Design Science

Designing emerging technologies taking into account upscaling

Lucas Riondet[1,2], Maud Rio[1], Véronique Perrot Bernardet[2] and
Peggy Zwolinski[1]

[1]*Univ. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, 38000 Grenoble, France*
[2]*I2M Bordeaux, UMR 5295, Eq. IMC Institut de Chambéry, Le Bourget du Lac, France*

Abstract

Under the umbrella concepts of upscaling and emerging technology, a wide variety of phenomena related to technology development and deployment in society are examined to meet societal imperatives (e.g., environment, safety, social justice). The design literature does not provide an explicit common theoretical and practical framework to clarify the assessment method to handle "an" upscaling. In this nebulous context, designers are struggling to identify the characteristics to anticipate the consequences of emerging technology upscaling. This article therefore first proposes a structuring framework to analyze the literature in a wide range of industrial sectors (energy, chemistry, building, etc.). This characterization brought to light five prevalent archetypes clarifying the concepts of upscaling and emerging technology. Then, a synthesis of invariants and methodological requirements for designers is proposed to deal with upscaling assessment according to each archetype, based on a literature review of existing design methods. This literature review process showed a disparity in treatment for some archetypes, regarding the industrial sector. A discussion is consequently proposed in the conclusion to guide design practices.

Keywords: Upscaling, Upscaling archetypes, Emerging Technologies, Design for Sustainability, Absolute sustainability, Deployment, Scaling up, Scaling-up, Complex system, Absolute Environmental Sustainability Assessment

Received 12 October 2023
Revised 09 July 2024
Accepted 11 July 2024

Corresponding author
L. Riondet
lucas.riondet@grenoble-inp.fr

Des. Sci., vol. 10, e24
journals.cambridge.org/dsj
DOI: 10.1017/dsj.2024.33

1. Introduction

The upscaling of emerging technologies in design and engineering science seems to be regularly examined (Boess 2019; Wolniak *et al.* 2019; Tozik & Reich 2023). This phenomenon is usually referred to as a complex phenomenon involving the development and deployment of technology in society. However, the assessment of upscaling embodies multiple facets that mobilize in practice a wide scientific literature and multiple areas of expertise. Some of these areas of expertise are not integrated into the identified traditional design framework. Societal imperatives (environment, safety, social justice) are increasingly demanded to be considered in innovation (Huntjens 2021). In addition, a heterogeneous vocabulary referring to "scales" is used in the engineering literature to designate the relationship between technology and the society adopting it. The literature diversity associated with technology upscaling raises questions about the means that designers can identify to assess this phenomenon. Investigating how these resources align with societal ambitions is also crucial. This motivates the need for a literature clarification, to propose guidelines to designers that are relevant about the technology upscaling they are willing to study. This research paper therefore aims to answer the question: How can the phenomenon of "upscaling of emerging technology" be studied from the new perspectives of design communities? We split our research into two sub-questions: (1) How to characterize the concepts of emerging technology upscaling in the design communities? and (2) What are the engineering methods, practices and guidelines for assessing the "upscaling of an emerging technology" from a design integrative perspective? This review proposes a design theory based on the scientific literature from design and engineering communities to address the two research questions. This positions the contributions in integrated design defined as the intervention of actors and expertise in the design process of a system (e.g., a product or a service). This process aims to improve one or more aspects of the finished product (e.g., cost, quality, lead time; Pahl & Beitz 1996). Therefore, developing a design theory about emerging technology upscaling aims to make designers aware of the influence of their practices on the upscaling phenomenon. This theory conceptualizes different visions of the design of a technological product and is intended to be transferred to a practical audience of designers and engineers.

2. State of the art: the "upscaling of an emerging technology" as a catch-all phrase

Upscaling is a polysemic word and used in the scientific literature (Farmer 2002; Dijk, de Kraker & Hommels 2018; Moreno *et al.* 2018; Tsoy *et al.* 2020; Hjalsted *et al.* 2021; Thiede, Wiese & Herrmann 2021) in conjunction with number of terms related to scale: *scaling up* (Sanford *et al.* 2016; Wolniak *et al.* 2019; Belwal *et al.* 2020), *growing* (Cherp *et al.* 2021), *deploying a technology* (IRENA 2019b), *scaling* (Baumann & Lopatnikov 2017; Tanguy, Bahers & Athanassiadis 2020), *reaching a level or an industrial/commercial scale* (Piccinno *et al.* 2016; Ehrler *et al.* 2020; Verlinden 2020; Bobbe *et al.* 2023), *improving the scalability* (Nordelof 2019; Leccisi & Fthenakis 2021), using a *scaling law* (Baumann & Lopatnikov 2017), *downscaling* (Ryberg *et al.* 2020; Hjalsted *et al.* 2021), *ecology and economy of scale* (Gwehenberger *et al.* 2007) and so forth. The abundance of keywords alone does not help to clearly define the upscaling and therefore turns this word into an umbrella term. As such, upscaling has a different meaning depending on the design community and the disciplinary field (e.g., chemical engineering (Balgobin & Evrard 2020), waste treatment sector (Barbero & Toso 2010), energy sector (Rae, Kerr & Maroto-Valer 2020), food sector (Hardman, Clark & Sherriff 2022), building sector (Tanguy *et al.* 2020), goods production engineering (Koulin, Sewell & Shaw 2015) or nanoengineering (Moschou & Tserepi 2017)). Indeed, *upscaling a technology* or system can refer to technology maturity issues, industrial techno-economic optimization, technology deployment strategies or technical integration and/or social acceptance issues.

2.1. Defining an emerging technology

The same polysemy, identified for "upscaling", goes for the concept of "emerging technology". Three definitions of an *emerging technology* coexist in common designer language and are often concomitant with the terminology of an upscaling (Rotolo, Hicks & Martin 2015; Sims *et al.* 2017; Bergerson *et al.* 2020; Elshkaki 2021;

Xu *et al.* 2021): emerging technology as a promising but unmatured technology, a minor but growing technology, and emerging from a socio-technical vision.

- *A promising technology in a laboratory or a maturing technology:* In chemical and bioengineering fields, the subject of upscaling refers to an emerging technology or a process, to be understood as an early-stage technology in a laboratory. "Early-stage" and "emerging" are consistently used as synonymous by the life cycle assessment (LCA) community (Bergerson *et al.* 2020; Hung, Ellingsen, & Majeau-Bettez 2020). Additionally, institutions such as the European Commission or the International Energy Agency (IEA 2020) develop assessments and planification focused on technology maturity, relying on operational performance improvement together with lower cost (e.g., Horizon2020 2022 plan). These two types of sources are in line with defining an emerging technology as a promising and novel technology in a maturing process. Both push toward a definition mainly focused on technological maturity. An emerging technology is thus an immature technology with promising technical and/or environmental performance. This concept is not limited to the improvement of an existing technology. An emerging technology refers in that case to a non-mature technology poised to have a disruptive impact on society with regard to its supposed deployment.
- *A minor but growing technology, deployed in a market:* Also, from IEA publications, the necessary so-called "energy transitions" pull the development of technologies to satisfy a large part of the future energy needs of populations. Thus, an emerging technology in this context is not necessarily a novel or an early-stage technology but more an industrialized technology that is still marginal in the market. For instance, renewable energy systems such as wind power and photovoltaic are considered as "early adopted" technology by IEA (i.e., not *early-stage* technology). Both systems account together in 2020 for less than 4% of the world energy mix (IEA 2020; Ritchie, Roser & Rosado 2020). They are, however, purposed to become dominant in national energy mixes to satisfy carbon emission policies to tacking climate change. In addition, the concept of "materiality" defines the point at which a technology reaches 1% of the world's energy mix. Thus, the requested development of renewable energies in the transition scenarios turns them into emerging technologies in terms of market or energy mix integration (Kramer & Haigh 2009). This definition is consequently affiliated with the terms "technology adoption" and "materiality". Rotolo *et al.* (2015) detail five items from the scientometric domain to characterize an emerging technology: "Radical novelty, relatively fast growth, coherence, prominent impact and uncertainty and ambiguity". "Prominent impact" is relative to expectations, imaginary and "preferred technological future" that designers promote, "relatively fast growth" associated with rapid abundance in literature and "coherence" resulting from a normative phenomenon on vocabulary structuring the state of the art of the studied emerging technology. Xu *et al.* (2021) reuse three of them to detect emerging technologies in literature (relatively fast growth, radical novelty and prominent impact). Remarks that these characteristics are not specific to *any particular field of engineering or scientific literature.*
- *A technology emerging in a (socio-technical) system:* This interpretation of emerging technology is related to integration in a so-called sociotechnical system (i.e., society) as illustrated by Geels *et al.* (2017). The authors present "technology

niches" emerging or not in a sociotechnical system depending on its compatibility with the incumbent regime (e.g., regulations and policies, road infrastructure, industry structure, market and user practices, etc.). It is not a designer perspective but emergence-focused with a systemic vision. Integration issues are for instance addressed in the energy sector, where technologies must adapt to the power grid with geographical and techno-economic constraints. "Smart technologies" are in that context, defined as technologies helping new ones to be integrated (i.e., emerging technologies in the network; Rae *et al.* 2020). The food sector uses a different terminology (e.g., "technological innovations" and "food system") and emphasizes the social aspect of the emergence (Hardman *et al.* 2022). The emergence of technology is therefore both a technical and a social challenge, dealing with adoption by local populations, for example.

To summarize, terms relating to *upscaling* (or *scale*) and *emerging technologies* are used in the design and engineering literature repeatedly, without necessarily being connected to a clear definition. Our approach therefore aims to clarify the design vision by building a robust framework for analyzing the upscaling according to identified characteristics, as generic and cross-cutting as possible. This research defines such characteristics as "invariants". Then, the objective is to empower designers with guidelines directing toward assessment methods for upscaling emerging technologies regarding a set definition.

2.2. Defining the upscaling, as a transforming function

Previous research elaborated a literature reading hypothesis to characterize an upscaling process in engineering (Riondet *et al.* 2022). Following this hypothesis, the upscaling is assumed to be a "transforming function". Upscaling is a phenomenon applied to a subject and bringing it from one state to another. The methods used to assess the upscaling in design and engineering, revealed in the literature analysis of this review, that they are mainly techno-economic analysis (TEA). TEA is a method used to assess a process or product system based on technical and economic performance criteria (Zimmermann *et al.* 2020). Thus, an upscaling process is considered first as a techno-economic phenomenon. Based on the elements to be defined TEA referring to upscaling and emerging technologies, we proposed three interdependent characteristics for the upscaling of emerging technology: "*subject, goal and scope*" (see Figure 1).

The goal is based on a performance indicator. This means that the transforming function (i.e., the upscaling) can be represented on an indicator scale or domain. Moreover, the upscaling subject can be of a different nature, tangible or intangible (e.g., a product or service, an analysis boundary or a limit). Whether discipline-specific or not, methodologies to carry an upscaling rely on the scope defined linked to the goal. The subject is not necessarily the interest core of the scope. However, the scope is fully characterized by a type and the analysis boundary (or focus) pointing to the interest core.

This analysis framework enables designers to better define what they mean by *upscaling a technology* by characterizing "archetypes", *that is*, a facet of the upscaling reflecting a specific design vision. An archetype, in our work, is therefore built on three set invariants *goal*, *subject* and *scope.* Building archetypes is, therefore, a simple way to embody visions of technology upscaling and

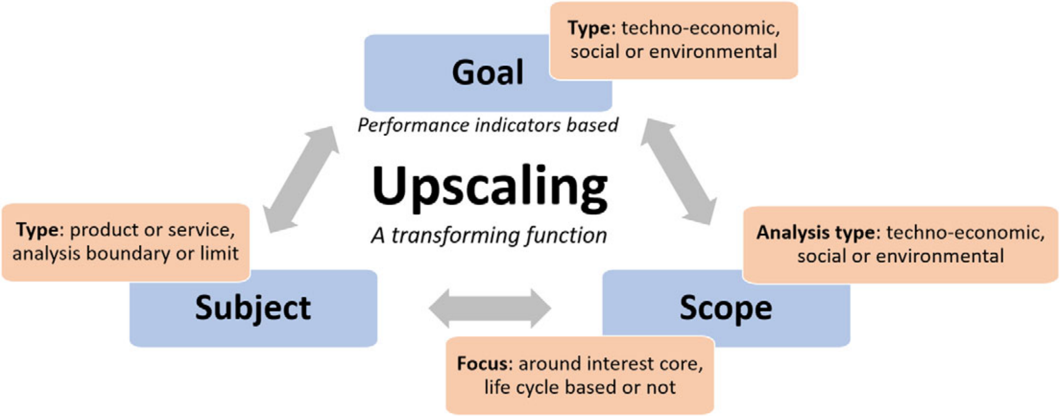


Figure 1. Hypothesis of literature reading: upscaling as a transforming function composed of three interdependent characteristics, also called "invariants", adapted from Riondet *et al.* (2022).

subsequently, help designers and engineers identify the associated approaches and methods. However, according to the best of our knowledge, no paper explicitly characterizes the *upscaling of emerging technologies* in design to societal expectations, including sustainability. Additionally, no paper defines the different design and engineering approaches and methods to deal with the identified archetypes. The present article therefore uses the formalism of Riondet *et al.* (2022) to deepen definitions and associated methods, to explore the links between the identified archetypes and the concept of emerging technology presented above and finally produce integrated guidelines for designers.

3. Method

3.1. Overview of the research methodology

Figure 2 illustrates the different stages of the applied methodology structuring this article, and shows the four ensuing results providing elements to address the research questions (1) (i.e., 1a and 1b) and (2).

As evoked in the Section 2, *upscaling* is considered as a techno-economic phenomenon that can be characterized via the characteristics of the analysis methods used to assess it. To do so, an "invariant" approach has been carried out, that is, the identification of elements common to several situations, enabling us to generate the missing homogeneous definition of a phenomenon.

This analysis revealed five upscaling archetypes (UAs) based on a review of a limited corpus of articles (fewer than 40 references). This review proposes to confront this conceptual framework with a larger corpus and to use it to structure our literature review process.

