

Scaling process intensification technologies: what does it take to deploy?

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ABSTRACT

Process intensification (PI) has emerged as a transformative approach to enhancing efficiency, sustainability, and economics across chemical and manufacturing industries. However, within its dedicated communities, there is recognition of a persistent gap in transitioning these innovations from laboratory-scale success to widespread industrial adoption. Scaling up PI technologies is far more complex than simply replicating laboratory conditions on a larger scale. Challenges such as the integration with existing units and processes, proving economic viability, and navigating regulatory requirements often impede the practical implementation of PI innovations. This paper aims to identify the key enablers for scaling up PI technologies by presenting a roadmap to bridge the gap between concept and commercialization. While robust engineering design frameworks and advanced modeling tools are crucial, interdisciplinary collaborations and lab-to-market partnerships (or integrated scaling collaborations) are equally critical to drive the successful adoption of PI at the industrial scale.

1. The definition dilemma in process intensification

Before addressing the pathways to making PI a commercial success, it is crucial to first come to a shared understanding of what PI encompasses, as differing interpretations can influence its implementation and impact. In 2019, I co-organized a 5-day workshop with Prof. David Fernandez Rivas (University of Twente) on “Educating in Process Intensification” at the Lorentz Center in Leiden, The Netherlands. The aim of the workshop was to identify actionable strategies for educating on PI to accelerate its adoption at the commercial scale. We invited representatives from academia, industry, and government, with backgrounds in science and engineering, pedagogy, and policy, to incorporate a wide range of perspectives. The key outcomes were synthesized into two papers co-authored with most of the participants [1,2]. Here, we introduced new semantics related to PI, where we do not only underscore the departure from classic unit-operations but also the focus of PI on the impacts of a process and its ties with Sustainable Development (Fig. 1).

Still today, professionals from both academia and industry often confuse PI with process optimization. Optimization focuses on fine-tuning and improving the performance of existing processes to maximize efficiency, reduce costs, or improve output. It does not require the

fundamental redesign that is instead involved in PI.

PI can be defined in a variety of ways, and different interpretations may all be valid. When evaluating technologies, it is often easier to identify what is not PI (e.g. the incremental improvements that optimization brings to an innovation) rather than conclusively determining what it is. What is clear, however, is that PI “significantly enhances” transport rates, leading to “significantly smaller” equipment. Historically, this “significantly smaller” aspect has been defined as a 100-fold reduction in size [3]. However, more nuanced definitions have been given, and they are summarized in a comprehensive book on the topic and the highly cited paper by A.I. Stankiewicz and J.A. Moulijn [4,5]. This latter also offer a list of equipment and methods that classify as PI provided they deliver order-of-magnitude improvements compared to traditional equipment.

PI can also be defined as the effort of short-circuiting all mass-transfer and heat-transfer limitations, reducing the process rates to the intrinsic kinetics, governed by molecular events, including those induced using a catalyst [6]. Therefore, finding opportunities to combine PI and catalysis is essential to maximize process output. Opportunities to innovate at the interface of PI and catalysis have been identified in a book chapter I authored [7].

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2. Opportunities in process electrification: the need for new techno-economic and life-cycle models

Integrating techno-economic analysis (TEA) and life cycle analysis (LCA) is essential to address the interconnections between technical, economic, and environmental impacts, enabling the identification of trade-offs and facilitating informed decision-making [8].

New technologies, such as those that classify as PI do not follow the common rules for LCA and techno-economics. Indeed, PI technologies are countered by uncertainty that require a nuanced treatment providing a probabilistic distribution [9]. Further, the available TEA data on PI technologies, besides being limited in number, relies mostly on equipment-based TEA, with static energy supply and price [10,11]. Moreover, most PI equipment is not widely available, and its price is hard to quantify, data availability being the main bottleneck to develop these models [8,12]. LCA methods that have been applied to traditional processes depending on grid electricity could be applied to PI technologies [13,14]. However, these studies also highlight the uncertainty surrounding future developments of electrified technologies as the availability and stability of the electricity grid is uncertain itself.

