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More rationality and inclusivity are imperative in reference transition scenarios based on IAMs and shared socioeconomic pathways - recommendations for prospective LCA

Anne de Bortoli [a,b,*], Alexis Chanel [a,c], Camille Chabas [d], Titouan Greffe [d], Estelle Louineau [d]

[a] CIRAIG, Génie Chimique, Polytechnique Montréal, 3333 Queen Mary Road, Montreal, Quebec, Canada
[b] LVMT, École des Ponts ParisTech, Institut Polytechnique de Paris, 6-8 avenue Blaise-Pascal, Cité Descartes, Champs-sur-Marne, France
[c] École Polytechnique Fédérale de Lausanne, Route Cantonale, 1015, Lausanne, Switzerland
[d] CIRAIG, Institut des Sciences de l'Environnement, Université du Québec à Montréal, 201 avenue du Président-Kennedy, Montreal, Quebec, Canada

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ABSTRACT

Prospective life cycle assessment (pLCA) is a key tool for evaluating future environmental impacts and supporting environmental policies. Recent pLCA methods integrate technological projections from transition scenarios modeled with integrated assessment models (IAMs), leveraging the shared socioeconomic pathways (SSPs) and representative concentration pathways developed within the framework of the Intergovernmental Panel for Climate Change (IPCC). However, this computational framework is influenced by subjective modeling choices within IAMs and SSPs, which can affect the robustness and relevance of future technological scenarios thus pLCA results. This article starts by highlighting these subjective choices through the lens of Science and Technology Studies, to then provide recommendations to enhance pLCA practices within this computational framework, especially through the selection of more (a) rational and (b) inclusive technological scenarios. The first step toward better practices is recognizing the inherited choices and limitations of borrowed models. Our recommendations then address the selection of future technological scenarios for pLCA: these scenarios could (a.1) account for the whole variability of mainstream transition scenarios from the latest IPCC report and its effect on pLCA results, (a.2) include only screened IPCC mainstream IAM scenarios based on proposed reality check criteria, (b.1) integrate scenarios rooted in alternative economic schools of thought, such as post-Keynesian economics or ecological macroeconomics, explore scenarios based on alternative (b.2) indicators prioritizing strong sustainability, justice, and well-being, and (b.3) societal narratives such as economic downscaling avenues and degrowth. Finally, we emphasize the need to incorporate ethical considerations into modeling, offering recommendations to (b.4) prioritize more equitable scenarios.

1. Introduction

1.1. The recent surge in prospective life cycle assessment practice

Prospective life cycle assessment (pLCA) has recently gained significant momentum in the industrial ecology community, driven by incremental developments that have made this approach more accessible [1,2]. Unlike static LCA which assumes a fixed production system (i.e. the technosphere) when assessing the environmental footprint of systems, pLCA incorporates future changes in both background and foreground systems to more accurately reflect the potential environmental impacts of long-lasting or future-deployed systems. This prospective approach is essential for environmental planning and safeguarding humanity, particularly in supporting decision-making aligned with the Paris Agreement [3], and more globally planetary boundaries [4–6]. Key advances in pLCA include THEMIS—the first framework to embed International Energy Agency (IEA) prospective energy scenarios directly within LCA [1] —and a subsequent large-scale model-coupling study that further tightened this integration. The latter work demonstrated that explicitly modelling future technospheres is

* Corresponding author. CIRAIG, Génie Chimique, Polytechnique Montréal, 3333 Queen Mary Road, Montreal, Quebec, Canada.
E-mail address: anne.debortoli@polymtl.ca (A. de Bortoli).

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critical for producing robust pLCA results [2]. More recently, the *premise* tool [7] has revolutionized and broadened the use of pLCA by providing an advanced, open-access, interoperable, and customizable model that promotes the reproducibility and transparency of harmonized pLCA studies, saving the LCA community significant time previously spent developing single-use, and often redundant, models.

Premise injects into background life cycle inventory (LCI) databases the technological evolutions projected by complex models under canonical societal and climate scenarios, to generate consistent prospective background technospheres. More precisely, *premise* duplicates the reference ecoinvent LCI database and modifies specific activities such as the prospective power generation and negative emission technologies (NET) deployment using output data from scenarios modeled in the context of the Coupled Model Intercomparison Project version 6 (CMIP6) and the Intergovernmental Panel on Climate Change (IPCC) [8]. A prospective LCI database generated with *premise* would for instance provide the European electricity consumption market in 2030 following a specific CMIP6 scenario. The reference societal scenarios used in the CMIP6 and *premise* are the most widely accepted to date [9]: the Shared Socioeconomic Pathways (SSP) [10–12], designed to standardize prospective modeling practices by improving their consistency, transparency, and results comparability. The climate targets considered are the Representative Concentration Pathways (RCPs), while the complex models used to solve the SSP-RCP objectives are Integrated Assessment Models (IAMs, for an overview see Nikas et al. [13]). IAMs – based on an economic, a land-use, and an energy-climate model - simulate the greenhouse gas (GHG) emissions induced by changes in economic activities and public policies [12]. They have a paramount role in climate policy analysis and climate discourses, as the IPCC's Working Group III uses them to develop mitigation scenarios read by numerous stakeholders and policy makers [14]. In that sense, the climate mitigation scenarios developed with IAMs within this IPCC framework are canonical and can be considered as reference transition scenarios used for environmental modeling and policy making. *Premise* 2.1.1 [15]. is linked to the SSPs-RCPs scenarios resolved by the IAM REMIND-MAgPIE [16], IMAGE [17], and TIAM-UCL [18]. These three IAMs, like the other ones used in the IPCC Assessment Report (AR) 6, will be qualified as "mainstream" IAMs as they are based on neoclassical economics, the mainstream modeling representation of the economy, like most of the forty-ish existing IAMs – understood as "process-based IAMs" that project cost-effective optimal mitigation pathways with detailed technologies [19].

Despite the massive enhancement and possibilities offered by IAM-based pLCA (IAMpLCA), the LCA community must remain vigilant on some limitations and risks linked to this emerging practice, in a constant effort to refine tools to delineate robustly more sustainable futures. Some first limitations, such as a limited technological and regional coverage in IAMs, were pointed out by current IAMpLCA developers [20], but a deeper understanding of IAM modelling assumptions and underlying vision is needed, despite the variability of IAM's structure making generalization somehow delicate. As LCA practitioners are neither economists nor IAMs or climate modelers, they may not fully apprehend the consequences of borrowing to other scientific disciplines, e.g., choosing one IAM, one SSP, or one RCP over another one. Indeed, according to Morgan [21], modelers in general tend to overlook the fact that all modeling inherently involves some degree of subjectivity, embedding underlying values and preferences.

1.2. Objectives of the article and disclaimer

The overall objective of this article is to critically reflect on IAMpLCA - i.e. unveil some implicit assumptions and their implications - to better understand the limitations of pLCA models and improve scientific practices. First, we examine how mainstream IAMs and SSPs contain inherent limitations to model energy system futures, which may lead to unfeasible or undesirable projections of energy and NET systems in prospective life cycle inventory (pLCI) background databases (section 2). Second, relying on Science and Technology Studies (STS), we further explain how modeling inevitably draws from social contexts due to different drivers influencing modeling, to then specifically discuss the implications of the economic representation chosen in mainstream IAMs (section 3). Third, we propose some avenues for more robust and inclusive pLCA practices, especially in the selection of technological scenarios to inject in pLCI databases (section 4).

