pLCA approach, using IEA energy scenarios to assess the life-cycle impacts of large-scale renewable electricity generation and CCS. They found that while the transition to low-carbon energy by 2050 reduced life-cycle GHG and pollutant emissions, it increased material demands, particularly from solar PV and wind deployment. Gibbon et al. [16] later used THEMIS to adapt LCA databases and multiregional input-output tables, forecasting technology and resource changes under a 2 °C climate mitigation scenario through 2050. Focusing on concentrating solar power, they highlighted regional variations in life-cycle GHG emissions and stressed the need for frameworks that consider the long-term effects of climate policies. Pehl et al. [17] applied IAM energy scenarios from REMIND and the THEMIS pLCA framework for ecoinvent to explore future low-carbon power technologies, confirming life-cycle GHG reductions despite potential increases in embodied impacts. Further examples have linked similar energy system models (ESM), such as the integrated MARKAL-EFOM System (TIMES) [18] and marginal electricity supply mixes into Ecoinvent for pLCA [19]. Likewise, life cycle indicators have also been integrated directly into IAMs and ESMs [20–23].

Later, Mendoza Beltran et al. [24] developed an approach that systematically integrates IAM scenarios on electricity to modify the LCIs of the LCA database ecoinvent [25]. Expanding this approach to multiple sectors, Sacchi et al. [26] introduced "Premise", an accessible and streamlined tool for integrating IAM scenarios into ecoinvent, allowing LCA practitioners to generate pLCI and conduct pLCA. In brief, Premise maps IAM variables to LCA activities. It generates prospective versions of the LCA database by adjusting technologies' penetration share, efficiency and emission factors for a specific scenario and year. Currently, Premise-generated databases use IAM scenarios from REMIND and IMAGE, considering sectoral changes related to electricity, steel, fuels, cement, and more. Premise has been used for conducting pLCA consistently, reproducibly, and transparently using REMIND and IMAGE scenarios on topics such as vehicles and batteries [27–29], hydrogen production [30,31], aviation [32], wind energy [33], ammonia [34], metals [35], cement [36,37], and the development of consequential pLCA approaches [38]. Our previous work has also integrated IMAGE scenarios through Premise to conduct a pLCA on lithium-ion batteries, evaluating the temporal mismatch effects between production GHG emissions and future recycling credits [39].

However, a critical limitation is that Premise includes scenarios only from two IAMs – REMIND and IMAGE – when there can be differences in scenario outputs and mitigation pathways between IAMs originating from varying sets of assumptions, regional and temporal scales, and modelling choices [3]. For example, in one of the latest Intergovernmental Panel on Climate Change Working Group III reports [40], IAM scenarios strongly agree on the overall uptake of renewable electricity and phase-out of fossil generation, but there are major differences in the technology shares and level of deployment for the specific CCS, wind, hydro, bioenergy, and solar technologies [41]. Hence, using a diverse range of IAM scenario outputs to interpret mitigation pathways helps to account for technological, socioeconomic, and epistemic uncertainties [42]. It is essential to consider how decarbonisation scenarios from different IAMs affect pLCA outcomes for both GHG and non-GHG environmental impacts. Expanding Premise to include new IAMs will diversify available scenarios and strengthen conclusions from pLCA, enabling more robust modelling of prospective environmental impacts.

This work introduces and makes available new scenarios from a third IAM - TIAM-UCL, a TIMES-based integrated assessment model [43] – into Premise for conducting pLCA, including major sectors such as electricity, fuels, and steel. In addition to enhancing scenario diversity, TIAM-UCL has an extensive focus on energy systems that aligns well with the representation of energy technologies in Premise. It also provides added benefits, such as an enhanced representation of fossil systems and their phase-out [44–46]. We first describe the general TIAM-UCL and Premise linking methodology (Section 2). To explore the importance of this new set of scenarios, we then apply Premise to conduct pLCA and assess the variation in the life-cycle impacts of the global electricity mix supplied to low-voltage consumers per 1 kWh across TIAM-UCL scenarios (Section 3.1 and Section 3.2). We compare these results with those obtained using IMAGE and REMIND to understand the influence of various climate mitigation technology mixes on pLCA results before concluding by discussing limitations and future work.

2. Methods

2.1. TIAM-UCL description

TIAM-UCL is a global energy-economy model representing energy systems across 16 regions from primary sources to end-use, aiming for cost-effective solutions to meet evolving energy needs under different climate, natural resource, and technological constraints (Fig. 1). Influenced by demographic and economic factors, the model dynamically adjusts energy supply to changing energy demands, identifying cost-effective pathways for emissions reduction to 2100. Relevant to achieving global net zero GHG emissions, the model includes CO_2 removal options such as afforestation/reforestation, bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). The minimisation of costs is done simultaneously across all periods (inter-temporal optimization), assuming “perfect foresight”, meaning that the global planner “knows” at all times which technologies are or will be available and required in the future. Real-world uncertainties are explored through scenario runs, each designed to examine different constraints or conditions and undergo constant model updates [4].

The models’ climate module ensures adherence to temperature targets (e.g., 1.5 °C or 2 °C limits) and extends beyond the year 2100 to maintain stable future global temperatures. The model can also use updated IPCC carbon budgets and handles non-CO_2 GHG emissions, with mitigation options for energy-sector emissions. Should mitigation options fall short, a costly backstop mechanism is used as a last resort to meet carbon or temperature limits. This mechanism highlights persistent emissions or budget excesses and often represents an emerging or currently unavailable technological solution that is too expensive for current market adoption.

For this work, TIAM-UCL was run under a SSP2 "Middle of the Road" future development, assuming moderate challenges for climate change mitigation and adaptation [5]. This was constrained under four different climate futures, as represented by representative concentration pathway (RCP) scenarios limiting radiative forcings by the year 2100 as follows (where RCP6.0, for example, refers to 6.0 W per square meter (W/m^2)):

- SSP2-RCP6.0 – “No climate action”. Slow GHG reduction pathway limiting warming to 2.6–4.8 °C by 2100. Some actions are taken to mitigate GHG emissions, but these are far less ambitious than expectations aligned to the Paris Agreement; fossil fuel phase-out and renewable technology uptake are slow.
- SSP2-RCP4.5 – “Baseline, Nationally Determined Contributions (NDCs)”. The current trajectory to reduce GHG emissions, limiting warming to 2.0–2.5 °C by 2100. A more significant effort is taken to mitigate GHG emissions compared to RCP6.0, which means that GHG emissions will peak and then gradually decline sooner but miss the recommendations of the Paris Agreement.
- SSP2-RCP2.6 – “Ambitious (<2.0 °C)”. A rapid GHG reduction pathway consistent with the Paris Agreement goals to avoid severe impacts of climate change, limiting warming well below 2.0 °C by 2100. This requires substantial decarbonisation of the global economy, significant shifts to renewable energy sources, and widespread adoption of carbon capture and storage technologies.
- SSP2-RCP1.9 – “Very ambitious (1.5 °C)”. The most accelerated GHG reduction pathway aligned with the Paris Agreement to limit warming to 1.5 °C by 2100. An even more aggressive decarbonisation and carbon removal efforts than RCP2.6, including the rapid phasing out of fossil fuels and large-scale carbon dioxide removal technologies.