Further, TEA is typically conducted at a TRL of at least 5, with increasing refinement up to TRL 9 [8,15]. Concerning LCA, it is usually carried out “ex post” after a technology’s deployment. However, LCA guidelines (ISO 14,044, 2006) [16] suggest that LCA as still suited to characterize technologies at TRLs 7–9. Recent research also indicates a growing trend in proposing methodological frameworks for the prospective application of LCA and TEA, even at very early TRLs (1–4) (Fig. 2) [8].

While the connection between PI and electricity-powered modular units might suggest greater commercialization challenges than traditional fossil-fuel-powered processes, it is crucial to recognize that PI technologies offer more opportunities for electrification. Achieving PI relies on key design features such as equipment geometry and symmetry

to maximize the surface area for transport-phenomena exchange [17]. In this context, using (clean) electricity to electrify surfaces or small components—such as the disc of a spinning disc reactor, a small magnetron generating microwaves, or a thin membrane—rather than entire reactor volumes reduces energy demands. This, in turn, lowers overall electrical consumption and decreases dependence on the grid.

Developing a successful technology at the commercial scale, implies working across several length and time scales: pm to nm for molecules, nm to μm for molecular clusters, nm to mm for particles and thin films, μm to cm for single and multiphase systems, mm to m for process units. With PI technologies the control at the smallest pm/nm scale can potentially be achieved by short-circuiting momentum, mass, and heat transfer limitations. It follows that the translation to process units and plants can be accomplished more swiftly compared to current process design practices. This is because, controlling the events at the molecular scale, translates into “having control” over them in the entire volume of the unit. For this reason, PI has been closely linked to Process System Engineering (PSE) [18]. PSE is a discipline aimed at executing technologies A to Z by process design including operations, optimization, and implementation, this latter requiring a deep understanding of business development (Fig. 3).

In the effort to provide an adapted techno-economic model for modular equipment, our team at Polytechnique Montréal related the concept of learning elasticity (β) to modular plants equipment costs, direct and indirect costs, and working capital [19]. β represents the investment for the implanted capacity of modular units and is linked to the characteristic dimension of a process item (n) with the relationship $b = 1/n - 1$ or $b = a - 1$, with a being the exponent relating investment and capacity in the widely adopted Chilton method [20–22].

In the same work we present a case study where we scale down and out (meaning that we reach economies of scale by numbering up the same process system), a 10 bbl per day gas-to-liquid (GtL) micro-refinery to convert wasted natural gas into Fischer-Tropsch fuels. Considering $b =$



Process Intensification is

“An approach “by function”, a departure from the conventional process design by unit operation.”

“It focuses not only on the process itself, but also on what happens outside or as a consequence of the process”.

Fig. 1. Promotional poster of the 5-days workshop held in Leiden (May 2019) on Educating on Process Intensification, together with examples of the updated semantics proposed by the participants [1].

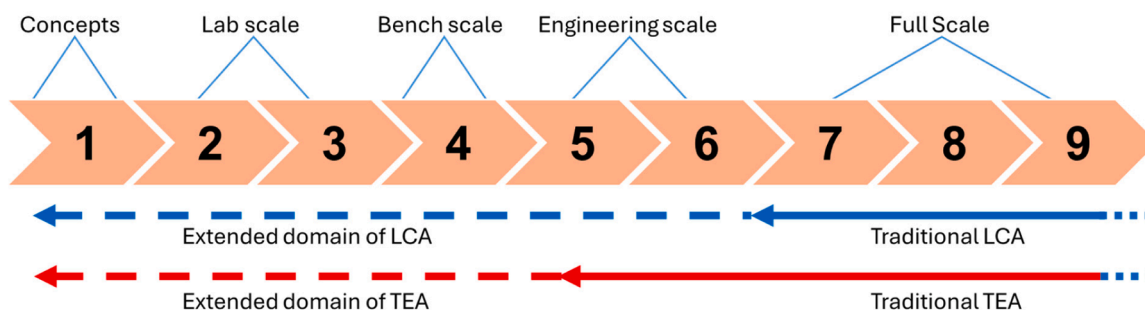


Fig. 2. Technology Readiness Level (TRL) for validated vs. extended (projectional) LCA and TEA. Adapted from [8].

