Harmonization of PV LCA studies | Approaches to life cycle toxicity impacts

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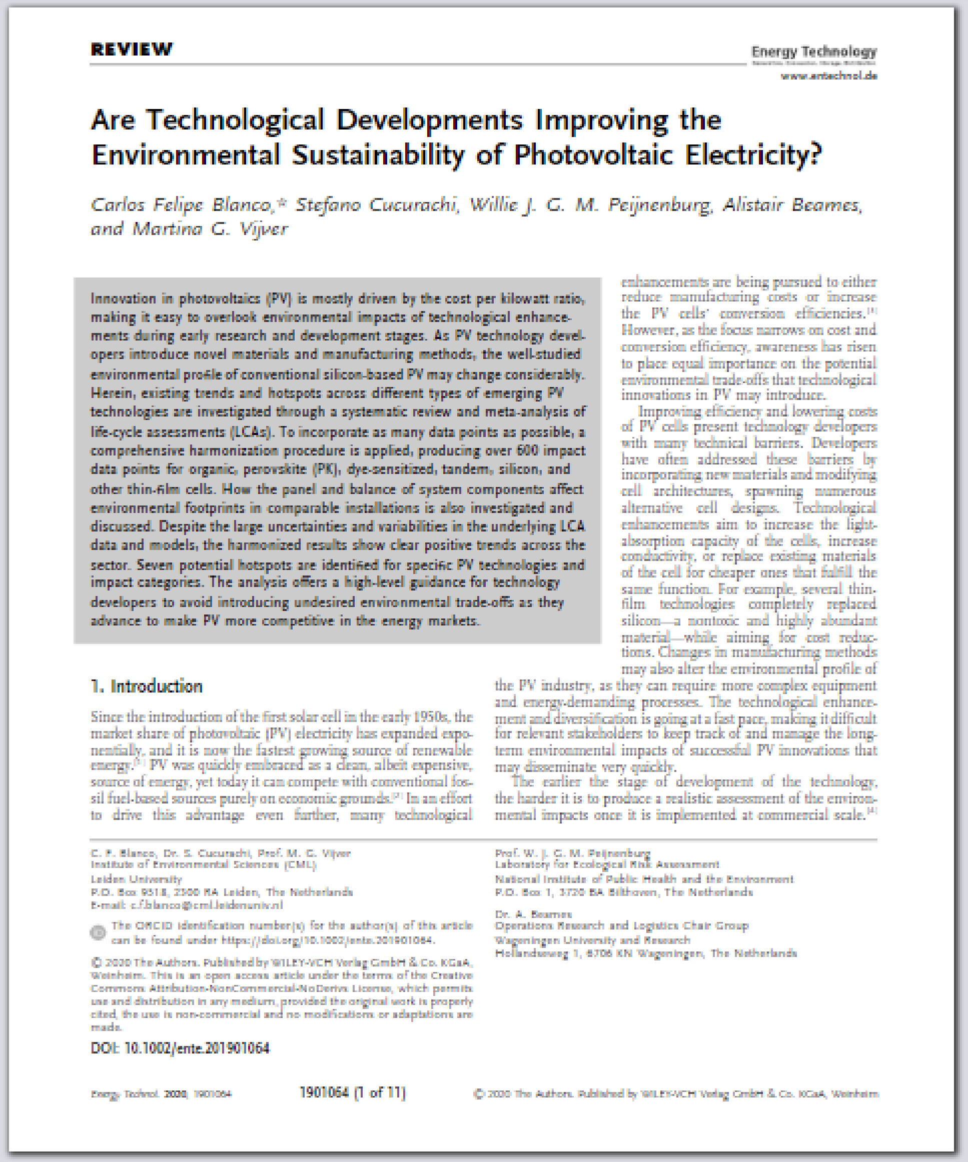
Image: Midjourney AI rendering of "solar" and "ecosystem" keywords

Research aims



REVIEW

Energy Technology
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Are Technological Developments Improving the Environmental Sustainability of Photovoltaic Electricity?

Carlos Felipe Blanco, Stefano Cucurachi, Willie J. G. M. Peijnenburg, Alistair Beames, and Martina G. Vijver*

Innovation in photovoltaics (PV) is mostly driven by the cost per kilowatt ratio, making it easy to overlook environmental impacts of technological enhancements during early research and development stages. As PV technology developers introduce novel materials and manufacturing methods, the well-studied environmental profile of conventional silicon-based PV may change considerably. Herein, existing trends and hotspots across different types of emerging PV technologies are investigated through a systematic review and meta-analysis of life-cycle assessments (LCAs). To incorporate as many data points as possible, a comprehensive harmonization procedure is applied, producing over 600 impact data points for organic, perovskite (PK), dye-sensitized, tandem, silicon, and other thin-film cells. How the panel and balance of system components affect environmental footprints in comparable installations is also investigated and discussed. Despite the large uncertainties and variabilities in the underlying LCA data and models, the harmonized results show clear positive trends across the sector. Seven potential hotspots are identified for specific PV technologies and impact categories. The analysis offers a high-level guidance for technology developers to avoid introducing undesired environmental trade-offs as they advance to make PV more competitive in the energy markets.

1. Introduction

Since the introduction of the first solar cell in the early 1950s, the market share of photovoltaic (PV) electricity has expanded exponentially, and it is now the fastest growing source of renewable energy.[1] PV was quickly embraced as a clean, albeit expensive, source of energy, yet today it can compete with conventional fossil fuel-based sources purely on economic grounds.[2] In an effort to drive this advantage even further, many technological enhancements are being pursued to either reduce manufacturing costs or increase the PV cells' conversion efficiencies.[3] However, as the focus narrows on cost and conversion efficiency, awareness has risen to place equal importance on the potential environmental trade-offs that technological innovations in PV may introduce.

Improving efficiency and lowering costs of PV cells present technology developers with many technical barriers. Developers have often addressed these barriers by incorporating new materials and modifying cell architectures, spawning numerous alternative cell designs. Technological enhancements aim to increase the light-absorption capacity of the cells, increase conductivity, or replace existing materials of the cell for cheaper ones that fulfill the same function. For example, several thin-film technologies completely replaced silicon—a nontoxic and highly abundant material—while aiming for cost reductions. Changes in manufacturing methods may also alter the environmental profile of the PV industry, as they can require more complex equipment and energy-demanding processes. The technological enhancement and diversification is going at a fast pace, making it difficult for relevant stakeholders to keep track of and manage the long-term environmental impacts of successful PV innovations that may disseminate very quickly.

The earlier the stage of development of the technology, the harder it is to produce a realistic assessment of the environmental impacts once it is implemented at commercial scale.[4]

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i. **Trends** in life cycle impacts of PV sector

ii. **Comparison** across technology types

iii. **Variability** of impact scores

iv. **Effects** of innovation on impact scores

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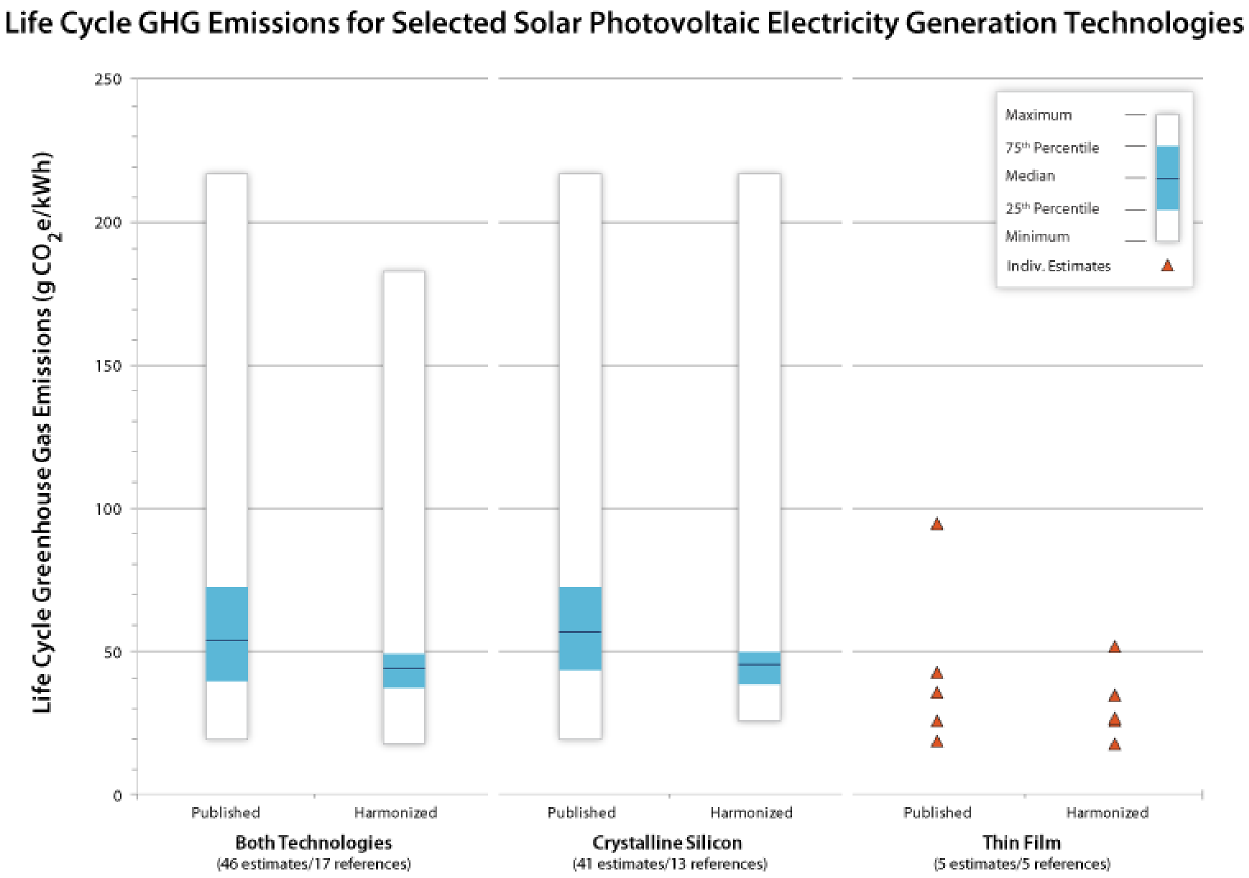
Methods