Before developing our argument, we want to emphasize three important points: i) We – the authors - are not economists. As so, we solely intended to highlight current criticisms on IAMs and SSPs drawn from published scientific literature as well as from exchanges with economists and IAM modelers while cultivating a certain knowledge humility [22] when approaching the topic; ii) We acknowledge the recent work done on IAMpLCA tools and some of us, as well as many of our colleagues, do use *premise*; iii) This commentary does not aim to dismiss previous immense efforts to progress in prospective modeling in the IAM and LCA communities. Rather, it is an introspection and dialogue on current practices to stimulate these two research communities and highlight additional efforts needed for a more inclusive, just, and robust consideration of possible futures - "possible" meaning a future that can occur according to fundamental laws of physics.

2. Reference transition scenario modeling: IAMs and SSPs display inherent limitations to model possible futures of energy and carbon removal systems

In this section, we highlight some characteristics of and mechanics in mainstream IAMs, as well as some specificities of the published five SSPs – that may lead to narrowing or misconceiving the range of possible futures of energy systems and carbon removal systems deployment.

2.1. Limitations of mainstream IAMs

2.1.1. A supply-led economic modeling forces high technological progress and penetration

A first group of limitations from using mainstream IAMs to draw possible technological futures to inject in LCA background databases relates to the economic modeling in these IAMs.

Mainstream IAMs are based on neoclassical economics, thus adopting a supply-led logic: Mercure et al. [23] provide a clear synthesis of the economic structure of current IAMs. In a supply-led economy, the production structures the economy far more than the demand [23,24]. Thus reducing final energy demand - one lever to decarbonization - can mainly be achieved through energy efficiency improvement and technology development [25]. Demand-side mitigations – such as energy consumption reduction policies or changes in lifestyles - are generally overlooked by mainstream IAMs to mitigate climate change [26,27]. Incidentally, several authors highlight the inability of supply-led models to realistically draw solutions to supply final energy demand projections [19,27], or question the possibility to reach net-zero without considering demand-side mitigations policies [27–35].

This mechanism tends to force very optimistic technological assumptions to reach decarbonization targets, especially important and fast energy efficiency improvements that are very optimistic when compared to historical trends ([36,37]), and important and fast carbon dioxide removal technology deployment. Some IAMs may even project unrealistic deployment of NETs capacity in scenarios used by pLCA practitioners. A prominent example is the projected carbon dioxide removal capacity in the SSP2-RCP2.6 scenario modeled with IMAGE: it reaches 1.5 $GtCO_2$ per year in 2030 while, according to current plans and assuming very optimistic projected failure rates (i.e. twice lower than historical failure rates), the estimated deployment of NETs would reach at best 0.25 $GtCO_2$ per year at that time, which is six times less [38]. Using *premise* with this scenario could hence provide flawed pLCIs, as the implausible deployment of NETs influences the projected optimal

deployment of other technologies, in particular energy systems.

The feasibility but also the desirability of large-scale NETs deployment to respect radiative forcing thresholds [25] is quite polarized [39,40]. On one hand, some researchers think that massive and quick research and development, as well as deployment investments, and an increased social acceptance can scale-up safe NETs [41]. On the other hand, many argue that counting on NETs large scale deployment to decarbonize is an irresponsible bet for several reasons including rebound effects, burden shifting [40,42–44], delays [41,44], costs [44,45], asymmetry in the climate-carbon cycle response between emissions and removals [46], and uncertain durability of the sequestration [40,47]. Optimistic technological assumptions must eventually lead to unrealistic technological scenarios, and thus to unrealistic pLCI background databases.

2.1.2. *The roles of institutions and finance have long been respectively missing and distorted*

Due to their supply-led lens, mainstream IAMs historically addressed decarbonization as a technological transition, while the unprecedented changes in technical systems (e.g., renewable energy penetration, efficiency gain) would also induce changes in consumptions and institutional structures [48]. Indeed, consumption markets are partly influenced by regulations and tax systems. As an example, property rights regimes and tax incentives differ among countries and influence technology diffusion [49]. Therefore, the transition is not only technical, but also social [50], and mitigation policies must be assessed on all their dimensions to avoid unexpected and unwanted results [51]. For example, the importance of several political or social barriers, e.g., willingness to pay higher electricity prices and overstanding or misjudgment towards new technologies – has been highlighted by Hafner et al. [52] and Li and Strachan [53]. Assessing these dimensions is also necessary to describe second-order effects, such as the rebound effect [54], as well as demand-driven solutions [49]. Mainstream IAMs recently focused on improving the inclusion of demand-side measures and simple energy aspects are especially well covered now [55], but rebound effects seem more difficult to capture. Rebound effect of energy efficiency measures is a typical example of such unexpected and unwanted outcome, as energy saved from adopting more efficient technologies can be partly reallocated to new additional usages, ultimately reducing expected savings [56,57]. These mechanics and their intensity are variable - from low effects to eroding more than half the expected energy savings - and depend on behavioral responses to energy efficiency improvements [58]. While there is no consensus on the magnitude of rebound effects [59], not considering them leads to overestimating the benefits of efficiency measures to decarbonize.

Finally, mainstream IAMs do not explicitly model the role of finance [60,61], which could end up in distorted views on possible technological futures. In fact, deploying a renewable energy system is necessary to decarbonize [62], but capital-intensive [63], and in neoclassical modeling, there is no investment through money creation [23]. Savings being optimally allocated to economic sectors with the highest rates of return on investment to maximize profit [23], technologies with low rates of return on investment are “crowded out” as they have no access to capital for investments [23,64]. Consequently, the deployment of renewable energy systems to achieve the transition is modeled as a constraint on economic development [23].

2.1.3. *Biophysical flow constraints are neglected*

Modeling of primary supply of fossil energies, metals, and non-metallic minerals in mainstream IAMs is based on simplistic and widely contested assumptions [61,65,66]. It is assumed that the most economically viable reserves will be exploited first, which is not aligned with the reality of past extraction and the interplay of socio-geopolitical factors [61]. Moreover, for instance, exhaustible fossil fuel resources are characterized through cost-supply curves [61]. Those curves operate under the assumption that supply of fossil fuels is dictated by the market price of fossil fuels, while in reality price can increase when supply does not increase fast enough [61]. Those assumptions could obviously lead to misprojecting future technologies.

First, renewable energy generation and distribution systems highly rely on strategic metals exposed to potential supply shortages. The International Energy Agency (IEA) regularly makes projections on metal demands due to the transition, and showed that mine production is unlikely to follow metal demands for at least three key metals for the transition - copper, lithium, and cobalt - even in their non-Paris Agreement compliant “stated policy scenario” [67–69]. As a result, large deployment of energy technologies using those metals in IAM scenarios may be unrealistic. Currently, lithium and cobalt are necessary to main lithium-ion battery technologies [70], while copper is used in all the transition technologies, such as electricity distribution networks, photovoltaic panels, wind turbines, and electric cars [71]. If technology flexibility could help reduce shortage risks on some metals [72], on the battery side for instance by switching from nickel-cobalt-based batteries to lithium-iron-phosphate chemistries or new battery technologies like sodium-ion and all-solid-state batteries [70] -, shortages in copper may lead to unfeasible projected scenarios [67–69].