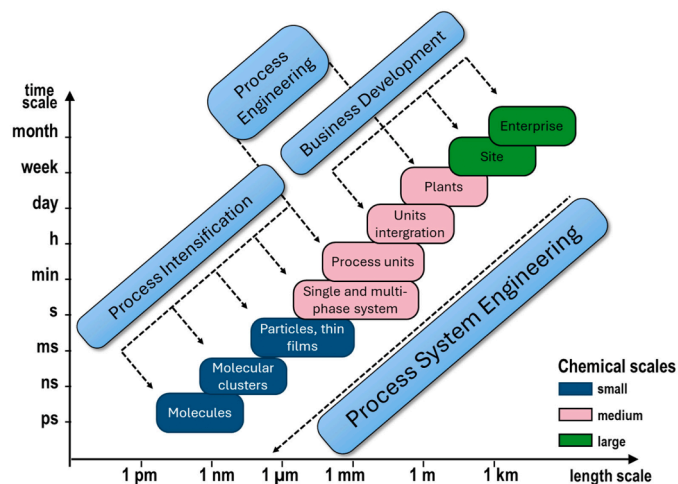


Fig. 3. Link between process intensification, process system engineering and business development. adapted from [6].

- 0.36, typical of chemical plants, the investment required for producing 100 units, each 100 times smaller in capacity, is comparable to the cost of a single 1000 bbl/day unit, estimated at \$1 million. The investment goes down as the number of units goes up.

Our team has extensively worked on modular GtL units. These compact systems designed for operation in remote areas offer advantages over stick-built facilities by minimizing on-site construction costs by utilizing prefabricated, containerized units that are ready for deployment. Achieving economic viability for distributed plants—such as a payback period of less than three years—relies on the production of standardized modules and innovative process design [23,24]. Finally, with the comeback of cottage industries and the trend towards modular plants, the economic concept of learning experience should be adopted more pervasively.

3. Drivers for process intensification implementation: industry-oriented vs. technology-oriented

In capital-intensive sectors such as the chemical and petrochemical industries, cost competitiveness has traditionally been achieved through a combination of scaling up production and technical advancements. Recently, within the process industry, there has been a growing shift toward constructing smaller, modular facilities instead of massive, traditionally built mega-projects [19].

During the 2019 Leiden workshop on Education on PI, the participants identified the main obstacles to commercial implementation of PI technologies, i.e., i) lack of success stories, ii) convenience of unit operations-oriented disciplines, iii) conservatism in upper management/risk aversion, iv) supply chain fragility, and v) perceived scalability issues. For a more detailed argumentation around these

bottlenecks, I refer the reader to these papers [1,2]. Some simplified approaches to help overcome these barriers are offered in Fig. 4. As highlighted in the previous section regarding the links between PI and PSE, interdisciplinary collaboration and lab-to-market partnerships (or integrated scaling collaborations) are equally crucial for driving the successful adoption of PI on an industrial scale.

Except a few PI technologies that have been commercially applied even before the PI became relatively mainstream (e.g. static mixers [25], divided wall columns [26], reactive distillation [27], and ultrasound processing for a narrow set of applications [28]), most PI technologies' applications have not past the lab-scale or have reached at most TRL 6 (being TRL 7 the first deployment stage).

It is becoming increasingly common to believe that PI will be effectively implemented in new processes and resource streams first, such as biomass and waste conversion or CO₂ capture and conversion, which are characteristic of the Climate Tech sector. Indeed, modern chemical production is largely concentrated in large, centralized facilities, which lack the flexibility to shift from fossil-based raw materials and energy sources to renewable alternatives [29]. Retrofitting PI to existing technologies may then follow later, once PI has been successfully demonstrated and validated with new resources, creating success stories (Fig. 4) [1,30]. To advance the TRL of any technology there are different funding types that are involved and may be gradually leveraged (see graphical abstract). In this context, funding opportunities for PI equipment and methods appear to be more technology-focused rather than industry- or sector-specific. This suggests that the most immediate priority for validating a PI technology is to demonstrate the performance and capabilities of the units or hardware across various processes, including resource-risky ones, rather than focusing solely on producing commodities or high-demand products. Although, as further substantiated below, the pharmaceutical industry represents an exception [31].

