The Reshoring Paradox: A Paracetamol Case Study

Authors

Dr. Aiperi Otunchieva
Reashika Das

Date
August 28, 2026

We make healthcare better, globally!

Arcondis AG
Hegenheimermattweg167b,
4123 Allschwil, Switzerland

T +41 61 717 82 00
info@arcondis.com
www.arcondis.com

Content

1. Executive Summary

European pharmaceutical companies are under growing pressure to reshore essential medicine production while also reducing environmental impact. This case study uses paracetamol API manufacturing to show that reshoring alone is not enough: without circular manufacturing, local production may simply reproduce linear, resource-intensive systems closer to demand.
Arcondis applied a localized, gate-to-gate Life Cycle Assessment to a 1,000 kg paracetamol API production scenario in a German industrial context, using ISO 14040:2026 approach. The assessment revealed that the largest environmental burdens were not in the core synthesis step, but in supporting operations such as filtration, packaging and drying.
By modelling acetic acid recovery through Double Effect Distillation, the study showed that circular recovery could transform a substantial gross manufacturing footprint into a net negative gate-to-gate balance. This result demonstrates how reshored pharmaceutical manufacturing can become more resilient, circular and data-driven when sustainability is embedded into process design from the start.

2. Strategic Context

Pharmaceutical resilience has become a strategic priority across Europe. The COVID-19 pandemic, geopolitical instability and recurring medicine shortages have exposed the risks of relying heavily on distant manufacturing hubs for active pharmaceutical ingredients (API). For essential medicines such as paracetamol, reshoring has become part of a broader debate about supply security, industrial sovereignty and patient access.
However, reshoring production does not automatically make pharmaceutical manufacturing more sustainable. If companies reproduce the same linear production systems within Europe, they may reduce supply-chain exposure while continuing to carry high resource use, waste generation and avoidable emissions. The strategic challenge is therefore not only where medicines are produced, but how they are produced.
This creates an opportunity to connect pharmaceutical reshoring with circular economy principles. Localized production can be redesigned around resource recovery, lower-impact utilities, reusable packaging, improved waste segregation and environmental data. Life Cycle Assessment becomes especially valuable in this context because it identifies where environmental burdens occur and which interventions create measurable impact.
The paracetamol API case highlights this shift. It shows that sustainability improvements are often found beyond the reaction chemistry itself, in the supporting factory systems that surround production: PW, steam, filtration, drying, packaging and recovery loops. For Europe's reshoring agenda to deliver long-term value, we consider the production option to be local, circular and operationally transparent.

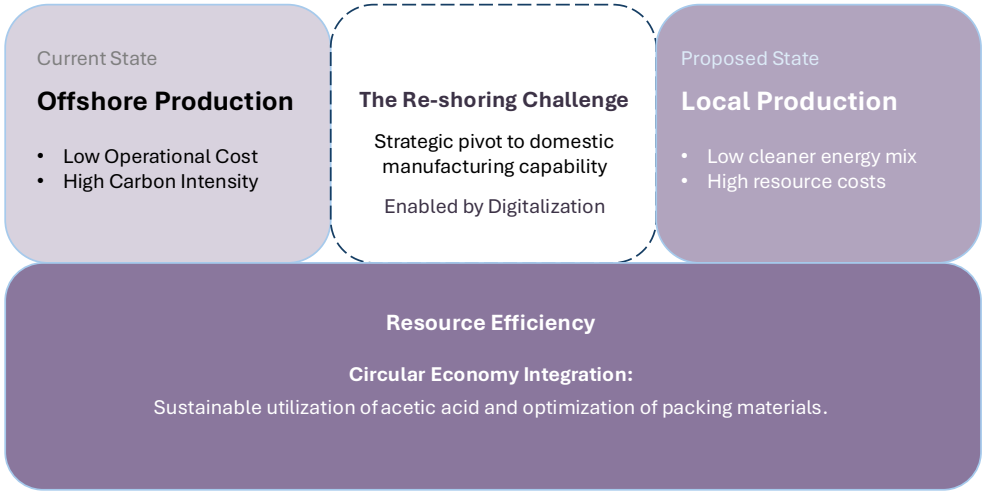

Figure 1: Conceptual framework of the pharmaceutical reshoring paradox and the role of resource efficiency.

3. Client Challenge

The understanding of the environmental impact of API manufacturing at process level was lacking. Generic industry averages could not provide enough detail to identify where interventions would matter most. The organization needed a clearer view of actual material and energy flows inside the production system.

