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Towards ecodesign for upscaling: an illustrative case study on photovoltaic technology in France

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Abstract

The upscaling of technology encompasses many facets a designer concerned with reducing environmental impacts must manage. Therefore, previous research proposed an environmental assessment for upscaling (EAU) methodology. This method hinges on Life Cycle Assessment (LCA) approaches (e.g., prospective, absolute) and coordinates the environmental modelling from an ecodesign perspective. The originality of this paper is to present an illustrative application on photovoltaic systems. The focus is on the modelling practices (step 3 of the method) using upscaling design levers and generating parametrized scenarios meant to be interpretable for a design team. Examples of data collection and upscaling modelling are provided for the upscaling of silicon-based photovoltaic technology in France from 2021 to 2050. This case study shows that integrating upscaling parameters, such as industrial process evolutions, the technology deployment strategy, and the socio-technical context associated with the technology upscaling phenomenon influence LCA results significantly. The paper, therefore, discusses recommendations for design teams to support them in assessing the environmental implications of their technology choices.

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1. Introduction

Ecodesigning, *i.e.*, integrating environmental aspects during the design process, should be based on a Life Cycle Assessment (LCA) methodology [1]. Various LCA approaches (e.g., prospective and dynamic) are developed to model a product or a service lifecycle's environmental impacts. For instance, The Absolute Environmental Sustainability Assessment (AESA), considers some environmental limits a product lifecycle must not exceed to be considered sustainable. It is opposed to a "relative" approach comparing products with each other and is based on the planetary boundary framework [2]. With this absolute vision in mind, the operationalization of life cycle engineering has been challenged. Recent publications address design mitigation options and design guidelines [3] that could be associated with specific modelling practices [4,5]. However, with case-based reasoning, previous research has shown the incompleteness of LCA guidelines about environmental assessment for upscaling (EAU) for designers [6]. It leads in previous work to the proposal of a methodology (see Fig. 1)

enabling design teams to anticipate the environmental impacts associated with the upscaling of a technology, by combining different LCA approaches, *e.g.*, prospective LCA with the AESA paradigm. Practically, the EAU method hinges on the identification of five designated necessary groups of parameters reflecting facets, also called "archetypes", of the upscaling of technology, *i.e.*, scaling-up, mass-producing, deploying a technology, integrating into a complex system and down-limiting [7]. In other words, these five upscaling parameters refer to different models to be combined to reflect the socio-technical reality of a technology upscaling and its potential environmental consequences. They are depicted in orange boxes in Fig. 1 and can briefly be defined as follows before being fully implemented in subsection 2.2.:

- technical parameters proper to the engineering studied object (*e.g.*, material consumption, energy yield, choice of a component or structure);
- industrial projections of the technical parameters due to industry improvements (*e.g.*, learning curves);

- deployment strategy of the studied object (e.g., production target over several years or decades);
- socio-technical context of the deployment strategy (e.g., climate change consequences on society);
- AESA or relative approach.

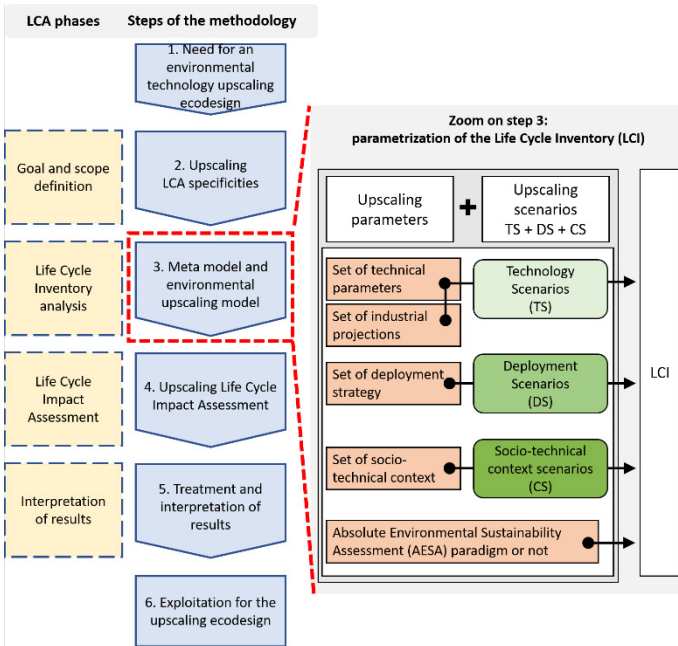


Fig. 1 – Overview of the EAU methodology (blue boxes) mirrored with the classic LCA phases (yellow boxes), focusing on step 3, dedicated to parametrize the Life Cycle Inventory (LCI) based on upscaling scenarios (right part).