For each scenario, TIAM-UCL output variables related to production volumes, consumption, carbon capture, and efficiencies for various energy technologies across electricity, steel, fuels, cement, biomass, heat, and direct air capture (DAC) are reported, in addition to general variables like GDP, population, and global temperature evolution. These are provided for 16 world regions for 5-year intervals between 2005 and 2050 and then 10-year intervals from 2050 to 2100. However, in this study, the temporal scope of the evaluation starts in 2025 to reflect the present day and ends in 2050 due to increasing model uncertainty in the later years. As an example, Fig. 2 shows the global TIAM-UCL electricity production mixes across the four scenarios. Scenario files are available in supplementary material 1 and are accessible in premise as of v.2.1.1.

2.2. Soft-linking TIAM-UCL to premise

Premise streamlines the creation of databases for pLCA by soft-linking scenarios from IAMs into the ecoinvent LCI database [47]. It

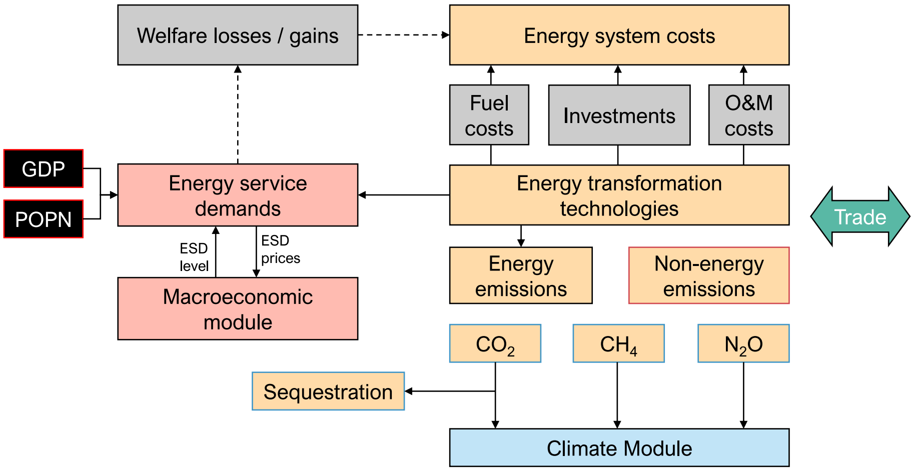

Fig. 1. General representation of TIAM-UCL, adapted from Ref. [39]. ESD – Energy service demands; GDP – Gross domestic product; POPN – Population.

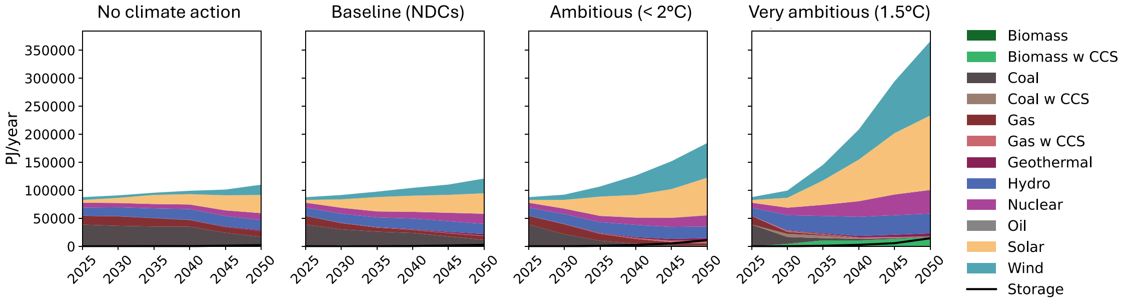

Fig. 2. TIAM-UCL world electricity production mix scenarios from 2025 to 2050. Individual generation technologies have been grouped into respective categories.

maps IAM regions and sector variables to corresponding ecoinvent regions and activities. IAM scenario files are imported, followed by applying transformations to the ecoinvent LCI, which involve adjusting technology shares, efficiencies, and emission factors for specific scenarios and years. This method results in transformed pLCIs of Ecoinvent, aligned with each chosen scenario and year. As such, geographic and variable mapping files were developed for TIAM-UCL and are provided in Premise documentation and supplementary material 1 [48].

Geographic mapping represented 16 world regions of TIAM-UCL consisting of individual (e.g., UK - United Kingdom) and grouped nations (e.g., WEU – Western Europe). Ecoinvent has a greater geographical resolution representing over 200 individual nations, in some cases further disaggregated into states or provinces (e.g., California, Québec, etc.) and aggregated groupings (e.g., Europe). Therefore, Premise uses a mapping file to match ecoinvent geographies with TIAM-UCL's. Premise treats LCA datasets with geographies within the same TIAM-UCL region identically (e.g., New Zealand and Australia belong to the TIAM-UCL region AUS, hence, both will become identical). Thus, applying region-specific projections often implies downscaling the geographical resolution of ecoinvent to match that of TIAM-UCL.

Mapping between TIAM-UCL variables and LCIs was developed, primarily focusing on production volumes and efficiencies available in supporting information 1 and Premise documentation. Detailed technology variables relate to electricity, fuels, steel production, and other sectors like cement, biomass, and DAC. TIAM-UCL variables were preprocessed to achieve appropriate mapping. Most mappings directly linked TIAM-UCL variables to corresponding ecoinvent activities. When no corresponding TIAM-UCL variable existed, no mapping occurred, leaving ecoinvent activities unchanged. Multiple TIAM-UCL technologies were sometimes aggregated into a single Premise variable due to a lack of specific ecoinvent activities. For example, TIAM-UCL included four geothermal electricity production variables - existing geothermal and three depths (shallow, deep, very deep) - which were aggregated into a single geothermal variable to link with an existing ecoinvent inventory. New Premise variables were created for technologies in TIAM-UCL but not in ecoinvent, linking them to similar existing ecoinvent activities while accounting for efficiency differences.