Second, land-use and biomass also play a key role in energy transition scenarios, both for carbon capture and energy production [73]. However, land-use and biomass consumption can be unrealistic in IAM scenarios. For example, the electricity generation from biomass modeled with REMIND-MAgPIE in the IPCC AR6 considers a capacity factor greater than 100 % after 2050 in SSP1, SSP2 and SSP5, which means that crops produce more than the maximum yearly production capacity (see calculations in supplementary information (SI 2)). The consequence of such assumption is the overestimation of electricity production from biomass, leading to underestimating the required installed capacity of other technologies producing electricity. It is therefore crucial to look under the hood of IAMs output data to better understand the credibility of pLCA results.

2.1.4. *Additional blind spots question the desirability of IAM-based scenarios*

Further limitations raise concerns about the pertinence of IAM-based scenarios, encompassing restricted or missing representation of climate damages, lack of consideration of non-climate planetary boundaries, as well as potential embedded neocolonialism.

The representation of climate damages varies among IAMs. A part of the modeling community argues that climate damages in mainstream IAMs are not sufficiently represented or even omitted for simplicity [66,74]. More widely, the precautionary principle is unevenly used among the IAMs with regards to specific physical thresholds that should not be crossed to ensure natural cycles preservation. While a temperature threshold can be considered in some modeling [75] and SSPs propose evolutions of air pollutant regulation stringency [12], other planetary boundary thresholds are overlooked, and limited attention is given to impacts beyond climate change. Some researchers argue that most IAMs fail to adequately capture the irreversible threats posed by human activities to societies and the planet. They contend that the Anthropocene is assessed narrowly, primarily from an anthropocentric perspective, neglecting its broader dimensions and disregarding the natural order [76,77].

Moreover, some authors consider that current SSPs and/or IAM scenarios are deeply unjust and colonial. Most scenarios assume that northern countries can keep on increasing production and energy consumption to the detriment of the poorest part of humanity [78]. Indeed, Parrique highlights that globalization follows an “extractive circuit”, in which richer countries import natural resources extracted in poorer countries without counterbalancing the environmental damages from extraction [79]. Hickel and Slamersak recall that, while 3 billion people currently live in energy poverty, little consideration is generally given to the Global South in mitigation scenarios: the Global North has the privilege of energy consumption levels per capita that are two to three

times higher than the Global South [78]. These facts can be seen as even more unjust when acknowledging that 92 % of the global excess GHG emissions incompatible with the Paris Agreement are attributable to consumption in the Global North [80], that the 10 % richest people, mostly located in the Global North, emit 48 % of GHGs while the 50 % poorest only emit 11.5 % of those [81], and that 39 countries from the Global North have already exceeded their collective fair share of a 1.5 °C carbon budget by more than 2.5 times [82]. These uneven dynamics are not widely discussed in IAM-based scenarios, what may legitimate those injustices [83]. This lack of consideration of the Global South dynamics is symptomatic of a North-rooted discourse about climate futures [84, 85].

2.2. Limitations of SSPs

All five SSPs assume global economic growth. Growth trends in SSPs narratives [10,11] and their quantitative translations [12,86,87] are the subject of heated debates, from too low [88] to too high [89,90], often judged according to considerations of regional differences and justice. Prominent examples are SSP1 and SSP5, which assume fast growth and better income convergence, and therefore require sizable deviations from decades-long, ubiquitous historical economic dynamics [91]. Growth rates, in terms of annual Growth Domestic Product (GDP) increase, range from 1.8 to 3.4 % on average for the 2010–2100 period in the marker quantitative assumptions [12], with SSP3 and SSP5 representing the lower and upper bounds, respectively [92]. In SSP5, the world's GDP is projected to increase by a factor of more than 10 over the same period [92]. Because decarbonizing takes time, maintaining economic growth leads to an increase in GHG emissions in the short-term, despite technological progress, such as improvements in energy efficiency. This, in turn, creates a greater need— depending on the climate target—to deploy NETs to offset the GHGs emitted under an increased production.

These five SSPs are qualified as basic narratives or "narrative starting points" that can thus be refined to be applied in more local contexts [10, 11]. They are said to "span an uncertainty space" and are supposed to largely cover possible development pathways and possible representative futures [11]. But this assumption of sufficient coverage of possible futures is increasingly contested [93,94]. If additional narratives are within consideration by the SSP developers, the systematic assumption of growth in all the narratives - from low to high growth rates - is not pointed out as an assumption to alter in additional SSPs [11], despite its effect on the level of necessary NETs development and its beyond-climate environmental consequences.

On the environmental side, the SSPs include different policy futures on air pollution [12]. While this is a first step toward a more integrated way of conceiving current and future environmental challenges, it neglects many other aspects of the environment, related to human health, biodiversity, and resources, that, similarly to climate change, jeopardize life on Earth.

2.3. Conclusion: consequences of unfeasible energy and carbon removal futures projected in pLCI background databases

All these limitations profoundly influence which future energy and NET systems are judged feasible and subsequently incorporated into pLCI databases. In turn, injecting unfeasible technological scenarios into pLCA background data can generate a truncated or biased picture of the future environmental consequences of human activities, yielding misguided recommendations for organising society sustainably within Earth's carrying capacity. IAM [19] and pLCA are not predictive instruments; rather, they are exploratory frameworks for analysing "what-if" futures. Yet this scenario-based—not predictive—purpose may be overlooked by end users, fostering the mistaken belief that model outputs could be forecasts.

Biases introduced in pLCA by technologically unattainable IAM scenarios can therefore lead to under- or over-estimate the future environmental impacts of assessed technologies—a pivotal concern, given that low-carbon energy sources and NETs rank very differently across environmental dimensions such as climate change contribution, land occupation, toxicity effects or abiotic resource requirements [39, 40]. pLCA results grounded in unrealistic assumptions may lead to wrong environmental ranking, and misidentification of burden shifting and key life-cycle contributors, providing a distorted vision of possible environmental futures, and undermining an efficient use of LCA in areas such as eco-design. Fully appreciating these caveats demands scrutiny of the social influences that shape model construction and, by extension, risk entrenching systemic inequities in decision-making processes.

3. Modeling necessarily draws from social contexts raising ethical challenges

3.1. Categories of drivers influencing modeling

According to science and technology studies, all models are "socially situated" [95–97]. This concept highlights that models are developed within intricate networks of social, cultural, and institutional influences, shaping both their structure and results [96,98]. Modelers operate within a framework of social dynamics, where negotiations, compromises, and adjustments are shaped by interactions with colleagues, supervisors, and stakeholders. These interactions create a co-production environment where scientific knowledge and social orders evolve simultaneously, influencing modeling practices and decisions [99,100].

Subjective biases also arise from the modelers' personal beliefs, prior experiences, and institutional norms. These biases are often embedded in methodological choices, such as the selection of impact mechanisms or the prioritization of certain parameters, reflecting both individual and collective priorities. For example, stakeholders, including industry partners and public agencies, play a significant role in shaping modeling objectives and outcomes, sometimes introducing external pressures that necessitate compromises between scientific rigor and practical applicability [101]. The iterative nature of modeling reinforces this dynamic, as feedback loops between stakeholders and modelers continually refine and adapt models, highlighting the socially constructed nature of decision-making models [100,102].