3.2. Literature review process

Indeed, because of the large number of articles using vocabulary referring to scale, it was not possible to use "classical" literature review methods. Thus, the methodology of literature reviewing can be described as follows: starting from

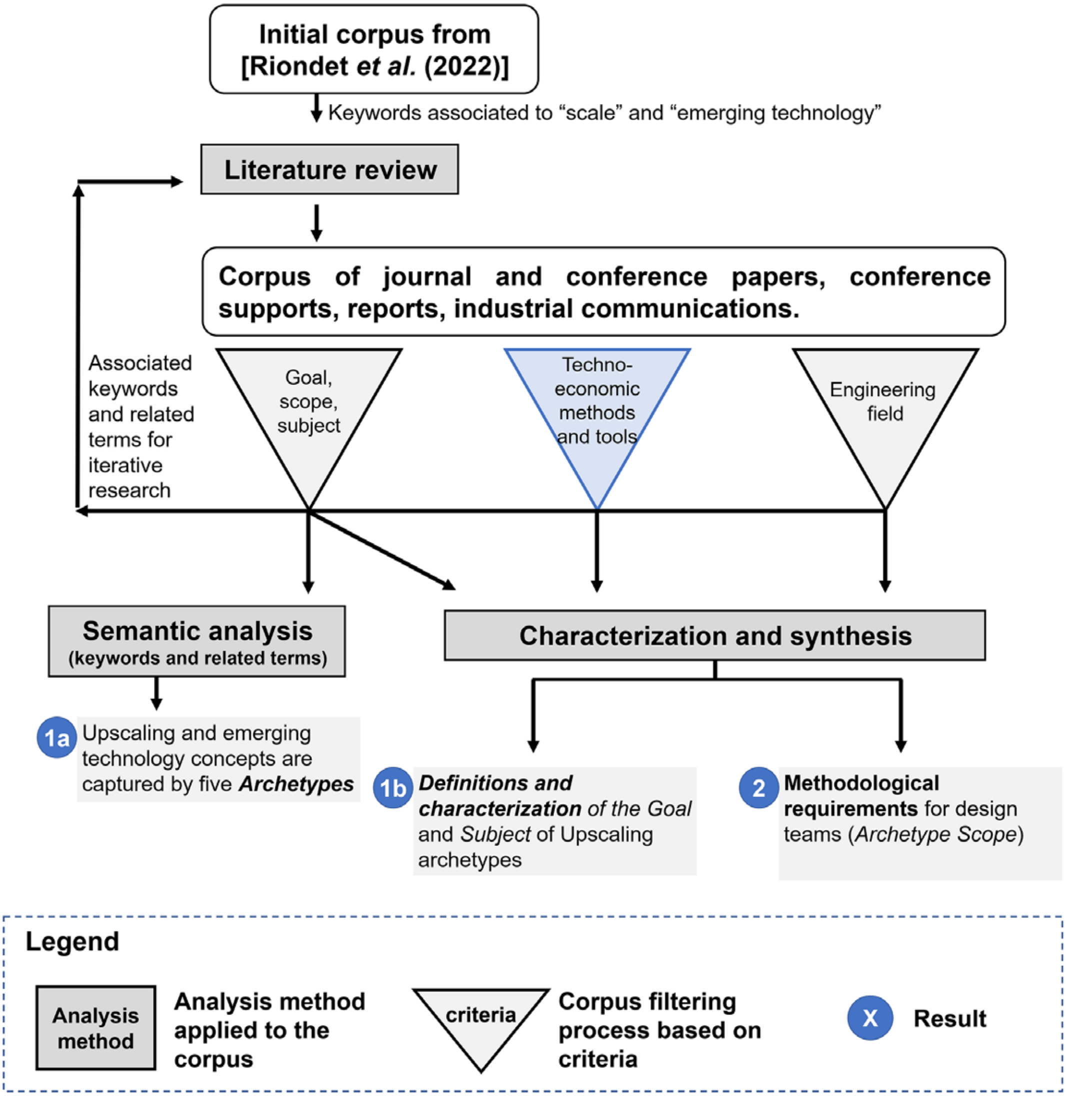


Figure 2. Overview of article methodology and ensuing results. Results 1a and 1b are responses for research question (1) and result 2 for the research question of the same number.

the references provided by Riondet *et al.* (2022), we iteratively expanded the number of reviewed references (corpus) based on two levers: specific search query strings based on keywords and search of reference affiliation in the corpus. Initially, keywords were chosen related to "upscaling", "scale", "scale-up", "scale up" and "emerging technology", and progressively driven by the selected articles (e.g., "deployment", "massification" or "downscaling" related to "planetary boundaries (PBs)"). The search queries were conducted on Web of Science and Elsevier over the years 2022 and 2023. The affiliations were processed manually on the references of previously selected papers, following successive criteria: "Are the terms *upscaling*, *scaling* or *scaling-up* used in the abstract or the text?", "Are there any words related to *scale* in the text?", "Is the meaning of a keyword like *upscaling* in other related articles used in this article and through which other keywords?". The reference is kept if the answer to these questions is positive. Additionally, the newly identified keywords are added to the search query strings. This process covers research works that, with a stricter keyword search, would have been ignored due to different vocabulary use. In addition, the selected literature has been restricted to the 10 following engineering fields (EFs): Chemical Engineering, Waste Treatment, Energy, Food, Building sector and Urbanism, Electronics and *Information and Communications Technologies* (ICT), Transport, Bioengineering, Nanoengineering and Production engineering. Were therefore excluded from the study upscaling definitions referring to numerical methods in fluids modeling science as a scientific field out of the design literature. For a review in this direction, consult Farmer (2002). The literature review process was maintained until a decrease of new information related to four criteria: *goal*, *subject*, *scope* associated with new upscaling definitions and new identified approaches or assessment methods referring to it. It ended with a corpus of 270 references, including research papers, conference supports and scientific reports.

3.3. Semantic analysis process

During the literature review process, a clustering was carried out on the corpus to identify the co-occurrences between keywords of articles which were associated with upscaling and emerging technology (i.e., words of the research queries). This was done to characterize interactions between archetypes and balance literature searches. The first step of this process was prepared with the software "VOSviewer". The software represents the keywords of selected articles on a map according to a proximity metric. Links are then drawn between co-occurring keywords for the same article. The co-occurrence threshold can be adjusted to represent only the most recurrent keywords. Finally, clusters are identified automatically by thresholding the number of co-occurrence links between a group of words. This makes it possible to group keywords that are used recurrently and document a common context. The second step of the semantic analysis was to complete the preliminary figure with terms identified in the papers and related to the same semantics but not presented as keywords by publishers or authors. VOSviewer is used in this literature analyses process to reveal visually the keywords and terms related to research domains the papers relate to. This brought about the state (result 1a) (see Figure 2) that UAs are consistent concepts in the literature, also covering the three "emerging technology" definitions.

3.4. Characterization and synthesis process

To complement the keyword analysis process, a systematic characterization of each archetype has been conducted on the Corpus. This led to an exhaustive definition of each of the UAs, with examples from several EFs. Moreover, a synthesis of the invariant elements, *that is, goal*, *subject* and *focus* as a constituent of the upscaling *scope* has been provided (result 1b). In parallel, design and engineering assessment methods for upscaling have been collected. Design guidelines have been extracted from them, based on methodological invariants for each UA. These generic guidelines have been produced independently from the EF (result 2). An engineering discipline filter has been added to assess the sector or activity influence on the availability of dedicated literature to upscaling.

4. Results

This section presents the results obtained from the research questions leading this research article. Sections 4.1 and 4.2 detail, respectively, the results 1b and 1a, characterizing the upscaling emerging technologies in the design communities. The Sections 4.3 and 4.4 are dedicated to support and guide the designer to assess an upscaling based on the given definition.

4.1. Definitions of archetypes

Structuring the reading of the design literature on upscaling, the following section deepens the definition of five archetypes of upscaling outlined in Riondet *et al.* (2022). These updated definitions are based on a robustness test of the reading hypothesis (see Section 1) given on a larger number of references than the one originally proposed. As a result, Table 1 synthetizes the definition and characterization of these five archetypes in terms of goal, subject and upscaling focus. Each archetype is also associated with keywords, to ease further research on this topic, and is illustrated referring to the nomenclature provided by Riondet *et al.* (2022). The five following subsections clarify and deepen each archetype definition by providing several engineering-based case study examples.

4.1.1. Archetype 1 – From laboratory to industrial scale: A productivity focus

The first archetype identified is assimilated to design processes turning a "prototype", usually developed in laboratories or *research and development* (R&D) departments, into a device/technology with industrial performances (Piccinno *et al.* 2016; Sanford *et al.* 2016; Crater & Lievense 2018; López-Vizcaíno *et al.* 2019). The "scale" characterizing the evolution between the laboratory to the industry is systematically identified as a maturity scale, often equated to the *technology readiness level* (TRL; Hetherington *et al.* 2014; Belwal *et al.* 2020; van der Giesen *et al.* 2020). This indicator has various definitions according to institutions and purpose (Buchner *et al.* 2019). However, a maturity scale usually evolves between 1 and 9, the latter corresponding to the industrialization phase. In the European Commission's definition of TRL (Council of Europe 2019), the upscaling can therefore be described as the process enabling a technology turn from the fourth level (prototyping) to the seventh level (prototype at the industrial scale), in one step or several if necessary (Moreno *et al.* 2018; López-Vizcaíno *et al.* 2019). Remark that the IEA also employs TRLs to categorize the technologies that will be used for the energy transition. Then, the TRL are grouped into four levels: prototype, demonstrations, early adoption and mature (IEA 2020). In other terms, to move "from laboratory scale to industrial scale" means increasing the technology maturity which can be transposed to productivity and/or size (Crater & Lievense 2018; Roy *et al.* 2021). In the PV industry, as another example, upscaling is assimilated to "upsizing", meaning, to increase the size of a solar cell, for a new technology (i.e., for OPV technology (Bernardo *et al.* 2021) or perovskite technology (da Silva Filho *et al.* 2021)), implying to adjust concomitantly its structure design to optimize its performances, such as the mechanical and thermal stability. Thus,

Table 1. Synthesis of upscaling archetypes definitions with associated keywords and symbolic illustration

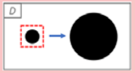
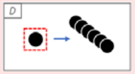
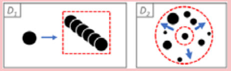
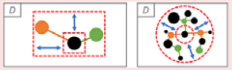
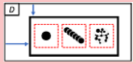
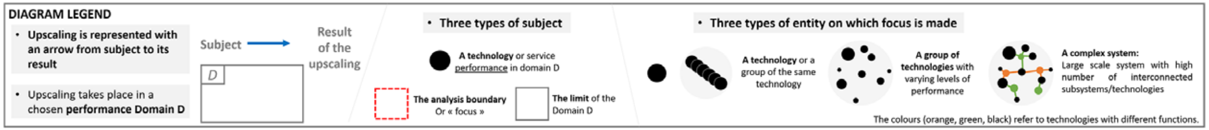
Upscaling archetype	Definition	Usual goal	Usual subject	Focus	Associated keywords	Illustration adapted from nomenclature provided by Riondet *et al.* (2022)
Archetype 1 Upsizing, scaling-up	Phenomenon generating a “prototype” at industrial or commercial scale	Maximize maturity (often associated with productivity)	Technology/service upscaled (e.g., maturing technology)	Technology upscaled	Technology readiness level (TRL), maturity, industrial scale, scale-up, pilot prototype, size, gigafactory, miniaturization, early-stage technology, scalability, novel technology, commercial scale, scale up, emerging technology, upscaling	
Archetype 2 Mass-producing	Phenomenon adapting a technology to be mass-produced	Maximize producibility	Technology/service upscaled (e.g., novel technology)	Technology upscaled in manufacture	Manufacturing readiness level (MRL1), learning by doing, mass-manufacturing, commercialization, design standardization, massification, industrialization process, economy of scale, scalability, novel technology, commercial scale, scale up, scaling, emerging technology, upscaling	
Archetype 3 Reaching a level, deploying	Phenomenon translating transitions requirements into technology sector perspective	Reaching a sufficient level of cumulated service	Technology upscaled / boundary of analysis (e.g., early adoption-diffused technology/niche technology)	The cumulated service of the group of produced technology	Large-scale deployment, market penetration, technology diffusion, market readiness level (MRL2), planification, terawatt level (TW), growth dynamic, reaching ‘materiality’, large-scale production, raw material criticality, transitioning, low-carbon transition, energy transition, levels, niche technologies, deployment, technology adoption, infrastructure, scale up, emerging technology, scaling up, upscaling	

Table 1. Continued

Upscaling archetype	Definition	Usual goal	Usual subject	Focus	Associated keywords	Illustration adapted from nomenclature provided by Riondet *et al.* (2022)
Archetype 4 Integrating a complex system	Integration phenomenon of a technology as a part of a larger and complex system	Maximize the efficiency of a complex system	Boundary of analysis	The technology interoperability to support its systemic integration	Grid integration, interoperability, acceptability, network, smart technology, complex system, urban metabolism, sociotechnical systems, societal transformation, multilevel, transition pathways, territory scale, transitions, levels, niche technologies, deployment, technology adoption, infrastructure, scaling, upscaling	
Archetype 5 Down-limiting, downscaling	Phenomenon tending to restrict technologies according to sustainability considerations	Assess the sustainability of a technology or a service	Science-based limit of the domain (socio-environmental limit)	The sustainability of a service provided by one or several products, or systems	Planetary boundaries, safe operating space (SOS), downscaling, carrying capacity, share of the SOS (SoSOS), absolute environmental sustainability assessment (AESA), justice principle, science-based target (SBT), absolute sustainability ratio (ASR), eco-effectiveness planetary scale, regional scale, product scale, allocation factor, characterization factor, normalization factor, scaling	



the upscaling subject consequently refers to the performance of a technology/production unit (i.e., size, productivity, stability, maturity). The objective of the upscaling is to increase the intensity of the production unit performance studied, to be considered as an "industrial" intensity.