2.3. *Prospective life cycle assessment*

Premise v.2.1.0 was used with the LCA database ecoinvent v3.9.1 with the "cut-off" system model. The four SSP2 scenarios from TIAM-UCL (Section 2.1) were selected to generate pLCIs from 2025 to 2050 with the workflow ending with Brightway-compatible LCA databases [49]. To investigate scenario diversity and inter-IAM comparisons equivalent databases are generated using REMIND SSP2 scenarios of Base, PkBudg1150 and PkBudg500 climate trajectories, equivalent to and IMAGE SSP2 scenarios of Base, RCP2.6 and RCP1.9, which are TIAM-UCL equivalents to "no climate action", "ambitious" (<2.0 °C), and "very ambitious" (1.5 °C) (Section 2.1). REMIND SSP2 scenario of NDC was also used to compare with the "baseline (NDCs)" scenario from TIAM-UCL, but no equivalent scenario was available from IMAGE.

Using the LCA software Brightway, the global electricity supply was assessed that is represented by the LCA dataset "market group for electricity, low voltage – World", which calculates the average global mix by considering distributed total production volumes across the 16 TIAM-UCL scenarios with a functional unit (FU) of 1 kWh of electricity generated and distributed to low-voltage consumers. Further contribution analyses for electricity generation technology mixes were conducted by selecting the most relevant example regions (e.g., "market group for electricity, high voltage" – WEU, Western Europe) and grouping individual technologies into their respective categories (e.g., coal, natural gas, biomass, etc.). The Environmental Footprints 3.1 (EF 3.1) life cycle impact assessment (LCIA) method assessed the environmental impact changes for selected activities; however, we modified the climate change (also "global warming potential" - GWP) indicator by attributing a characterisation factor of $-1/+1$ to uptake and emission of non-fossil CO_2 to consider net negative emission technologies [50] (e.g., the uptake of atmospheric CO_2 in biomass subsequently stored when producing electricity with CCS results in carbon removal, notwithstanding parasitic emissions). To help interpret the significance of the results of the environmental impact, the results were also normalized using the factors (NFs) provided by EF 3.1 [51]. Python scripts for these analyses are available in supplementary material 1 [48].

3. Results and discussion

3.1. *Global electricity mix pathways based on TIAM-UCL scenarios*

Fig. 2 shows TIAM-UCL's four pathways for electricity decarbonisation with distinct technology portfolios deployed to achieve their respective climate targets. In 2025, coal and natural gas electricity generation dominates the mix, with 62 % of the global supply. TIAM-UCL models the main technology types for coal: conventional hard coal and lignite and more efficient supercritical generation. At the same time, combined cycle gas turbines represent natural gas-based electricity. Meanwhile, low-carbon technologies such as impoundment hydro, nuclear, solar photovoltaics, and both offshore and onshore wind contribute 38 % collectively.

In the "no climate action" scenario there is a gradual increase in electrification demand with a slow phase-out of fossil generation accompanied by a steady uptake of solar and wind energy by 2050. Fossil electricity generation is projected to decline gradually to 47 % by 2040, followed by a more rapid decrease to 24 % by 2050. Meanwhile, the share of low-carbon technologies increases to 74 % by 2050, primarily driven by solar and wind. Despite the high shares of renewables by 2050, this scenario limits global warming to only 3.0 °C, underscoring the need for significantly greater and more rapid rates of electricity decarbonisation to achieve more stringent climate targets. For the "baseline (NDCs)" scenario, which corresponds to the current trajectory, a similar trend is seen albeit faster decarbonisation whereby fossil generation declines to 27 % and 15 % by 2040 and 2050, with minor CCS deployment.

The "ambitious" scenario (<2.0 °C) in line with the Paris Agreement shows that a more concerted effort is needed by 2035 to rapidly phase-out fossil generation to 21 % and accelerate low-carbon uptake with a substantial increase in electrification demands. By 2050, low-carbon technologies must make up 90 % of the mix with some battery energy storage and CCS deployment. Achieving the "very ambitious" scenario (1.5 °C) requires the most aggressive action by 2035, requiring non-CCS coal and natural gas to decrease to 4 %, and allowing an additional 4 % with CCS deployed. Additionally, biomass gasification and combustion with CCS (BECCS) is deployed to reach 7 % of the global supply in 2035. From 2035 onwards, the electricity grid is decarbonised, consisting of well over 95 % of low-carbon sources, predominantly from solar and wind.

Ultimately, TIAM-UCL prioritises solar, wind, hydropower, nuclear, and BECCS technologies for decarbonisation. CCS-fitted coal and natural gas see limited deployment in the "very ambitious" scenario (1.5 °C) in 2030 and 2035 as a transitional technology, being quickly phased out after that. This aligns with the common consensus, such as the IPCC suggesting that the greatest decarbonisation opportunities for energy supply are in solar and wind, while fossil with CCS has relatively limited benefits [52].

3.2. Life-cycle environmental impacts of decarbonising the future global electricity mix

Fig. 3 shows that the evolving technology mixes in TIAM-UCL lead to varying LCA results across different time periods and scenarios. Firstly, LCA supports the TIAM-UCL low-carbon technology options for electricity decarbonisation, demonstrating that their adoption across all scenarios reduces the life-cycle climate change impact (Fig. 3, "climate change" subfigure). For example, TIAM-UCL aims to achieve complete decarbonisation by 2035 in the "very ambitious" scenario (1.5 °C), with the energy mix comprising over 95 % low-carbon options. This shift results in the climate change impact showing a 100 % reduction compared to 2025 levels.