- Harmonization to reduce *modeling* variability and uncertainty:
  - Selection and screening (PRISMA)
  - Harmonization (Hsu et al., 2012 NREL LCA Harmonization Project)

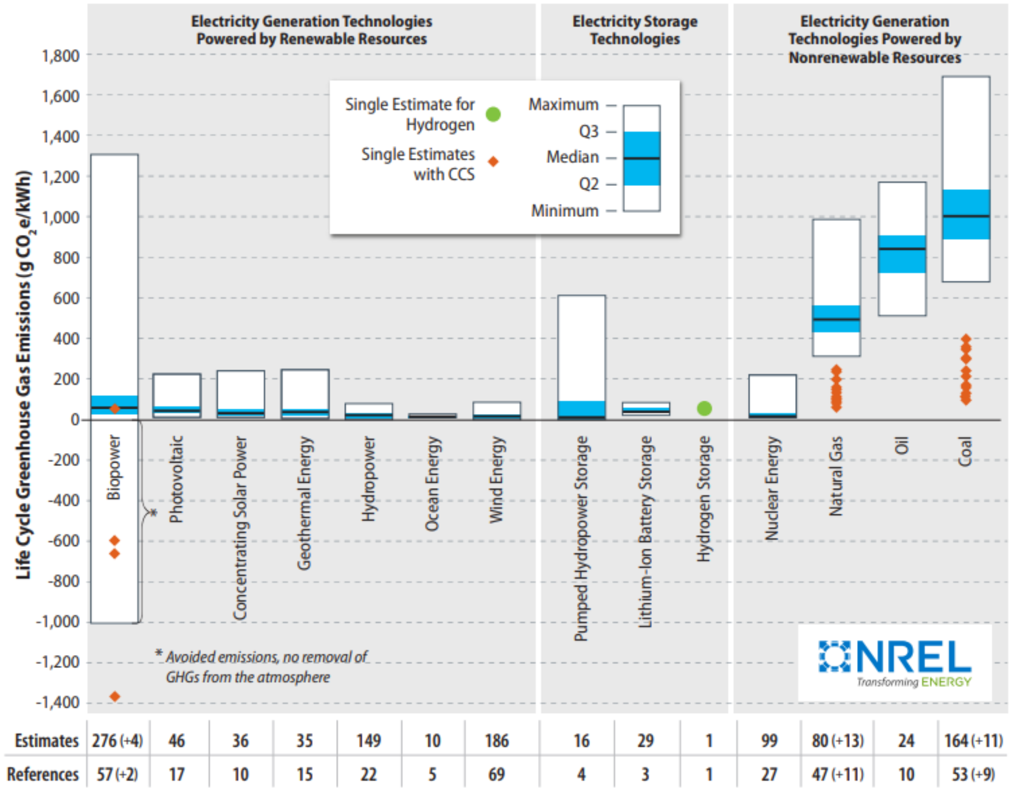
- Assess *technological* variability and effects
  - Summary statistics
  - Comparison with reference system, conventional silicon PV modelled before 2010
  - Meta-analysis with Random Effects Model

Methods: harmonization



NREL (2012)

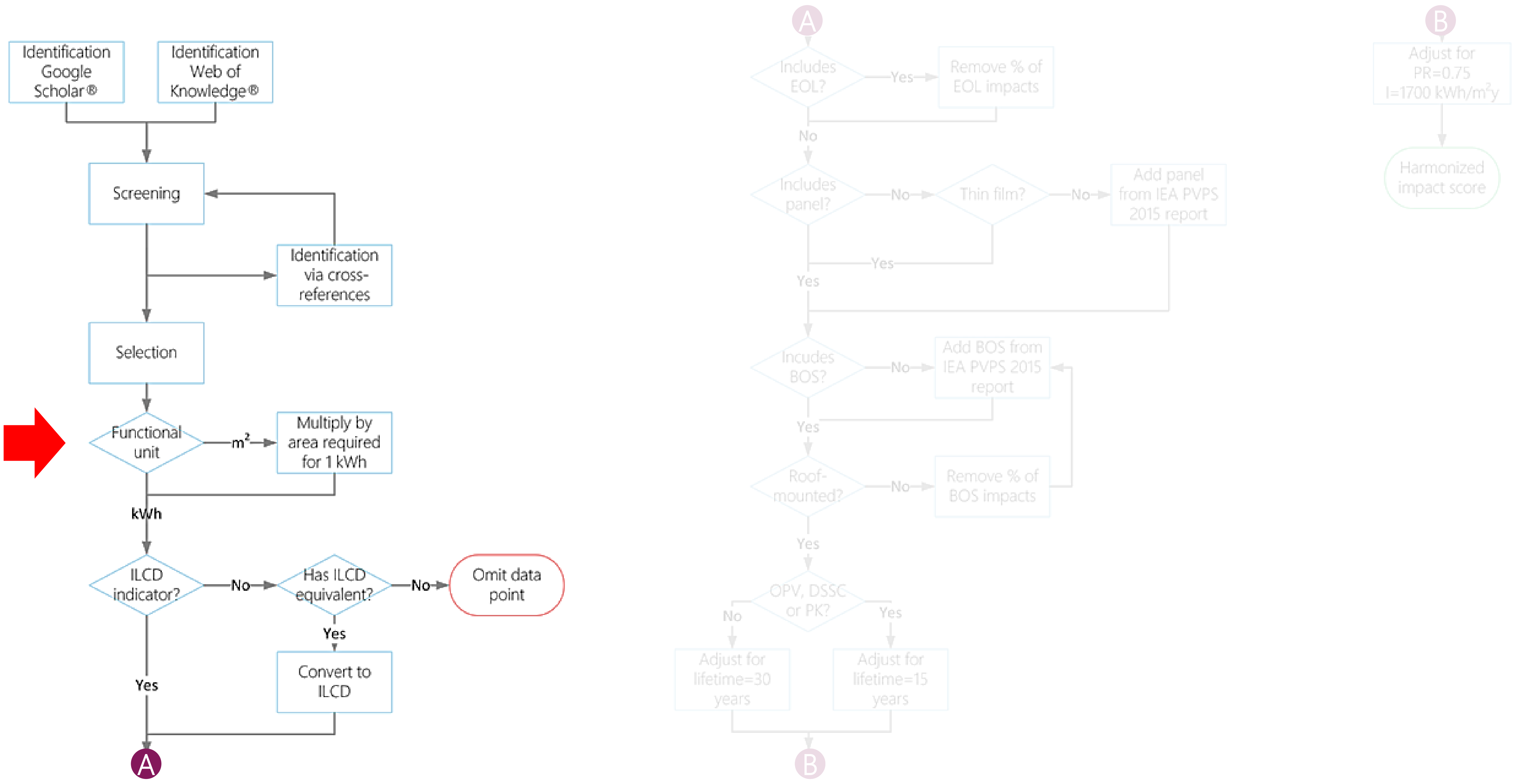
Figure 2. Life cycle greenhouse gas emission estimates for selected electricity generation and storage technologies, and some technologies integrated with carbon capture and storage (CCS).