Institutional cultures also play a key role. Different "modeling schools," often tied to universities and national contexts, create variations in methodologies and impact assessment practices [103,104]. For example, regional differences affect how LCA studies address weighting and assessment methods [105]. Collaborative environments may foster group consensus but can limit innovation by reinforcing established methods [102].

The hierarchical structure within research organizations influences modeling practices. Senior researchers often set norms that junior team members adopt, which become institutionalized over time [100,106]. Bourdieu's concept of academic hierarchy highlights how these dynamics shape the acceptance of methods, sometimes constraining methodological diversity [107]. Demographic factors, such as gender and diversity, are less studied but have a significant impact. Packett et al. demonstrated that including gender perspectives can broaden stakeholder considerations and highlight overlooked issues [108]. Another dimension is interdisciplinary borrowing, where models "travel" between fields, often carrying assumptions from their original developers [101,109]. In IAMpLCA, transition scenarios from IAMs are adopted without always adapting embedded assumptions, potentially affecting model outcomes [105]. External stakeholders, including industry partners, also shape LCA modeling through research funding [110]. Policy-driven models may embed assumptions aligned with political goals [98,111], and stakeholder involvement can influence scenario selection [112].

Addressing these challenges requires acknowledging the socially situated nature of models, enhancing transparency, and promoting

reflective practices. IAMs and LCA are not exempt from common modeling biases, their development is not a neutral process. Being models, they are shaped by social, cultural, economic, and institutional contexts that influence methodological choices and underlying assumptions [104,105,113–115]. These influences affect IAM results and diffuse into IAMpLCI datasets, further underscoring the importance of acknowledging and addressing biases in IAMpLCA frameworks.

These socially situated influences do not only affect modeling quality or internal consistency: they also carry ethical implications. The methodological choices embedded in IAMpLCI frameworks reflect implicit value judgments about whose perspectives count, which futures are prioritized, and which trade-offs are deemed acceptable. Failing to recognize these dimensions can reinforce dominant worldviews while marginalizing alternative or justice-oriented approaches to sustainability [74,85].

3.2. The choice of a unique economic paradigm in SSPs and mainstream IAM modeling

3.2.1. SSPs and mainstream IAMs envision a growth-based economy despite its criticized relation with wellbeing

Economic growth has been promoted by Western authors since the late 17th century as a central driver of social progress [116–118]. It is embedded in a broader capitalist paradigm, which views individual interest, private property, specialization, markets, and technological innovation as the foundations of prosperity [116,119–122]. This view has shaped institutions, lifestyles, and global power relations over the last three centuries [122]. By integrating these economic assumptions, SSPs and mainstream IAMs not only perpetuate intellectual and institutional lock-in but also raise ethical issues. As they prioritize economic efficiency and growth, they overlook alternative visions of well-being and justice, and make normative choices about how the costs and benefits of transition pathways could be distributed [85]. The endorsement of existing distributions of wealth and power raises questions of procedural and distributive justice that remain largely unaddressed in most models [74,85,114,116–118,123,124,125,126].

Since all models inherently involve subjective assumptions, the selection of economic parameters similarly requires interpretative judgment. Prospective modeling based on mainstream IAMs and using SSPs is grounded in the neoclassical economic paradigm, where societal well-being is predominantly assessed through economic indicators, especially GDP. However, GDP has been the subject of criticism since the 1960s, particularly because it has been proven to be an unreliable proxy for human well-being [123–128]. According to the economics of happiness, GDP growth does not increase happiness but rather amplifies desires [129]. Looking at Average Weighted Index of Social Progress scores by continent over the last fifty years, the world's top socially developed regions - Europe and North America - have displayed social regression since the nineties, associated with a decrease in quality of life and well-being [114]. Indeed, GDP growth can be associated with greater inequalities, particularly within countries [130], and a growing body of evidence suggests that inequalities negatively impact population health and well-being [131].

For instance, the United States has experienced a steady rise in inequality [132], and a dramatic increase in the use of mental health medications. Antidepressant usage has grown by 400 % over the past two decades, with 10 % of individuals aged 10 and older consuming these medications [133]. Paradoxically, this occurs in a country often heralded as an example of financial prosperity, characterized by strong competitiveness and annual GDP growth ranging from 2.2 % to 4.4 % over the past 50 years [134].

In fact, GDP was historically developed as a tool to rebuild countries and revive economies after the world wars and the Great Depression [135], not to increase well-being per se. Combined with the supply-driven approach of mainstream IAMs, the systematic assumption of economic growth in the SSPs constrains the range of possible futures, limiting them to a predetermined set of techno-economic scenarios [136]. Within this framework, technology becomes an adjustable variable used to try to reconcile economic growth with climate goals.

As recommended by the Stiglitz-Sen-Fitoussi Commission [137], alternative indicators to GDP should be adopted in policy assessments and societal narratives to better serve a global well-being.

3.2.2. Green growth as a solution to the ecological crisis may be a hazardous bet

Green growth gained traction in the early 2000s as an attempt to address ecological challenges without renouncing to a growth imperative. Promoted by leading international institutions such as the Organization for Economic Co-operation and Development (OECD) and the United Nations, this paradigm argues that economic and environmental goals can align through technological innovation, efficiency gains, and market-based instruments [131,132].

However, to solve the current environmental crisis, such decoupling of environmental damage from economic growth must be 1) absolute – meaning GDP growth must be associated with a reduction in environmental impacts [138], 2) of a sufficient magnitude to bring environmental impacts below Earth's bearing capacities, 3) fast enough to go back in a safe operating space before reaching tipping points, 4) global, and 5) permanent [79].

Current claims of decoupling are contested by scientists. No decoupling between GDP and GHG emissions has been observed either on a global scale or over a long period of time to identify it as a feasible long-term avenue rather than a possible temporary occurrence [138,139]. Even in Northern European countries often considered as ecological models, Tilsted et al. concluded that decoupling achievement were i) focused only on climate change – neglecting other environmental issues such as nitrogen and phosphorus cycles, two of the nine planetary boundaries [140]–, ii) based on territorial emissions – overlooking imported emissions, which can be substantial especially for rich countries with outsourced industries –, iii) reliant on optimistic carbon budgets, iv) dismissive of equity principles, including differentiated responsibilities and capabilities, and v) ignorant of country-specific conditions [141]. As no absolute, sufficient, fast, global and permanent decoupling satisfying the definition from Parrique et al. [79] has been observed, a review of 179 articles concluded that absolute decoupling is currently not observed and that "in the absence of robust evidence, the goal of decoupling rests partly on faith" [138]. Some researchers even question the feasibility of such decoupling, arguing that the dynamics of a growth-based economy inevitably leads to an increasing production, which is inherently linked to increasing environmental impacts [79,142–145].

As a conclusion, relying on green growth is hardly a universally accepted solution to the socio-ecological crisis, as absolute decoupling has not been demonstrated as feasible. Expecting decoupling to materialize in the future remains a speculative gamble, and applying the precautionary principle could therefore encourage the exploration of alternative approaches to move away from the growth imperative.