Within the aggregated results, the pLCA scenarios also show how the impacts of individual technologies evolves. Fig. 4 shows current and future climate change impact for selected technologies. Consistent with the electricity mix climate change impact in Fig. 3, solar, wind, nuclear, hydro, and BECCS have substantially lower climate change impact than coal and natural gas technologies (Fig. 4). For example, supercritical coal generation combined with CCS could reduce the climate change impact of conventional coal from 1.07 to 0.18 kg CO_2e kWh^{-1},

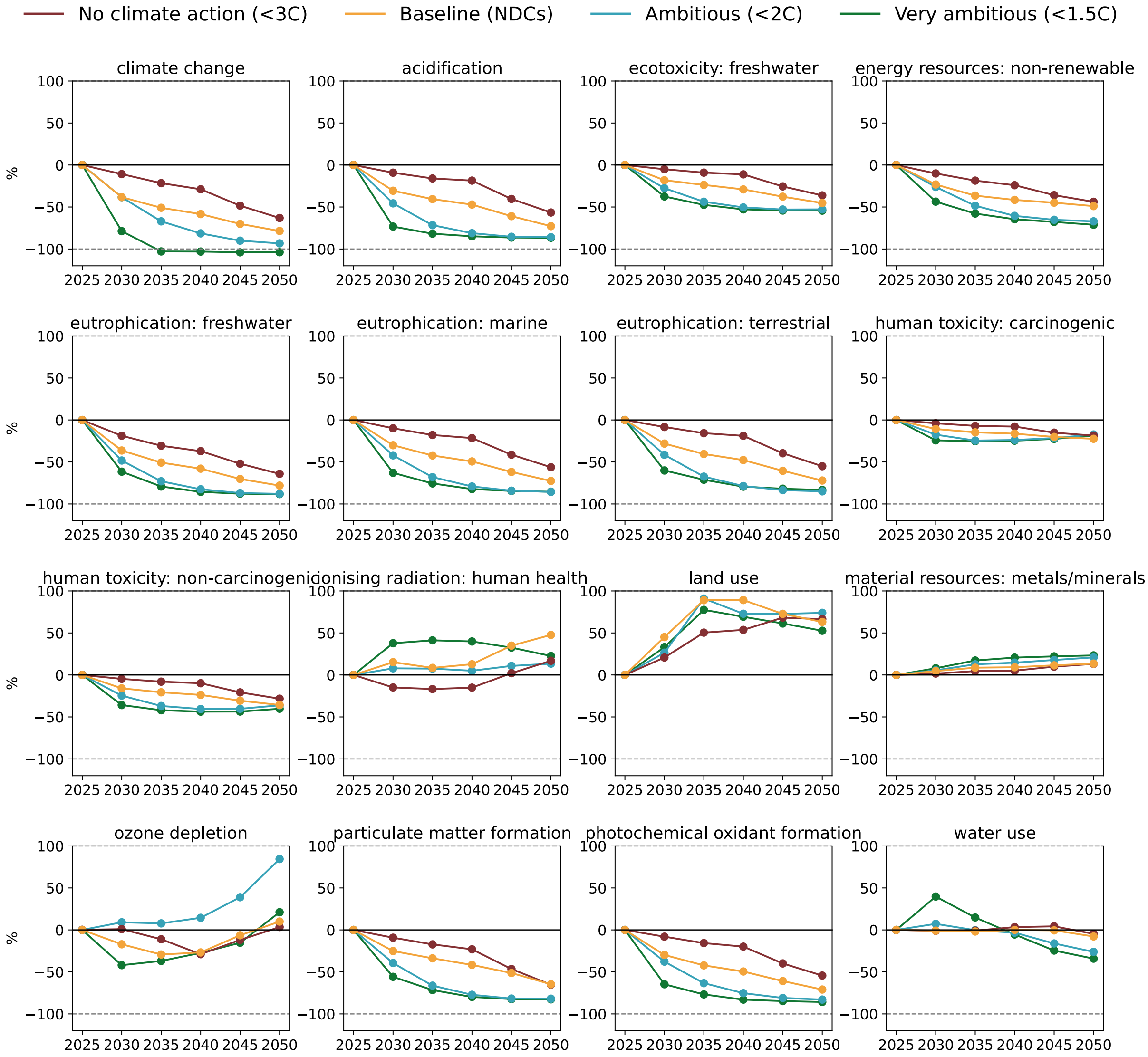

Fig. 3. pLCA results for generating and supplying 1 kWh of global low-voltage electricity according to the EF 3.1 impact assessment method across the TIAM-UCL scenarios. Results are presented as percentage difference scores from the baseline year, 2025.

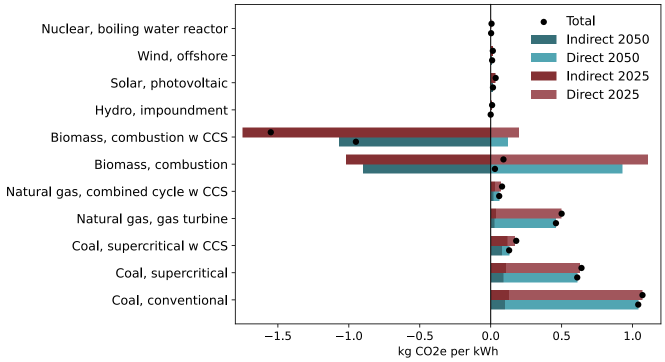

Fig. 4. Current and future pLCA results of different electricity generation technologies, based on WEU region and the "very ambitious" scenario (1.5C). "Direct" represents on-site emissions while "indirect" impacts represent embodied emissions such as manufacturing and fuel production. Selected technologies represented are based on the most dominant TIAM-UCL technologies and their respective ecoinvent LCI: Nuclear, boiling water reactor – nuclear; Wind, offshore – wind, 1–3 MW turbine; Hydro, impoundment – hydro, reservoir, alpine region; Solar, photovoltaic – photovoltaic, commercial; Biomass, combustion w CCS – wood-burning power plant, post, pipeline 200 km, storage 1000m; Biomass, combustion – at wood burning power plant; Natural gas, combined cycle w CCS – natural gas-fired combined cycle power plant, post, pipeline 200 km, storage 1000m; Natural gas, gas turbine – natural gas, gas turbine; Coal, supercritical w CCS – hard coal-fired power plant, ultra-super critical, oxy, pipeline 200 km, storage 1000m; Coal, supercritical – hard coal, supercritical; Coal, conventional – hard coal.

potentially attaining 0.13 kg CO_2e kWh^{-1} by 2050 in the "very ambitious" scenario (1.5 °C) due to efficiency improvements and infrastructure decarbonisation. However, the climate change impact remains significantly higher than current and future renewable technologies, which are well below 0.05 kg CO_2e kWh^{-1}, due to the embodied emissions in coal mining and the inefficiencies of uncaptured CO_2 emissions from coal combustion.

