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30th CIRP Life Cycle Engineering Conference.

Assessing energy technologies sustainability: upscaling photovoltaics using absolute LCA

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Abstract

The upscaling of a technology has different facets that should be considered with anticipatory environmental assessment to deem its sustainability before industrialization. The Life Cycle Assessment (LCA) methodology is widely used to assess a product sustainability based on technologies. LCA is however usually applied after technology deployment, as a comparative approach validating the efficiency of the previous technology usage. Anticipatory LCA developments are therefore needed to help designers and engineers to investigate the sustainability of future technology implementations. This article paves the way to enhance ex-ante (or prospective) studies with an absolute sustainability framework, thus demonstrating the incompleteness of current developments on the upscaling from the designer's perspective. This is achieved through a case study applied on two photovoltaic technologies, silicon mono-crystalline and silicon/perovskite tandem in France, and in the current and the 2050 perspectives. Results show that assigning absolute sustainability targets at the technology level provides a new design framework, resulting in a go/no-go strategy. The minimal environmental performance requirements associated to technology deployment conditions through scenarios are identified. During this process, however, questioning the temporal and spatial scope of the study remains crucial to design a sustainable technology and the corresponding service it provides.

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1. Introduction

Energy production is the sector of human activity that contributes most to climate change [1]. In an energy transition framework, the production of low-carbon energy is a major objective, which pushes energy technology developers in a singular position. Life Cycle Assessments (LCA), following ISO standards [2], are carried out often retrospectively (*i.e.* post-ante assessment), which implies that results are not integrated in the design process. Referring to the sustainability framework for upscaling as a phenomenon with different facets to be considered defined in previous research [3], this paper focuses on the difficulties faced by designers to deal with these multiple facets of the upscaling of technology. In particular,

there is a multiplicity of stakeholders and expertise to integrate in the environmental impact assessment. The purpose of this paper is to provide designers with an illustration of the benefit of implementing these archetypes perspectives in design, and consequently demonstrate the incompleteness of current upscaling assessments.

1.1. Context: Sustainability Assessment of Technologies

To reach sustainable targets, technology designers need to anticipate the sustainability of a technology they intend to be mass-produced. A full application of the LCA ISO standards is however not well adapted to early design stage, and rather suits to a post-ante assessment. Several methodological supports for future-oriented perspectives (*i.e.* ex-ante or prospective LCA)

are provided by the literature, dealing with the common issues faced by designers such as data collection, modelling, interpretation and uncertainties. One of the main issues regarding the uncertainties strongly relates to the technology maturity, that is usually evolving during the design process [4]. LCA method for emerging technologies therefore requires to be integrated at each stage of the design process, and can be the fruit of collaboration between the technology expert and a LCA practitioner [5].

1.2. Research background and problem statement

Referring to the upscaling assessment framework published in [3], upscaling is defined in this research as a phenomenon (confering several facets) presented through the following *Archetypes*: upsizing from laboratory to industrial scale (Archetype 1), mass producing related to industrial engineering (Archetype 2), reaching a level of cumulated service (Archetype 3), integrating a complex system (Archetype 4) and down-limiting related to absolute sustainability (Archetype 5, see section 2). These archetypes correspond to different viewpoints of the upscaling of a technology or a service and hence draw on the expertise of numerous stakeholders. Scientific and economic actors, such as researchers, companies, public agencies and governments, produce studies and data required to feed these archetypes but not necessarily produced for direct use by designers. Data collection for assessing the technology upscaling can therefore result in a complex investigation, crossing multi-expertise. For instance, national policies, strategies and feasibility studies of energy transition (e.g. carbon neutrality targets), are partly driven by the upscaling of low-carbon energy technologies (e.g. photovoltaic and wind power). But the upscaling guidelines [4, 5], as complete as they are, do not integrate such data and studies and correspond to upscaling archetypes 1 and 2 only. Designers are therefore not equipped to deal with the multiple facets of technology upscaling, and are therefore limited in their environmental assessment. This research hypothesis considers this issue through the integrated design vision: the multiplicity of stakeholders and expertise to integrate in design to cover the multiple facets of upscaling requires additional support. There is a benefit of implementing these archetypes completeness perspectives during the design process associated to technology-based products. This research paper intends consequently to demonstrate the incompleteness of current upscaling assessments methodologies accessible to designers through a case study (sections 2 and 3), and formulate a method proposition to complete the upscaling assessment (section 4).