In this sense, entrepreneurship can propel the adoption of PI by tackling the opportunities mentioned above. Entrepreneurs are often willing to take calculated risks and secure funding to scale PI solutions that may not initially appeal to traditional, risk-averse organizations. Entrepreneurs can forge partnerships between academia, industry, and government to create interdisciplinary collaborations and lab-to-market pathways. Academic entrepreneurship deserves a special mention in driving sustainable technologies' implementation. Academics developing technologies that have the potential to be sustainable seem to score higher in "sustainable orientation" compared to academic entrepreneurs that have a simple interest in sustainability disconnected from technology and vice versa [32]. However, technical expertise alone is insufficient to drive the adoption of technologies: incubators and accelerators should be engaged early in the development process to validate the market potential and ensure its alignment with industry needs (see graphical abstract).

Considering market trends is key to implement any new technology. In 2024 Health has been the most venture capital (VC) funded sector in Europe (\$ 7.9B), followed by the Energy Sector (\$ 7.2B). In the same year the first leading segment by VC investment was Industrial Technology (\$ 3.3). In the United States (US) the most funded sectors were

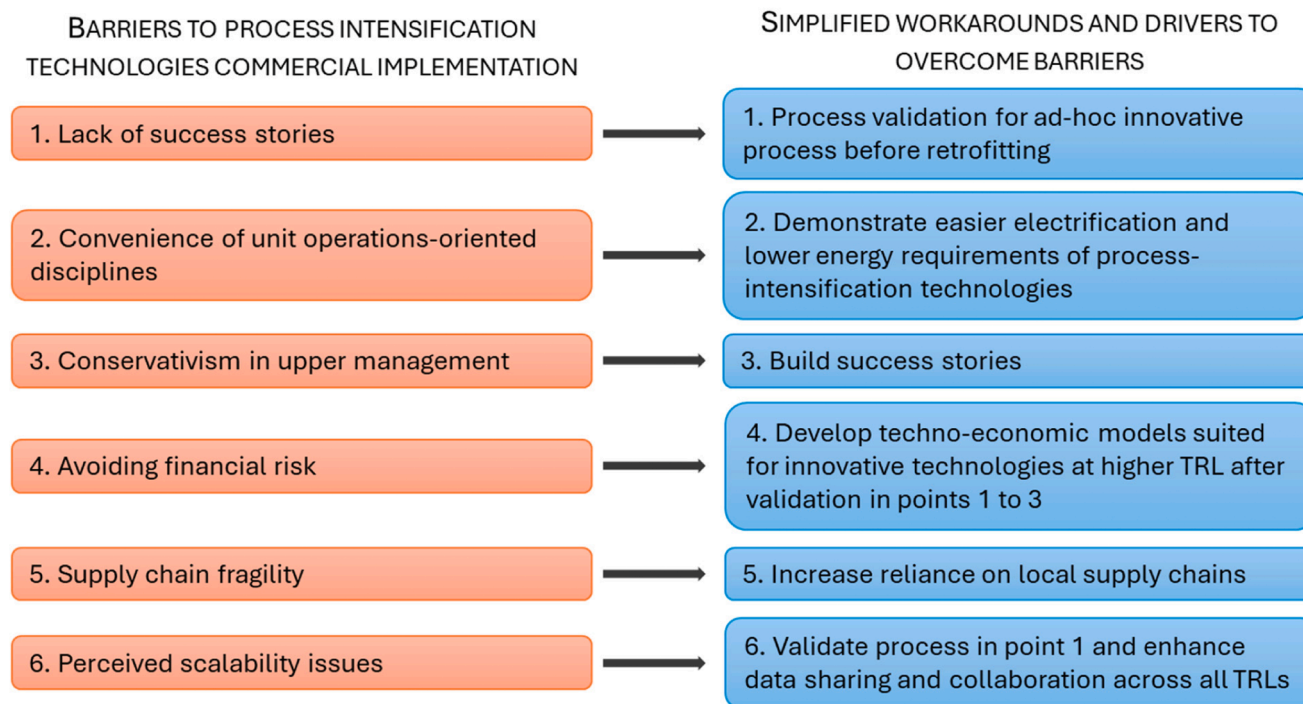


Fig. 4. Main barriers to the commercial implementation of Process Intensification technologies identified in [1], with opportunities and drivers to overcome them.