It can be noted that, on the one hand, the "industrial scale" supposedly reached TRL 7 depends mainly on the discipline and technology, and can vary from 2 (Sanford *et al.* 2016) to 10 or more orders of magnitude (Crater & Lievense 2018). For instance (da Silva Filho *et al.* 2021) in photovoltaic engineering, refers to cell area upscaled from 0.1 cm^2 to 10 or 100 cm^2, while (Crater & Lievense 2018) in bioengineering, increases the production capacity of a fermentation process from 0.5–10 L to 20–200 kL with a scale factor of several thousand orders of magnitude. On the other hand, some technologies are upscaled continuously (e.g., increased in size) even after their industrialization (TRL = 9). For instance, commercial wind turbines are intended to measure 230–250 m and account for 15–20 *megawatt* (MW) of installed capacity in 2030, compared to, respectively, 220 m and 12 MW in 2021 (IEA 2020). In that regard, the initial definition can also encompass the miniaturization process and yield maximization in photovoltaic cell engineering, for instance, as a process leading to increase the productivity per unit of device. Finally, this archetype definition can be expanded to the production unit itself. For instance, Sallerström *et al.* (2022) use this definition to designate the expansion of a "repair workshop", remaining on an artisanal scale. Conversely, the term "gigafactory" refers to the idea of increasing the productivity of an industrial process unit or system. In other words, "megafactories" can be assimilated to the result of the upscaling of classic factories to improve their productivity, sometimes up to an explicit scale (i.e., the "megawatt" or "gigawatt-scale" of yearly produced battery capacity (Chordia, Nordelöf & Ellingsen 2021)).

4.1.2. Archetype 2 – Mass-producing: A producibility and manufacturability focus

The second archetype of upscaling refers to the mass production of given products and design processes. The upscaling would be carried out to facilitate and amplify this mass production. While the first archetype is rather associated with research activities, archetype 2 (*mass-producing*) is predominantly represented in industrial engineering. This implies more specific approaches depending on the industrial sector or the companies. Consequently, examples are numerous but transverse properties conferred by archetype 2 are "learning by doing" culture, being supported by standards, well-established methods, as well as empirical industrial knowledge.

Indeed, according to Kramer & Haigh (2009), "scale-up means learning by doing, which takes time in the energy industry". Depending on the industrial sector, a longer temporality than the previous archetype, up to decades, is applied. Concerning the link with standards, authors call for the creation of dedicated databases (e.g., Bioengineering Platform to Industrialize Biotechnology (Culler 2016) and/or creation or alignment with existing standards (Koulin *et al.* 2015; Moschou & Tserepi 2017)). Regulatory uncertainty and lack of standards are an identified barrier to upscaling, especially for certain domains such as food supply with new products (e.g., edible insect in the United Kingdom (Yang & Cooke 2021)).

The focus is made on "fabricability" and "producibility" in this UA, which means integrating in design additional economic and industrial constraints. For instance, the "panelization" in electronics (i.e., units connected as a single array to be manufactured simultaneously) is identified as a means to upscale a product by adapting its shape to processes for mass production (Moschou & Tserepi 2017). As a consequence, and based on the model of indicator TRL, the *manufacturing readiness level* indicator (MRL1) is used to reflect a manufacturing capability risks scale from 1 to 10. It notably incorporates material, costs and funding, quality, standards and facilities aspects (Manufacturing Readiness Level (MRL) Deskbook 2022). In this framework, the goal of upscaling could be expressed as reaching the 10th level titled "Full rate production demonstrated and lean production practices in place". Other metrics such as maturity life cycle (or product life cycle stage) from 0, passing to 30 (industrialization) to 90 (obsolete technology) in microelectronics seem to transpose the MRL from the point of view of the technology developed (Baudry 2013). In this case, the indicator integrates the decline of the studied technology, which is not the case for MRL or TRL.

Thus, the upscaling addressed in this subsection aims at finding the optimal process configuration to massively produce something, while reducing the associated production costs (Moschou & Tserepi 2017; Yang & Cooke 2021). To summarize, the goal of archetype 2 is to massively duplicate a product (i.e., at "industrial scale", under profitability implicit conditions), and the subject is the product to be massively produced.

4.1.3. Archetype 3 – Reaching a level and/or managing a deployment: A cumulative service focus

The third archetype identified is assimilated to the processes enabling and managing a technology deployment. This deployment, as a transition, is "purposive" (Geels *et al.* 2017), which means that products manufactured are considered as a group or fleet, having to satisfy a certain level of requirements. In other terms, upscaling in this subsection could be considered as the implementation of transitioning for a sector or a technology (i.e., photovoltaic industry or *electric vehicles* (EV)). This level of cumulated service can be defined relatively to:

1. Past technology deployments observed in other industries. Historical dynamics, following an S-curve trend, give orders of magnitude of critical mass to reach. Also called "materiality", this quantity can be used to study current or future technology deployment (Kramer & Haigh 2009; Cherp *et al.* 2021).
2. A maturity or a share of the market. An example could be increasing renewable energy sharing in the energy mix. The *market readiness level* (MRL2) is an indicator of assessing the risks for emerging technology deployment in an emerging market (Bergerson *et al.* 2020) and can be used to characterize a level to reach in this example. In the line, Sims *et al.* (2017) use the indicator current technology adoption rate (Sims *et al.* 2017).
3. An environmental pressure such as climate change and following scenarios to struggle climate shifts. For instance, the "terawatt (TW) level" in the renewable energy industry sector refers to the order of magnitude of 1 TW of capacity installed, and is considered as a titanic industrial and political challenge, but essential to achieve (Verlinden 2020). The electrical vehicle industry, and more broadly, technology industries involved directly in energy transition face similar constraints.

In practice, these three ways to define the thresholds/goals of cumulated service are independent and not necessarily coherent with each other. For instance, Cherp *et al.* (2021) confronted "materiality" for wind and solar power with 1.5°C-compatible scenarios and concluded that "some 1.5°C and 2°C pathways pose serious feasibility concerns", which supposes a premature slowdown of the deployment dynamic or a different political and industrial context of deployment.

Thus, and more than for the others, archetype 3 (*reaching a level*) relies on the foresight approach and future-oriented scenarios. Archetype 3 expresses a phenomenon of form of long-term technology deployment (i.e., several decades) on a global (IEA 2020; IRENA 2019a,b) or national scale (Veyrenc *et al.* 2022). In other terms, and unlike the second archetype of upscaling, "the industrialization is not an aim" in itself (Riondet *et al.* 2022). Archetype 3 equates industrialization as a means to intensify to reach a (sufficient) cumulated service threshold for a specific technology sector. This sufficiency threshold is defined by societal requirements, including sustainability constraints.

4.1.4. Archetype 4 – Integrating a complex system: A interaction focus

The fourth archetype requires first to define a "complex system". A complex system, according to Amaral & Ottino (2004), integrates a large number of units or subsystems, interacting strongly with each other and their environment. Subsystems need not to be "neither structureless nor identical". They can evolve at different time scales and have different lifetimes. Cluzel (2012) and Kim *et al.* (2020) added that complex systems are large-scale systems with a very limited long-term predictability during the design phase and are "supervised by human decisions and management". Such systems can be entirely technical (i.e., a national electricity grid) or socio-technical. Also referred as "networks", complex systems involve interactions with human behavior and social and political phenomena (Dijk *et al.* 2018).

The concept of "urban metabolism", in the building sector and urbanism, is another designation to define a complex system with material or energy loops. The objective of the upscaling in archetype 4 is to integrate a system into a complex system or an urban metabolism, and then to improve its efficiency and/or its extent. It is the case for new public transport design in a city (Onat *et al.* 2017) or city farming implementation into the food system (Hardman *et al.* 2022) for instance. To implement this integration, the upscaling is applied considering the boundary of the analysis. Onat *et al.* (2017) define this process as "broadening the scope of analysis from product-level assessment to national and global levels". Archetype 4, in a wide framework, applies an "up-and-down zoom" focusing iteratively on the complex system and the designed technology as a subsystem. In other words, archetype 4 gives an expression of the study scope variation (i.e., its scale). This archetype highlights the technology integration issues by varying the scope of the study.

4.1.5. Archetype 5 – Down-limiting or downscaling: An absolute sustainability focus

The fifth archetype appears strongly linked to the PB framework and the concept of absolute sustainability: Rockström *et al.* 2009 proposed a theoretical framework based on environmental and systemic Earth science-based results. The so-called PBs depict limits that mankind should not cross to guarantee habitability on Earth. The PB paradigm hinges on the concept that human activities are included in a planetary system regulated by nine socio-ecological phenomena, including climate change. Humanity, including industrial development, is therefore summoned to stay in a Safe Operating Space (SOS) to ensure the stability of this biochemical system. This framework has been updated four times between 2009 and 2023 (Steffen *et al.* 2015; Lade *et al.* 2020; Persson *et al.* 2022; Richardson *et al.* 2023). As presented by Hauschild, Kara & Ropke (2020) referring to absolute sustainability, the goal is not to design a more sustainable product but a sustainable one. Hauschild (2015) set the basic principles for targeting "eco-effectiveness", as a trade-off between the societal value of the product and the related environmental damages. In that context, "downscaling" and "down-limiting" refer to generating local expressions of global environmental limits (such as PBs) on the technology scale to limit its unsustainability. This process is also called operating a share of the Safe Operating Space (SoSOS) or defining *carrying capacities.*

Those socio-environmental limits the product must not exceed are defined by designers. This challenges the relationship between technology, society and the environment by raising technical and environmental constraints with social justice expectations (Bjørn *et al.* 2020; Ryberg *et al.* 2020; Hjalsted *et al.* 2021). A well-known example would be the concept of "carbon budget" allocated to a country, a specific human activity or a product, to limit global warming below two degrees Celsius (i.e., the global threshold associated with the SOS). Each environmental impact indicators are addressed in this approach, not only the climate change. The downscaling is applied to an absolute environmental limit to assess the sustainability of a product, or a system. Archetype 5 (*down-limiting*) captures, more than the others, the imperatives associated with sustainability expectations from society. Until recently, it has been identified as a research field in development.

4.2. Interactions between upscaling and emerging technology concepts and archetypes

As mentioned in Section 1, archetypes represent facets of the phenomenon of upscaling. They are sometimes evoked as characteristics in a given definition. Rae *et al.* (2020) exemplify this aggregated vision on the case of *smart local energy system* (SLES). Authors provide a definition for upscaling comprising four characteristics overlapping the first four archetypes: "growing" (archetype 1), "replication" (archetype 2), "accumulation" (archetype 3) and "transforming" (archetype 4). This latest characteristic reflects the adaptation of the studied object to the surrounding context of its implementation. This fits well to the archetype 4 definition, by defining the context as the complex system to be integrated. The five archetypes could also be interpreted as visions of the upscaling from different disciplines' points of view or different activity-skill perceptions: research and development, manufacturing engineering, planning and industrial management, systemic engineering, and finally, environmental engineering and justice. Based on such definition process the associated keywords in the related domain literature material have been collected (see **Table 1**, column 6). This content is organized on **Figure 3** based on each archetype identified literature co-occurrence (represented as grey circles). Keywords at the center of the figure are shared by several archetypes. For instance, "Scaling [2–4–5]" means that the word "scaling" is used in relation to UAs 2, 4, and 5. Words framed in red are explicitly related to scale or level concerns. This figure therefore aims at helping designers to identify UAs interactions and to reinterpret keywords in the light of the established archetypes' definitions.

4.2.1. Upscaling archetype interactions

Four main observations can be drawn from this proposed vision of the literature findings:

- Archetypes 1 and 2 are linked with the scalability property, as the hybridization of upsizing and massification and vocabulary associated with a "commercial scale" and economic consideration.
- Archetypes 2 and 3 are linked with vocabulary related to "large-scale production".
- Archetypes 3 and 4 are linked with "large-scale deployments", "levels" and "infrastructures" considerations.
- Archetype 5 is isolated from the others which is justified by the fact that it is a relatively new sustainability paradigm, not particularly integrated in the design process or engineering communities. The vocabulary used in the literature material consulted is therefore different despite the term "upscaling" in common with other archetypes.

Note that this representation justifies the use of "upscaling" as a generic term, because it appears in the lexical fields of all archetypes. The term "scale-up" coming from chemical engineering, seems specific to archetype 1, unlike "to scale up" which is a more widespread verb.

4.2.2. Emerging technology definitions and interaction with upscaling archetypes

Complementarily to the "scale" vocabulary analysis, the words framed in black in Figure 3 are explicitly related to emerging technology concerns. This representation reveals in the literature study the interactions between upscaling and emerging technology concepts, in line with the three main definitions provided by the literature and detailed in Section 2; an emerging technology as a promising but unmatured technology, a minor but growing technology, and emerging from a socio-technical vision. Now confronting UA to the concept of "emerging technology", our main observations are:

- Emerging technology" and "upscaling" are aligned concepts with the first definition – "maturing technology"–included in archetype 1.
- The second definition – "growing technology" – is covered with the first three archetypes with "novel technology" and "technology diffusion".
- The third definition – "emerging in a sociotechnical system" – is related to archetypes 3 and 4 with "niche technology" to be deployed, and "technology adoption" associated challenges.
- More broadly, the three definitions are more or less divergent and not necessarily consistent with each other as the defined object differs. It depends on the context, discipline study and authors.