2. Application: Upscaling Technology Design in an Absolute Sustainability Perspective for Energy Transition

2.1. Introduction to the case study

This study case investigates a practical way to implement absolute sustainability principle in an energy system design perspective based on data and prospective studies in literature. It results in the illustration of a down-limiting method (as Archetype 5 of upscaling [3]), applied to the process design development of photovoltaic systems. Referring to the methodology for addressing absolute sustainability in

engineering, one of the key tasks is to delimit a *safe operating space* (SOS) to identify *how good is a technology, versus how best is a technology* [6]. In other words, moving from relative to absolute environmental assessment and promoting a design under (environmental) constraints. Literature provides a generic methodology to define these environmental constraints limits and chose the allocating rules and on justice principle [7, 8]. Energy provision is however a service, and its country disparities in terms of availability and use complexifies the applicability of such methods, as energy system designers are used to “tangible” products. This study therefore builds on existing research and brings up a necessary discussion on what analyses are required to study the resulting service rather than the energy device only, e.g. a photovoltaic (PV) panel, and on how this might improve the completeness of its upscaling assessment (cf. section 4).

2.2. Defining a French energy production SOS

This section outlines the methodology used to define a local share of the global SOS (SoSOS) over time for the climate change indicator in carbon dioxide equivalent (CO₂eq). Abdoli *et al.* (2020) published a similar methodology with a different perspective [9]. This contribution leads to the characterization of sustainable photovoltaic technology mixes in 2050, while we focus on the characterization of the potential improvement margin over time for two PV technologies from an eco-design framework. The goal is to build a SoSOS with regard to a unit of electricity production (1kWh) and comparable with classic energy system LCA results based on a functional unit of 1kWh from 2020 to 2050. This method is divided in two steps, one requiring to collect data from the French government and the second involving scenarios of national electricity production.

First, the National Low Carbon Strategy, voted in 2015 by the French government [10] defines annual carbon budgets from 2015 to 2050 to ultimately reach carbon neutrality in 2050. As shown in Fig. 1 (to be read with the right y-axis in grey), the yearly carbon budget attributed to the French energy sector in 2020 accounts for 52 Mega tons (Mt) of CO₂eq. Then, the curve (in gray) follows a decreasing slope from 2020 to 2025, a shallower trend between 2025 and 2031 and a constant slope between 2032 and 2050 until it reaches the value of 2 Mt CO₂eq. This brings France to neutrality in 2050 considering the other activity sectors that will absorb the remaining emissions, so-called greenhouse gas (GHG) sinks [10]. This corresponds to the application of a sharing principle to allocate a part of the “global carbon budget” (*i.e.* the SOS in terms of GHG emissions) to the French energy sector (*i.e.* electricity production). The hypothesis set to create this first SoSOS will not be questioned in this paper. The second step to define a SoSOS over time consists of redistributing the previous SoSOS with regard to electricity production over time. To do so, it is necessary to collect prospective scenarios on electricity production until 2050. The *Réseau de Transport d'Electricité* (RTE), the electricity transmission system operator in France published in 2021 different power production pathways to reach carbon neutrality by 2050 [11]. These scenarios are represented by blue curves in Fig. 1 (to be read with the left y-axis).