Enterprise Software (\$70.6B) and Health (\$45.9B), while the most funded segments were Generative Artificial Intelligence (GenAI) model makers and AI Data Preparation and Generation (\$ 40.0B+ combined), while Industrial Technology ranked only 14th (\$ 2.6B). China raised the second highest VC total of any country in 2024 (\$ 38.5B) after United States (\$ 198.2 B), of which 38 % shares went to Deep Tech. Climate Tech VC funding deserves a special mention. It reached \$ 21B, \$ 14B, and \$ 8B in Europe, United States and China, respectively, in 2023 (dropping by 25 % compared to 2021). Overall, Climate Tech VC investment increased by 12.5x within the last decade (2023 vs 2013), while still being subject to several fluctuations [33].

Climate Tech encompasses several segments, the most prominent being energy, food, mobility, water tech, industry and carbon tech. These latter two include subsegments where industrial technologies, such as those categorized as “PI”, may attract funding (e.g. mining and metals, plastic recycling, sustainable cement for “industry”, and carbon utilization for “carbon tech”). In Europe, where significant VC funding is being directed toward Industrial Technology and Climate Tech, PI technologies find a promising and supportive environment to advance. PI also offers significant investment opportunities to modernize and enhance the efficiency of traditional pharmaceutical manufacturing processes [34] considering the ever growing investment in the Health sector.

4. Conclusions

Commercializing Process Intensification (PI) technologies presents unique challenges and opportunities. While PI holds transformative potential for improving economics and sustainability, its deployment beyond laboratory scales is hindered by barriers such as risk aversion, supply chain fragility, and scalability concerns. Distinguishing it from optimization and focusing on its impact on sustainability is key to having a shared understanding and fostering interdisciplinary collaboration beyond academia. It is key to validate PI technologies at the early stage involving risk-taking entrepreneurs, incubators, and accelerators with knowledge of market demand and investment opportunities, as well as combining TEA and LCA to partially de-risk uncertainties at low

TRL. New techno-economic models adapted for modular units, such as learning elasticity, are crucial to correctly characterize investment and de-risk PI technologies. Proving the effectiveness of PI to create value from new resource streams (e.g. waste and biomass) can open the doors to wider adoption and retrofitting opportunities with traditional feedstock. There are nevertheless regions and sectors that seem more favorable for PI technologies, e.g. Climate Tech and pharmaceutical manufacturing. With growing venture capital and government backing, particularly in Europe, PI has stronger potential to support more sustainable industrial practices.

CRediT authorship contribution statement

Daria C. Boffito: Conceptualization, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