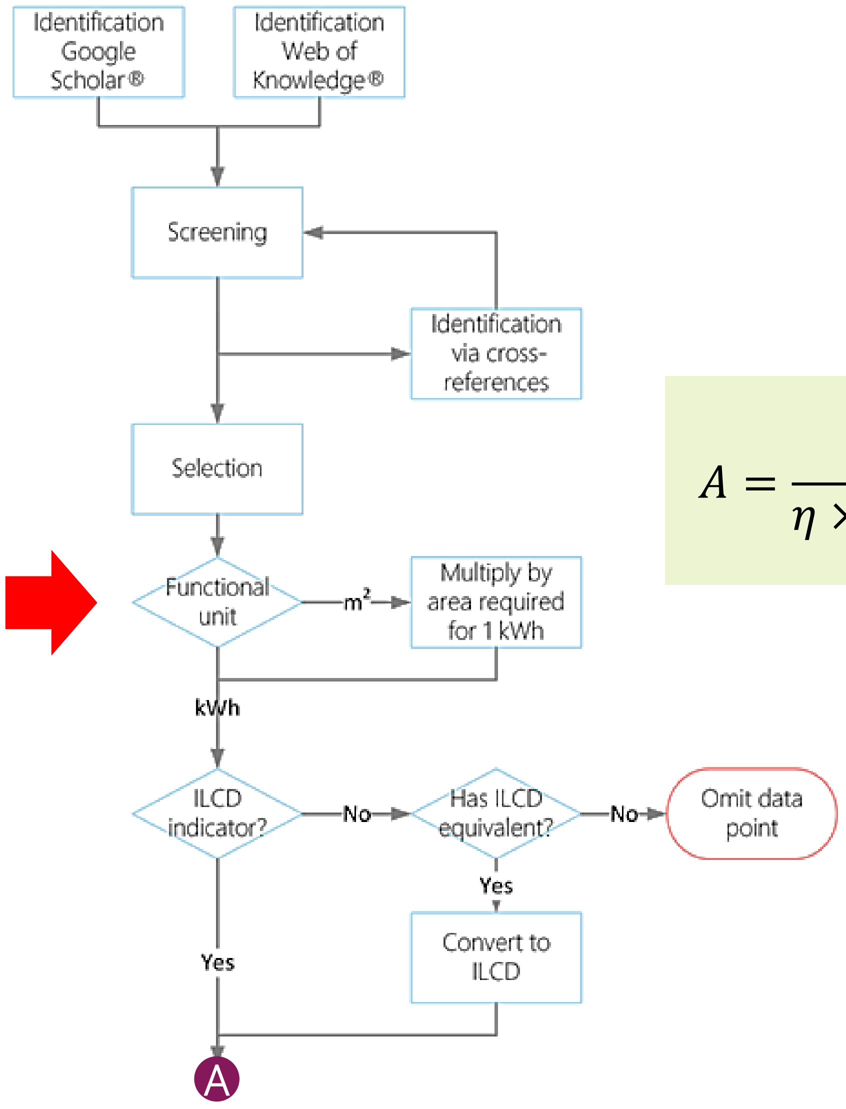
NREL (2021)

Hsu DD et al (2012) Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation. J Ind Ecol 16(S1):S122–S135. https://onlinelibrary.wiley.com/doi/epdf/10.1111/j.1530-9290.2011.00439.x.