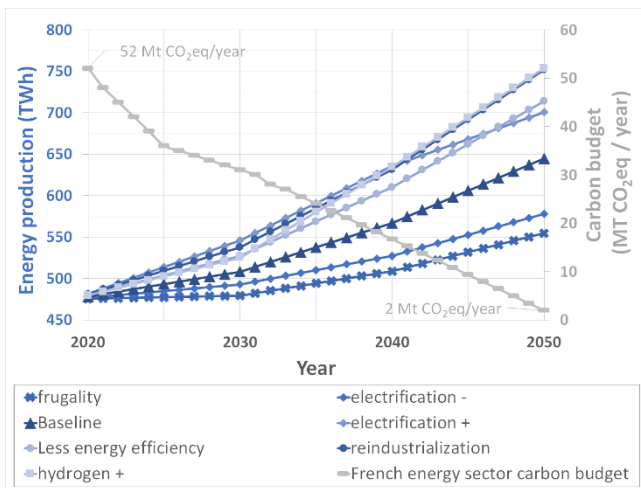


Fig. 1 - Energy production of France from 2020 to 2050 following 7 prospective scenarios (in blue) from RTE adapted from [11] and corresponding French carbon budget associated to the energy sector adapted from [10].

This results in the following seven scenarios with specific narrative, ranked from least to most productive in terms of energy produced in 2050: (i) *Frugality* (or sufficiency): implies the reduction of energy consumption per capita over time, (ii) *Electrification* “-”: corresponds to partial and slow electrification of other activity sectors including transport, (iii) *Baseline* scenario: implies a gradual electrification and strong energy efficiency improvement, (iv) *Electrification* “+”: corresponds to total and rapid electrification of activity sectors with decarbonized hydrogen production, (v) *Less energy efficiency*: represents a scenario with less energy efficiency implementation than the baseline scenario, including in the heating of building sector. (vi) *Reindustrialization*: models a re-localization of manufacturing industries, (vii) *Hydrogen*: production and used of decarbonized hydrogen as a vector of energy transition more than in the baseline scenario [11]. These scenarios are consistent with the objective of carbon neutrality for France in 2050, which allows for a single carbon budget curve. Even in the frugality scenario, the electricity production, according to RTE, is meant to increase based on population growth compensation and a more or less sustained and fast electrification of other activity sectors. The SoSOS allocated to the production in France of 1kWh is therefore defined as follows:

$$SoSOS_{\{1kWh\}i}(t) = \frac{\text{French Energy sector carbon budget (t)}}{\text{Energy production following the RTE scenario } i(t)}$$

with “i” the chosen RTE scenario (frugality, baseline, reindustrialization, etc.). For one selected RTE scenario, the resulting SoSOS, like the carbon budget and the energy production, evolve annually (see Fig. 1). It means that the constraint on energy production (*i.e.* on energy system designers) is gradually increasing over time until 2050. The result of this approach is thus seven time-dependent SoSOS from 2020 to 2050 in terms of climate change indicator for the production of 1kWh of electricity. These dynamic SoSOS are considered independent of the technology mix. It defines a threshold not to overtake for the production of 1 kWh of energy

to be considered as sustainable relatively to the climate change indicator.

2.3. Study case of photovoltaics in France

This section is dedicated to present attributional LCA results for energy production from PV systems in France in 2020 to be confronted with the SoSOS defined in section 2.2. A photovoltaic system, as shown in Fig. 2 is composed of an active part, the module, transforming more or less efficiently the solar energy into electricity according to the technology. In our case, the mono-crystalline silicon (c-Si) technology for the most mature and the tandem c-Si/perovskite technology as emerging and potentially more productive. Then, *balance of system* (BOS) components (*e.g.* structure, cables, inverter, transformer, etc) are integrated to manage mechanical and electrical constraints, including to adapt the energy supplied to the grid (*i.e.* DC/AC current conversion).

Concerning the scope of the LCA, Fig. 2 presents five generic life cycle stages considered in a LCA following the standards [2]: 1. raw material mining and purification (*e.g.* metallurgical grade silicon production), 2. conversion of raw material into material (*e.g.* solar grade silicon production), 3. component production and assembly (*e.g.* wafer production and cell assembly into modules), 4. installation use and maintenance and 5. End of Life (EoL) treatment (*e.g.* energy recovery or partial recycling of copper/aluminium). The grey arrow represents the transport of components between and into stages. The electricity network and energy storage interactions are usually neglected (*cf.* discussion in section 4.3).