Finally, the concept of UAs, in addition to characterizing the upscaling, captures the different definitions of emerging technology. From this state and to study the upscaling of emerging technology, archetype will be used as a unifying analysis

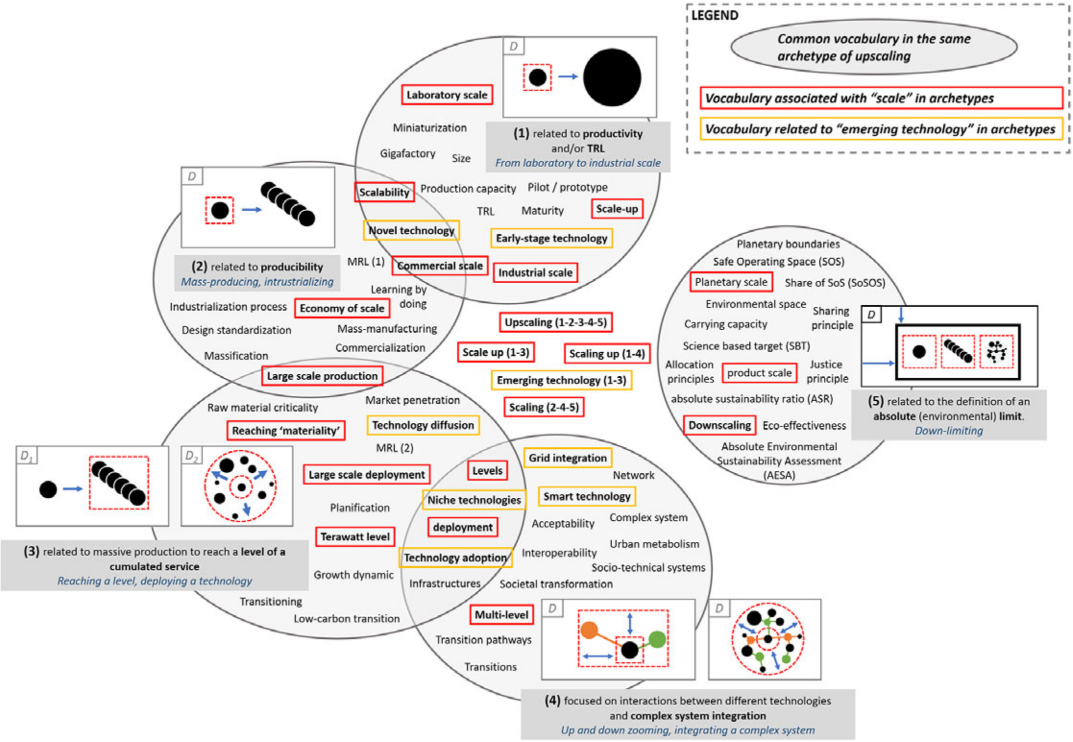


Figure 3. Representation of interactions between archetypes illustrated by their associated semantic fields.

tool. In other words, assessing the upscaling of an emerging technology involves studying UAs.

4.3. Upscaling assessment methods for designers, by archetype

Designers need to be familiar with the methods available to analyze or anticipate the upscaling of a technology. In other terms, the scope of an upscaling (see Section 4.1) is based on analysis methods and tools. This section therefore tends to characterize the scope of upscaling and establish generic methodological principles, depending on the archetype. The literature study was extended to identify the methods for researchers, engineers and planners (as designers), to assess or anticipate a technology/service upscaling. A synthesis of these methods and principles is available in Section 4.4 (Table 2). The findings detailed in this section show that the existing methods are mainly driven by technical-economic or socio-technical considerations, and rarely by environmental aspects rigorously. Only archetype 3 and archetype 5, present environmental considerations.

4.3.1. Archetype 1 – From laboratory to industrial scale

Increasing productivity/size/stability and increasing maturity from laboratory scale to industrial scale, both require in the chemical industry some discussions between researchers and chemical engineers. This process leads to "empiric rules" and guidelines to deal with upscaling hazards. This discussion appears necessary

Table 2. Synthesis for designers of assessments, methodological requirements and recommendations for scope, according to upscaling archetypes.

			Recommendations for scope	
Upscaling archetype	Techno-economic assessments	Methodological requirements	Geographical/temporal	Clauses and constraints
Archetype 1 Upsizing, scaling-up	Scaling laws, expert guidelines, theoretical limits, thermodynamic optimization (pinch analysis)	• Define the specific technical expertise • Ensure strong interactions between researchers and engineers • Implement a future-oriented design	Mainly use phase focused, integrative life cycle. Studied: the product. Expertise's timescale is over months	• Due to maturity focus, attention must be paid to which incumbent technology the emerging technology is compared • Foreground system modeling caution and clear scenario of use phase, implying data production and data collection challenges
Archetype 2 Mass-producing	Design for X (e.g., manufacturing)	• Follow an integrative and normative approach • Develop techno-economic expertise • Identify the stakeholders of the value chain	Lifecycle-based, regionalized approach if possible over the value chain. Studied: The product system. Expertise's timescale is over the years	• Industrial trend focus • Standardization challenges • The more lifecycle-based (end of life issues) possible
Archetype 3 Reaching a level, deploying	Scenario-based approach, stock-flow modeling (MFA analysis), mathematical optimization	• Develop a market maturity and sectorial long-term expertise • Characterize a cumulative technology's performance • Set up scenario expertise and specific data uncertainty management	Large spatial/social scale (regional, national – sectorial or group of technology). Studied: The industry sector associated with the product. Phenomenon's timescale is over decades	• Rigorous scenario hypothesis and natural resources focus • Sectorial modeling and data issues • Background system modeling caution. The more lifecycle-based possible
Archetype 4 Integrating a complex system	Multilevel analysis, network approach, mathematical optimization	• Mobilize a system dynamic engineering with interoperability focus • Adopt a culture of trade-offs from optimization modeling or socioeconomic expertise	Large geographical scale (the one of the complex system). Studied: the complex system interacting with the product. Spatial/geographical properties focus.	• Interaction modeling and data issues • Constraints strongly dependent on case studies and engineering field (possibly

Table 2. Continued

Upscaling archetype	Techno-economic assessments	Methodological requirements	Recommendations for scope	
			Geographical/temporal	Clauses and constraints
		• More broadly, develop a multidisciplinary approach	Phenomenon's timescale varies from real-time to decades	compatible with a product–service system vision)
Archetype 5 Down-limiting, downscaling	Justice/social and physical principle, economic allocation (input–output modeling)	• Observe fair allocation methods (i.e., justice principles) and strictly define the service being studied • Manage the data collection associated with the service (usually techno-economic-based) • Monitor methodological development (for product) from AESA (indicators, sharing principles)	Focused on services provided to humans, lifecycle-based with possible regional focus (national/sectorial)	• Focus on human activity, not industrial activities or products specifically • Modeling and sharing principle challenges (techno-economic-based and/or social science-based) • Refer to Ryberg *et al.* (2020). To apply as soon as possible in technology development

because of the intrinsic risks induced by the upscaling to the production site (i.e., heat evacuation for exothermic reactions). Each context forces R&D teams to "choose the correct conditions to scale" (Laird 2010).

On the one hand, empirical rules and guidelines both illustrate the predominance of *design of experiments* (DoEs) found in the methods associated with scaling-up a process or a system (Ceschin 2014; Baumann & Lopatnikov 2017; Camburn *et al.* 2017). For instance, López-Vizcaíno *et al.* (2019) carried out a step-by-step upscaling on a chemical process (e.g., electrochemically-assisted soil remediation) with four experimental setups based on different capacity productions. The aim was to determine the effect of scale on techno-economic parameters, including the total annual cost of a processing unit. Their work illustrates a "scaling law" development. This model usually translates a simplified relationship between design parameters and characteristics of the designed system, often in the form of a power law. These extrapolation models are sometimes combined with techno-economic limits to qualify their validity domain (i.e., mechanical strength limit for the size of a vessel in the chemical industry or thermodynamic yield of reverse electrodialysis process) (Baumann & Lopatnikov 2017; Moreno *et al.* 2018). The Shockey–Queisser limit is another example of a theoretical limit used in research. It represents, in photovoltaic science, the maximum yield value obtainable for a specific cell technology. Researchers, such as Ehrler *et al.* (2020), use it to characterize the remaining room for improvement in a cell yield according to its structure/composition. Different types of PV technologies are then responses to overtake the limit associated with incumbent individual Si cells (i.e., tandem technology).

On the other hand, due to the cost engaged by such experimentations, numerical tools are also used to simulate, optimize, or study a system (Piccinno *et al.* 2016; Moreno *et al.* 2018; Tsoy *et al.* 2020; Patel *et al.* 2023). The main characteristic of optimization is the looping of energy and/or material fluxes. The structure of the laboratory system switches from linear but inefficient, to a more efficient, parallelized and looped structure (Shibasaki, Fischer & Barthel 2007). This approach is embedded in the *systems-oriented design* (SOD). In this speciality pinch analysis is an example of thermodynamic assessment enabling designers to minimize the energy consumption of a system by reusing residual heat (or cold) for pre-heating steps. Note that these numerical tools hinge on theoretical models and empirical know-how that have been capitalized during anterior (or parallel) experimentation phases. Consequently, a combination of experimentation and numerical simulations strengthen the upscaling management (Belwal *et al.* 2020; da Silva Filho *et al.* 2021).

Several requirements to carry a scaling-up could be summarized as follows:

- Control the technology maturity level and plan accordingly.
- Consider the specific technical expertise of the technology to be upscaled (i.e., theoretical law and/or scaling law, identification of leverages of improvement in the performance design).
- Integrate the design of experiments expertise, to produce lacking data and documents upscaling models.
- Ensure a strong interaction between researchers in laboratories and engineers in the industry (leading to guidelines and preventive lock-in identification in case of upscaling).

These specificities are mostly relevant in the chemical industry and are transmutable to other sectors.

4.3.2. Archetype 2 – Mass-producing

Mass-producing a technology relies on industrial engineering known how. It aims at developing the corresponding value chain, or adapting the structure of the technology to the existing value chains in an economic model-based perspective. In other terms, archetype 2 follows a normative process driven by industrial planning. This planning is historically based on "learning by doing" methodologies (i.e., industrial sector specific) and usually based on trend extrapolation models.

For instance, in Thiede *et al.* (2021), two groups of upscaling strategies related to additive manufacturing are compared: one optimizing the existing production system parameters (operative strategy) and the second focused on the production system change in terms of machine or technology chosen. Each of these strategies is characterized according to several performance indicators (time, cost, quality, "sustainability" and flexibility). This comparison results in a confrontation between three processes and guidelines depending on the economic model chosen (i.e., produced volume desired). In this case, the so-called sustainability indicator reflects the energy demand of the machine. This indicator in our view is inappropriate and reveals the difficulties of integrating environmental assessment methods in design, which should involve multiple environmental impact categories (e.g., the nine planetary boundaries), as well as sustainability issues that include additional sociocultural criteria.

Another example of product design adaptation to mass production constraints based on a numerical model can be taken from Koulin *et al.* (2015). The shape of a product (wind power) has been adapted (optimized) to eliminate an energy-cost-effective manufacturing step (a rolling process) and then facilitates mass production by enabling its automation.

Panelization, in electronics, is also a shape optimization to facilitate the mass production of microchips. This production organization for discontinuous processes imposes nonfunctional shape standards to products to increase the number of produced units per batch. In that context, adapting an emerging technology, even from a different industrial sector (i.e., bioengineering), to this production technique would accelerate its upscaling by capitalizing on existing production means (Moschou & Tserepi 2017).

Learning curves and empirical models, such as Moore's Law, remain the most representative methodology to support this UA (Basnet & Magee 2016). However, as with any extrapolated model, hypotheses sustaining the identified trends are not always explicit (i.e., validity domain). They reflect an improvement phenomenon over time, up to decades, as a consequence of production system optimization and industrial know-–how development. Such model is used in several industrial sectors for midterm planification (i.e., electronics, photovoltaics, agriculture) (Marra, Pannell & Abadi Ghadim 2003; Fischer *et al.* 2019). In other terms, learning curves are phenomenological models used to continue a historical trend. They do not, however, provide a systemic understanding of the factors maintaining the trend. The contextual information to interpret their validity domain is rarely presented.

Complementarily, databases concerning the product's process parameters and value chain structure are developed to enhance the skills related to massification. Such available database (if any) can be interpreted as an indicator of the maturity of the upscaling management in a specific industrial sector (Culler 2016; Yang & Cooke 2021). Archetype 2 (*mass-producing*) is based on past centuries of industrial developments, linked to globalization. The business model associated with the mass production scheme is therefore a key parameter linked to the industrial sector(s) involved. This context has motivated the emergence of life cycle engineering, a group of methodologies based on a systemic and integrative approach in industry to support designers with "Design for X" (X stands for manufacturing for instance). It enables the implementation of the industrialization of a product while minimizing cost and externalities (M. Hauschild *et al.* 2020). Industrial engineering know-how, market regulation, policies, trading rules, labor standards, supply chain organization, etc. are crucial factors that push designers to explore product and process developments, as well as include value-based perceptions in the upscaling assessment they conduct (Yang & Cooke 2021).

To conclude on, methodological requirements associated with the mass-producing UA to designers are the following:

- Control of the manufacturing maturity level and conduct development planning accordingly.

- Design with integrative and normative approaches developed in industrial engineering.
- Define the product's life cycle and its evolution over time associated with a chosen business model (cf. design for life cycle engineering methods).
- Choose relevant indicators of performance/value, clarify data collection on purpose, and integrate the ongoing technical/industrial/economic planning, to the upscaling model (e.g., evolution of processes, varying product design over time, correctly identifying costs and benefits).

4.3.3. Archetype 3 – Reaching a level and/or deploying a technology

Deploying a technology to reach a level of cumulated service hinges, more than other archetypes, on a foresight approach from a technology sector perspective. Foresight (or prospective) approach uses models to study potential futures and assess their plausibility (as well as their desirability). Archetype 3 (*reaching a level*) follows consequently a decision-support approach, mainly based on scenarios. Some typologies exist but there is no consensus on the way to produce scenarios (Gall, Vallet & Yannou 2022). This situation leads to a great diversity of models and the associated indicators of feasibility or reliability.

On the one hand, sectorial consortium (e.g., IRENA 2019b) or specialized researchers (e.g., Kramer & Haigh 2009; Verlinden 2020; Khalifa *et al.* 2021; Vidal *et al.* 2021) propose a desired deployment of technologies (i.e., renewable energy, electric vehicle) often represented as an S-curve (or exponential curve) from now to a specific time horizon (2030, 2050 or 2070). This model is phenomenological (i.e., descriptive of a past trend) and could be considered as one scenario of deployment among others.