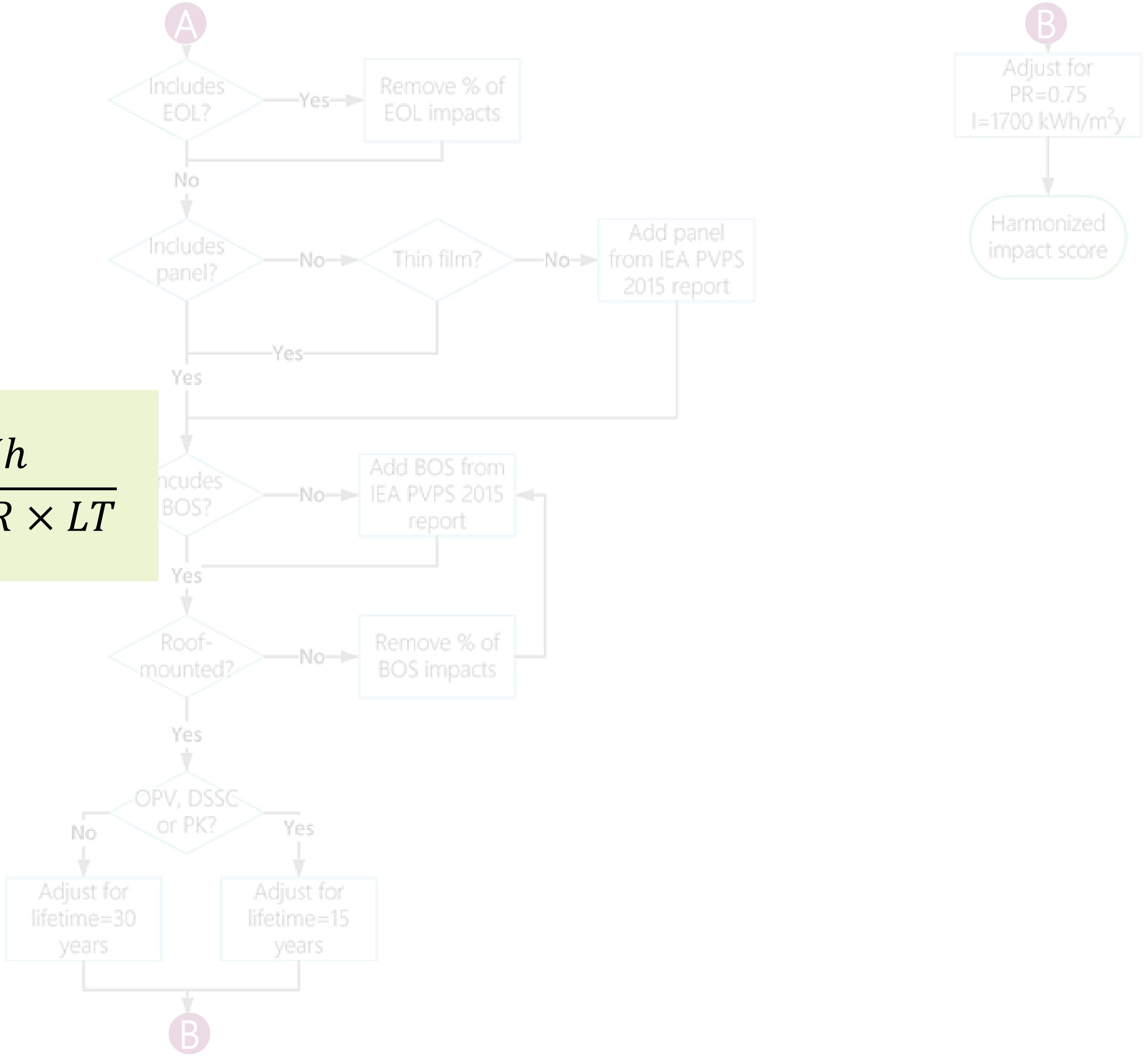
Methods: harmonization



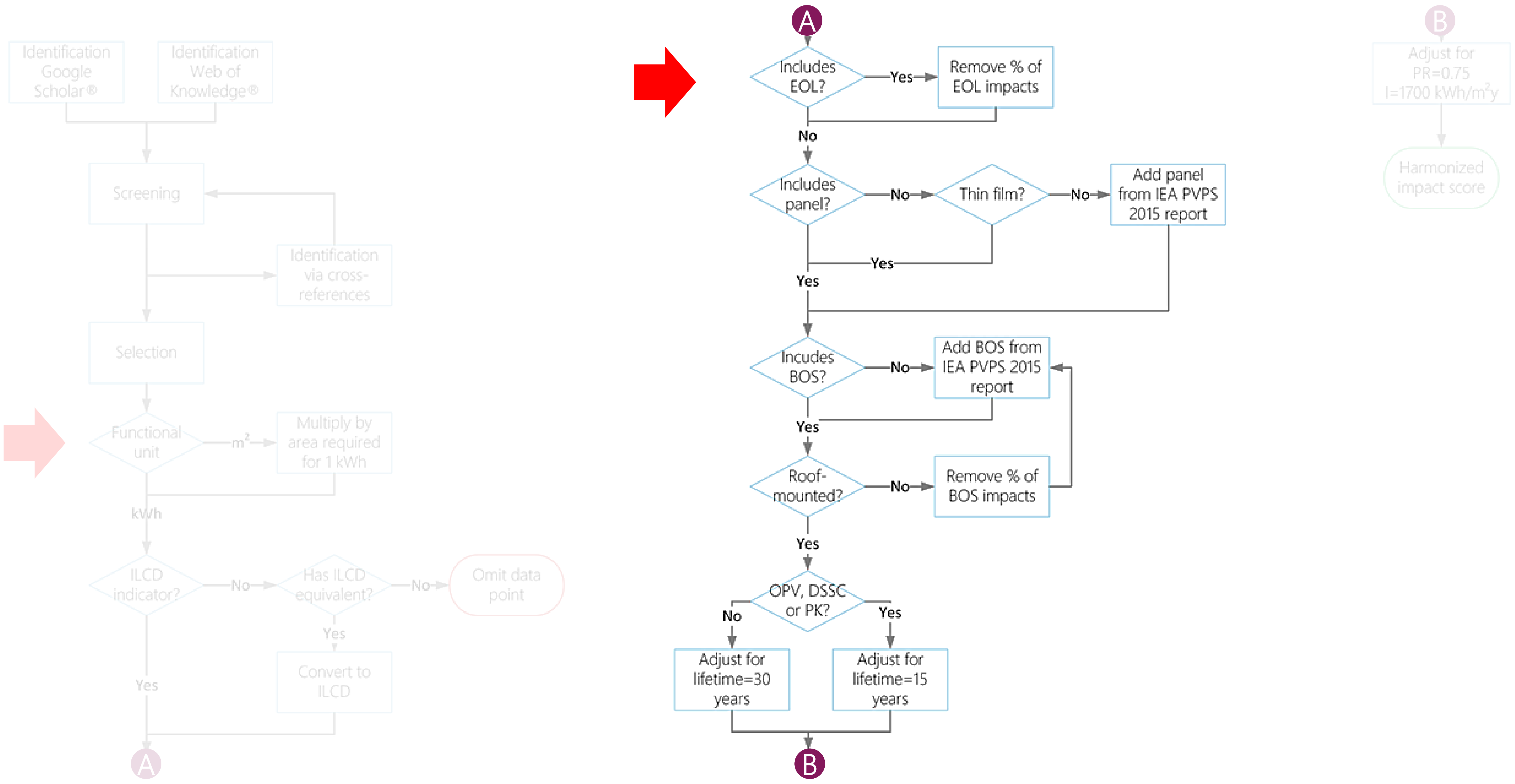
Methods: harmonization



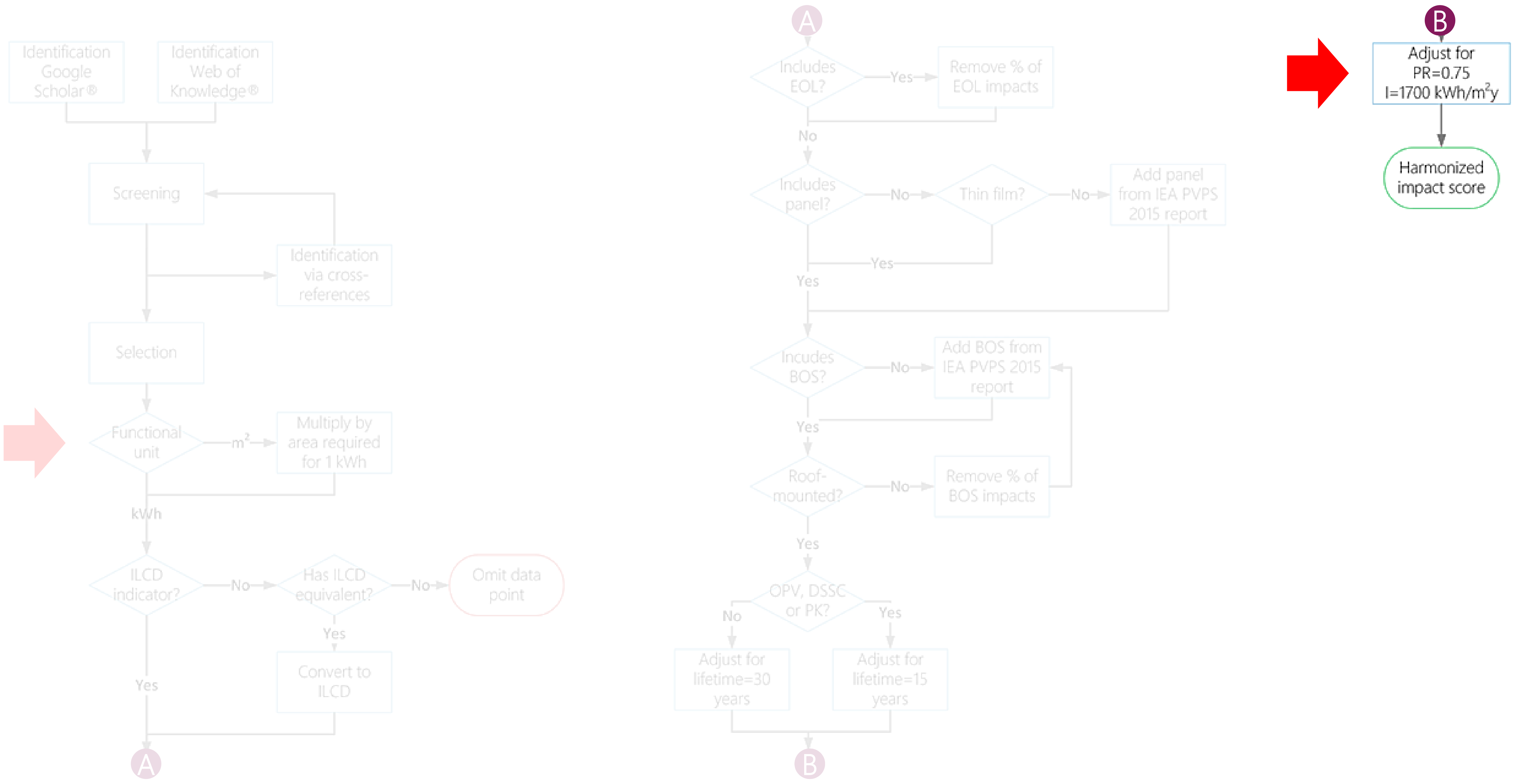
$$A = \frac{1\ kWh}{\eta \times I \times PR \times LT}$$