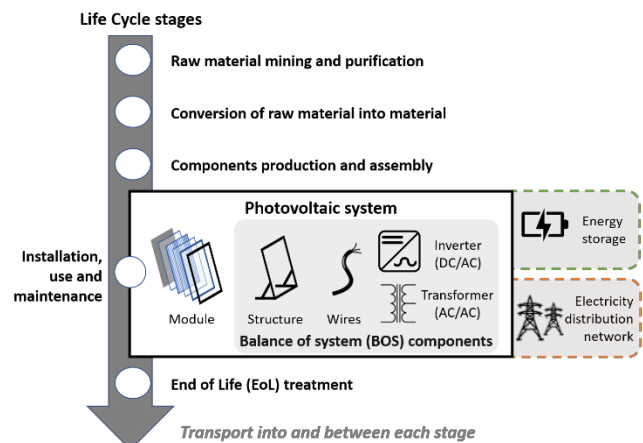


Fig. 2 - Elements composing a PV system (in black box) and associated generic life cycle stages. Energy storage (dash boxed in green) and grid (dash boxed in orange) interactions are usually excluded from the perimeter.

2.4. LCA of PV system (goal and scope)

The objective of the study is to compare the potential environmental impacts (only GHG emissions in our case) for the year 2020, with a view to the year 2050 for the two technologies: c-Si and tandem c-Si/perovskite. To do so, three studies have been compiled to use representative results from 2020 and the near future: the “INCER-ACV” (2020) [12] study, the study of Fthenakis and Leccisi (2021a) [13] for c-Si technology, and Fthenakis *et al.* (2021b) for the tandem technology [14]. Each study considers the first four life cycle stages and include the BOS in their perimeter, as depicted in Fig. 2. Publications [13] and [14] neglect the EoL stage due to

lack of data. The functional unit in PV systems, is usually presented for designers in unit of capacity installed (kWp). This prevents designers from studying performance results depending on the location. The study being, however, carried out in France, the unit of energy instead of power capacity is preferred in this paper. The functional unit chosen is therefore 1kWh of energy delivered to the French electricity grid. The variation in the location of the studies is reflected in the uncertainties in the result graphs. Concerning the tandem system module and as an emerging technology at a laboratory scale, hypotheses have been set to assess its upscaling to industrial scale (*i.e.* implementation of archetype 1, upsizing). The time horizon of this technology upscaling is not specified, which is an issue for designers addressed in the results and discussion section. The lifetime and the energy efficiency of the module being key parameters in PV environmental assessments, several values of a lifetime (from 10 to 30 years) have been documented for this emerging technology to assess the variability of results (see section 3.1). The tandem system is assumed to reach 28% energy efficiency. The lifetime for c-Si system is considered by default equal to 30 years and its energy efficiency is 20.5%. To deepen the hypothesis of the LCA results used in this paper, please consult [12–14].

3. Results

The point of absolute sustainability is to set environmental constraints not to be overtaken for a sustainable potential technology. In the goal of reaching French carbon neutrality, Fig. 3 presents the CO₂eq emissions c-Si PV technology, on average associated with the production of 1kWh generated in 2020 and the corresponding SoSOS in accordance with the French carbon neutrality goal following the baseline scenario.