This paper focuses on the application of EAU method step 3 to provide answers to the research question, “How to environmentally model the upscaling of a technology into an LCA framework within an ecodesign perspective?”. Based on a concrete case study, it therefore details the composition of sets of the upscaling parameters leading to *upscaling scenarios*, composed of 1) a technology configuration, 2) a *deployment strategy*, and 3) a *socio-technical context* (green boxes in Fig. 1), to reflect the design choices and their implications on environmental (e.g., damage) aspects. To do so, we propose a

simplified case study on the upscaling of photovoltaic (PV) systems in France. Thus, to contextualize the focus on the 3rd step of the methodology, subsection 3.1 briefly reviews all the six steps presented in Fig. 1. Then subsection 2.2 details an example of the modelling practice associated with step 3 and the necessary development of a “meta model” related to environmental upscaling assessment. The result analysis is conducted in subsection 2.3. Lastly, section 3 provides guidelines for design teams about EAU and absolute sustainability based on the results obtained. This methodology is meant to be iterative. The paper illustration could, therefore, be taken as the first run of several iterations along the PV system design process handled by designers to converge to a suitable LCI.

2. Research investigation and results

2.1. EAU application to the PV system deployment in France

Step 1: definition of the need for an environmental technology upscaling ecodesign. In this study case, the objective is to ecodesign the deployment of a PV technology in France, assuming to be part of a design team in charge of the PV system’s components “cell” and “module”. The planned PV deployment follows the strategy of the French electricity transmission system operator (named RTE) [8]. It must respect the carbon budgets defined by the French government in relation to the Paris Agreement. By extension, this technology deployment can be addressed within the AESA paradigm: target carbon neutral ambition by 2050 to keep our societies inside the Earth’s safe operating space (SOS). Fig. 2 presents the proposed framework to carry this environmental upscaling assessment, adapted from [2], assuming groups of PV system lifecycles installed successively over the years, all starting at the beginning of a given year, having the same duration and accruing depending on annual installed capacity demand. It formalizes the environmental aspects of the total cumulated installed capacity (i.e., the PV panel park) studied on a given date (red zones), confronted with a share of the global SOS, i.e., an absolute environmental limit (green line). As we shall