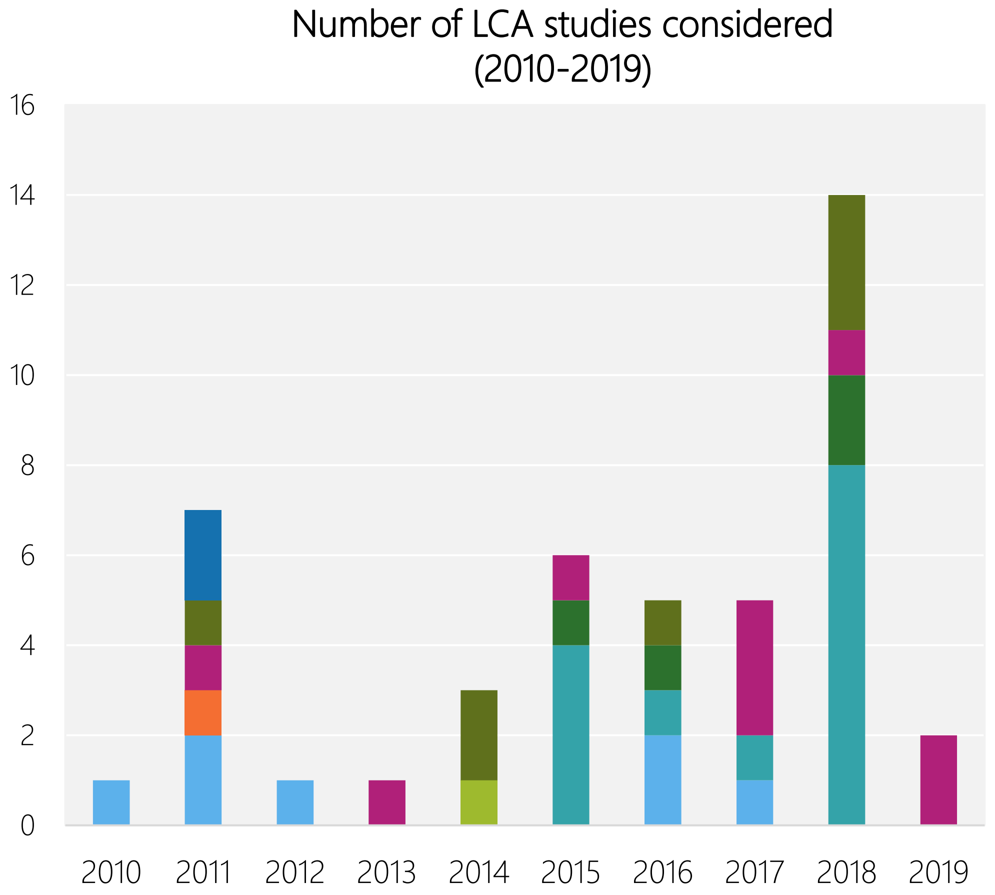
Methods: harmonization

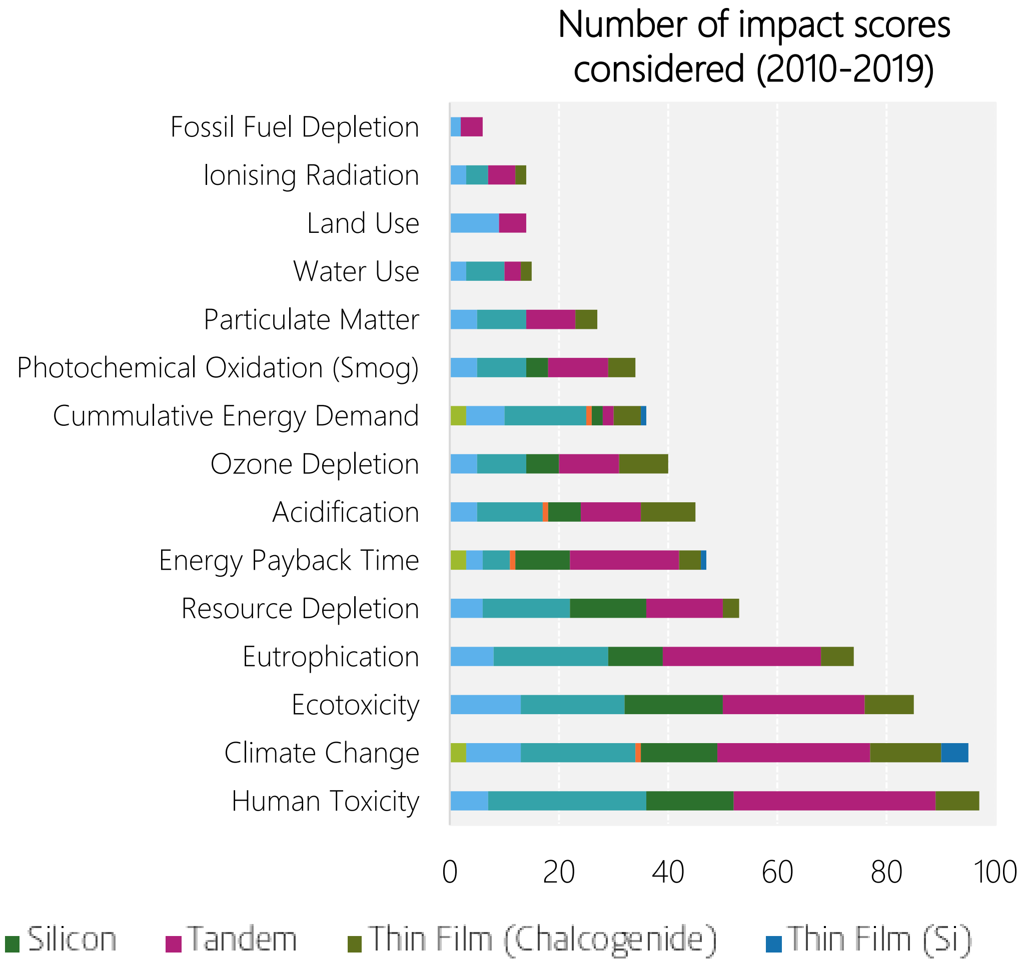


Methods: harmonization

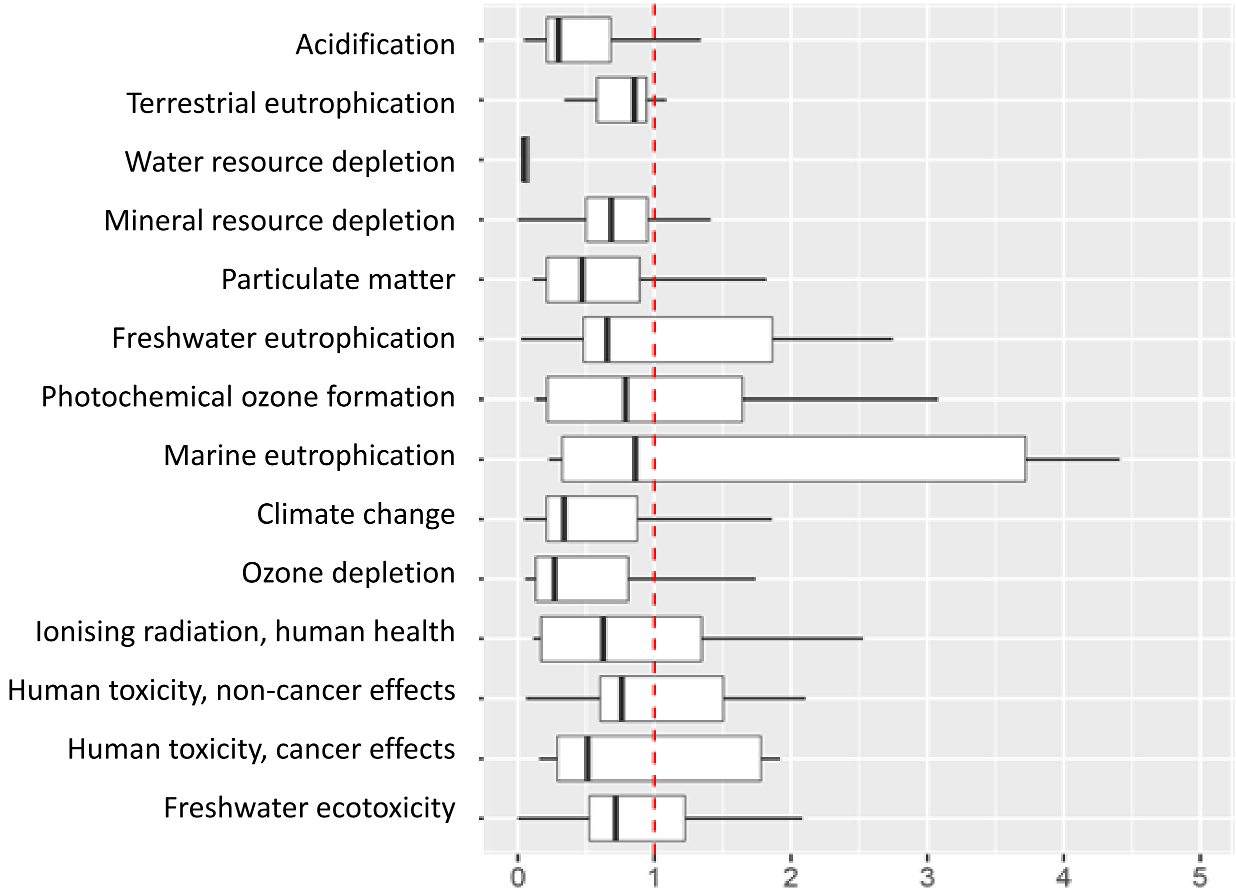


Results: studies & LCIA scope



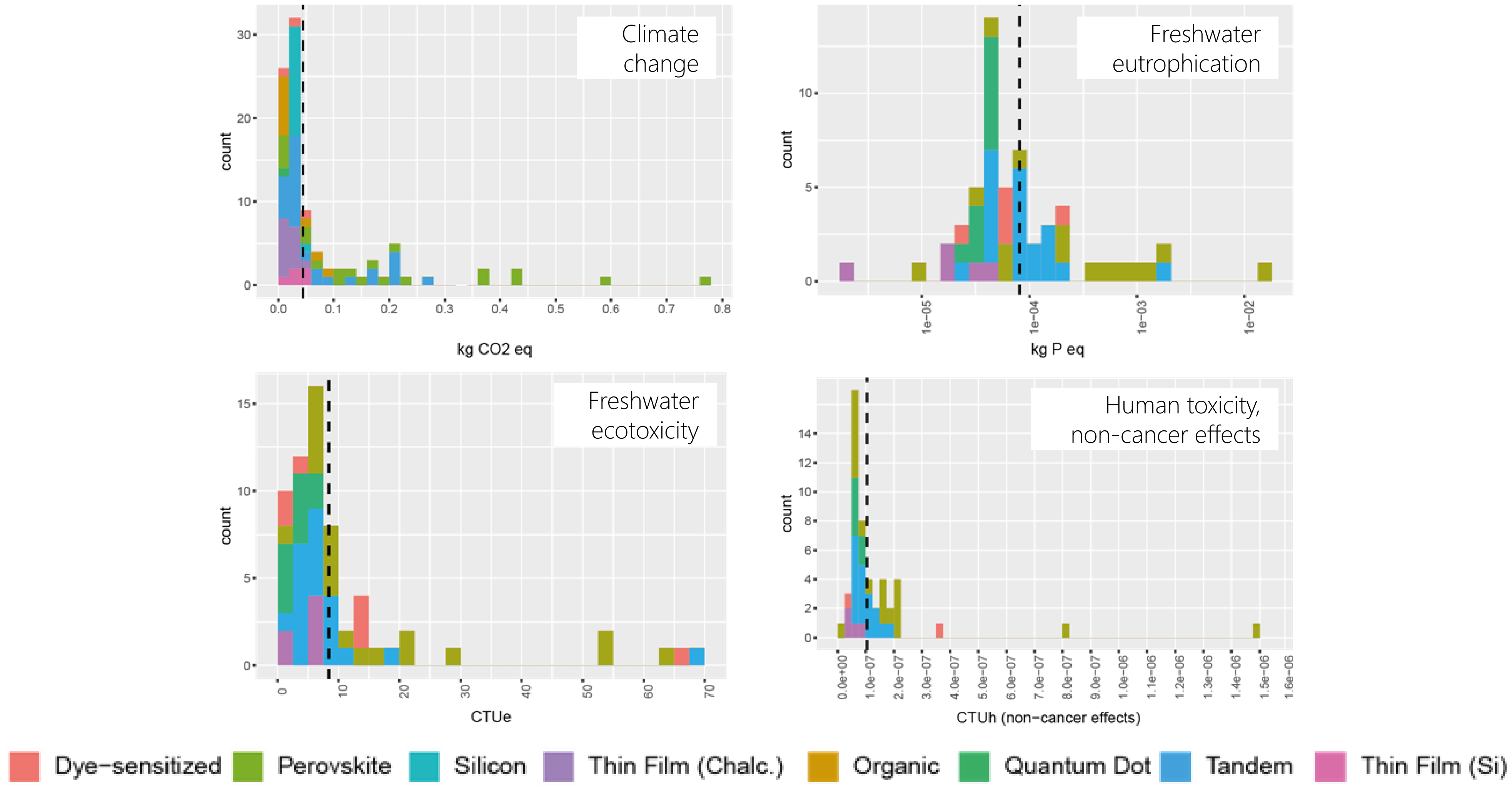


Results: variability in impact scores (across technologies)



Emerging PV impact scores Relative to single-Si rooftop PV (ecoinvent v3.4)