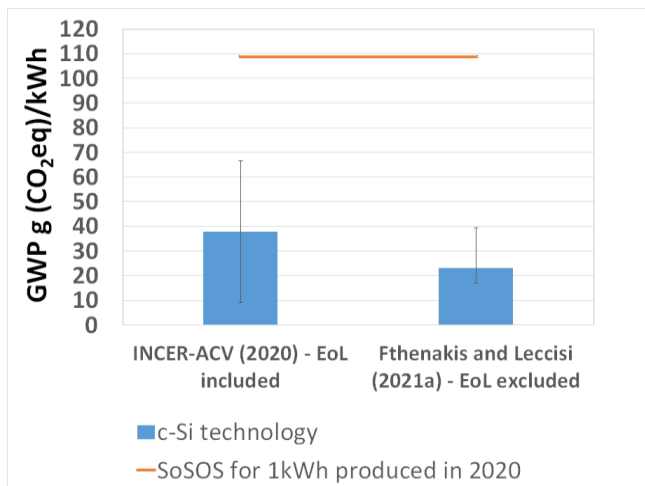


Fig. 3 - CO₂eq emissions attributed to the production of 1kWh of electricity from c-Si PV technology in France in 2020 adapted from [12] and [13] compared to the SoSOS (in orange) in accordance with the French carbon neutrality goal.

Uncertainties bars show the sensibility analysis of key parameters in the LCA (energy efficiency, solar irradiation, raw material composition, manufacturing processes, EoL treatment, etc) for [12] and variation of location and solar irradiation (from 1000 to 2000 kWh/m²/year) for [13]. From these two retrospective studies on the incumbent PV technology that is the c-Si-technology and relatively to the SoSOS in 2020, the energy production can be estimated

sustainable for 2020. Remark that the EoL stage is not negligible, which is the only prospective (*i.e.* future-oriented) aspect of the study.

3.1. Go/no-go strategy in design

In the design framework, it is necessary to anticipate the environmental impacts of the designed/upscaled technology. The comparison of classic results of prospective LCA with the SoSOS as presented in the previous section, provides elements to develop a go/no-go strategy in a prospective perspective. As an example of emerging PV technology, the tandem PV technology is not yet existing in 2020 at industrial scale. Moreover, at first order, the *Global Warming Potential* (GWP) of a panel is influenced by its lifetime and its efficiency. Their improvements are thus crucial and well identified levers for designers. Fig. 4 presents the prospective estimation of GWP for the perovskite/c-Si tandem technology, depending on its lifespan, provided by Fthenakis *et al.* (2021b) [14]. Note that for an equivalent lifetime (30 years), the impacts of tandem PV are lower, notably because its energy efficiency is higher than that of c-Si PV (28 instead of 20.5 for c-Si). Authors do not give a timeframe for these improvements. This study is therefore compared to the SoSOS for one unit of energy produced in 2020, 2030, 2040 and 2050 following the baseline scenario. Uncertainties bars represents the variation of these limits depending on the chosen RTE scenario. This graph shows that PV system designers need to improve the lifetime of tandem PV technology by up to 10 years before 2030 and, in the worst case, by up to 20 years before 2040 for the resulting energy production to be sustainable for 2030 and 2040, respectively, and from the GWP perspective. If PV system designers consider satisfying these constraints unachievable or unrealistic, a "no-go" strategy will be applied to redirect research to other more promising technologies. Note that, the EoL stage being excluded from the scope of the study, a more drastic deadline should be considered. Fig. 3 and Fig. 4 shows the completion of the usual analysis charts from PV LCA studies and therefore used by designers to consider

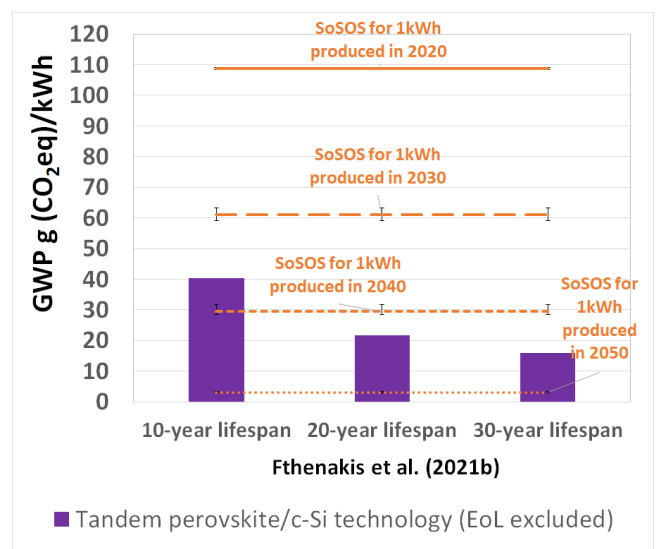


Fig. 4 - CO₂eq emissions estimation for the production of 1kWh of electricity from upscaled tandem perovskite/c-Si PV technology adapted from [14] compared to the SoSOS in 2020, 2030, 2040 and 2050 in accordance with the French carbon neutrality goal.