References

- [1] D. Fernandez Rivas, D.C. Boffito, J. Faria-Albanese, J. Glassey, N. Afraz, H. Akse, K. V.K. Boodhoo, R. Bos, J. Cantin, Y.W. Chiang, J.M. Commenge, J.L. Dubois, F. Galli, J.P. Gueneau de Mussy, J. Harmsen, S. Kalra, F.J. Keil, R. Morales-Menendez, F.J. Navarro-Brull, T. Noël, K. Ogden, G.S. Patience, D. Reay, R. M. Santos, A. Smith-Schoettker, A.I. Stankiewicz, H. van den Berg, T. van Gerven, J. van Gestel, M. van der Stelt, M. van de Ven, R.S. Weber, Process intensification education contributes to sustainable development goals. Part 1, *Educ. Chem. Eng.* 32 (2020) 1–14, <https://doi.org/10.1016/j.ece.2020.04.003>.
- [2] D. Fernandez Rivas, D.C. Boffito, J. Faria-Albanese, J. Glassey, J. Cantin, N. Afraz, H. Akse, K.V.K. Boodhoo, R. Bos, Y.W. Chiang, J.M. Commenge, J.L. Dubois, F. Galli, J. Harmsen, S. Kalra, F. Keil, R. Morales-Menendez, F.J. Navarro-Brull, T. Noël, K. Ogden, G.S. Patience, D. Reay, R.M. Santos, A. Smith-Schoettker, A. I. Stankiewicz, H. van den Berg, T. van Gerven, J. van Gestel, R.S. Weber, Process intensification education contributes to sustainable development goals. Part 2, *Educ. Chem. Eng.* 32 (2020) 15–24, <https://doi.org/10.1016/j.ece.2020.05.001>.
- [3] C. Ramshaw, in: *Proceedings of the 1st International Conference on Process Intensification in the Chemical Industry*, Antwerp, 1995.
- [4] A. Stankiewicz, T. van Gerven, G. Stefanidis, *The Fundamentals of Process Intensification*, 1st ed, Wiley-VCH, Weinheim, 2019.
- [5] A. Stankiewicz, J.A. Moulijn, *Process intensification: transforming chemical engineering*, *Chem. Eng. Prog.* 96 (2000) 22–33.
- [6] D.C. Boffito, D.F. Rivas, Process intensification connects scales and disciplines towards sustainability, *Can. J. Chem. Eng.* 98 (2020) 2489–2506, <https://doi.org/10.1002/cjce.23871>.
- [7] D.C. Boffito, T. van Gerven, Process intensification and catalysis, in: J. Reedijk (Ed.), *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*, Elsevier, Waltham, 2019, pp. 1–16, <https://doi.org/10.1016/B978-0-12-409547-2.14343-4>.
- [8] R. Mahmud, S.M. Moni, K. High, M. Carbajales-Dale, Integration of techno-economic analysis and life cycle assessment for sustainable process design- A review, *J. Clean Prod.* 317 (2021) 128247, <https://doi.org/10.1016/j.jclepro.2021.128247>.
- [9] J. Bergerson, S. Cucurachi, T. P. Bringing a life cycle perspective to emerging technology development, *J. Ind. Ecol.* 24 (2020) 6–10, <https://doi.org/10.1111/jiec.12990>.
- [10] P.A. Pichardo, S. Karagöz, T. Tsotsis, R. Ciora, V.I. Manousiouthakis, Technical economic analysis of an intensified integrated gasification combined cycle (IGCC) power plant featuring a sequence of membrane reactors, *J. Membr. Sci.* 579 (2019) 266–282, <https://doi.org/10.1016/j.memsci.2019.03.011>.
- [11] S. Sadula, A. Athaley, W. Zheng, M. Ierapetritou, B. Saha, *ChemSusChem* 10 (2017) 2566, <https://doi.org/10.1002/cssc.201700183>.
- [12] S. Yaser Khojasteh, B.A. Saville, H.L. MacLean, Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies, *Int. J. Hydrog. Energy* 42 (2017) 18894–18909, <https://doi.org/10.1016/j.ijhydene.2017.05.219>.
- [13] A. Mendoza Beltran, B. Cox, C. Mutel, D.P. van Vuuren, D. Font Vivanco, S. Deetman, O.Y. Edelenbosch, J. Guinée, A. Tukker, When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment, *J. Ind. Ecol.* 24 (2020) 64–79, <https://doi.org/10.1111/jiec.12825>.
- [14] E. Zschieschang, P. Pfeifer, L. Schebek, Life cycle assessment in Chemical and Micro reaction engineering, *Chem. Eng. Technol.* 36 (2013) 911–920, <https://doi.org/10.1002/ceat.201200635>.