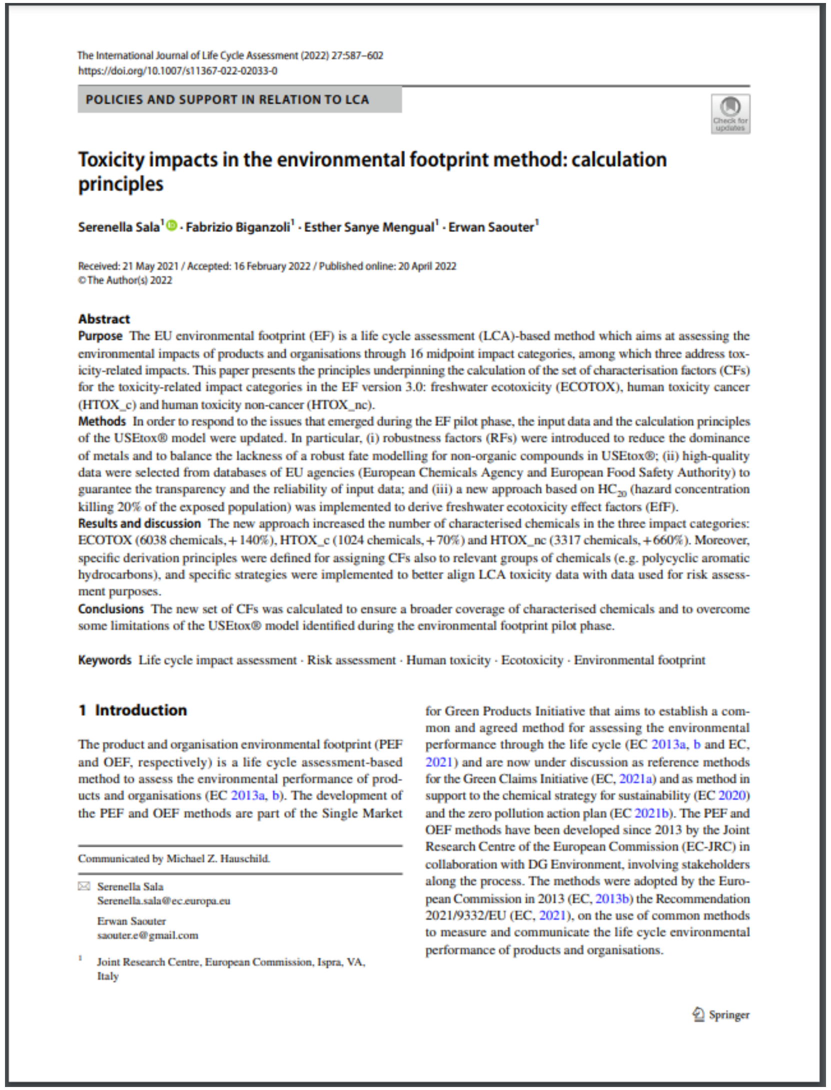
Results: variability in impact scores (within technologies)



Emerging PV impact scores per PV cell technology

Toxicity impacts in LCA

- ✓ Freshwater ecotoxicity: 6038 chemicals
- ✓ Human toxicity (cancer): 1024 chemicals
- ✓ Human toxicity (non-cancer): 3317 chemicals)



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POLICIES AND SUPPORT IN RELATION TO LCA

Toxicity impacts in the environmental footprint method: calculation principles

Serenella Sala[1] · Fabrizio Biganzoli[1] · Esther Sanye Mengual[1] · Erwan Saouter[1]

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Abstract

Purpose The EU environmental footprint (EF) is a life cycle assessment (LCA)-based method which aims at assessing the environmental impacts of products and organisations through 16 midpoint impact categories, among which three address toxicity-related impacts. This paper presents the principles underpinning the calculation of the set of characterisation factors (CFs) for the toxicity-related impact categories in the EF version 3.0: freshwater ecotoxicity (ECOTOX), human toxicity cancer (HTOX_c) and human toxicity non-cancer (HTOX_nc).

Methods In order to respond to the issues that emerged during the EF pilot phase, the input data and the calculation principles of the USEtox® model were updated. In particular, (i) robustness factors (RFs) were introduced to reduce the dominance of metals and to balance the lackness of a robust fate modelling for non-organic compounds in USEtox®; (ii) high-quality data were selected from databases of EU agencies (European Chemicals Agency and European Food Safety Authority) to guarantee the transparency and the reliability of input data; and (iii) a new approach based on HC_{20} (hazard concentration killing 20% of the exposed population) was implemented to derive freshwater ecotoxicity effect factors (EfF).

Results and discussion The new approach increased the number of characterised chemicals in the three impact categories: ECOTOX (6038 chemicals, + 140%), HTOX_c (1024 chemicals, + 70%) and HTOX_nc (3317 chemicals, + 660%). Moreover, specific derivation principles were defined for assigning CFs also to relevant groups of chemicals (e.g. polycyclic aromatic hydrocarbons), and specific strategies were implemented to better align LCA toxicity data with data used for risk assessment purposes.

Conclusions The new set of CFs was calculated to ensure a broader coverage of characterised chemicals and to overcome some limitations of the USEtox® model identified during the environmental footprint pilot phase.

Keywords Life cycle impact assessment · Risk assessment · Human toxicity · Ecotoxicity · Environmental footprint

1 Introduction

The product and organisation environmental footprint (PEF and OEF, respectively) is a life cycle assessment-based method to assess the environmental performance of products and organisations (EC 2013a, b). The development of the PEF and OEF methods are part of the Single Market for Green Products Initiative that aims to establish a common and agreed method for assessing the environmental performance through the life cycle (EC 2013a, b and EC, 2021) and are now under discussion as reference methods for the Green Claims Initiative (EC, 2021a) and as method in support to the chemical strategy for sustainability (EC 2020) and the zero pollution action plan (EC 2021b). The PEF and OEF methods have been developed since 2013 by the Joint Research Centre of the European Commission (EC-JRC) in collaboration with DG Environment, involving stakeholders along the process. The methods were adopted by the European Commission in 2013 (EC, 2013b) the Recommendation 2021/9332/EU (EC, 2021), on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

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Toxicity data M.I.A.!

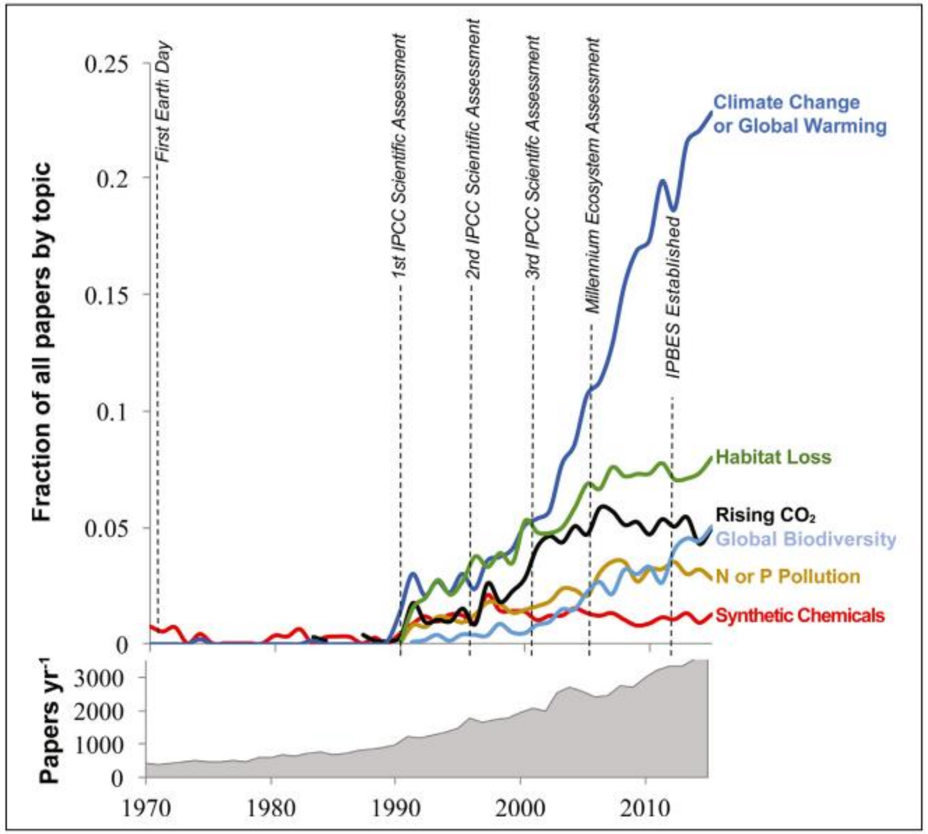
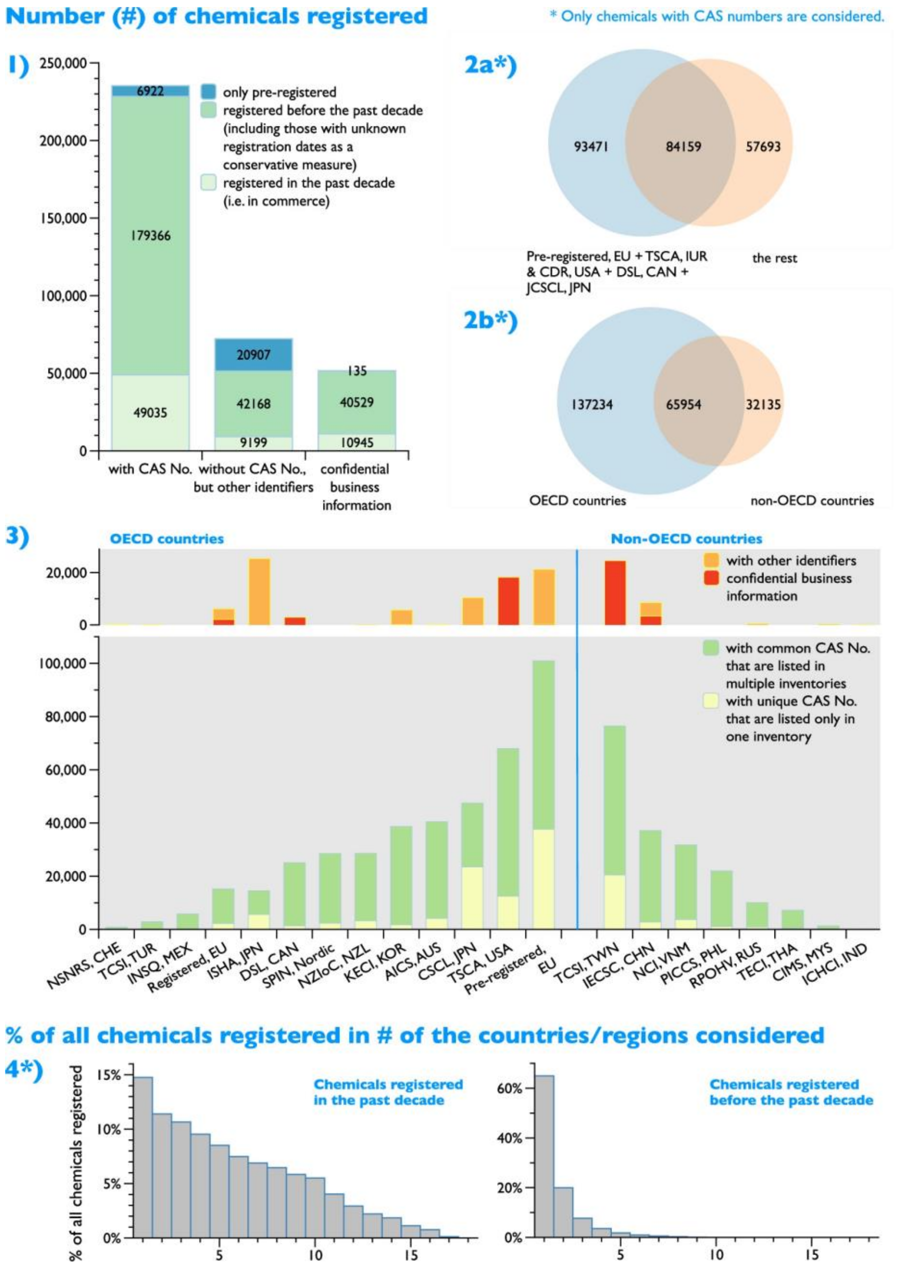