environmental impacts. This work should be taken as a proof of concept of integration in the design process of the absolute environmental sustainability framework.

4. Discussion

4.1. Averaged GWP and dynamic SoSOS comparison issue

Results show the feasibility of integrating a SoSOS in a retrospective or a prospective vision for a specific year, assuming a constant ratio of GWP per kWh produced. In other words, the device sustainability has been estimated at a precise date of time, current or future, based on static environmental impacts. This study is focused on the estimation of the timescale for technology improvement requirements in France to fulfil the Paris agreement. The main issue of comparing SoSOS depending in time (*i.e.* dynamic) with averaged environmental impact over the whole life cycle of a device is illustrated in Fig. 5. Considering a c-Si panel installed in 2020 (in dashed blue) and a tandem panel installed in 2030 (in dashed purple) with a lifetime of 30 years, with an averaged GWP over time (*i.e.* static), the same level of environmental performance is maintained over time (23 g and 16 g of CO₂eq/kWh respectively). The sustainability threshold is crossed in 2042 for c-Si technology, and at the horizon of 2045 for tandem technology. In other words, all things being equal, the energy provided by a panel installed in 2020, can be considered sustainable until 2042 for c-Si technology and until 2045 for the tandem technology. Given this artefact at the system level, no technology will be sustainable over its lifetime, disregarding the possible variations of its impacts over time as exposed in [15] with the terminology “temporal issue 3”. A robust go/no-go strategy therefore requires additional phenomena than usual ones to be considered, including the distribution over time of the environmental impacts (*e.g.* up to 75% of PV devices GWP is attributed to its manufacturing phase, within the year of the installation of the PV system [13, 14]). The following section discusses several research tracks focusing on the prospective study scope required to define this go/no-go strategy for designers of PV technology in an upscaling perspective.

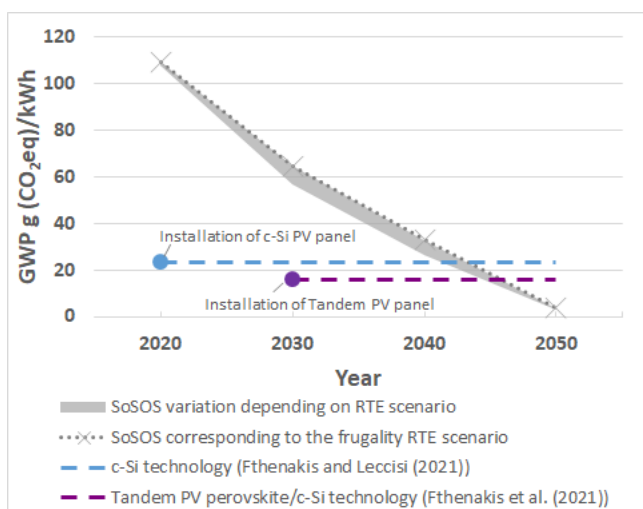


Fig. 5 - Comparison between averaged GWP associated to c-Si (blue) and tandem (purple) PV systems over their lifetime and a dynamic SoSOS (grey dashed line).

4.2. The temporal scope of the study

This study, as a proof of concept calls for complementary assessments with regard to the prospective LCA framework. In an eco-design context is commonly distinguished the foreground system, depending on the design and industrial parameters (*i.e.* foreground system) to the background system, as an imposed techno-economic context. This context leads to characterize the margin of improvement of a given technology regarding several influence perimeters, namely in terms of temporal evolution.