Table 1. Points raised during the paracetamol API process

Challenge area	Why it mattered
Process transparency	A need to understand which production steps contributed most to the environmental footprint.
Hidden utility impacts	Supporting operations such as filtration, water purification and drying were suspected to be significant but were not fully quantified.
Packaging and waste	Packaging materials created both carbon impact and solid waste, but their contribution needed to be measured.
Circular recovery potential	Acetic acid was generated as a by-product, creating an opportunity to assess whether recovery could reduce the net footprint.
Reshoring implications	The need for evidence that localized production could be designed as a more sustainable model rather than a relocation of existing burdens.

4. Strategic Ambition

The ambition was to move beyond a conventional reshoring discussion and define what sustainable, localized pharmaceutical manufacturing could look like in practice. There was a need to understand how paracetamol API production could be assessed not only as a supply-security question, but as an opportunity to redesign manufacturing around circularity and resource efficiency.

Table 2: The principles of the desired future state of the production

Future-state principle	Description
Local	API production is closer to European demand, reducing exposure to fragile global supply chains.
Circular	Valuable by-products are recovered and reused instead of being treated as waste.
Data-driven	Manufacturing decisions are informed by plant-specific process data rather than generic assumptions.
Resource-efficient	Utilities, water systems, drying operations and packaging are optimized alongside the chemistry.
Operationally actionable	LCA findings are translated into practical improvement initiatives and investment priorities.

This ambition reframed LCA from a retrospective reporting exercise into a decision-support tool. The goal was not simply to calculate a footprint, but to show where the manufacturing system could be redesigned to reduce emissions, recover value and support a more resilient pharmaceutical industry.

5. Arcondis Approach

Arcondis applied a localized, gate-to-gate Life Cycle Assessment of 1,000 kg of paracetamol API production within a German industrial context. The assessment followed ISO 14040:2026 approach and used inventory data to reflect the production system.

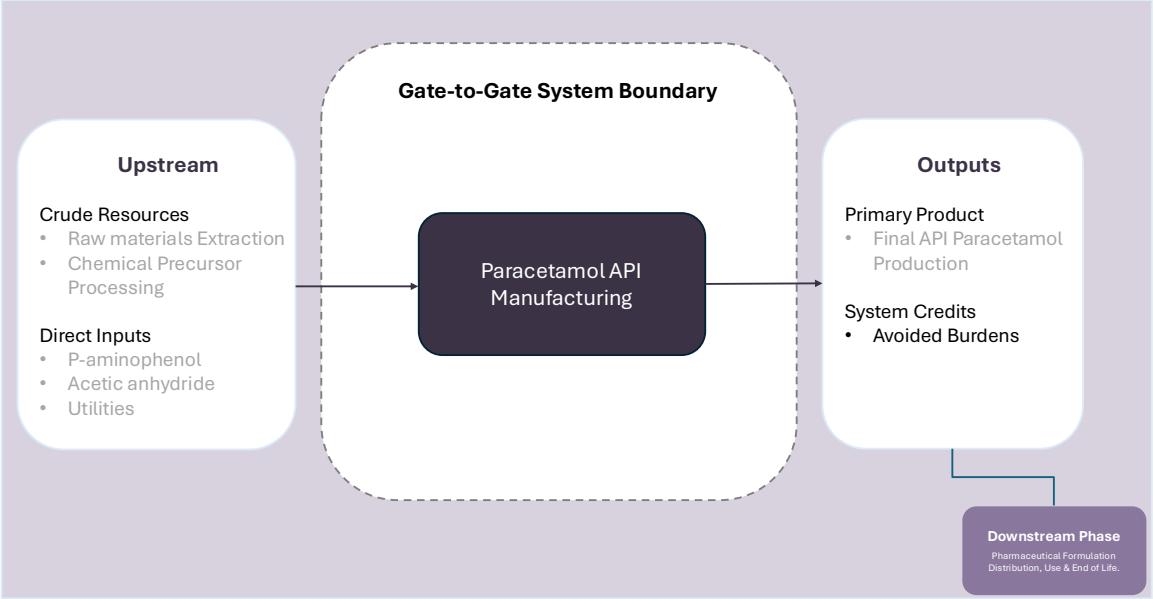

Figure 2: Gate-to-Gate system boundary for API paracetamol.

The analysis covered the material and energy flows from p-aminophenol and acetic anhydride entering the facility through to the final API and recovery stages. This allowed Arcondis to assess the manufacturing system at process-step level and not rely on high-level industry averages. The approach focused on five areas.

5.1. Defining the system boundary

The assessment used a gate-to-gate boundary for API paracetamol production. This made it possible to isolate the environmental performance of the manufacturing process itself, while clearly distinguishing it from upstream raw material production and downstream distribution.
This boundary was important because it allowed the team to evaluate the internal factory account and identify where operational interventions could directly improve performance.