Therefore, the life-cycle perspective supports TIAM-UCL recommendations to limit CCS deployment while focusing on solar and wind. Moreover, technologies like solar PV could realise over 50 % reductions in climate change impact from 0.04 to 0.02 kg CO_2e kWh^{-1} by 2050 given decarbonisation benefits in upstream energy and materials for manufacturing. Furthermore, Fig. 3 shows that BECCS deployment can lead to negative-carbon electricity mixes from 2035 such as in the "very ambitious" scenario (1.5 °C) due to the upstream uptake of biogenic CO_2 that is captured during combustion and assumed to be permanently stored.

Beyond climate change impact, Fig. 3 shows that a phase out of coal and natural gas in all scenarios could see notable environmental co-benefits in ten other impact categories. For example, reducing coal-based electricity generation eliminates harmful life-cycle sulfur dioxide and nitrogen oxides from coal combustion and mining, which can mitigate over 90 % of impacts in categories such as acidification (as seen in Fig. 5), particulate matter, and photochemical oxidant formation. Many more upstream emissions linked to coal mining such as phosphates, hydrocarbons, chlorides, chromium, arsenic, and mercury are eliminated leading to substantial benefits across categories such as eutrophication and toxicities.

However, five environmental trade-offs could also be seen in Figs. 3 and 5. In the "very ambitious" scenario (1.5 °C), ionizing radiation could increase by up to 50 % due to increased nuclear shares in some regions. Resource consumption of minerals and metals could also increase up to 30 % due to increased demand for tellurium, silver, copper, and gold in wind and solar power plants. Water use could see temporary increases in 2030 and 2035 because of increased electricity shares in hydro in certain regions, which causes evaporation in reservoir-type installations. One of the most significant trade-offs throughout all scenarios is land use linked to solar and BECCS, which could increase by over 100 % (Fig. 3); although solar power's land footprint could be overestimated if solar expansion was instead achieved by prioritising urban and industrial roof installations. Furthermore, in the "ambitious" scenario (<2.0 °C), ozone depletion could increase due to the increased shares of battery storage, which currently requires tetrafluoroethylene for the vanadium-redox flow battery chemistry, leading to upstream halogenated hydrocarbon emissions such as CFC-12 and R-10. These are, however, expected to be phased out under the Montreal Protocol.

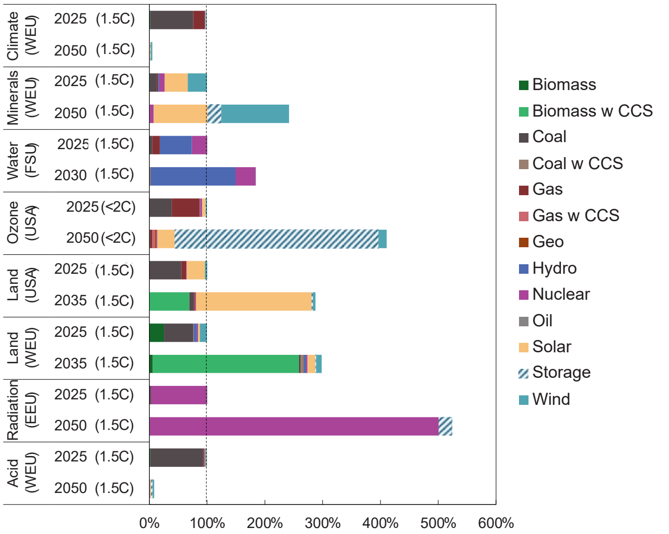

Fig. 5. Percentage normalized contribution analysis relative to 2025 values for electricity generation in selected impact categories, regions, years, and scenarios for trends of interest shown in Fig. 3.

3.3. Normalisation and importance of life-cycle indicators

The IAM decarbonisation scenarios demonstrate life-cycle reductions in multiple environmental impact categories, potential trade-offs are also identified that present risks for decision-makers. However, interpreting the broader significance of these environmental trade-offs is challenging using midpoint LCIA indicators alone. Therefore, normalising the LCA-based results against global inventories and population (e.g. climate change impact divided by the global average kg CO_2e per person) can aid in interpreting the potential significance of the results; see Fig. 6 – heat maps where darker colours indicate greater significance.

This reveals that, compared to global averages per person, the most significant categories could be freshwater eutrophication, non-renewable energy resources, non-carcinogenic human toxicity, climate change, and acidification, all of which are projected to decrease across all future scenarios (Fig. 3). However, the consumption of metals and minerals is also identified as a potentially significant category, with its impact increasing in all scenarios. Additionally, ionizing radiation may become increasingly important, indicating that the previously noted percentage increases may be indeed a cause of concern. In contrast, despite the greatest percentage increases being observed in land use and ozone depletion, this normalisation suggests that these results may be relatively insignificant compared to global per capita projections for both categories. While ozone depletion significance could be expected to remain low due to substance phase-outs under the Montreal Protocol, land use significance is more uncertain. Increased land use from solar and biomass expansion, along with potential rising per capita demands in food production and housing, may see normalisation factors significantly change. Given also the use of outdated 2010 normalisation factors, there is significant uncertainty in normalised results and