The PV designer's levers integration

This system corresponds to the usual design parameters: energy efficiency, lifetime, and raw material composition. As stated in section 3.1, energy efficiency and lifetime are the main improvement contributor to the reduction of PV environmental impacts. However, these improvements only have effect from one panel generation to another and not on a specific installed PV panel as studied in the results section.

The PV industrial's levers integration

This system consists of manufacturing process efficiency, relying on industrial trend of improvement (*e.g.* silicon wafer slicing process, tandem process scalability, or EoL treatment maturation). These evolutions can be implemented following learning curves and scaling laws provided by PV sectorial experts [14, 16]. These variations are also carried out from a panel generation to another.

The national and intersectoral's evolution integration

The background system is by definition out of the expertise and levers of a technology designer. However literature demonstrated that variability of prospective LCA results are strongly affected by background system data [15]. As an example, the EoL stage is simultaneously a part of the foreground system (*e.g.* selection of components by the designer and the choice of technology for the recycling process), and the background system generally presented as an energy-intensive activity involving dynamic effects consideration. Thus, recycling could be overestimated in an energy transition context, because it is assumed to occur 30 years before the actual time in a static study (*i.e.* EoL allocation in 2020 instead of 2050 as in [13]), when energy consumption is more carbon intensive. There is still no consensus on modeling EoL, which leads designers to neglect it, in addition to the lack of data. The energy transition implementation (and resulting carbon intensity decrease) in data can be supported by the PREMISE framework [17]. This tool returns prospective inventory database considering different scenario of climate pathways (*e.g.* IPCC pathways [1]). This enables for instance to estimate the decarbonation of energy consumed in manufacturing and recycling processes over time.

4.3. The spatial scope (or Energy providing is a service)

As stated in the introduction, energy providing is a service, meaning that the scope of the study must integrate the Life Cycle of all systems required to provide the service, and this depends on time: the intermittency of PV systems is manageable today without energy storage. It is, however,

meant, according to RTE, to be compensated with a grid management and energy storage system. This implies, for the same service, expanding the scope of the evaluation due to the evolution of the complex system (*i.e.* the national power grid) in which PV systems are increasingly integrated. Literature provides some examples of renewable energy intermittency management studies adding within the study perimeter required storage energy systems (*e.g.* battery integration in the perimeter [18], see green part in Fig. 2) and modification of the grid in reaction to cumulated PV installed capacity (*e.g.* [19], see orange part in Fig. 2). Ideally, these two types of analysis should have been carried out to consider the upscaling of energy production from PV technologies.

4.4. Regarding the upscaling framework

As the proof of concept, this assessment of PV technologies upscaling is not intended to be exhaustive. Several upscaling archetypes however have been fully or partially carried out or evoked to tend towards exhaustiveness.

- Archetype 1 is considered for the tandem PV technology based on [14].
- Archetype 2 is indirectly taken into account from the methodology and data used in [2, 12, 13] and could be assessed with parametrized modelling to integrate learning curves provided by the literature [16].
- Archetype 3 is partially considered due to the use of deployment RTE scenarios to define the SoSOS [11]. Cumulated phenomena linked to the PV deployment are, however, not explicitly in the scope of the paper.
- Archetype 4 is out of the scope of this paper. Energy storage systems, and additional infrastructures required to assure grid stability could be included in further work as presented in [13, 18, 19].
- Archetype 5 has been implemented with the definition of an energy production SoSOS based on external expertise for one environmental indicator [10]. A generalization must be implemented.

5. Conclusion

This article presents a study case of assessment of the upscaling of a photovoltaic technology based on prospective and absolute LCA framework. It proves the incompleteness of current LCA methodologies, providing sustainability time constraints for upscaling designers to develop a go/no-go strategy. To enforce such strategy consistently, supplementary methods must be developed, including time-dependent LCA result representation. Two research tracks were evoked in the discussion: prospective methodology clarification for designers and an assessment of the scope consistency with respect to the technology upscaled and the related service provided.

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