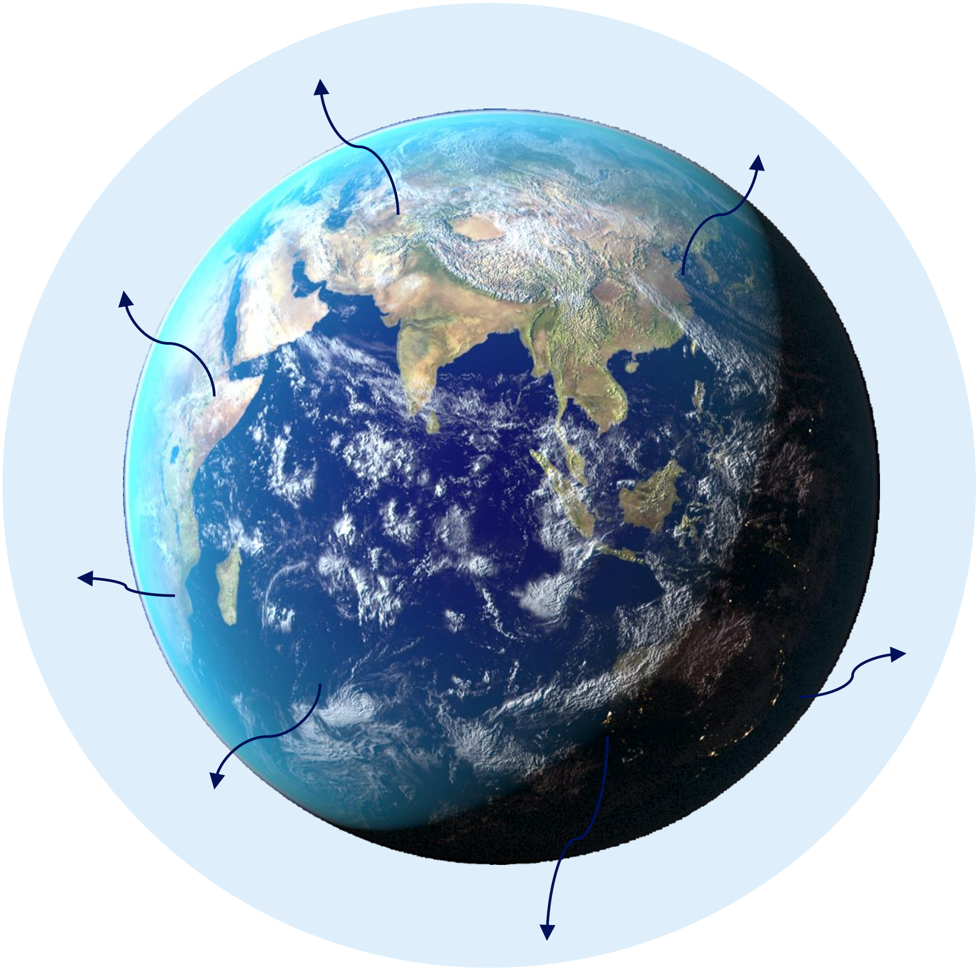
Figure 2. Total publications and the proportion of published papers including global-change driver terms in the top 20 ecology journals (Table 1) according to the highest total citations reported in the ecology section of the ISI Web of Science for the period 1970–2015.

Gessner, M. O. (2017). Synthetic chemicals as agents of global change. Frontiers in Ecology and the Environment. https://doi.org/10.1002/fee.1450

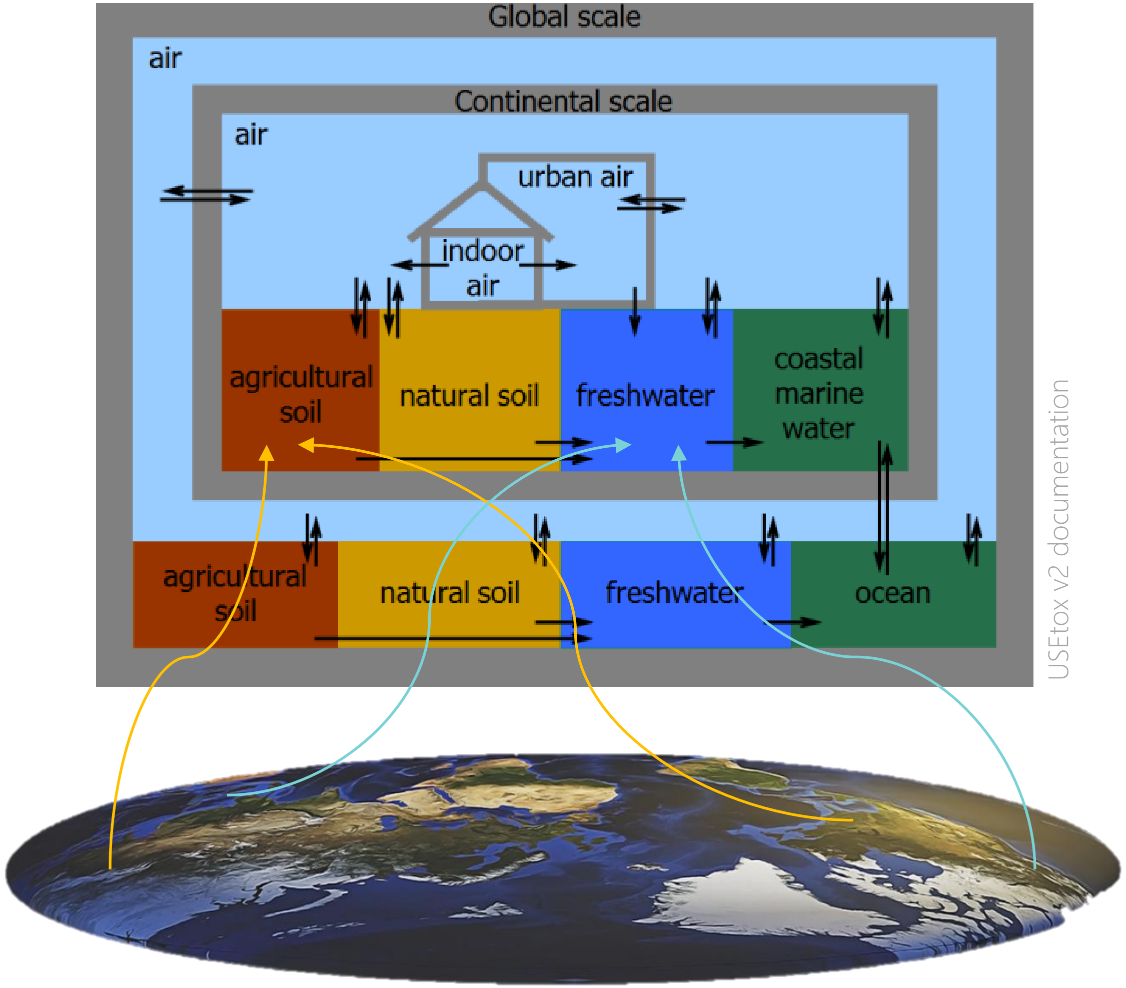


Zhanyun Wang, Glen W. Walker, Derek C. G. Muir, and Kakuko Nagatani-Yoshida. Environmental Science & Technology 2020 54 (5), 2575-2584 DOI: 10.1021/acs.est.9b06379

(Lack of) spatial & temporal aspects in LCIA



Climate change, ozone depletion:
1 compartment, well-mixed
Short transport time, long residence time



Human toxicity, freshwater ecotoxicity
Many (disconnected compartments), not well-mixed
Long transport time, highly variable residence time

Toxicity impacts in LCA

Basic checks:

- Emissions (environmental flows) included in the inventory?
  - Needs case-study specific emission scenarios including manufacturing and operation…
  - …but also End-of-Life (e.g., incineration and landfilling of bottom ash, etc.)
- Characterization factors exist for the substances of concern?
  - With luck, EF3.0 has it
  - Otherwise, the additional data collection and modelling effort is not trivial and requires considerable expertise beyond LCA
  - … and this goes for all chemical precursors, it's "life cycle"!