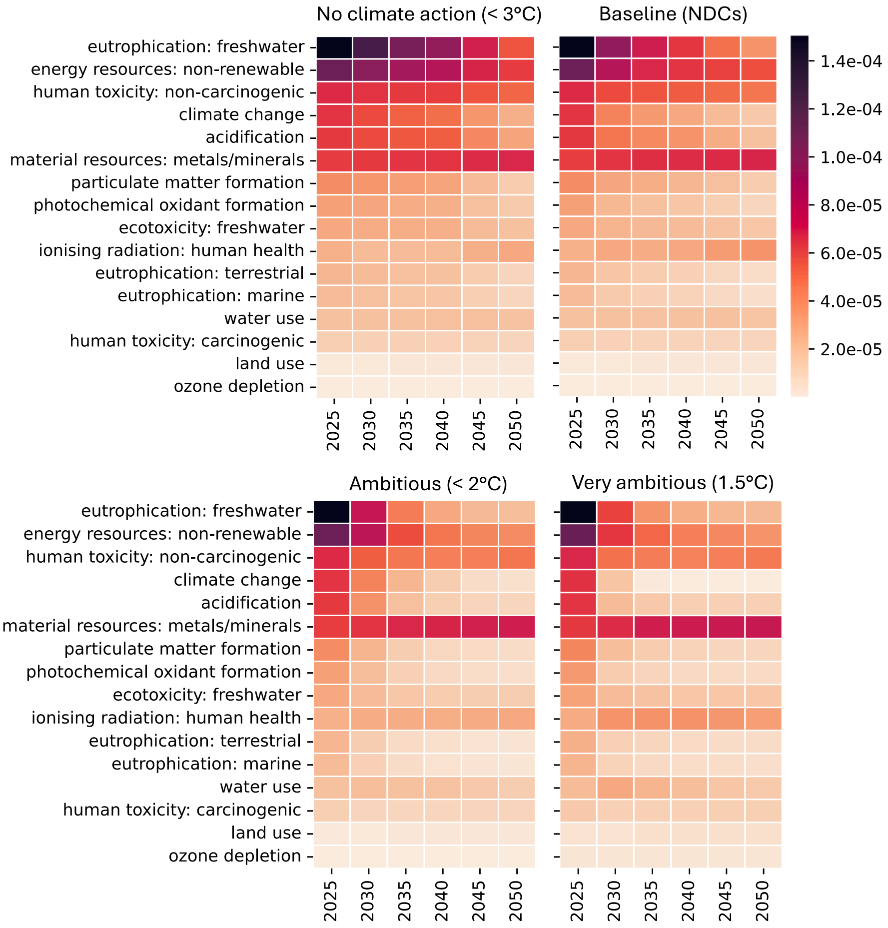

Fig. 6. LCIA results for electricity normalized according to EF 3.1. Normalisation factors are based on relevant emissions per person [47].

interpretation should take caution in prospective assessments.

Therefore, while deploying low-carbon technologies could indicate some environmental risks, such as shortages in critical materials, other trade-offs may occur in categories of lesser significance. Our analysis demonstrates substantially more environmental benefits particularly in categories that could be of higher significance, suggesting that IAM decarbonisation scenarios and the associated low-carbon technologies can lead to increasingly positive environmental outcomes. However, as discussed, normalisation factors are subject to great uncertainty and should be carefully interpreted.

3.4. Comparison of outcomes between IAMs

3.4.1. Paris Agreement: scenarios limiting global warming to 1.5–2.0 °C

Equivalent scenarios from TIAM-UCL, IMAGE, and REMIND exhibit both similarities and differences in their life-cycle environmental impacts on the global electricity mix due to variations technology deployment. Fig. 7 shows that to achieve the “very ambitious” (1.5 °C) scenario aligned to the Paris Agreement, all IAMs show rapid and complete electricity decarbonisation by 2035. However, they achieve this objective through different technology mixes (see supplementary material 3 for figures [48]).

For instance, BECCS plays a significant role in TIAM-UCL and IMAGE, leading to a negative climate change impact, while it sees minimal deployment in REMIND. Both TIAM-UCL and REMIND anticipate a rapid decline in fossil fuel generation by 2035, but during this decline, TIAM-UCL deploys noteworthy shares of CCS for fossil generation. In contrast, IMAGE relies on substantial shares of natural gas with CCS from 2035 onwards, making up over 15 % of the share by 2050, while little to no fossil generation with CCS is projected in REMIND or TIAM-UCL by 2050. Solar deployment is most favoured by REMIND, which sees a share of over 50 % by 2050, while TIAM-UCL favours it less (36 %), with more distributed shares in nuclear, hydro, BECCS, and wind. IMAGE shows the least favourable solar deployment (26 % by 2050), mainly due to its greater shares of gas with CCS and BECCS technologies. Similar trends and conclusions apply to the “ambitious” scenarios (<2.0 °C), although IMAGE shows significant coal and natural gas shares beyond 2040, where these have been largely phased out in TIAM-UCL and REMIND.

Despite differences in low-carbon technology deployment, Fig. 7 shows that the IAMs show similar life-cycle environmental co-benefits in the ten categories discussed in Section 3.2, many of which could be considered among the most important. The overall decline of fossil generation across the IAMs leads to consistent reductions in areas such as acidification, eutrophication, and toxicities. While TIAM-UCL and REMIND are closely aligned, IMAGE shows smaller co-benefits in categories like non-renewable energy resources, eutrophication, and particulate matter, as it retains natural gas generation, albeit CCS-fitted.

For environmental trade-offs, all IAMs show steady increases in metals and minerals usage as low-carbon technologies are deployed which is a category of potential high significance. However, there are notable differences in ionizing radiation—another potentially significant category. TIAM-UCL and IMAGE can show increases due to higher reliance of nuclear shares, while REMIND shows decreases due to reduced nuclear shares. Similarly, REMIND shows co-benefits in ozone depletion linked to fossil generation decline while TIAM-UCL and IMAGE can see increases due to the deployment of battery storage. In contrast, REMIND leads to the greatest increases in land use due to its