3.2.3. If green growth was environmentally efficient, would it be desirable?

A scientific approach to ecology, such as that proposed by the concept of green growth, may reduce the multidimensional socio-ecological crisis to a problem of environmental optimization, thereby narrowing its scope compared to the broader perspective of political ecology, i.e., the assessment of the relationships between human societies and their natural environment, focusing on issues of power, social inequalities, and conflicts related to resource access and environmental management [146–149]. But green growth remains rooted in the same capitalist logic as traditional growth: it assumes that ecological limits can be managed through innovation and market coordination, without questioning underlying production and consumption patterns. This continuity has led several scholars to question whether green growth represents a true transformation or a reformist adaptation of the status

quo [79,146].

From this broader ecological perspective, ensuring that society operates within planetary boundaries is not sufficient to resolve the ecological crisis, which also has fundamental social dimensions.

Certain schools of thought within political ecology - such as degrowth, ecofeminism, and eco-socialism - even argue that social issues are a direct consequence of the current techno-economic system. For instance, the degrowth movement asserts that a growth-driven techno-economic model is inherently destructive, unjust, and alienating [142–145]. From this perspective, green growth cannot provide a genuine solution, as it perpetuates existing socio-ecological issues. Instead, these approaches advocate for a fundamental transformation of institutions, societal goals, and lifestyles to address the crisis at its roots [142–145].

3.2.4. Alternative theoretical models to green growth and economic liberalism

Since the nineties, researchers have envisioned alternative techno-economic systems beyond the current growth-based system. They have explored ideas such as democratic planning of the economy, which, simply put, involves making production decisions democratically rather than being led by markets [147]. For example, Durand and Keucheyan [148] described a set of institutions and operational principles aimed at achieving democratic planning. Similarly, Laurin-Lamothe, Legault and Tremblay-Pepin have popularized four alternative theoretical economic models, each varying in levels of centralization and decentralization, as well as in work organizations [149]. Finally, Bookchin advocates for a more decentralized model, which he calls "libertarian municipalism" [150].

This search of alternative systems even raises interest from public institutions. As an example, the European Research Council funded the REAL project in 2023 to build an alternative framework to envision and model post-growth societies [151].

3.3. Ethical challenges in IAMs and climate scenario modeling

3.3.1. Overview of ethical challenges in IAMs

IAMs, while critical tools for guiding climate policy, are increasingly scrutinized for their embedded ethical challenges, which stem from their design assumptions, prioritization of certain values, and exclusion of diverse perspectives. IAMs often marginalize alternative perspectives, perpetuating inequalities by prioritizing cost-effectiveness over equity [74]. Practices like discounting and Negishi weights (i.e., aggregation of individual preferences or welfare into a single measure that represents a social welfare function while ensuring equilibrium and computational feasibility) exacerbate intergenerational and global inequities by favoring current wealthier nations and passing mitigation burdens onto future generations [152,153]. Furthermore, IAMs' emphasis on techno-economic solutions, particularly land-intensive NETs like Bioenergy with Carbon Capture and Storage (BECCS), raises concerns about land dispossession, biodiversity loss, and the displacement of indigenous and marginalized communities, particularly in the Global South [154–156]. The epistemic authority granted to IAMs restricts inclusivity, excluding underrepresented voices and knowledge systems, which entrenches cognitive and cultural injustices [84,157]. IAMs frequently underrepresents distributive justice, failing to adequately account for inequality and the ethical trade-offs associated with various climate scenarios [158]. This lack of representation raises critical questions about whose futures are prioritized and who bears the burdens and benefits of IAM-derived mitigation pathways. The normative nature of IAM assumptions, such as the discounting of future generations or geographical disparities in impact allocation, underscores the need for greater attention to equity in modeling practices [85].

Recent studies have made notable efforts to integrate distributional concerns, equity, and poverty eradication into IAMs and scenario design (e.g., [159–161]). However, such contributions remain relatively marginal in the broader IAM landscape and are not yet reflected in the core SSP narratives or mainstream tools used in prospective LCA, such as *premise*. Our critique thus highlights systemic tendencies in dominant IAM pathways rather than denying the existence of alternative modeling approaches.

3.3.2. The example of discount rates as an ethical challenge

The discount rate choice is a prominent example of how IAMs can embed ethical biases. A discount rate is a tool used in economics to determine the present value of future costs and benefits. It reflects the importance we attach to future outcomes, as opposed to immediate ones. A discount rate can be qualified as "high" if it is higher than the economic growth. The higher the discount rate, the more the present is favored, reducing the perceived importance of long-term impacts, while a lower rate than economic growth gives more weight to the future. In the context of climate modeling, the choice of discount rate significantly influences policy recommendations, as it determines the extent to which future costs or benefits are considered in current decision-making. High discount rates favor short-term benefits over long-term sustainability, while lower rates emphasize intergenerational equity. Some rates sometimes prioritize present well-being to the point of leading to ethically indefensible outcomes (e.g., one death next year would be worth more than a billion deaths in 500 years) [74].

Debates about discount rates reveal ethical disagreements about how to balance the interests of future generations with those of the current generation [98]. These issues highlight the need to reassess discounting practices in IAM models to ensure that policies are both ethically sound and intergenerationally equitable. To address these ethical concerns, transition scenario developers should adopt a transparent and inclusive approach to defining the discount rate. The rate selected should be carefully documented, with clear justification of its value and underlying assumptions. Ideally, models should incorporate sensitivity analyses to examine how varying discount rates influence policy recommendations and technology deployment outcomes. For example, comparing low rates, which prioritize intergenerational equity, with higher rates, which emphasize short-term benefits, could help illuminate the trade-offs involved.

3.4. Synthesis: a step back on IAMpLCA modeling practice

Incorporating models developed by other teams or disciplines into one's work risks introducing their social and epistemic influences without full awareness [105]. Fig. 1 illustrates how SSPs, RCPs, and IAMs feed IAMpLCA: when integrating IAM-based technological projections into LCA, all assumptions from the original modeling are mechanically inherited, including the methodological and epistemic choices of all the initial design teams. For example, mainstream IAMs and SSPs currently used in IAMpLCA approaches often assume the continuation of economic liberalism and a (green) growth paradigm for the next three to eight decades, depending on the model's time horizon, basing themselves on the mainstream neoclassical economics school of thought.

Yet, integrating the results of an existing model inevitably involves adopting the original team's decisions, compromises, and ethics, which can affect the accuracy and relevance of (p)LCA outcomes. These models, designed within a specific disciplinary context, may not be directly transferable to other contexts without appropriate adjustments. Failing to adapt them risks compromising the integrity and reliability of the resulting model, making the interpretation of results complex, if not untenable [101,105,109].