On the other hand, more holistic models assess the co-emergence of groups of technologies. For instance, electricity storage technologies are intended to emerge in parallel with renewable energy technologies to struggle with their intermittency. However, their developers, mainly institutional (i.e., IEA, ADEME), usually set some performances or some cumulated service targets, for each separated industrial sector assessed (IEA 2020; ADEME 2021). For instance, the *Réseau de Transport d'Electricité* (RTE), the French electricity transmission system operator presented in 2021 that six power production pathways to reach carbon neutrality by 2050 (Veyrenc *et al.* 2022). Other organizations, focusing, for instance, on agriculture technologies include milestones without stating a particular pathway (Sims *et al.* 2017). Watari, Nansai & Nakajima (2020) present a literature review of prospective criticality for 48 chemical elements. These elements are presented sorted by 10 technology categories, making explicit the link between material, product's scale and technology expected deployment.

These two types of propositions are often criticized in terms of feasibility or reliability with regard to historical trends (Breyer *et al.* 2017; Cherp *et al.* 2021) and to the associated raw material demands (Rietveld *et al.* 2019; European Commission *et al.* 2020; Elshkaki 2021).

A material demand analysis is usually carried out with a *material flow analysis* (MFA). Note that different methodological formats of MFA exist according to the perimeter of the study (e.g., national, industrial, enterprise or product level). A synthesis of these methods and their specificities is available in the guide of the *Organisation for Economic Co-operation and Development* (OECD) published in 2008 (OECD 2008). In the archetype 3 case, *material system analysis* (MSA) and an economy-wide MF analysis (EW-MFA) are usually conducted. Relying on the analysis provided by this method, the “criticality of raw material” appears as the main constraining feasibility indicator to elaborate plausible scenarios of technology deployment in the energy, digital or mobility (Bobba *et al.* 2020; van Exter *et al.* 2021). Again, no consensus has been found in literature to characterize the criticality of a material, leading on again to multiple methodological choices. Schrijvers *et al.* (2020) and, more recently, Hackenhaar *et al.* (2022) documented some non-exhaustive lists of methodology according to the goal, the scope, the outcomes and the operability of the criticality assessment methods targeted.

Hofmann *et al.* (2018) point out, however, the difficulty for materials scientists and engineers to adopt such assessment methods, deeming that the political and environmental issues these methods address do not fall within the scope of their expertise. In addition, temporal validity of indicators involve regular update of data and a fine understanding of their computation. In addition, the temporal validity of indicators involves regular updates of data and a fine understanding of their computation. It is important to note that MFA and criticality assessments hinge together on material demand data, which was not systematically documented in the European Union before 2012 prior to the Commission Decision has defined the roles and responsibilities of the organism “Eurostat” (Commission 2012).

More generally, assessments at such scales (regional, national) are data intensive and consequently studies are made possible generally by public organizations with data collection authorities. Additionally, Hofmann *et al.* (2018) note that criticality assessment better corresponds to the scale of the product, than of the material. Ferro & Bonollo 2019 endorse this vision providing an example of the integration of criticality indicators in classic material selection for product design. Criticality assessment would therefore benefit from life cycle engineering, for instance, to evaluate the dissipation of resources (e.g., Charpentier Poncelet *et al.* 2021).

Finally, and concerning data management issues, Maier *et al.* (2016) presented a framework to characterize uncertainties in a prospective approach: “Thinking about future uncertainty in terms of multiple plausible futures, rather than probability distributions, has implications in terms of the way uncertainty is quantified or described, the way system performance is measured and the way futures strategies, designs or plans are developed”. This transitioning archetype is thus associated with long-term planification methods, supposing existing models to support decision perspective by providing criteria of go/no-go or at least validity/reliability indicators. This vision is usually referred to as the prospective or foresight approach and relies on:

- A control of the market maturity level and/or a clear goal with a time and spatial perimeter focus on a technology or an industrial sector (e.g., carbon neutrality of China for 2060, TW photovoltaic installed capacity in Europe in 2050).
- A technology’s performances characterization (implying data collection difficulties).
- Industrial sector data and engineering models (i.e., capacity production, material and/or power flows).
- A scenario expertise and a specific data uncertainty management (quality, accuracy, sensitivity) and a model validity domain investigation (i.e., hypothesis review).

Ideally with a distinction between fields of possible evolution of technological, and industrial including the background context. More broadly, it refers to foresight (or prospective) expertise belonging to a long tradition of thinking (Berger 1964).

4.3.4. Archetype 4 – Integrating a complex system

Designing complex product systems or integrating technology into a complex system relies, more than other UAs, on a systemic approach focused on subsystem interactions between the designed product and its sociotechnical environment (more or less technical or social).

An intelligible example is for designing and managing a power plant or a storage site, both depending on existing grid characteristics (Fitó *et al.* 2022). Concerning the optimization approach, many different models exist (LP, MILP, master investment algorithms) and are applied to different geographical scales, from city to global scale, with varying optimization horizons (e.g., from an hour to several years). For more detailed information about optimization models dedicated to energy system planning, refer to Cuisinier *et al.* (2021). Tanguy *et al.* (2020) present a very literal study case of up-and-down zooming on a port city, identified as an urban metabolism interacting with other regions of varying geographical scales (local, national and global). MFA and network representation (e.g., Sankey diagram) are very suitable for such assessments. Commercial software is also used to design a digital twin of a local grid composed of power sources, storage and consumer sites (e.g., industrial site, houses) and size of it, based on simulations covering several years ("Seed Energy – Odyssey" 2022).

Another example of complex system design is given by Metais *et al.* (2022) investigating the three different modeling possibilities to consider the performance dependency between charging infrastructures and batteries for electrical vehicles (i.e., node-based, path-based, tour-based approach). The key parameters reviewed in 287 articles applied to that study case are the charging station location, its power capacity and its interoperability carried out by interface devices (AC/DC converters) that can be partly embedded in each vehicle. The optimization goal, however, varies in the literature: some studies aim at maximizing the number of EVs charged, others at minimizing the infrastructure cost for a given demand and some, fewer, intend to minimize the distance to a charging station. The design trade-offs resulting from these optimizations drastically differ, which consequently highlights the importance of stating the goal of the optimization study and the design parameters chosen to conduct this optimization.

Optimization can also deal with interdisciplinarity, for example, with an agriculture-energy system, developed by Barlow *et al.* (2021). This complex system is composed of three subsystems: an irrigation network, crops and an electricity microgrid. Designing the microgrid implies consequently to quantifying the energy demand for water pumping and households, which itself depends on crops. Thus, minimizing electricity cost in this model leads to optimizing the irrigation subsystem. The authors regret economic profit to be used as the indicator, and rather argue in favor of "social benefit" optimization. One of the main drawbacks of the optimization approach is to set predefined rules/constraints that could not be effective all along the simulation which reduces its accuracy for long-term forecasting. This drawback is especially significant in models depending on climate assumptions, for renewable energy planning for instance (van Beuzekom, Hodge & Slootweg 2021). The robustness of the conclusions of such optimization can then be threatened if data assumptions concerning climate change evolve. Evaluation methods therefore exist to assess the "credibility" of a model and are applied to complex systems modeling, including so-called multiagent models (Li *et al.* 2021). System dynamic models are another type of model used at varying scale (e.g., house to global scale) to describe and define evolution pathways depending on design or planning decisions.

On the one hand, for local scale (e.g., house or city scale), complex system analysis hinge on network biophysical models and also on local system analysis (LSA) assessing the fluxes between urban area and nearby ecosystems (OECD 2008). These models are used in the system design approach, illustrated by Toso, Luthe & Kiss (2018) giving multiple examples of food waste and water treatments (Barbero & Toso 2010; Toso *et al.* 2018). This approach focuses on the product's service integrating design interactions with its environment (e.g., rainwater or heat) and stresses the valuation of coproducts to satisfy human needs.

On the other hand, on a larger scale (i.e., national or global scale) global biophysical models are completed by socioeconomic modeling (e.g., IMAGE, REMIND, MEDEAS, WORLD3) to do long-term prospective exercise concerning climate or resources management (Meadows *et al.* 1972; Capellán-Pérez *et al.* 2020; IPCC 2022). For instance, the "*shared socioeconomic pathways*" (SSPs) are scenarios used by the *Intergovernmental Panel on Climate Change* (IPCC) to model five global socioeconomic pathways driven by climate policy assumptions distributed between mitigation and adaptation to climate change.

Note that these two developments of system dynamic models are both less, but still, affected by the long-term assumption's uncertainties. This implies recurrent upgrading to meet upscaling assessments and designers' road maps.

The literature study investigated in this research shows that in general terms, human behavior and social aspects, in the energy or mobility sector, are less studied with social science methodologies compared to urban, waste or food/agriculture sectors where they are more prevalent.

The example of the upscaling (i.e., integration) of urban farming in the food system given by Hardman *et al.* (2022) illustrates this phenomenon. Barriers have been characterized such as the financial one, soil contamination and interactions with urban areas (i.e., vandalism or on the contrary involvement of the community). The authors call for a data-driven approach to identify "market opportunities and revenue streams" to strengthen the business model and best practices. Sims *et al.* (2017) added social organization (e.g., social norms, collective actions and private–nongovernmental issues) as a key barrier to the adoption of climate technologies in the agri-food sector.

Finally, Ceschin & Gaziulusoy (2019) review multiple examples of models used to consider a product environment, including a system design approach, in a design for sustainability goal, and elaborate a multilevel analysis framework of product design methods. It encourages designers to assess their product based on multi-scale vision, from material or component, to sociotechnical systems, and even product–service system vision. This up-and-down zooming on product requires different modeling skills, from technical expertise to social science-based analysis (e.g., consumption habits, community practices, sociotechnical system dynamics). By framing the design problem and the scope of the design intervention, this framework pushes for interdisciplinary practices of design and supports designers to integrate into their practices other expertise models. Thus, archetype 4 (*integrating*) is associated with network models and/or techno-social approaches hinging on:

- System dynamic engineering, requiring specific resource management (data and computing) due to the high complexity of models with different levels of integration (product/service).
- Interoperability between models linked to the product/service integrated in a complex system.
- Culture of trade-offs from optimization modeling or socioeconomic expertise.
- Multidisciplinary approach.

4.3.5. Archetype 5 – Down-limiting or downscaling

As opposed to the first four archetypes, archetype 5 (*down-limiting*) is intrinsically bound to an environmental sustainability paradigm as it is associated with the PB framework. Ryberg *et al.* (2020) develop the main assessment method supporting this archetype, called *absolute environmental sustainability assessment* (AESA). It discusses the sustainability of a product calculating an *absolute sustainability ratio* (ASR). This implies for the numerator the LCA application to collect the product's environmental impacts. The denominator of the ASR is the allocated the environmental space (SoSOS or carrying capacity) associated with the product's scale. These two quantities have to be computed in the same environmental indicators. This necessity brought about two approaches: Ryberg *et al.* (2020) developing PB indicators for LCA and Bjørn & Hauschild (2015) translating PB framework into classic LCA indicators. Both promote the definition of the carrying capacities at the product's scale supported by sharing principles and the analysis of the resilience capacities of the environment.

A sharing principle is an allocation rule founded on ethics, economic and social expertise. Ryberg *et al.* (2020) identify seven distributive justice theories (utilitarianism, prioritarianism, difference principle, luck egalitarianism, egalitarianism, sufficientarianism and libertarianism) and define recommendations for assigning a SoSOS depending on the studied system and geographical and temporal constraints. Following the clause and constraints of the chosen justice theory, the SoSOS assigned to human beings on the geographical and temporal scope is then assigned to industrial units based on the value created for humans on this scope. This expertise is also referred to as defining *science-based targets* (Smith 2024).

Finally, Kara, Herrmann & Hauschild (2023) advocate the operationalization of such an approach by proposing a six-step methodology, including a LCA. This research work synthesizes the design levers to integrate the PB framework into the design with optimization perspectives.

Thus, archetype 5 (*down-limiting*) is associated with an absolute sustainability framework hinging on:

- Justice principles to define and allocate a SoSOS aligned to the technological system being upscaled.
- Methodological developments for AESAs, lifecycle-based.
- A focus on human activity and not only on industrial activities.

The result of the chosen method is then injected into an environmental method to assess the absolute environmental sustainability of the technology-based product or service under development.

4.4. Synthesis for upscaling archetype assessment

Table 2 presents a synthesis of the techno-economic methods, as a summary for designers of methodological requirements identified in the literature study conducted in the previous sections, combined with the recommendations for scope and for each archetype.

This table is therefore intended to guide design teams in the assessment of upscaling. Designers are encouraged to question their upscaling objectives and compare them with those of the archetypes.

Further research findings could complete and revise the recommendations in the coming years by the interested communities, according to new methods, case studies, demonstrating feasibility or incompatibility.

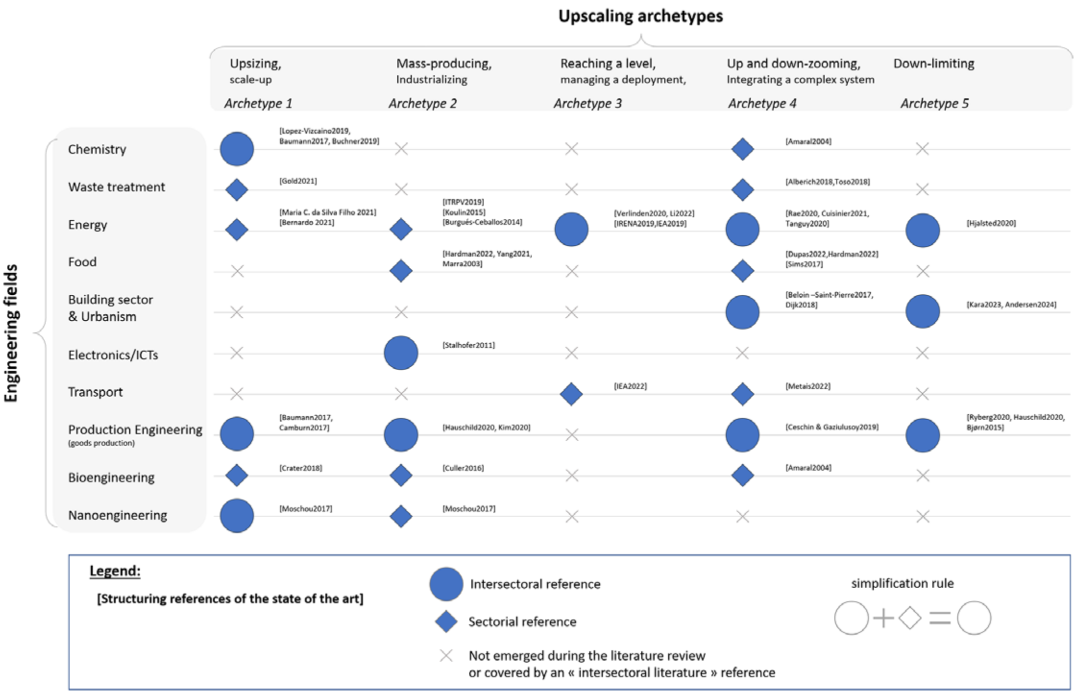
5. Discussion

5.1. How to apply archetypes while designing technology upscaling?

For each UA, definitions, tools, practices and methodological invariants have been detailed in the previous sections. The literature review process also revealed a disparity in the practices of designers depending on their object of study and their EF. This disparity questions the practical relevance of UAs presented above. This section therefore proposes a visual framework to detail this disparity of methods adoption regarding the archetype and the EF involved. It depicts a representation of our literature review and could help designers to deal with UAs use.