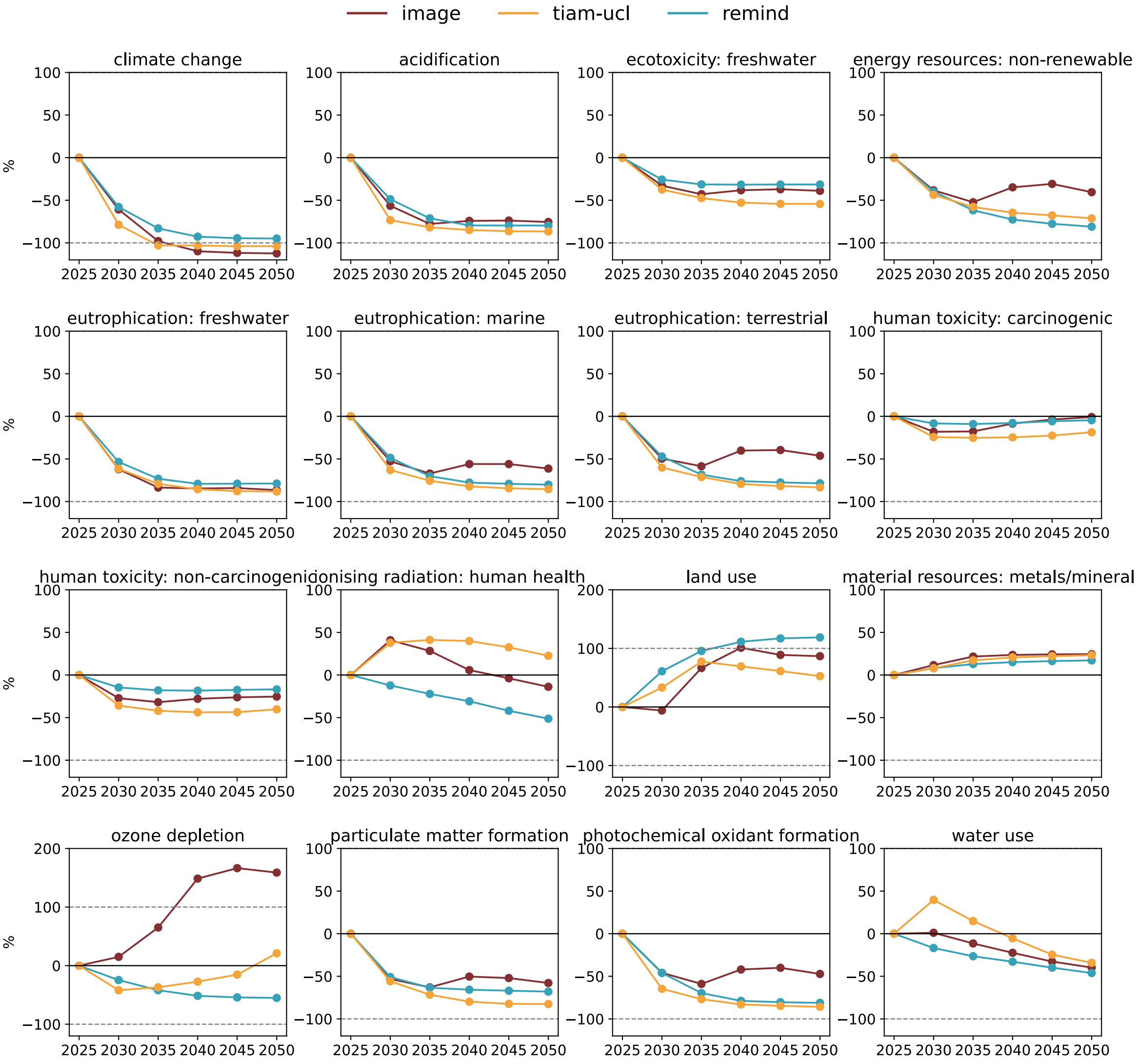

Fig. 7. pLCA results for EF 3.1 midpoint indicators for the generation and supply of 1 kWh of low-voltage electricity globally, using scenarios from TIAM-UCL, IMAGE, and REMIND considering the "very ambitious" (1.5C) equivalent pathway. Results are presented as percentage difference scores from the baseline year 2025.

much greater reliance on solar compared to TIAM-UCL and IMAGE. Despite sizable IAM differences in ozone depletion and land use, these categories could hold the least significance (Fig. 6).

3.4.2. *Scenarios for no climate action and Nationally Determined Contributions*

In the "no climate action" scenarios, which miss the Paris Agreement targets and may only limit global warming to 3.0 °C, IAMs show sharp contrasts (see supplementary material 3 for underlying figures [48]). For instance, IMAGE shows limited climate change impact reductions from 2025 to 2050 as it projects fossil generation to remain consistent. Meanwhile, TIAM-UCL and REMIND can still predict climate change impact reductions of over 50 % by 2050. Although both models reach similar outcomes for 2050, REMIND shows faster decarbonisation due to a quicker initial coal phase-out rate. For other environmental categories similar trends are observed as in Section 3.3.1, albeit at different magnitudes. Nonetheless, TIAM-UCL and REMIND still produce electricity decarbonisation even without climate action due to continuing trends in solar and wind expansion (albeit still overshooting Paris Agreement objectives) while IMAGE forecasts little to no changes. In the "baseline (NDCs)" scenario - corresponding to limiting global warming to around 2.5 °C based on the current global trajectory and only available for REMIND and TIAM-UCL - both models exhibit very similar decarbonisation pathways, projecting a reduction in climate change impact by just over 50 % by 2035 and a steady approach toward decarbonising 80 % of electricity by 2050. Both models demonstrate the same ten environmental co-benefits discussed previously. However, TIAM-UCL shows similar trade-offs concerning ionizing radiation and ozone depletion, with higher impacts on water use compared to REMIND. Conversely, REMIND exhibits greater impacts on land use.

3.4.3. *Implications for pLCA and IAMs*

The different IAM outcomes indicate careful consideration should be taken in pLCA studies that select and use IAM future scenarios. For climate change outcomes, the IAMs all produce climate change impact reductions in scenarios aimed at limiting global warming to 1.5–2.0 °C. Therefore, pLCA using these scenarios from any of the three IAMs should yield consistent conclusions, provided correct adjustments are made using Premise to account for net-negative carbon flows (e.g., BECCS) in the IPCC 2021 method.

However, the "no climate action" (<3.0 °C) scenarios yield different degrees of decarbonisation over time between the IAMs. Therefore, pLCA studies should consider how this affects their outcomes. For example, this is already evident in pLCA studies on lithium-ion batteries.

Šimaitis et al. [35] used "no climate action" (<3.0 °C) and "ambitious" (<2.0 °C) IMAGE scenarios, showing that manufacturing lithium iron phosphate (LFP) batteries could reduce climate change impact by 7 % and 50 % from 2020 to 2050, respectively. Meanwhile, Xu et al. [27] used equivalent REMIND scenarios on LFP batteries and observed much more significant reductions of 50 % and 85 %. These results may inform different conclusions for decision-makers that could have been attributed solely to the choice of IAM.

Furthermore, since the IAMs utilise different low-carbon technologies, this results in differences in other impact categories beyond climate change impact. Although all IAMs show that phasing out fossil fuels leads to environmental co-benefits in ten categories, IMAGE can have smaller co-benefits due to its greater resistance to fossil phase-out and reliance on CCS. IMAGE and TIAM-UCL can have greater impacts in ionizing radiation and ozone depletion due to nuclear and battery storage shares, while REMIND shows the greatest land use impacts due to its aggressive solar deployment. Therefore, it is important for pLCA studies to carefully consider their choices of IAMs and scenarios, including (i) their relevance to the study goals and scope; (ii) how their environmental outcomes could be influenced by different choices and their wider significance; and (iii) how potential changes in outcomes informs interpretation and decision-making. It is important for studies to use a broad range of IAM scenarios to explore many possible outcomes and sensitivity test the robustness of their LCA results.