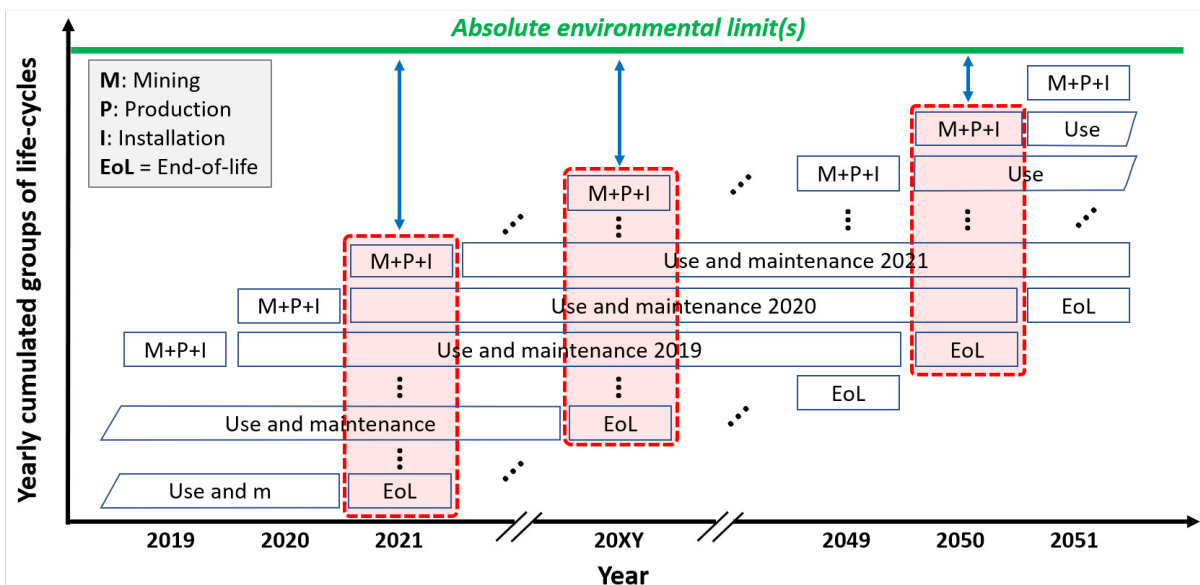


Fig. 2 – Framework of absolute sustainability proposed for PV panel deployment from 2021 to 2055, assuming a lifespan of 30 years. The analysis characterizes the difference (blue arrows) between the sum of every participation of the cumulated groups of PV system lifecycle in a particular year (red dashed boxes) and the defined absolute limit with regard to a specific environmental indicator (upper green line). Adapted from [10].

see, such a framework enables the representation of the temporal evolution integration consideration (e.g., technological improvements and evolution of the background system) and prompts design teams to consider the End-of-Life (EoL) of past and present installed systems while designing future systems. **Step 2: upscaling specificities** concerning LCA approaches, invites to consider the LCA-based modelling needs accordingly to upscaling assessment needs defined in step 1. In our case study, this step drives us to choose an “anticipative” (i.e., prospective) and absolute (i.e., PB-LCA) approach of LCA. Available databases and means of computation involve an attributional approach. Moreover, and as detailed in subsection 2.2.1, industrial trends have been modeled over time, enabling to integrate a partial time dependency of the Life Cycle Inventory (i.e., dynamic LCI). Thus, we selected an LCA approach (attributional) that is prospective absolute with a dynamic LCI. As the deployment strategy is defined at the national scale, a focus will be made on cumulative effects, including total material consumption. The Functional Unit (FU) corresponds to the need for installed energy capacity between 2020 and 2050 following an RTE scenario. For FU based on unit of produced energy, see previous work [6]. The studied systems include the photovoltaic modules and exclude the Balance of System (BOS), which is composed of inverters and AC-DC devices. No storage or panel support is considered. The perimeter encompasses all the stages from cradle to grave with the PV panels’ End-of-Life (EoL) stage as illustrated in Fig. 2. **Step 3: meta model and environmental upscaling models.** This step involves a combination of technology scenarios, deployment scenarios and socio-technical context modelling to produce a parametrized LCI for PV system upscaling in France. It is illustrated in subsection 2.2. **Step 4: Upscaling Life Cycle Impact Assessment (LCIA).** This stage refers to database selection for LCI computation (defined in step 3) and characterization factors of environmental impact indicators:

- prospective inventory data were computed with Brightway2 V2.4.4 and a superstructure generated from PREMISE [9] in February 2023 with ecoinvent database V3.8 through Activity Browser V2.9.1.
- usual characterization factors were selected to fit with the environmental limits (i.e., carrying capacity) proposed by [10]. A focus is made on climate change indicator (“GWP100”).

Step 5: treatment and interpretation of results. Illustrated in subsection 2.3. **Step 6: exploitation for the upscaling ecodesign.** This step involves turning LCA results into comprehensive guidelines for stakeholders of the studied upscaling. It is excluded from the scope of this paper.

2.2. Focus on step 3: meta model and upscaling environmental upscaling model

As no generic model exists to deal with the multiple facets of the upscaling of a technology, design teams have to coordinate several models from variable sources and potentially from different scientific disciplines (i.e., to operate a “meta model”) to finally parametrize the LCI and explore summations of technology scenarios, deployment scenarios and socio-technical context scenarios as depicted in Fig. 1.

2.2.1. Technology scenarios

As the introduction mentions, a technology scenario hinges on a set of selected design parameters and industrial projections. From a technical perspective, the proposed PV module model depends on two identified design parameters:

- the cell size (called G1, M6, M10, M12),
- the cell structure (whole cell or half-cell).