- [15] A.D. Patel, K. Meesters, H. Uil, E. de Jong, K. Bloka, M. Patel, Sustainability assessment of novel chemical processes at early stage: application to biobased processes, *Energy Environ. Sci.* 5 (2012) 8430–8444, <https://doi.org/10.1039/C2EE21581K>.
- [16] International Organization for Standardization (ISO) 14040, *International Standard Environmental Management - Life Cycle Assessment - Principles and Framework*, 2006.
- [17] T. van Gerven, A. Stankiewicz, Structure, energy, synergy, time—The fundamentals of process intensification, *Ind. Eng. Chem. Res.* 48 (5) (2009) 2465–2474, <https://doi.org/10.1021/ie801501y>.
- [18] Q. Li, A. Somoza-Tornos, J. Grievink, A.A. Kiss, Challenges and opportunities for process intensification in Europe from a process systems engineering perspective, *Front. Energy Res.* 12 (2024) 1340635, <https://doi.org/10.3389/fenrg.2024.1340635>.
- [19] G.S. Patience, D.C. Boffito, Distributed production: scale-up vs experience, *Adv. Manuf. Process.* 2 (2020) e10039, <https://doi.org/10.1002/amp2.10039>.
- [20] P.F. Ostwald, Economy of scale for manufacturing systems, *J. Manuf. Sys.* 8 (4) (1989) 267–273, [https://doi.org/10.1016/0278-6125\(89\)90004-6](https://doi.org/10.1016/0278-6125(89)90004-6).
- [21] D.I. Garnett, G.S. Patience, Why do scale-up power laws work? *Chem. Eng. Prog.* 89 (1993) 76–78.
- [22] D.I. Garnett, Money= $k \times \text{People}^4$, *Chem. Tech.* 22 (22) (1992) 477.
- [23] R.S. Benson, J.W. Ponton, Process miniaturisation : a route to total environmental acceptability? *Chem. Eng. Res. Des.* 71 (1993) 160–168.
- [24] D. Braide, C. Panaritis, G. Patience, D.C. Boffito, Gas to liquids (GTL) microrefinery technologies: a review and perspective on socio-economic implications, *Fuel* 375 (2024) 132385, <https://doi.org/10.1016/j.fuel.2024.132385>.
- [25] R.K. Thakur, C. Vial, K.D.P. Nigam, E.B. Nauman, G. Djelveh, Static mixers in the process industries—A review, *Chem. Eng. Res. Des.* 81 (2003) 787–826, <https://doi.org/10.1205/02638760322302968>.
- [26] M. Bhargava, A.P. Sharma, Introduction to dividing-Wall columns, *Chem. Eng. Prog.* (2019) 30–34.
- [27] G.J. Harmsen, Reactive distillation: the front-runner of industrial process intensification: a full review of commercial applications, research, scale-up, design and operation, *Chem. Eng. Process.* 46 (9) (2007) 774–780.
- [28] D. Meroni, R. Djellabi, M. Ashokkumar, C.L. Bianchi, D.C. Boffito, Sonoprocessing: from concepts to large-scale reactors, *Chem. Rev.* 122 (3) (2022) 3219–3258.
- [29] D.E. Resasco, B. Wang, D. Sabatini, Distributed processes for biomass conversion could aid UN sustainable development goals, *Nat. Catal.* 1 (2018) 731–735, <https://doi.org/10.1038/s41929-018-0166-6>.
- [30] E. Pahiya, S. Golshan, B. Blais, D.C. Boffito, Perspectives on the process intensification of CO₂ capture and utilization, *Chem. Eng. Process.* 176 (2022) 108958, <https://doi.org/10.1016/j.cep.2022.108958>.
- [31] N. Yazdanpanah, Continuous manufacturing in the pharmaceutical industry, *Chem. Eng. Prog.* (2021) 28–35.
- [32] Ruiz-Ruano A.M., Puga J.L., The measurement if sustainable orientation in academic entrepreneurs, in: L.G. Chova, A.L. Martinez, I.C. Torres (Eds.), *Proceedings of the ICERI2015: 8th International Conference of Education, Research and Innovation Proceedings*, Seville, 2015, pp. 6758–6762.
- [33] Dealroom.co, 2025 accessed on 2025 January 17th.
- [34] D. Müller, L. Klein, J. Lemke, M. Schulze, T. Kruse, M. Saballus, J. Matuszczyk, M. Kampmann, G. Zijlstra, Process intensification in the biopharma industry: improving efficiency of protein manufacturing processes from development to production scale using synergistic approaches, *Chem. Eng. Process.* 171 (2022) 108727, <https://doi.org/10.1016/j.cep.2021.108727>.