4. Recommendations for better prospective LCA practices

4.1. Overview of recommendations

Based on the shortcomings highlighted in sections 2 and 3, we

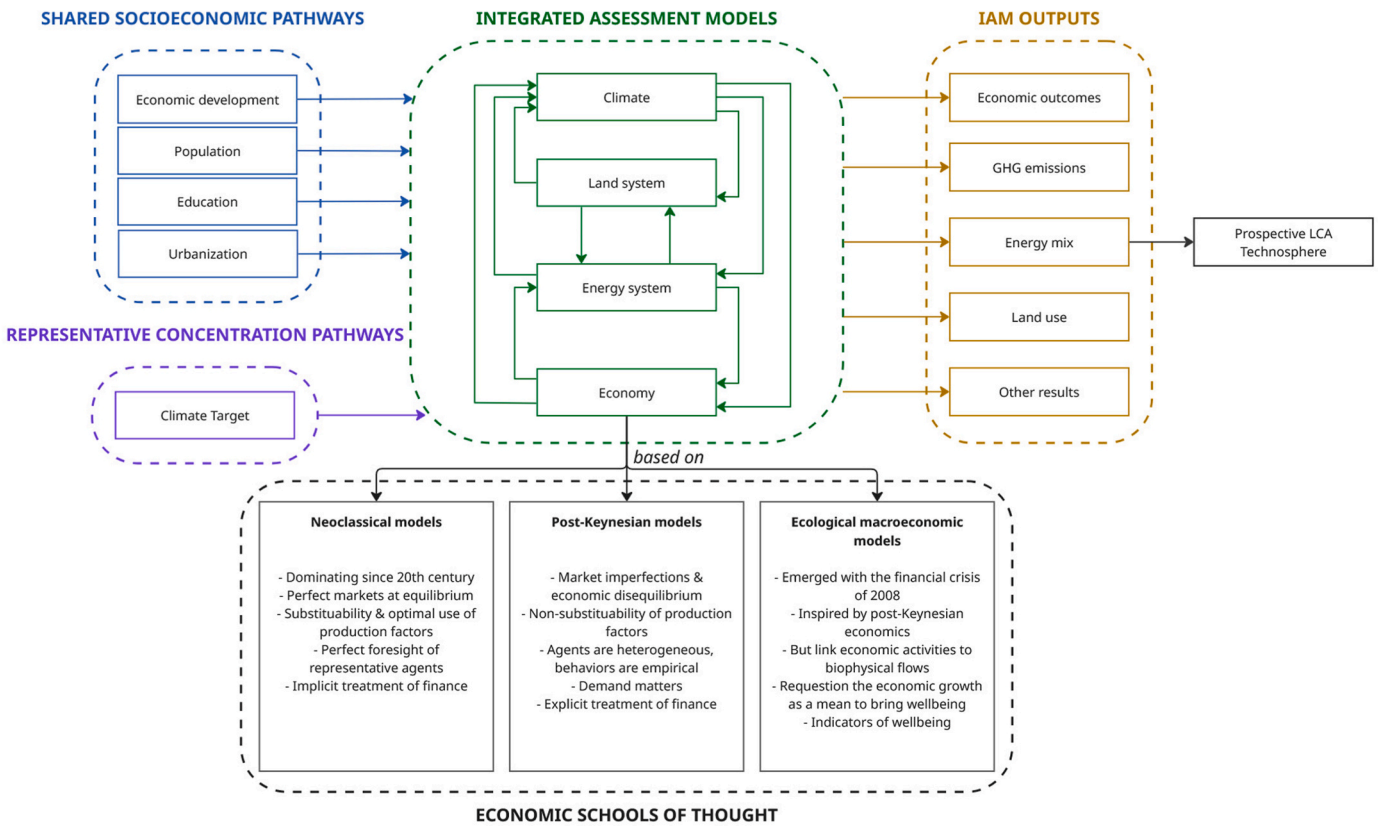

Fig. 1. Articulation between Shared Socioeconomic Pathways, Representative Concentration Pathways, Integrated Assessment Models, Economic schools of thought, and IAM-based prospective LCA.

encourage the LCA community to approach IAMpLCA with dexterity and caution, and the IAM modelers to push further their iterative developments. In this section, we provide specific recommendations to target the different limitations addressed earlier in this article. An overview of the limitations, recommendations, targeted audience, and associated ethical challenges is provided in Table 1, before discussing these recommendations into more detail.

4.2. Recognize the inherited choices and limitations of borrowed models

We observed that the limitations of the default IAM-SSP-based transition scenarios used in *premise* are never mentioned in the 23 recent studies employing the tool (see Supplementary Information, Table S1). While the authors of these studies might be aware of the scenarios' limitations, they do not disclose them to their readers. We recommend that the LCA community become more cognizant of the methodological and epistemic choices inherited from the original design team when adopting a borrowed model. We hope that sections 2 and 3 of this work can contribute to fostering this awareness.

We believe that, through collaborative efforts, the community can deepen its understanding of IAMs, SSPs, and their derived scenarios. Over time, we anticipate that this awareness will become widespread, and that explaining the limitations of borrowed models, as well as how these limitations are addressed, will become standard practice.

4.3. Make the most of mainstream IAM scenarios

4.3.1. Consider the consequence of the variability of mainstream transition scenarios on pLCA results

Mainstream IAMs employ different modeling mechanics and make varying technical, pricing, and other potentially subjective assumptions, resulting in significantly different technological outcomes in their scenarios. Using the full scenario ensemble as proposed by Guivarch et al. [162], i.e. considering all available scenarios from the latest IPCC assessment report (AR6) to generate pLCI databases with an uncertainty range - e.g. by propagating the variability from the technological background to the output inventory results - could provide valuable insights into the variability of pLCA outcomes within the IPCC's envisioned futures. Beyond methodological rigor, considering the full variability of mainstream scenarios also raises ethical questions about the legitimacy of selectively relying on certain visions of the future while excluding others. As highlighted by Beck and Krueger, and Asefi-Najafabady et al., each scenario embeds normative choices that influence whose interests are prioritized and what futures are made thinkable or actionable [74,113].

Moreover, this approach would require substantial computing resources and would necessarily include outlying scenarios based on unrealistic assumptions. As a result, this method is only partially satisfactory.

4.3.2. Select more conservative mainstream IAM scenarios, within a likely feasible space

To take a step further, we recommend adopting a more selective approach to choosing scenarios for use in pLCA. This could involve prescreening plausible scenarios and, if needed, selecting extreme scenarios relating to energy systems and NET deployment to better illustrate variability. Such an approach requires 'looking under the hood' of IAM-SSP-based scenarios [163], which entails examining IAM parameters and outputs to determine whether the results of a computed transition scenario fall within a likely feasible space. For instance, in this article, we assessed the rationality of NET deployment from IMAGE and the biomass capacity factor from REMIND-MAgPIE within the AR6 transition scenarios. This type of analysis can help identify and select more realistic scenarios for use in pLCA.

Table 1
Overview of prospective scenarios limitations, recommendations, targeted audiences, and associated ethical challenges.