The literature identifies these selected design parameters as influencing the technical performances (e.g., power) and the material consumption (e.g., silicon, aluminum or silver) per system. Additionally, PV panels are assumed to be monofacial, 1.7m² large, weigh 17 kg, and be p-type doped. Fig. 3 displays the influence of the cell size on the power capacity for four PV module configurations in 2021, according to [11] (see colored triangles). It shows that the larger the cells, the more powerful the module is. Moreover, based on learning curves and trend projections for the coming decade from the yearly reports “International Technology Roadmap for Photovoltaic” (ITRPV) [14,15], we extrapolated industrial projections between 2020 and 2032 for each technology. This extrapolation transposes the projected improvement trend for G1 cells to other sizes of cells (M6, M10, M12) based on polynomial regression model (green formula in the top part of Fig. 3).

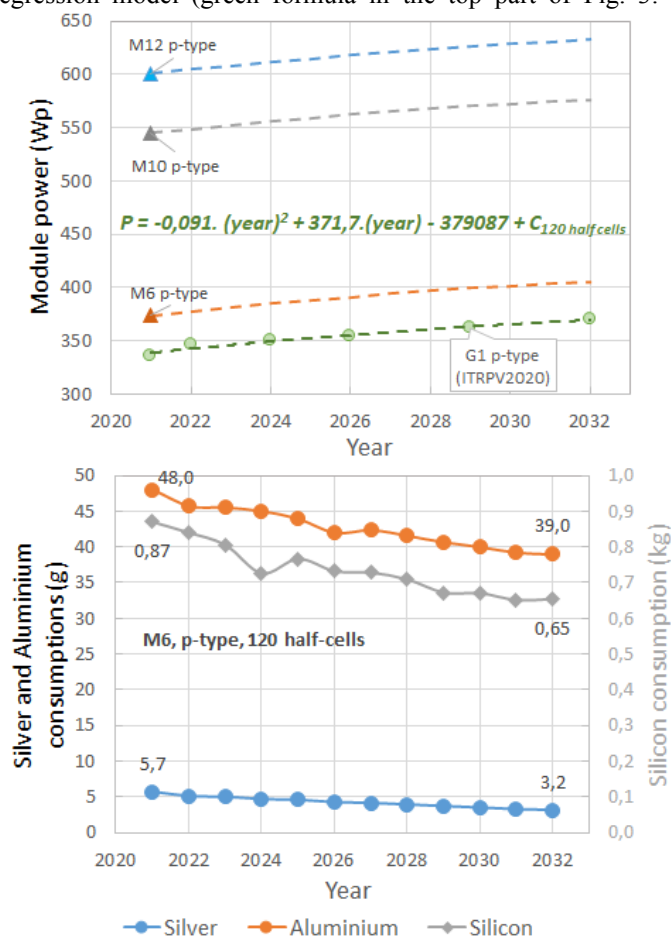


Fig. 3 – For a module of 120 half-cells: (Top) rebuilt data for module installed capacity depending on the cell size and time (Down) corresponding material consumption for an unframed module composed of M6 p-type cells.

Again, in this case study, the objective is not to model a complete PV system properly but to illustrate with a simplified model the modelling practices and to manage the influence of

design parameters on the environmental impacts resulting from the upscaling of a technology. Finally, ITPV reports provide projections for unframed PV module material consumption for silver, silicon, and aluminium, as exemplified in the bottom part of Fig. 3 for a panel composed of 120 M6 half-cells. After 2032, since there is no source offering any projection, a prospective exercise would consist of scriptwriting continuing improvement trends or anticipating new configurations. We adopted a conservative approach in this case study, assuming that these physico-technical improvements will reach a final value in 2032 and stagnate until 2050. Thus, the two characteristics, power capacity and material consumption (*cf.* Fig. 3) contribute to parametrize the LCI, in this case, a part of the foreground system, based on set technical parameters and industrial projections constituting technology scenarios. Regarding the rest of the inventory, the three considered life cycle stages, Mining, Production and Installation (MPI), Use and maintenance, and EoL, are not directly parametrized, and data were collected from [14]. This includes a set rate for material recycling, but not the use of recycled materials.

2.2.2. Deployment scenarios

With respect to Fig. 2, the deployment strategy corresponds to the number of panels installed per year over a period of time. This can be likened to the company's planning for future production. In this paper, a long-term vision on a national scale was chosen by selecting two mid-range of the six RTE scenarios, differing in installed photovoltaic capacity. RTE details the scenarios in greater detail (see [8]). The aim is to exemplify the diversity of possible strategies to reach carbon neutrality in 2050. The two selected scenarios are as follows:

- Scenario **N03**: 13% of the French electricity production from PV; 70 GW of installed capacity in 2050.
- Scenario **M23**: 22% of the French electricity production from PV; 125 GW of installed capacity in 2050.