5.2. A framework for visualizing the selected literature for upscaling assessment

Figure 4 synthesizes the content of the Section 4.3 with an EF perspective. This representation is called the “matrix UA–EF” for UAs by EFs. This framework aims to identify available and most relevant methods for upscaling assessment. Each geometric shape represents one or more references identified as fruitful during the literature review. These references are articles and scientific reports and are sorted by related UAs and EFs. The proposed references have been selected according to the criteria of being synthetic or dense in terms of information. This structure aims to guide the reader toward the most structuring literature. Interdisciplinary methods (large dots) are distinct from disciplinary-specific methods (small squares). Dots refer as much as possible to review articles. Crosses reveal the non-emergence of relevant references in a specific EF, or default in the process of literature review. Crosses do not mean that literature is nonexistent, but rather that it is not sufficiently structured or prevalent to be identified as dedicated to the upscaling assessment. Such figure may also indicate that cross-field or generic methods from another EF encompass this upscaling application. In that case, large full dots in the corresponding UA column would cover this lack.



Upscaling archetypes

Engineering fields	Upsizing, scale-up *Archetype 1*	Mass-producing, Industrializing *Archetype 2*	Reaching a level, managing a deployment, *Archetype 3*	Up and down-zooming, Integrating a complex system *Archetype 4*	Down-limiting *Archetype 5*
Chemistry	● [Lopez-Vizcaino2019, Baumann2017, Buchner2019]	×	×	◆ [Amaral2004]	×
Waste treatment	◆ [Gold2021]	×	×	◆ [Alberich2018,Toso2018]	×
Energy	◆ [Maria C. da Silva Filho 2021] [Bernardo 2021]	◆ [ITRPV2019] [Koulin2015] [Burgués-Ceballos2014]	● [Verlinden2020, Li2022] [IRENA2019,IEA2019]	● [Rae2020, Cuisinier2021, Tanguy2020]	● [Hjalsted2020]
Food	×	◆ [Hardman2022, Yang2021, Marra2003]	×	◆ [Dupas2022,Hardman2022] [Sims2017]	×
Building sector & Urbanism	×	×	×	● [Beloin –Saint-Pierre2017, Dijk2018]	● [Kara2023, Andersen2024]
Electronics/ICTs	×	● [Stalhofer2011]	×	×	×
Transport	×	×	◆ [IEA2022]	◆ [Metais2022]	×
Production Engineering (goods production)	● [Baumann2017, Camburn2017]	● [Hauschild2020, Kim2020]	×	● [Ceschin & Gaziulusoy2019]	● [Ryberg2020, Hauschild2020, Bjørn2015]
Bioengineering	◆ [Crater2018]	◆ [Culler2016]	×	◆ [Amaral2004]	×
Nanoengineering	● [Moschou2017]	◆ [Moschou2017]	×	×	×

Legend:

[Structuring references of the state of the art]

● Intersectoral reference

◆ Sectorial reference

× Not emerged during the literature review or covered by an « intersectoral literature » reference

simplification rule

○ + ◇ = ○

Figure 4. The matrix UA–EF, presenting a selected literature for upscaling assessment according to the upscaling archetypes and engineering fields. For simplification, when several references are identified, only the most inter-sectorial (circle) is represented.

Thus, archetypes 1 (*upsizing*) and 4 (*integrating into a complex system*) are the most widely documented in the selected domains of engineering. Both also have multiple structuring references due to the diversity of approaches (e.g., techno-economic or socio-technical) and differences of skills and representations that can be inter-sectorial but not necessarily compatible with all EFs. Archetype 2 (*mass-producing*) appears to be more clustered around the production of engineering and electronics due to intrinsic methodologies that are widespread in all other engineering sectors. Archetype 3 (*reaching a level*) appears to be less documented than others due to its link with planning methodologies of climate change mitigation, which are more recent and can therefore be less common in engineering. Likewise, Archetype 5 (*down-limiting*) covers recent research developments but potentially concerning every EF. Archetype 5 is for the moment affiliated with a small number of structuring references (Hauschild *et al.* 2020; Ryberg *et al.* 2020; Hjalsted *et al.* 2021; Kara *et al.* 2023; Andersen *et al.* 2024). Case studies are expected to be developed over coming years.

5.3. Use of the matrix UA–EF as a support tool for designers

As for Table 2, Figure 4 is non-exhaustive and is meant to be completed by the design communities as any design method. This methodological framework is adapted for design teams wishing to identify the relevant (or at least existing) methods adapted to study all facets of an upscaling (i.e., archetypes). It enables readers to determine if an UA is addressed or not in the scientific literature according to two criteria: by sector or EF (horizontally) or by archetype (vertically).

A horizontal reading implies to consider if all archetypes are addressed in a specific activity sector. It leads to the expectation of a common vocabulary in the design team (due to the object of study) and possibly a "simpler" appropriation if the goal is to integrate new practices.

If a node is missing from this reading, the vertical reading is required. This cross-reading process brings about an interdisciplinary practice: users emphasize on assessment methodologies potentially transferable or adaptable from other EFs. In that regard, Figure 4 offers enough sources to ensure a cross-reading and cover all the archetypes for each EF.

Ideally, as many of these five archetypes should be assessed to monitor the upscaling of a technology in a complete way. In practice, products and their uses lend themselves more or less well to existing assessment methods. Moreover, EFs have varying degrees of maturity in applying the selected TEA. In that context, Figure 4 depicts the treatment of the upscaling phenomenon from engineering and design point of view. In case of lack of literature, this socio-technical phenomenon may exist in the corresponding EF, and perhaps these aspects have not (yet) been captured by engineering and design approaches. Future research may refine the specifics of upscaling assessment in each engineering domain. More broadly, despite archetype 3 (*reaching a level*) and archetype 5 (*down-limiting*) being related to socio-environmental aspects, only techno-economic methods and practices have been compiled in this review. This offers therefore a partial overview of the upscaling assessments that may need to be carried out to anticipate and design it. Complementing this review with similar work but from other types of analysis (e.g., environmental, political, social) related to UAs would also be fruitful for design teams aiming for the sustainability of their practice.

6. Conclusion

The aim of this review was to clarity the definition of the sentence "upscaling of emerging technologies" for designers. This review proposed a characterization formalism. Based on it, five archetypes are identified in the literature of design and engineering: *scaling-up* or *upsizing*, *mass-producing*, *reaching a level* or *deploying*, *up-and-down zooming* or *integrating in a complex system and down-limiting.* Each of them is associated with a specific meaning and definition embodying a perception of the upscaling. Each archetype relates to an inner and coherent lexical field, sometimes interacting with another archetype. The emerging technology concept is also, relatively to the upscaling phenomenon, polysemic. Three definitions, available in the literature, are therefore criticized from each UA perspective. The review demonstrates that UAs cover all of them. Additionally, the majority of engineering and design literature referring to anticipating or managing an upscaling of a product are techno-economic or socio-technical assessments. Thus, this review compiles methods and practices available in the design literature to assess the upscaling of a(n emerging) technology, depending on the five archetypes. Some methods are generic and interdisciplinary, and some are specific to an EF (e.g., chemical engineering). Moreover, design guidelines are proposed to support upscaling assessment practices by designer. These guidelines include examples of methods and tools, methodological requirements and recommendations for study scope.

Finally, the review offers as a discussion medium an illustration of the identified most structuring literature references (e.g., reviews or case studies). This formalism is named "matrix UA–EF". It enables readers to consult the disparity of available methods and practices adoption regarding the UA and the EF. Matrix UA–EF can be considered as an attempt to guide designers in finding the best available techno-economic assessments to assess their upscaling case. In that regard, this representation paves the way to interdisciplinary additions purposed to study the phenomenon of technology upscaling from other perspectives (e.g., environmental, social).

Author contribution

L.R.: Conceptualization, methodology, investigation, data curation, writing – original draft. V.P.-B. and M.R.: Formal analysis, supervision, writing – review and editing. P.Z.: Validation, supervision, writing – review and editing.

Financial support

This work has been supported by the Carnot Energies du Futur Institute and the Carnot ARTS Institute.

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 review.

References

ADEME, 2021 *Transition(S) 2050, Decide Now Act for Climate*. Agency for Ecological Transition (ADEME). https://transitions2050.ademe.fr/en.

Amaral, L. & **Ottino, J.** 2004 Complex systems and networks: Challenges and opportunities for chemical and biological engineers. *Chemical Engineering Science* **59** (8), 1653–1666; doi:10.1016/j.ces.2004.01.043.

Andersen, S. C., **Petersen, S.**, **Ryberg, M.**, **Molander, L. L.** & **Birkved, M.** 2024 Ten questions concerning absolute sustainability in the built environment. *Building and Environment* **251**, 111220; doi:10.1016/j.buildenv.2024.111220.

Balgobin, T. & **Evrard, D.** 2020 A framework for modelling emerging processes' upscaling from an environmental perspective. In *27th CIRP Life Cycle Engineering Conference (LCE2020) Advancing Life Cycle Engineering: From Technological Eco-efficiency to Technology that Supports a World that Meets the Development Goals and the Absolute Sustainability*, **90**, pp. 154–158; doi:10.1016/j.procir.2020.01.055.

Barbero, S. & **Toso, D.** 2010 Systemic design of a productive chain: Reusing coffee waste as an input to agricultural production. *Environmental Quality Management* **19** (3), 67–77; doi:10.1002/tqem.20254.

Barlow, T., **Biddanda, M.**, **Mendke, S.**, **Miyingo, E.**, **Sicko, A.**, **Papalambros, P. Y.**, **Chien, C.-C.** & **O'Neal, W.** 2021 A system design optimization model for integrated natural resource conservation and development in an agricultural community. *Proceedings of the Design Society* **1**, 273–282; doi:10.1017/pds.2021.28.

Basnet, S. & **Magee, C. L.** 2016 Modeling of technological performance trends using design theory. *Design Science* **2**, e8; doi:10.1017/dsj.2016.8.

Baudry, I. 2013 Caractérisation des process de fabrication microélectroniques pour l'éco-conception des futures technologies (partenaire industriel STMicroelectronics) (Doctoral Dissertation). Université de Grenoble, Grenoble, France. https://hal.archives-ouvertes.fr/tel-00957329/.

Baumann, C. & **Lopatnikov, A.** 2017 Scaling laws: Uses and misuses in industrial plant and equipment replacement cost estimates. *The MTS Journal* **33** (2), 38–44.

Belwal, T., **Chemat, F.**, **Venskutonis, P. R.**, **Cravotto, G.**, **Jaiswal, D. K.**, **Bhatt, I. D.**, **Devkota, H. P.** & **Luo, Z.** 2020 Recent advances in scaling-up of non-conventional extraction techniques: Learning from successes and failures. *TrAC Trends in Analytical Chemistry* **127**, 115895; doi:10.1016/j.trac.2020.115895.

Berger, G. 1964 L'Attitude prospective. *Management International* **4** (3), 43–46.

Bergerson, J. A., **Brandt, A.**, **Cresko, J.**, **Carbajales-Dale, M.**, **MacLean, H. L.**, **Matthews, H. S.**, **McCoy, S.**, **McManus, M.**, **Miller, S. A.**, **Morrow, W. R.**, **Posen, I. D.**, **Seager, T.**, **Skone, T.** & **Sleep, S.** 2020 Life cycle assessment of emerging technologies: Evaluation techniques at different stages of market and technical maturity. *Journal of Industrial Ecology* **24** (1), 11–25; doi:10.1111/jiec.12954.

Bernardo, G., **Lopes, T.**, **Lidzey, D.** & **Mendes, A.** 2021 Progress in upscaling organic photovoltaic devices. *Advanced Energy Materials* **11** (23), 2100342; doi:10.1002/aenm.202100342.

Bjørn, A., **Chandrakumar, C.**, **Boulay, A.-M.**, **Doka, G.**, **Fang, K.**, **Gondran, N.**, **Hauschild, M. Z.**, **Kerkhof, A.**, **King, H.**, **Margni, M.**, **McLaren, S.**, **Mueller, C.**, **Owsianiak, M.**, **Peters, G.**, **Roos, S.**, **Sala, S.**, **Sandin, G.**, **Sim, S.**, **Vargas-Gonzalez, M.** & **Ryberg, M.** 2020 Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environmental Research Letters* **15** (8), 083001; doi:10.1088/1748-9326/ab89d7.

Bjørn, A. & **Hauschild, M.** 2015 Introducing carrying capacity-based normalisation in LCA: Framework and development of references at midpoint level. *The International Journal of Life Cycle Assessment* **20** (7), 1005–1018; doi:10.1007/s11367-015-0899-2.

Bobba, S., **Carrara, S.**, **Huisman, J.**, **Mathieux, F.** & **Pavel, C.** 2020 *Critical Raw Materials for Strategic Technologies and Sectors in the EU. A Foresight Study*. European Commission.