Uncertainty and variability

$$CF = FF \times XF \times EfF$$

- On data for ***EfF***: *"When toxicity data for at least two species were available, the HC20 was directly derived from the SSD curve (chronic EC10). However, the fewer data the lower the reliability. In fact, uncertainty is estimated to be of 4 orders of magnitude when only two species are available"* (Van Zelm et al. 2007, in Sala et al., 2022).

- On variability in ***FF:*** *"the Kd values can vary over several orders of magnitude for a given metal as a function of soil properties…"* (Allison & Allison, 2005 in Groenenberg, 2011)

- On overall model uncertainty of USEtox: *"…3 orders of magnitude uncertainty on the individual factors (…) means that contributions of 1%, 5% or 90% to the total toxicity score can be interpreted as essentially equal, but significantly larger than those of a chemical contributing to less than 1 per thousand or less than 1 per million of the total score"* (Fantke et al., 2017)

Takeaways

- Toxicity impact categories: handle with care!
  - Especially for metals
- Best practices I've collected:
  - ✓ Model operational (yield-related) parameters as best as possible to capture potential benefits/drawbacks of the technology in the field
  - ✓ Include <u>all</u> plausible EOL scenarios, separately: best-case/worst-case, break-even analysis, etc.
  - ✓ Combine LCA with chemicals risk assessment, criticality assessment and social due diligence, LCC.. *especially for metals*
  - ✓ Always do uncertainty analysis…
  - ✓ …and global sensitivity analysis
- We need more harmonization, based on <u>sensitivity!</u>

Image: Midjourney AI rendering of "solar" and "probability distribution" keywords

Thank you.

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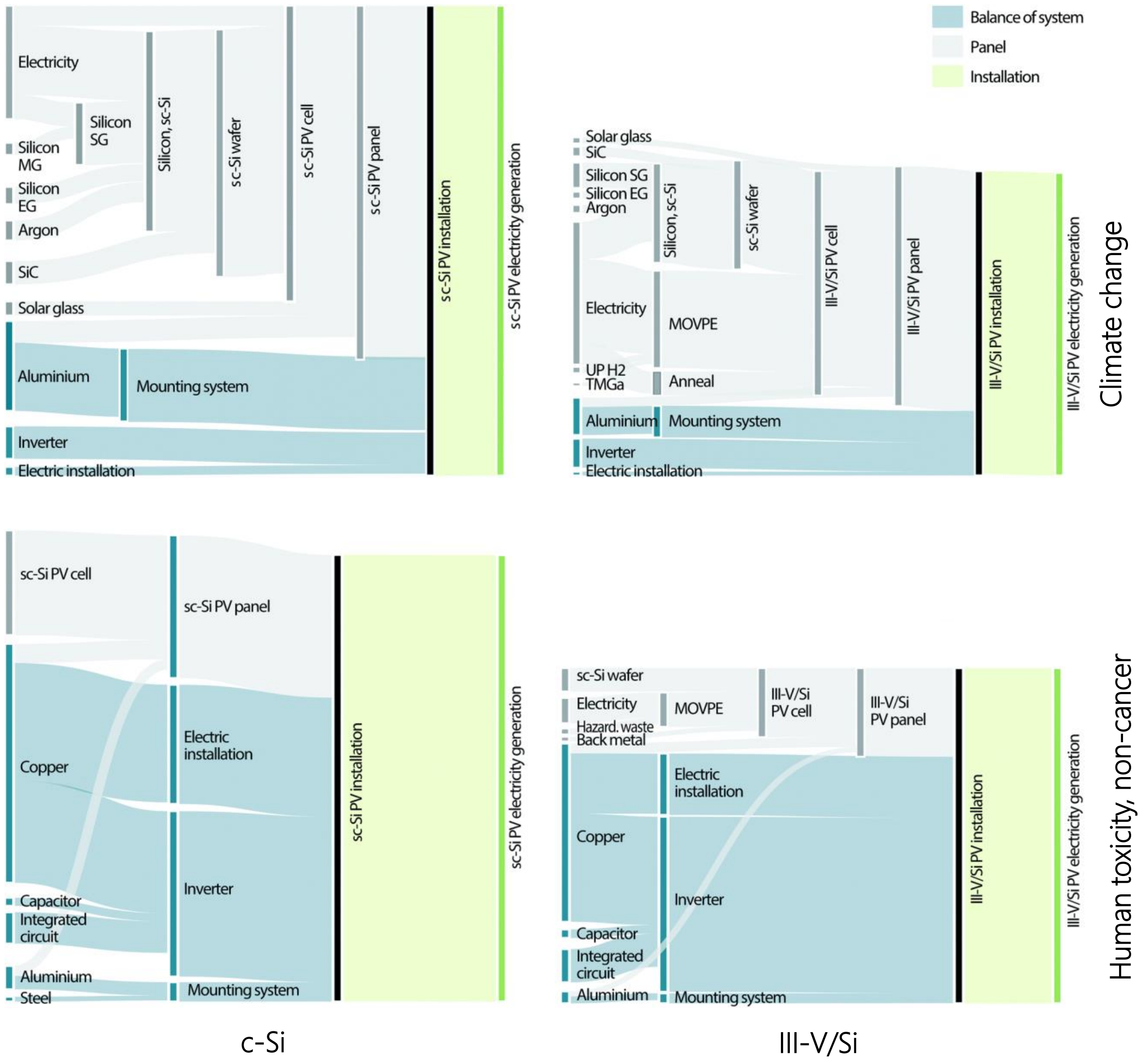
Backup slide: contribution analysis



Blanco C.F., Cucurachi S., Dimroth F., Guinée J.B., Peijnenburg W.J.G.M. & Vijver M.G. (2020), Environmental impacts of III–V/silicon photovoltaics: life cycle assessment and guidance for sustainable manufacturing, Energy and Environmental Science 13(11): 4280-4290.

In USEtox v2.0 documentation

Inorganics are all specified as 'indicative', reflecting the relatively high uncertainty associated with estimates of fate, exposure and effects for this substance group. In contrast to organic compounds, for which the substance-to-substance variations in transport properties can be attributable to basic chemical properties such as solubility ratios, variations in transport properties for inorganic substances depend in complex ways on a range of media properties. The solid/liquid partitioning of inorganic substances in soil can depend on several mineral components as well as the pH, redox potential (EH) and cation-exchange capacity. As a result, there can be significant variations of chemical mobility over very small geographic scales. Hence, it is difficult to identify the appropriate regional "bulk" transport properties for metals, as is done for organic chemicals. In addition, inorganic species are not "removed" by chemical reactions in the same way that most organic chemicals are transformed by actions such as biodegradation, photolysis, and hydrolysis. The biodegradation of an organic chemical in soil, water, or sediment effectively removes it from the system, but species such as lead, cadmium, and arsenic can only be truly removed from water, soil, or sediment by advection and tend to persist for very long time periods. However, many inorganic species can be effectively removed by sequestration in a chemical form that is chemically and biologically unavailable. The magnitude and variability of this process is often difficult to quantify, but can be very important for both fate and exposure assessment. Finally, relative to organic chemicals there are large uncertainties in determining how the variations in observed bioaccumulation and bioavailability come about (in both aquatic and terrestrial food webs). There have not been sufficient experiments to provide the data needed to address the nature and mechanism of the variations of these processes for inorganic species.

In USEtox v2.0 documentation

3.3.2 Interpretation and use of USEtox characterization factors

The following recommendations have been published (Rosenbaum et al. 2008) and are reiterated here with some minor updates and modifications. The toxicity potentials, i.e. characterization factors, must be used in a way that reflects the large variation of more than 15 orders of magnitude (i.e. a factor of 1015 between the lowest – least toxic – and the highest – most toxic – characterization factor) between chemical characterization factors of all substances currently covered in USEtox as well as the 3 orders of magnitude uncertainty (see Rosenbaum et al. 2008) on the individual factors. This means that contributions of 1%, 5% or 90% to the total toxicity score can be interpreted as essentially equal, but significantly larger than those of a chemical contributing to less than 1 per thousand or less than 1 per million of the total score. Disregarding the fact that the orders of magnitude of predicted impacts far outranges the orders of magnitude of the uncertainty analysis has been a major cause of complaints about the variability of these factors across impact assessment methods, whereas the most important chemicals were often the same within a factor 1000 across those methods. In practice, this means that for LCA practitioners these toxicity potentials are very useful to identify the 10 or 20 most important chemicals pertinent for their comparative applications, while implying a motive to disregard hundreds of other substance emissions whose impacts are by far less significant (and likely of negligible importance for comparative decisionmaking) for the considered products. Toxicity impact scores thus enable the identification of all chemicals contributing more than e.g. 1/1000th to the total score. In this context it is usually more meaningful and thus recommended to plot and compare toxicity impact scores on logarithmic scales, avoiding the over-interpretation of small differences of a factor.