Considering that all PV panels have a lifespan of 30 years, Fig. 4 shows the resulting annual needs for PV capacity installation between 2020 and 2051 by following these two scenarios. It

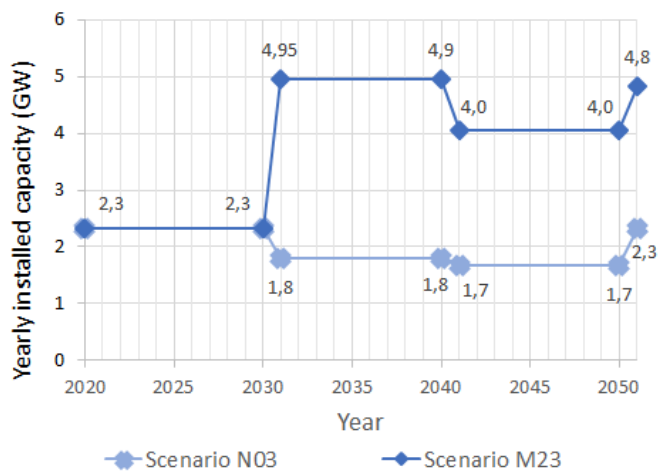


Fig. 4 – Yearly installed capacity of PV systems in France following two RTE scenarios, N03 and M23, assuming a constant lifetime of 30 years for PV panels.

will be divided by the unitary power capacity (*cf.* Fig. 3) to define the number of needed modules and parametrize the LCI for both scenarios. Regarding the EoL stage, RTE does not

provide specific assumptions; we therefore considered quantities of broken PV systems from 2020 to 2030 from [15] and extrapolated with RTE scenarios until 2050.

2.2.3. Socio-technical context

The socio-technical context refers to all the required hypotheses to be specified to consider the evolutions of the background system of the study. It includes both technical aspects (*e.g.*, improvement of techniques, energy decarbonization) and socio-economic aspects (*e.g.*, habits and customs, markets and substitutions of uses, investments) that ultimately influence the results of the LCIA. This significant number of assumptions can be a barrier to developing a forward-looking (*i.e.*, prospective) approach from scratch. It is also possible to draw hypotheses on existing scenarios. In our case, we will use the scenarios “Shared Socioeconomic Pathways” (SSP), notably used by the IPCC in IAM models, and integrated into PREMISE to provide prospective LCIs [9]. These scenarios are parametrized considering two elements:

- the type of policies at the global scale regarding socio-economic challenges for mitigation and adaptation to climate change. Five types of SSP are identified. The SSP5, called “fossil fueled development” implies intense mitigation challenges. Conversely, the SSP4, titled “inequality”, mainly sets challenges for adaptation as it considers no particular compensation mechanisms for the fact that different populations are not affected equally. The SSP3 (“regional rivalry”) can be seen as the worst case, implying significant socio-economic challenges for mitigation and adaptation. SSP1 (“sustainability”) implies low socio-technical challenges as human societies structure themselves efficiently to deal with mitigation and adaptation to climate change. Finally, SSP2 (“middle of the road”) is a trade-off of the other scenarios.
- Global warming mitigation targets, *e.g.*, 1.9, 2.6, 3.5, 6.0° C. Given that some of these targets might be unlikely to reach according to the type of SSP (*e.g.*, SSP3-1.9°C), in this paper, results are presented taking the scenario SSP2-base, equivalent to 3.5°C of global warming.