Bobbe, T., **Opeskin, L.**, **L¨uneburg, L.-M.**, **Wanta, H.**, **Pohlmann, J.** & **Krzywinski, J.** 2023 Design for communication: How do demonstrators demonstrate technology? *Design Science* **9**, e3; doi:10.1017/dsj.2023.1.

Boess, S. U. 2019 Design contributions to building technology: Goals, interfaces and responsiveness. *Proceedings of the Design Society: International Conference on Engineering Design* **1** (1), 3211–3220; doi:10.1017/dsi.2019.328.

Breyer, C., **Bogdanov, D.**, **Gulagi, A.**, **Aghahosseini, A.**, **Barbosa, L. S.**, **Koskinen, O.**, **Barasa, M.**, **Caldera, U.**, **Afanasyeva, S.**, **Child, M.**, **Farfan, J.** & **Vainikka, P.** 2017 On the role of solar photovoltaics in global energy transition scenarios: On the role of solar photovoltaics in global energy transition scenarios. *Progress in Photovoltaics: Research and Applications* **25** (8), 727–745; doi:10.1002/pip.2885.

Buchner, G., **Stepputat, K.**, **Zimmermann, A.** & **Schomacker, R.** 2019 Specifying technology readiness levels for the chemical industry. *Industrial & Engineering Chemistry Research* **58** (17), 6957–6969; doi:10.1021/acs.iecr.8b05693.

Camburn, B., **Viswanathan, V.**, **Linsey, J.**, **Anderson, D.**, **Jensen, D.**, **Crawford, R.**, **Otto, K.** & **Wood, K.** 2017 Design prototyping methods: State of the art in strategies, techniques, and guidelines. *Design Science* **3**, e13; doi:10.1017/dsj.2017.10.

Capellán-Pérez, I., **de Blas, I.**, **Nieto, J.**, **de Castro, C.**, **Miguel, L. J.**, **Carpintero, Ó.**, **Mediavilla, M.**, **Lobejón, L. F.**, **Ferreras-Alonso, N.**, **Rodrigo, P.**, **Frechoso, F.** & **Álvarez-Antelo, D.** 2020 MEDEAS: A new modeling framework integrating global biophysical and socioeconomic constraints. *Energy & Environmental Science* **13** (3), 986–1017; doi:10.1039/C9EE02627D.

Ceschin, F. 2014 Sustainable Product-Service Systems: Between Strategic Design and Transition Studies. doi:10.1007/978-3-319-03795-0.

Ceschin, F. & **Gaziulusoy, I.** 2019 *Design for Sustainability: A Multi-Level Framework from Products to Socio-Technical Systems* (1st ed.). Routledge; doi:10.4324/9780429456510.

Charpentier Poncelet, A., **Helbig, C.**, **Loubet, P.**, **Beylot, A.**, **Muller, S.**, **Villeneuve, J.**, **Laratte, B.**, **Thorenz, A.**, **Tuma, A.** & **Sonnemann, G.** 2021 Life cycle impact assessment methods for estimating the impacts of dissipative flows of metals. *Journal of Industrial Ecology* **25** (5), 1177–1193; doi:10.1111/jiec.13136.

Cherp, A., **Vinichenko, V.**, **Tosun, J.**, **Gordon, J.** & **Jewell, J.** 2021 National growth dynamics of wind and solar power compared to the growth required for global climate targets. *Nature Energy* **6** (7), 742–761; doi:10.1038/s41560-021-00863-0.

Chordia, M., **Nordelöf, A.** & **Ellingsen, L. A.-W.** 2021 Environmental life cycle implications of upscaling lithium-ion battery production. *The International Journal of Life Cycle Assessment* **26** (10), 2024–2039; doi:10.1007/s11367-021-01976-0.

Cluzel, F. 2012 Eco-design implementation for complex industrial systems (Doctoral dissertation). Ecole Centrale Paris, Châtenay-Malabry, France. http://www.theses.fr/2012ECAP0037.

Commission, E. 2012 *2012/504/EU: Commission Decision of 17 September 2012 on Eurostat* [EUR-Lex - Access to European Union Law]. https://eur-lex.europa.eu/eli/dec/2012/504/oj.

Council of Europe. 2019 Annexe G. of Commission implementing decision C(2019)4575 [Internet]. [cited 2022 Feb 15]. Available from: https://ec.europa.eu/transparency/documents-register/detail?ref=C(2019)4575&lang=en

Crater, J. & **Lievense, J.** 2018 Scale-up of industrial microbial processes. *FEMS Microbiology Letters* **365** (13), fny138; doi:10.1093/femsle/fny138.

Cuisinier, E., **Bourasseau, C.**, **Ruby, A.**, **Lemaire, P.** & **Penz, B.** 2021 Techno-economic planning of local energy systems through optimization models: A survey of current methods. *International Journal of Energy Research* **45** (4), 4888–4931; doi:10.1002/er.6208.

Culler, S. 2016 A bioengineering platform to industrialize biotechnology. *Synthetic Biology* **10**, 42–51.

da Silva Filho, J. M. C., **Gonçalves, A. D.**, **Marques, F. C.** & **de Freitas, J. N.** 2021 A review on the development of metal grids for the upscaling of perovskite solar cells and modules. *Solar RRL* **6**, 2100865; doi:10.1002/solr.202100865.

Dijk, M., **de Kraker, J.** & **Hommels, A.** 2018 Anticipating constraints on upscaling from urban innovation experiments. *Sustainability* **10** (8), 2796; doi:10.3390/su10082796.

Ehrler, B., **Alarcón-Lladó, E.**, **Tabernig, S. W.**, **Veeken, T.**, **Garnett, E. C.** & **Polman, A.** 2020 Photovoltaics reaching for the Shockley–Queisser limit. *ACS Energy Letters* **5** (9), 3029–3033; doi:10.1021/acsenergylett.0c01790.

Elshkaki, A. 2021 Sustainability of emerging energy and transportation technologies is impacted by the coexistence of minerals in nature. *Communications Earth & Environment* **2** (1), 186; doi:10.1038/s43247-021-00262-z.

European Commission, Directorate-General for Internal Market, I., Entrepreneurship and SMEs, Blengini, G., El Latunussa, C., Eynard, U., Torres De Matos, C., Wittmer, D., Georgitzikis, K., Pavel, C., Carrara, S., Mancini, L., Unguru, M., Blagoeva, D., Mathieux, F. & Pennington, D. 2020 *Study on the EU's list of critical raw materials (2020). Final Report.* Publications Office; doi:10.2873/11619.

Farmer, C. L. 2002 Upscaling: A review. *International Journal for Numerical Methods in Fluids* **40** (1), 63–78; doi:10.1002/fld.267.

Ferro, P. & Bonollo, F. 2019 Materials selection in a critical raw materials perspective. *Materials & Design* **177**, 107848; doi:10.1016/j.matdes.2019.107848.

Fischer, M., Woodhouse, M., Herritsch, S. & Trube, J. 2019 *International Technology Roadmap for Photovoltaic (ITRPV), 2018 Results* (No. 10). VDMA Photovoltaic Equipment, Germany.

Fitó, J., Vallée, M., Ruby, A. & Cuisinier, E. 2022 Robustness of district heating versus electricity-driven energy system at district level: A multi-objective optimization study. *Smart Energy* **6**, 100073; doi:10.1016/j.segy.2022.100073.

Gall, T., Vallet, F. & Yannou, B. 2022 How to visualise futures studies concepts: Revision of the futures cone. *Futures* **143**, 103024; doi:10.1016/j.futures.2022.103024.

Geels, F. W., Sovacool, B. K., Schwanen, T. & Sorrell, S. 2017 The socio-technical dynamics of low-carbon transitions. *Joule* **1** (3), 463–479; doi:10.1016/j.joule.2017.09.018.

Gwehenberger, G., Narodoslawsky, M., Liebmann, B. & Friedl, A. 2007 Ecology of scale versus economy of scale for bioethanol production. *Biofuels, Bioproducts and Biorefining* **1** (4), 264–269; doi:10.1002/bbb.35.

Hackenhaar, I., Alvarenga, R. A., Bachmann, T. M., Riva, F., Horn, R., Graf, R. & Dewulf, J. 2022 A critical review of criticality methods for a European life cycle sustainability assessment. *Procedia CIRP* **105**, 428–433; doi:10.1016/j.procir.2022.02.071.

Hardman, M., Clark, A. & Sherriff, G. 2022 Mainstreaming urban agriculture: Opportunities and barriers to upscaling city farming. *Agronomy* **12** (3), 601; doi:10.3390/agronomy12030601.

Hauschild, M., Kara, S. & Ropke, I. 2020 Absolute sustainability: Challenges to life cycle engineering. *CIRP Annals-Manufacturing Technology* **69** (2), 533–553; doi:10.1016/j.cirp.2020.05.004.

Hauschild, M. Z. 2015 Better – But is it good enough? On the need to consider both eco-efficiency and eco-effectiveness to gauge industrial sustainability. *Procedia CIRP* **29**, 1–7; doi:10.1016/j.procir.2015.02.126.

Hetherington, A., Borrion, A., Griffiths, O. & McManus, M. 2014 Use of LCA as a development tool within early research: Challenges and issues across different sectors. *International Journal of Life Cycle Assessment* **19** (1), 130–143; doi:10.1007/s11367-013-0627-8.

Hjalsted, A., Laurent, A., Andersen, M., Olsen, K., Ryberg, M. & Hauschild, M. 2021 Sharing the safe operating space: Exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels. *Journal of Industrial Ecology* **25** (1), 6–19; doi:10.1111/jiec.13050.

Hofmann, M., Hofmann, H., Hagelüken, C. & Hool, A. 2018 Critical raw materials: A perspective from the materials science community. *Sustainable Materials and Technologies* **17**, e00074; doi:10.1016/j.susmat.2018.e00074.

Horizon2020, 2022 *Horizon 2020.* European Commission. https://research-and-innovation.ec.europa.eu/funding/fundingopportunities/funding-programmes-and-open-calls/horizon-2020en.

Hung, C., **Ellingsen, L.** & **Majeau-Bettez, G.** 2020 LiSET: A framework for early-stage life cycle screening of emerging technologies. *Journal of Industrial Ecology* **24** (1), 26–37; doi:10.1111/jiec.12807.

Huntjens, P. 2021 *Towards a Natural Social Contract: Transformative Social-Ecological Innovation for a Sustainable, Healthy and Just Society*; doi:10.1007/978-3-030-67130-3.

IEA, 2020 *Energy Technology Perspectives 2020*. https://www.iea.org/reports/energy-technology-perspectives-2020

IPCC, 2022 *Global Warming of 1.5°c: IPCC Special Report on Impacts of Global Warming of 1.5°c above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (1st ed.). Cambridge University Press; doi:10.1017/9781009157940.

IRENA, 2019a *Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects. A Global Energy Transformation*. International Renewable Energy Agency.

IRENA, 2019b *IRENA Future of Wind: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects*. International Renewable Energy Agency.

Kara, S., **Herrmann, C.** & **Hauschild, M.** 2023 Operationalization of life cycle engineering. *Resources, Conservation and Recycling* **190**, 106836; doi:10.1016/j.resconrec.2022.106836.

Khalifa, S. A., **Mastrorocco, B. V.**, **Au, D. D.**, **Barnes, T. M.**, **Carpenter, A. C.** & **Baxter, J. B.** 2021 A circularity assessment for silicon solar panels based on dynamic material flow analysis. In *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, pp. 560–563; doi:10.1109/PVSC43889.2021.9519117.

Kim, H., **Cluzel, F.**, **Leroy, Y.**, **Yannou, B.** & **Bris, G. Y.-L.** 2020 Research perspectives in ecodesign. *Design Science* **6**, e7; doi:10.1017/dsj.2020.5.

Koulin, G., **Sewell, I.** & **Shaw, B.** 2015 Faceted monopile design suitable for mass production and upscaling. *Procedia Engineering* **114**, 385–392; doi:10.1016/j.proeng.2015.08.083.

Kramer, G. & **Haigh, M.** 2009 No quick switch to low-carbon energy. *Nature* **462** (7273), 568–569; doi:10.1038/462568a.

Lade, S. J., **Steffen, W.**, **de Vries, W.**, **Carpenter, S. R.**, **Donges, J. F.**, **Gerten, D.**, **Hoff, H.**, **Newbold, T.**, **Richardson, K.** & **Rockstr¨om, J.** 2020 Human impacts on planetary boundaries amplified by earth system interactions. *Nature Sustainability* **3** (2), 119–128; doi:10.1038/s41893-019-0454-4.

Laird, T. 2010 How to minimise scale UP difficulties. In *Scale-Up*, pp. 51–56. Chemical Industry Digest.

Leccisi, E. & **Fthenakis, V.** 2021 Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV. *Progress in Photovoltaics* **29** (10), 1078–1092; doi:10.1002/pip.3442.

Li, N., **Dong, L.**, **Zhao, L.**, **Gong, G.** & **Zhang, X.** 2021 A credibility evaluation method for complex simulation systems based on interactive network analysis. *Simulation Modelling Practice and Theory* **110**, 102289; doi:10.1016/j.simpat.2021.102289.

López-Vizcaíno, R., **Yustres, A.**, **Sáez, C.**, **Cañizares, P.**, **Asensio, L.**, **Navarro, V.** & **Rodrigo, M.** 2019 Techno-economic analysis of the scale-up process of electrochemically-assisted soil remediation. *Journal of Environmental Management* **231**, 570–575; doi:10.1016/j.jenvman.2018.10.084.

Maier, H., **Guillaume, J.**, **van Delden, H.**, **Riddell, G.**, **Haasnoot, M.** & **Kwakkel, J.** 2016 An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling & Software* **81**, 154–164; doi:10.1016/j.envsoft.2016.03.014.

Manufacturing Readiness Level (MRL) Deskbook, 2022 Office of the Secretary of Defense Manufacturing Technology Program.