Ultimately, differences in IAM scenarios (including technology mixes) are rooted in their input and modelling approaches [3,4,53]. As an example, both TIAM-UCL and REMIND assume perfect foresight, enabling them to model theoretically efficient pathways by assuming decision-makers have complete knowledge of future events and policies. This approach identifies the most cost-efficient long-term climate strategies but may overlook short-term uncertainties and practical challenges. In contrast, IMAGE operates without foresight, relying on current information and immediate conditions. This results in more realistic short-term dynamics but could lead to suboptimal long-term pathways, as it may miss opportunities for early investments in low-carbon technologies due to the lack of anticipation of future policies and advancements. As a result, we see TIAM-UCL and REMIND show faster and greater decline in fossil fuel use, lower reliance on CCS, and more uptake of solar compared to IMAGE. However, there are several complex and interlinked factors within IAMs that contribute to these differences and should be carefully interpretated [3,4,53].

3.5. *Limitations and further work*

We acknowledge some limitations and areas for further work. Firstly, mapping and integrating TIAM-UCL scenarios with Premise and ecoinvent introduces an uncertainty layer. Due to current data availabilities, approximations, simplifications, and aggregations for technologies were necessary, inevitably, there are some minor discrepancies between IAMs and pLCA outcomes. For example, TIAM-UCL supercritical and ultra-supercritical coal generation technologies were mapped to similar ecoinvent activities but adjusted by changing efficiencies to reflect TIAM-UCL specifications. However, in some cases, this approach generalises the original ecoinvent inventories, which may have provided greater specificity in regional efficiencies. As a result, it might not accurately reflect real-world variations in inventories or operational efficiencies. Therefore, continuous iteration and updates are important as new LCIs become available. Additionally, geographical mapping from TIAM-UCL to ecoinvent reduces the spatial resolution to only 16 aggregate regions. Although TIAM-UCL robustly accounts for technology availability and costs in each aggregate region, its primary focus is on long-term global decarbonisation pathways under various scenarios that assume perfect foresight. Consequently, TIAM-UCL scenario outputs and their regional mapping to ecoinvent may not fully capture localised policies, or short-term decision-making as seen in myopic foresight.

The study scope focused on global electricity supply. Future studies are encouraged to investigate the life-cycle decarbonisation interdependencies of the broader energy system, such as fuels and steel. Additionally, the life-cycle approach evaluates the impact per unit of electricity generated, which may not fully reflect the broader impacts of increased electrification demands and its role in climate mitigation across different end-use sectors. It is also important to delve deeper into LCIA methods to quantify the wider significance of environmental co-benefits and trade-offs of energy transitions beyond midpoint indicators. While EF3.1 normalisation factors captured some of this discussion, they are subject to uncertainties, such as outdated global inventory data, regional variations, and temporal mismatches when applying them to future scenarios.

Lastly, while the addition of TIAM-UCL to Premise has increased scenario diversity, the focus, as with other IAMs, is primarily on energy systems. While this is valuable for assessing climate and related impacts, other impacts, such as toxicities and resource use, are more uncertain. These factors can be influenced by changes in mining practices, shifts toward a circular economy (e.g., increased recycled content), and fluctuations in characterisation factors, which are currently not considered in Premise. Moreover, given the differences in pLCA outcomes that IAMs can yield, it would be an interesting avenue to establish the linking of life-cycle indicators back into the IAMs to see how potential solution spaces for technology mixes change. For example, linking potential life-cycle decarbonisation of low-carbon technology manufacturing or critical material shortages.

4. Conclusions

This study has increased scenario diversity within Premise and pLCA by introducing four new scenarios from TIAM-UCL for major energy sectors such as electricity, steel, and fuels. We investigated the life-cycle environmental impacts of TIAM-UCL's future global electricity supply using ecoinvent v3.9.1 and EF 3.1, finding climate change impact reductions in all decarbonisation scenarios due to the phase-out of fossil fuels and the uptake of low-carbon technologies. This transition showed evident environmental co-benefits in at least ten categories, such as acidification, eutrophication, and toxicities, with normalisation highlighting their high significance. However, adopting low-carbon technologies showed potential trade-offs in five categories, notably mineral and metal usage, and ionizing radiation. Trade-offs in land use and ozone depletion showed significant increases but were identified as categories of potentially lower significance (based on the EF3.1 midpoint normalisation approach).

We compared pLCA outcomes between TIAM-UCL, IMAGE, and REMIND scenarios, demonstrating variability in the magnitude and rates of environmental benefits and trade-offs. These were due to varying low-carbon technology deployments despite common decarbonisation objectives. However, all IAM scenarios aligned with the Paris Agreement (1.5–2.0 °C) showed consistent climate change impact reductions and environmental co-benefits in ten categories, all linked to the phase out of fossil fuels. However, critical differences in pLCA outputs were observed:

1. TIAM-UCL and REMIND showed steady electricity decarbonisation in the "no climate action" (<3.0 °C) scenarios, while IMAGE showed limited decarbonisation with resistance to changes in the electricity mix.
2. IMAGE presented smaller environmental co-benefits in all scenarios due to its reliance on fossil natural gas generation fitted with CCS.
3. REMIND had greater land use impacts due to its aggressive solar deployment (assuming land use that does not utilise urban and roof-based integration the use of mainly). In contrast, IMAGE and TIAM-UCL showed more significant trade-offs in ionizing radiation and ozone depletion from higher nuclear and battery storage shares.

In conclusion, while low-carbon energy transitions pose some life-cycle environmental risks, there are more climate and environmental co-benefits. For pLCA studies, the choice of IAMs and scenarios significantly influences results, necessitating careful evaluation for relevance, environmental outcomes, and implications for decision-making. Practitioners are advised to utilise multiple IAM scenarios to investigate several potential outcomes and assess the sensitivity and rigor of pLCA results. Future work should enhance technology and geographic resolutions between IAMs and life-cycle inventories, broaden the focus to the entire energy system, investigate LCIA methods and underrepresented categories such as toxicities, and integrate life-cycle indicators into IAMs to explore new technology solutions.

CRediT authorship contribution statement

Joris Šimaitis: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Validation, Writing – original draft. **Isabela Butnar:** Data curation, Methodology, Resources, Writing – review & editing. **Romain Sacchi:** Data curation, Methodology, Resources, Software, Writing – review & editing. **Rick Lupton:** Conceptualization, Supervision, Writing – review & editing. **Christopher Vagg:** Supervision, Writing – review & editing. **Stephen Allen:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve manuscript readability and aid proofreading procedures. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication[48].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.115298.

Data availability

All underlying data and scripts are available in the supplementary material provided with this article, and will be made available on the University of Bath data repository once published

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