2.2.4. Absolute environmental sustainability paradigm

As can be deduced from previous temporal representations and recommended in [2], the life cycle inventory must be identified as a flow per unit of time to be compared with environmental limits. Similarly, the absolute limits must be computed in a unit comparable to the life cycle impact assessment. Lastly, it is necessary to define a Share of the global SOS (SoSOS) for the studied system, here, the entire PV deployment in France. In our case, this local environmental limit is partly based on the “national low carbon strategy” voted in 2015 by the French government to respect the Paris Agreements and reach carbon neutrality in 2050. Consequently, it plans to decrease carbon budgets between 2015 and 2050 for France, divided by the industrial sector, including the energy sector. This corresponds to the factors “%_A” and “%_B” of the definition of SoSOS, as follows:

$$SoSOS^i(t) = SOS \cdot \%_A \cdot \underbrace{\%_{0B}(t)}_{\downarrow} \cdot \underbrace{\%_{0C}^i(t)}_{\uparrow} \quad (1)$$

with $\%_A$ the ratio of the French population to the global population, assumed constant, $\%_{0B}(t)$ the ratio of the energy sector to the French industry, “i” the chosen deployment scenario (M23 or N03), and $\%_{0C}^i(t)$ the ratio of the PV installed capacity to the total French power capacity for a set of deployment scenarios. Two SoSOS are obtained based on the two deployment scenarios considered. Additionally, since the coefficients evolve over time, so does the resulting SoSOS (cf. subsection 2.3). The definition principle is based on climate change policies but can be transposed onto other environmental indicators, provided a global carrying capacity is defined. Attention should be paid to “compensation” assumptions in climate policies and potentially with “material depletion” and recycling but are not allowed for other indicators such as freshwater eutrophication.

2.2.5. Upscaling scenarios

As illustrated in Fig. 1, the environmental upscaling assessment relies on designing one or several upscaling scenarios, combining sets of design parameters (i.e., technology configuration), a deployment strategy, a socio-technical context modelling and a corresponding SoSOS. It brings about upscaling scenarios to be tested. Only one scenario is presented in this paper among the 16 possible with the considered technology and deployment scenarios: the one corresponding to PV panels upscaling, including cell-size M6 with half-cells, following a M23 RTE scenario in a SSP2-Base context scenario. Once again, this research paper focuses on the feasibility of the method and less on the exhaustivity of the analysis. An exploratory approach would instead use more scenario management methodology such as [16] to group assumptions and diminish accurately the possibilities. Explore extreme cases of socio-technical context (SSP1-1.5°C versus SSP3-7°C) can be accurate options. Similarly, it may be fruitful to custom directly into PREMISE the preregistered scenarios with additional data or different assumptions and implement

the interaction between the upscaling with the background data modelling (e.g., French electricity mix changes). However, it implies extra expertise on the part of the design team.

2.3. Step 5: treatment and interpretations of results

This step of the EAU methodology consists of confronting a technology configuration’s environmental aspects with a corresponding SoSOS and comparing the scenarios to identify one or more that are environmentally sustainable. As an illustration, Fig. 5 represents results associated with the formalism of Fig. 2 applied to climate change indicator. As a reminder, this represents the potential environmental impacts, here CO₂ equivalent emissions, for the yearly cumulated lifecycle stage for the necessary quantity of PV panels to supply the need defined in an RTE scenario between 2020 and 2050. In that scenario, using a simplified model, the upscaling of PV systems can be considered environmentally sustainable until 2045 as the sum of the cumulated greenhouse gas emissions (bars) is below the SoSOS curve (M23 blue curve). Emissions are predominant in the MPI stage (purple) all over the run, increasing proportionally to the number of installed PV systems for the “Use and maintenance” (orange) phase and are progressively negligible compared to other stages for the EoL stage until 2050. This latest point is consistent before 2050 but potentially underestimated because it is assumed that the first installed panels have not yet reached the end of their lifecycle in 2050. The effect of continuous technology improvement modelling (in the foreground and background systems) is hardly visible until 2030, when the simulated installed capacity rises sharply, consequently increasing CO₂ eq emissions after 2030, but not directly proportionally to the installed capacity increase.

3. Discussion: PV modelling limits and ecodesign practice

This paper provides a proof of concept for the data collection and modelling practices relative to the upscaling environmental assessment, to support the design teams for decision making. A PV designer aiming at the same “upscaling goal” as presented in step 1 in subsection 2.1, would have refine