Marra, M., **Pannell, D. J.** & **Abadi Ghadim, A.** 2003 The economics of risk, uncertainty and learning in the adoption of new agricultural technologies: Where are we on the learning curve? *Agricultural Systems* **75** (2), 215–234; doi:10.1016/S0308-521X(02)00066-5.

Meadows, D. H., **Meadows, D. L.**, **Randers, J.** & **Behrens, W. W.** 1972 *The Limits to Growth, Club of Rome*. Universe.

Metais, M., **Jouini, O.**, **Perez, Y.**, **Berrada, J.** & **Suomalainen, E.** 2022 Too much or not enough? Planning electric vehicle charging infrastructure: A review of modeling options. *Renewable and Sustainable Energy Reviews* **153**, 111719; doi:10.1016/j.rser.2021.111719.

Moreno, J., **Grasman, S.**, **van Engelen, R.** & **Nijmeijer, K.** 2018 Upscaling reverse electrodialysis. *Environmental Science & Technology* **52** (18), 10856–10863; doi:10.1021/acs.est.8b01886.

Moschou, D. & **Tserepi, A.** 2017 The lab-on-PCB approach: Tackling the μTAS commercial upscaling bottleneck. *Lab on a Chip* **17** (8), 1388–1405; doi:10.1039/C7LC00121E.

Nordelof, A. 2019 A scalable life cycle inventory of an automotive power electronic inverter unit-part II: Manufacturing processes. *The International Journal of Life Cycle Assessment* **24** (4), 694–711; doi:10.1007/s11367-018-1491-3.

OECD, 2008 *Measuring Material Flows and Resource Productivity. The OECD Guide*, Vol. **1**. Organization for Economic Co-operation and Development.

Onat, N., **Kucukvar, M.**, **Halog, A.** & **Cloutier, S.** 2017 Systems thinking for life cycle sustainability assessment: A review of recent developments, applications, and future perspectives. *Sustainability* **9** (5), 706; doi:10.3390/su9050706.

Pahl, G. & **Beitz, W.** 1996 *Engineering Design* (ed. K. Wallace). Springer; doi:10.1007/978-1-4471-3581-4.

Patel, A., **Gami, B.**, **Patel, P.** & **Patel, B.** 2023 Biodiesel production from microalgae *Dunaliella tertiolecta*: A study on economic feasibility on large-scale cultivation systems. *Biomass Conversion and Biorefinery* **13**, 1071–1085; doi:10.1007/s13399-020-01191-1

Persson, L., **Carney Almroth, B. M.**, **Collins, C. D.**, **Cornell, S.**, **de Wit, C. A.**, **Diamond, M. L.**, **Fantke, P.**, **Hassellöv, M.**, **MacLeod, M.**, **Ryberg, M. W.**, **Søgaard Jørgensen, P.**, **Villarrubia-Gómez, P.**, **Wang, Z.** & **Hauschild, M. Z.** 2022 Outside the safe operating space of the planetary boundary for novel entities. *Environmental Science & Technology* **56** (3), 1510–1521; doi:10.1021/acs.est.1c04158.

Piccinno, F., **Hischier, R.**, **Seeger, S.** & **Som, C.** 2016 From laboratory to industrial scale: A scale-up framework for chemical processes in life cycle assessment studies. *Journal of Cleaner Production* **135**, 1085–1097; doi:10.1016/j.jclepro.2016.06.164.

Rae, C., **Kerr, S.** & **Maroto-Valer, M. M.** 2020 Upscaling smart local energy systems: A review of technical barriers. *Renewable and Sustainable Energy Reviews* **131**, 110020; doi:10.1016/j.rser.2020.110020.

Richardson, K., **Steffen, W.**, **Lucht, W.**, **Bendtsen, J.**, **Cornell, S. E.**, **Donges, J. F.**, **Dr¨uke, M.**, **Fetzer, I.**, **Bala, G.**, **von Bloh, W.**, **Feulner, G.**, **Fiedler, S.**, **Gerten, D.**, **Gleeson, T.**, **Hofmann, M.**, **Huiskamp, W.**, **Kummu, M.**, **Mohan, C.**, **Nogués-Bravo, D.**, **Petri, S.**, **Porkka, M.**, **Rahmstorf, S.**, **Schaphoff, S.**, **Thonicke, K.**, **Tobian, A.**, **Virkki, V.**, **Wang-Erlandsson, L.**, **Weber, L.** & **Rockström, J.** 2023 Earth beyond six of nine planetary boundaries. *Science Advances* **9** (37), eadh2458; doi:10.1126/sciadv.adh2458.

Rietveld, E., **Boonman, H.**, **Harmelen, T. V.**, **Hauck, M.** & **Bastein, T.** 2019 Global energy transition and metal demand. doi: 10.13140/RG.2.2.25790.54086

Riondet, L., **Rio, M.**, **Perrot-Bernardet, V.** & **Zwolinski, P.** 2022 For an upscaling assessment integration in product design. *Procedia CIRP* **109**, 89–94; doi:10.1016/j.procir.2022.05.219.

Ritchie, H., **Roser, M.** & **Rosado, P.** 2020 *Energy*. Our World in Data. https://ourworldindata.org/energy.

Rockström, J., **Steffen, W.**, **Noone, K.**, **Persson, Å.**, **Chapin, F. S. I.**, **Lambin, E.**, **Lenton, T. M.**, **Scheffer, M.**, **Folke, C.**, **Schellnhuber, H. J.**, **Nykvist, B.**, **de Wit, C. A.**, **Hughes, T.**, **van der Leeuw, S.**, **Rodhe, H.**, **Sörlin, S.**, **Snyder, P. K.**, **Costanza, R.**, **Svedin, U.**, **Falkenmark, M.**, **Karlberg, L.**, **Corell, R. W.**, **Fabry, V. J.**, **Hansen, J.**, **Walker, B.**, **Liverman, D.**, **Richardson, K.**, **Crutzen, P.**, & **Foley, J**. 2009 Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society* **14** (2), art32; doi: 10.5751/ES-03180-140232.

Rotolo, D., **Hicks, D.** & **Martin, B. R.** 2015 What is an emerging technology? *Research Policy* **44** (10), 1827–1843; doi:10.1016/j.respol.2015.06.006.

Roy, S., **Radivojevic, T.**, **Forrer, M.**, **Marti, J.**, **Jonnalagadda, V.**, **Backman, T.**, **Morrell, W.**, **Plahar, H.**, **Kim, J.**, **Hillson, N.** & **Martin, H.** 2021 Multiomics data collection, visualization, and utilization for guiding metabolic engineering. *Frontiers in Bioengineering and Biotechnology* **9**, 612893; doi:10.3389/fbioe.2021.612893.

Ryberg, M. W., **Andersen, M.**, **Owsianiak, M.** & **Hauschild, M.** 2020 Downscaling the planetary boundaries in absolute environmental sustainability assessments - A review. *Journal of Cleaner Production* **276**, 123287; doi:10.1016/j.jclepro.2020.123287.

Sallerström, P., **Sundin, J.**, **Kurilova-Palisaitiene, J.** & **Sundin, E.** 2022 Scaling up repair workshops to remanufacturing facilities for household appliances as a service. *Procedia CIRP* **105**, 43–48; doi:10.1016/j.procir.2022.02.008.

Sanford, K., **Chotani, G.**, **Danielson, N.** & **Zahn, J. A.** 2016 Scaling up of renewable chemicals. *Current Opinion in Biotechnology* **38**, 112–122; doi:10.1016/j.copbio.2016.01.008.

Schrijvers, D., **Hool, A.**, **Blengini, G. A.**, **Chen, W.-Q.**, **Dewulf, J.**, **Eggert, R.**, **van Ellen, L.**, **Gauss, R.**, **Goddin, J.**, **Habib, K.**, **Hagel¨uken, C.**, **Hirohata, A.**, **Hofmann-Amtenbrink, M.**, **Kosmol, J.**, **Le Gleuher, M.**, **Grohol, M.**, **Ku, A.**, **Lee, M.-H.**, **Liu, G.**, **Nansai, K.**, **Nuss, P.**, **Peck, D.**, **Reller, A.**, **Sonnemann, G.**, **Tercero, L.**, **Thorenz, A.** & **Wäger, P. A.** 2020 A review of methods and data to determine raw material criticality. *Resources, Conservation and Recycling* **155**, 104617; doi:10.1016/j.resconrec.2019.104617.

Seed Energy – Odyssey, 2022. https://seed-energy.fr/odyssey.html.

Shibasaki, M., **Fischer, M.** & **Barthel, L.** 2007 Effects on life cycle assessment – Scale up of processes. In *Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses: Proceedings of the 14th CIRP Conference on Life Cycle Engineering*, Waseda University, Tokyo, Japan, (pp. 377–381). Springer London. doi: 10.1007/978-1-84628-935-4_65.

Sims, R., **Flammini, A.**, **Santos, N.**, **Pereira, L. D.**, **Carita, A.**, **Bracco, S.** & **Oze, D.** 2017 *Adoption of Climate Technologies in the Agrifood Sector*. Food and Agriculture Organization of the United Nations.

Smith, J. 2024 *Driving Ambitious Corporate Climate Action*. Science Based Targets. https://sciencebasedtargets.org/.

Steffen, W., **Richardson, K.**, **Rockström, J.**, **Cornell, S. E.**, **Fetzer, I.**, **Bennett, E. M.**, **Biggs, R.**, **Carpenter, S. R.**, **de Vries, W.**, **de Wit, C. A.**, **Folke, C.**, **Gerten, D.**, **Heinke, J.**, **Mace, G. M.**, **Persson, L. M.**, **Ramanathan, V.**, **Reyers, B.** & **Sörlin, S.** 2015 Planetary boundaries: Guiding human development on a changing planet. *Science* **347** (6223), 1259855; doi:10.1126/science.1259855.

Tanguy, A., **Bahers, J.** & **Athanassiadis, A.** 2020 Outsourcing of urban metabolisms and its consequences: A multiscale energy flow analysis of a french port-city. *Resources Conservation and Recycling* **161**, 104951; doi:10.1016/j.resconrec.2020.104951.

Thiede, S., **Wiese, M.** & **Herrmann, C.** 2021 Upscaling strategies for polymer additive manufacturing: An assessment from economic and environmental perspective for SLS, MJF and DLP. *Procedia CIRP* **104**, 653–658; doi:10.1016/j.procir.2021.11.110.

Toso, D., **Luthe, T.** & **Kiss, T.** 2018 *The systemic design approach applied to water treatment in the alpine region.* https://rsdsymposium.org.

Tozik, S. & **Reich, Y.** 2023 A framework for analysis and design of dynamic ad hoc socio-technical systems. *Proceedings of the Design Society* **3**, 151–160; doi:10.1017/pds.2023.16.

Tsoy, N., **Steubing, B.**, **van der Giesen, C.** & **Guinée, J.** 2020 Upscaling methods used in ex ante life cycle assessment of emerging technologies: A review. *The International Journal of Life Cycle Assessment* **25** (9), 1680–1692; doi:10.1007/s11367-020-01796-8.

van Beuzekom, I., **Hodge, B.-M.** & **Slootweg, H.** 2021 Framework for optimization of long-term, multi-period investment planning of integrated urban energy systems. *Applied Energy* **292**, 116880; doi:10.1016/j.apenergy.2021.116880.

van der Giesen, C., **Cucurachi, S.**, **Guinée, J.**, **Kramer, G. J.** & **Tukker, A.** 2020 A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production* **259**, 120904; doi:10.1016/j.jclepro.2020.120904.

van Exter, P., **Bouwens, J.**, **Bosch, S.**, **Bosch, S.**, **Favrin, S.**, **Zeijlmans, S.**, **Sprecher, B.**, **van der Vlies, D.**, **Wirtz, A.** & **van Oorschot, J.** 2021 Towards a circular energy transition. Technical Report. Metabolic. https://www.metabolic.nl/publications/towards-a-circular-energy-transition/.

Verlinden, P. J. 2020 Future challenges for photovoltaic manufacturing at the terawatt level. *Journal of Renewable and Sustainable Energy* **12** (5), 053505; doi:10.1063/5.0020380.

Veyrenc, T., **Houvenage, O.**, **Assaiante, C.**, **De Lauretis, S.**, **Di Bono, P.**, **Dubois, A.**, **Le Du, M.**, **Leonard, C.** & **Rious, V.** 2022 *Futurs énergétiques 2050.* https://www.rte-france.com/analyses-tendances-etprospectives/bilan-previsionnel-2050-futurs-energetiques.

Vidal, O., **Le Boulzec, H.**, **Andrieu, B.** & **Verzier, F.** 2021 Modelling the demand and access of mineral resources in a changing world. *Sustainability* **14** (1), 11; doi:10.3390/su14010011.

Watari, T., **Nansai, K.** & **Nakajima, K.** 2020 Review of critical metal dynamics to 2050 for 48 elements. *Resources Conservation and Recycling* **155**, 104669; doi:10.1016/j.resconrec.2019.104669.

Wolniak, P., **Sauthoff, B.**, **Lachmayer, R.** & **Mozgova, I.** 2019 Scaling of technical systems using an object-based modelling approach. *Proceedings of the Design Society: International Conference on Engineering Design* **1** (1), 1603–1612; doi:10.1017/dsi.2019.166.

Xu, S., **Hao, L.**, **Yang, G.**, **Lu, K.** & **An, X.** 2021 A topic models based framework for detecting and forecasting emerging technologies. *Technological Forecasting and Social Change* **162**, 120366; doi:10.1016/j.techfore.2020.120366.

Yang, Y. & **Cooke, C.** 2021 Exploring the barriers to upscaling the production capacity of the edible insect sector in the United Kingdom. *British Food Journal* **123** (4), 1531–1545; doi:10.1108/BFJ-04-2020-0310.

Zimmermann, A. W., **Wunderlich, J.**, **Müller, L.**, **Buchner, G. A.**, **Marxen, A.**, **Michailos, S.**, **Armstrong, K.**, **Naims, H.**, **McCord, S.**, **Styring, P.**, **Sick, V.** & **Schomäcker, R.** 2020 Techno-economic assessment guidelines for CO2 utilization. *Frontiers in Energy Research* **8**, 5; doi:10.3389/fenrg.2020.00005.