Limitation	Recommendation	Targeted audience	Ethical challenge
Insufficient awareness of embedded assumptions in IAM scenarios	Systematically disclose limitations of borrowed IAM-SSP scenarios (and when possible their implications for LCA results)	LCA practitioners	**Transparency and epistemic responsibility**: failing to disclose the value-laden nature of borrowed data perpetuates the illusion of objectivity and prevents informed interpretation of results
High variability and realism flaws in IAM outputs	Use the full ensemble of scenarios to reflect variability	LCA practitioners	**Systematic biases** in most popular models (e.g. mainstream IAMs) could result in output distributions centred on unrealistic values, giving a false insight of median environmental impacts
	Pre-screen scenarios using rationality criteria		**Risk of misleading certainty**: selective use of scenarios can conceal uncertainty range and promote biased policy outcomes, undermining precaution and robustness
Implausible assumptions in mainstream IAMs (e.g., NET deployment, biomass yields)	Prioritize conservative scenarios aligned with physical and historical constraints	LCA practitioners	**Moral hazard and burden-shifting**: overreliance on speculative technologies offloads responsibility onto future generations and vulnerable ecosystems
Over-reliance on neoclassical economics in IAMs	Integrate scenarios from alternative economic models (post-Keynesian, ecological macroeconomics) via tools like the *superstructure*	LCA practitioners / IAM modelers	**Ideological lock-in**: the dominance of a single economic worldview limits pluralism and suppresses alternative visions of prosperity and justice
Absence of societal narratives diverging from economic growth	Complement SSPs with narratives including different trends of post-growth	IAM modelers / LCA practitioners	**Injustice by exclusion**: marginalizing alternative socio-political futures restricts democratic debate and reinforces dominant power structures
	Incorporate alternative indicators to GDP in SSPs to aim at improving well-being	IAM modelers / LCA practitioners	
Ethical assumptions (e.g., discount rate, equity metrics) often opaque or unexamined in IAMs	Favor scenarios with transparent, justified ethical choices and better equity consideration	LCA practitioners	**Lack of ethical reflexivity**: ignoring or obscuring normative assumptions impairs accountability and the ethical legitimacy of assessments
IAMs not designed with equity or justice in mind	Develop IAMs that better integrate distributive justice, include diverse voices, and explore multiple ethical framings	IAM modelers	**Procedural and distributive injustice**: current IAMs risk reinforcing inequalities by failing to model them fairly or to include those most affected by the transitions
Discount rates affect intergenerational justice but are rarely disclosed or varied	Conduct sensitivity analyses and promote use of lower discount rates closer to GDP growth	IAM modelers	**Intergenerational equity**: high discount rates devalue future well-being, compromising the rights and interests of future generations
IAM-based modeling excludes marginalized perspectives	Involve ethicists and representatives of vulnerable communities in scenario design	IAM modelers	**Recognition and representation**: without inclusion of marginalized groups, scenario design perpetuates epistemic injustice and social exclusion

As a precautionary principle, we recommend prioritizing more conservative scenarios from mainstream IAMs that:

- Include future parameters and constraints that align more closely with historical trends, avoiding overly optimistic assumptions about future technologies, such as drastic energy efficiency improvements
- Incorporate static or, preferably, dynamic biophysical flow constraints, such as:
  - o Potential availability of metals, considering, in order of preference, annual primary and secondary productions, reserves, or resources
  - o Maximum availability of land occupation for bio-based resources respecting biodiversity preservation and other land-related needs
- Set realistic constraints on NET deployment

Industrial ecology tools can be integrated with LCA and IAMs to impose biophysical flow constraints on scenario results [164]. In particular, linking material flow analysis (MFA) or agent-based modelling to IAMs clarifies the material feasibility of projected futures. Although such couplings remain technically demanding [165], the recent MESSAGEix-Materials v1.0.0 release provides a proof of concept: it connects the MESSAGEix-GLOBIOM IAM with MFA to represent circular economy measures explicitly. Broadening this approach will require further large-scale development, building on recent work by Bieuville, who quantified metal demand in IAM scenarios and optimized energy mixes to alleviate potential metal bottlenecks [72].

The general precautionary approach that we recommend not only aligns with technical realism but also responds to ethical concerns regarding feasibility, equity, and representation. Overly optimistic scenarios, especially those relying on speculative NET deployment or drastic efficiency gains, can obscure burdens on vulnerable populations or future generations [74,85,122].

Implementing these recommendations requires transparency regarding the assumptions and modeling approaches used to generate IAM-based scenarios. One of the primary goals of the 15-year-old Integrated Assessment Modeling Consortium was to enhance such transparency, resulting in a database hosted by the International Institute for Applied Systems Analysis [166]. This database serves as a first valuable resource to select plausible transition scenarios to generate pLCI datasets, but more parameters could be informed, as well as indicators of likelihood. Increased transparency around scenario assumptions is not only a scientific imperative, but also an ethical one. IAM scenarios often reflect implicit value judgments—such as discount rates or equity weights—that carry real distributive consequences, yet are rarely interrogated by end-users in downstream modeling like pLCA [74,85,113].

4.4. Use scenarios based on alternative economic schools of thought: post-Keynesian and ecological-macroeconomic modeling

Although most IAMs are based on neoclassical economics, some employ alternative representations of the economy to address its limitations. For example, post-Keynesian economic models simulate the evolution of consumption and production using empirically validated behavioral equations, without assuming market equilibrium, as is typical in neoclassical models [52,167]. IAMs grounded in post-Keynesian economics, such as E3ME [168] and GINFORS [169], simulate economic drivers through empirical behavioral equations, move beyond equilibrium assumptions, and account for economic imperfection, potentially capturing more realistic futures.

Building on the foundations of post-Keynesian economic representations, ecological-macroeconomic models place greater emphasis on physical flows within the economy [170]. IAMs based on ecological-macroeconomics link economic activities to biophysical flows, enabling them to consider biophysical bottlenecks in their scenarios. For instance, MEDEAS - the first ecological-macroeconomic IAM [66]—and its extension, the WILIAM IAM [171], incorporate these dynamics into their projections.

Considering transition scenarios in pLCA background from "non-mainstream" IAMs based on alternative economic schools of thought such as the existing E3ME, GINFORS and MEDEAS would allow for a broader and more accurate exploration of the potential future impacts of transition choices. Furthermore, integrating these scenarios into pLCI databases is already technically feasible using the *superstructure* tool [172]. A step further would be to use these models to develop strong sustainability transition scenarios, i.e. scenarios respecting the nine planetary boundaries, with IAMs directly embedding an environmental assessment and constraints on control variables from the planetary boundaries' framework.

4.5. Consider alternative indicators and narratives in SSPs

A new trend in modeling approaches moves away from pure techno-solutionism and explores new socio-economic patterns [173], including downscaling and degrowth. Here, downscaling refers to reducing the size of the current economy, whereas degrowth refers to the political movement of degrowth, calling for a profound transformation of the techno-economic system, with structural implications far beyond simply reducing the scale of the current one. "Post-growth" qualifies societies emerging after such radical transformations, as their organization would not require economic growth to function.

4.5.1. Integrating alternative well-being indicators in SSPs

Scholars have been developing alternative indicators that go beyond purely economic metrics since the 1970s, to better capture well-being and sustainability. Early initiatives, such as the Genuine Progress Indicator [174,175] and the Human Development Index [176], aimed to integrate social and environmental dimensions into economic analysis. More recently, and following recommendations from the Stiglitz-Sen-Fitoussi Commission, composite indicators presented in dashboards have become increasingly common. These dashboards, such as the OECD's Better Life Index [177], offer a more holistic and nuanced view of societal progress by considering multiple dimensions of well-being without aggregating them. The WISE database [178] compiles alternate indicators to GDP from different databases to address wellbeing, inclusion and sustainability concerns. Adopting such indicators in alternative SSPs could significantly improve the relevance of pLCA by ensuring that technological pathways are not mostly evaluated through the lens of economic growth. Instead, integrating social and environmental metrics would provide a more comprehensive understanding of the potential impacts of future transitions. Nonetheless, some caution is warranted as such frameworks may still implicitly reduce well-being to a number, an optimized economic output, rather than treating it as a fundamental societal shift [179]. Additionally, recent works have highlighted some limitations of composite indicators, questioning their transparency, coherence, comparability, and practical applicability [137,180,181]. To further pursue the reflection, recommendations include involving populations in the development of indicators to actually reflect what matters to their well-being [137,181], considering regional specifications in the definition of well-being [180], documenting transparently the normative choices leading to their development, and paying attention to their political consequences [137,182,183].