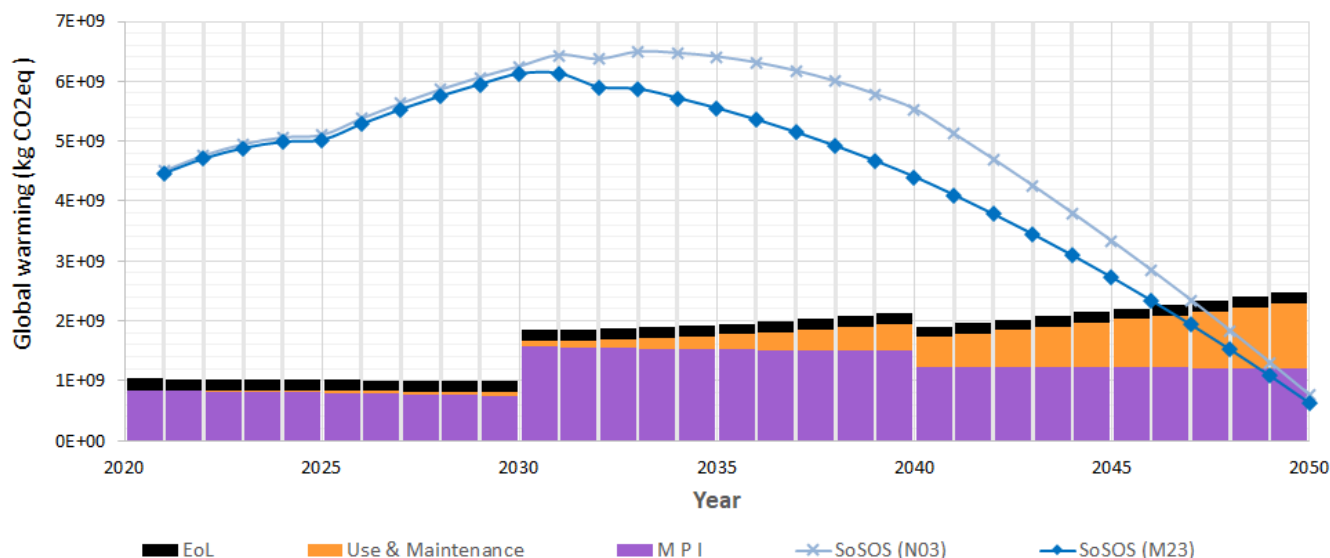


Fig. 5 – SoSOS/Carbon budgets (blue curves) and results of LCIA for the upscaling scenario M6/half cells - M23-SSP2-base.

the technical assumptions to turn it into a robust case study. It is accessible through PV specialist expertises with industrial trends [17] and updated LCA models (e.g., [18]). However, it is crucial to adopt a systemic approach: the technical considerations of the studied system interact with other industrial phenomena that ultimately influence the environmental impacts. That is why “deployment strategy” has to be defined with the technical design as they interact via the study perimeter. For the PV case, BOS designs, including power conversion systems, strongly depend on the type of installation. Typical designer concerns will be: precisising these characteristics would imply defining the targeted market and therefore the deployment strategy (e.g., 10% of RTE scenario). Same reasoning goes for energy storage, and adaptation to the distribution network depends on local technical conditions and type of installations. Furthermore, increasing power capacity for PV panels would entail adapting the associated power devices and potentially worsening the resulting environmental impacts. This may illustrate a classic burden-shifting due to design optimization without a systemic and multi-criteria approach [19]. Thus, trade-off stands on a multi-stage analysis, as presented in Fig. 5, but also on a multicriteria assessment, and following sensitivity analysis in regard to the parameters chosen. Integrating at least material consumption and freshwater eutrophication indicators is necessary in this study, due to the electronics involved. More broadly, environmentally assessing an upscaling in a design context supposes challenging different expertise from the design teams (technical and lifecycle engineering, company management, temporal risk analysis, standards, design guidelines) about the environmental benefits and burden of any technical improvement suggestion.

4. Conclusion

This paper illustrates the Environmental Assessment for Upscaling (EAU) methodology developed in previous research, through a comprehensive case study based on the photovoltaic sector. The six steps are applied with a focus on the third step, detailing the modelling approach dealing with the upscaling of a technology, that constitute a challenging step for the design team. Several modelling assumptions for photovoltaic product design and data have been chosen as examples. This case study exemplifies the EAU method output on a simplified model, given for an attributional prospective, absolute LCA with a partial dynamic inventory, computed to assess the environmental sustainability of the upscaling of a photovoltaic technology regarding climate change. This illustration highlights the existing difficulties designers face in such a process, the type of data computing required to provide practicable results, and the opportunity to strengthen the EAU models in research.

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