4.5.2. Consider downscaling avenues

Early modelling efforts investigate economic downscaling pathways that preserve the prevailing liberal economic system while abandoning perpetual GDP growth as a policy objective. Illustrative strategies include reductions in global consumption and the development of low-technology solutions. For instance, Keyßer and Lenzen explore audacious complementary scenarios with reductions in the global GDP increase starting in 2020 to start plateauing between 2035 and 2050 depending on the scenario [184]. Li et al. [185] and Kikstra et al. [186] further explored the evolution of consumption in an adapted version of MESSAGEix compatible with a growth-agnostic scenario. These first studies answer some common criticisms geared towards CMIP6's scenarios: the energy consumption per capita between the Global South and North converges, and reliance on decoupling, NETs, as well as fast technological progress and energy system decarbonization are minimized. Using these scenarios in pLCA thanks to *premise* and the *superstructure* tools, and building upon them, constitute promising avenues for our pLCA practices.

4.5.3. Shift the reflection further to degrowth or other political ecology propositions

As mentioned previously, political ecology encompasses various schools of thought, including degrowth, which centers on three main concerns: sustainability, justice, and autonomy [79,142,143,145,187].

To our knowledge, no computational model explicitly incorporates autonomy concerns as outlined in these theoretical models yet. However, some computational models do attempt to include justice considerations by exploring alternative indicators for assessing equity and well-being [188]. Examples include the LowGrow model in Canada [189] and the EUROGREEN model in France [190]. These models incorporate the Gini coefficient to assess household income inequality, the unemployment rate, and the average number of hours worked in the case of LowGrow, or the labor share - defined as "the fraction of post-tax value added paid to employed workers as wages" - in EUROGREEN. While these indicators remain partial and rooted in the current economic system, they represent an initial step toward expanding our conception of possible futures and opening discussions on their desirability.

However, simply including those indicators into models would still result in decisions based on computed complex calculations performed by a small group of experts. As a result, the critique of expertocracy and technocracy shared by some advocates of degrowth and, more broadly, in political ecology [191] would remain unaddressed. Therefore, political ecology's role in pLCA is not merely to integrate alternative indicators but also to foster awareness among practitioners about critical perspectives on environmental impact assessment.

4.6. Include ethics in prospective environmental modeling

Our last recommendation surpasses the LCA community as it must be addressed by scenario developers, and the IAM community. To address the ethical challenges of climate mitigation scenario modeling that we previously highlighted, IAM developers and practitioners must implement several critical changes to better integrate justice and equity into their models. Diverse stakeholders—such as ethicists, economists, and representatives of vulnerable communities—could be actively involved in the model design process. This approach ensures that a plurality of perspectives is incorporated, allowing IAMs to reflect a more balanced and inclusive view of climate futures. Second, transparency should be paramount: all ethical assumptions embedded in IAM frameworks should be clearly documented and justified, allowing users to understand the limitations of the model [95–97].

Furthermore, equity metrics, such as income distribution, access to resources, and climate vulnerability, should be integrated into IAM scenarios [192,193]. These metrics are essential for explicitly representing justice considerations, ensuring that outputs account for the varying capacities and vulnerabilities of different populations, and ethical appraisals of scenario outputs should be expanded, to identify and address potential justice and equity trade-offs to ensure that the solutions proposed are not only technically feasible but also socially just.

As practitioners of pLCA, we also strongly recommend paying particular attention to the discount rates used in the creation of the underlying transition scenarios chosen to project technospheres, whenever these data are available. Ideally, models should incorporate sensitivity analyses to examine how varying discount rates affect policy recommendations and technology deployment outcomes. For example,

comparing low discount rates that prioritize intergenerational equity with higher rates that emphasize present-day benefits could help illuminate the trade-offs involved. We also advocate favoring scenarios with discount rates close to the economic growth rate in order to promote intergenerational equity [194,195], which aligns with the fundamental definition of sustainability [196].

5. Conclusion

The prospective dimension of LCA is essential for more robustly evaluating the future environmental impacts of systems and supporting ecological planning across various scales. The latest pLCA methods integrate technological foresight derived from climate mitigation scenarios modeled with IAMs, leveraging the SSPs and RCPs developed within the IPCC framework. However, this computational framework is influenced by subjective modeling choices within IAMs and SSPs, which can affect the robustness of pLCA results. In particular, mainstream IAMs, rooted in economic liberalism, may inadequately address long-term well-being by over-relying on supply-driven technological solutions. Therefore, incorporating demand-side solutions and alternative well-being indicators, such as those from the WISE database, could enhance the robustness and relevance of prospective LCA practices. This article highlights and puts in perspective these subjective choices through the lens of en science and technology studies, and provides recommendations to enhance prospective LCA practices within this computational framework, especially through the selection of more (a) rational and (b) inclusive technological scenarios.

The first simple step toward better practices is to recognize the inherited choices and limitations of borrowed models. Our recommendations then address the selection of technological scenarios to incorporate into prospective modeling such as background inventory databases in LCA. These scenarios could (a.1) account for the variability of mainstream transition scenarios from the latest IPCC report and its effect on pLCA results, (a.2) include only screened IAM-based scenarios from the IPCC, based on proposed realism criteria, (b.1) integrate scenarios rooted in alternative economic schools of thought, such as post-Keynesian economics or ecological macroeconomics, that are not currently considered in reference scenarios, or explore (b.2) indicators representing (strong) sustainability, justice, and well-being, and (b.3) scenarios based on divergent societal narratives from the current SSPs, such as downscaling avenues and degrowth trajectories. On the environmental side of sustainability, an enthralling perspective would be to use IAMs to directly develop strong sustainability transition scenarios. Last, we emphasize the importance of incorporating ethical considerations into prospective environmental modeling, addressing critical modeling choices in scenario development, and offering recommendations to (b.4) prioritize more equitable scenarios.

The scenarios included in the IIASA database and covered in recommendations (a) are primarily constrained by the futures considered valid in the last IPCC report, which might be overly restrictive in certain aspects. However, recommendations (b) on broadening the scope of transition scenarios considered in pLCA, while being a less normative and more inclusive and robust approach, risks increasing variability in LCA results. Such high variability may make recommendations more complex thus lead to action paralysis. How to make use of highly variable results from pLCA will still need to be elucidated by the LCA community.

CRediT authorship contribution statement

Anne de Bortoli: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Alexis Chanel:** Conceptualization, Investigation, Writing – original draft, Visualization. **Camille Chabas:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Titouan Greffe:** Conceptualization, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Estelle Louineau:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

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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

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Data availability

All data used for this manuscript is available in supporting information files.

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