5.2. Building a plant-specific inventory

Arcondis mapped key material and energy flow across the production system, including:

- Inputs, such as p-aminophenol, acetic anhydride, water and auxiliary materials.
- Utilities, including electricity, thermal energy, PW and WFI systems.
- Process stages, including acetylation, crystallization, filtration, drying, packaging and recovery.
- Outputs, including paracetamol API, acetic acid by-product and solid waste streams.

Using plant-specific inventory data improved the relevance of the results. It showed where burdens occurred in the actual operating context, rather than where generic datasets might suggest they should occur.

5.3. Quantifying process-step contributions

The assessment calculated the contribution of each process step to Global Warming Potential. The initial assumption was that the core chemical synthesis would dominate the footprint. Instead, the analysis showed that the major hotspots were in the

surrounding manufacturing system. Filtration contributed 49.18% of the gross process footprint, packaging contributed 25.11%, and drying contributed 16.39%. Acetylation and crystallization together accounted for a relatively small share of the gross Global Warming Potential. This revealed that the environmental burden was concentrated in supporting operations rather than the core reaction chemistry.

Table 3: Process steps and their contribution to gross Global Warming Potential

Process step	Contribution to gross GWP
Filtration	49.18%
Packaging	25.11%
Drying	16.39%
Acetylation and crystallization	Relatively small share

This finding changed the improvement logic. The priority was not only greener synthesis, but also optimization of factory systems.

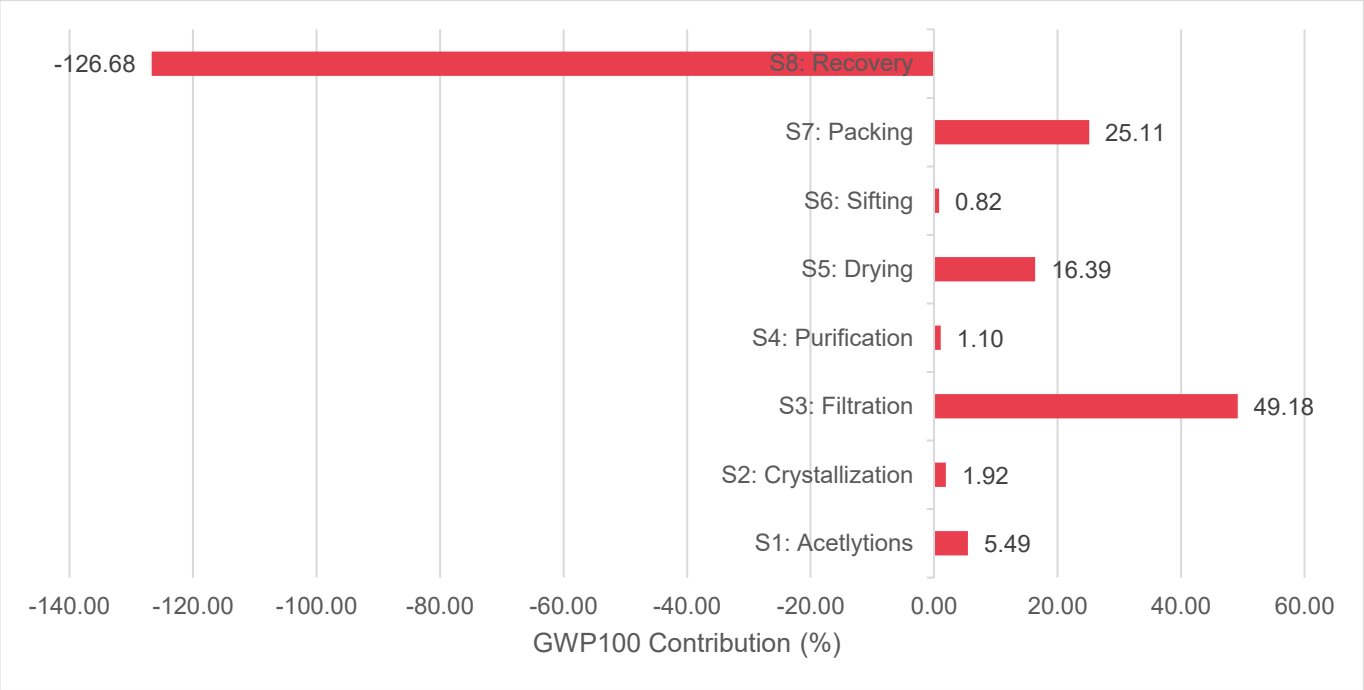

Figure 3: Process step contribution analysis for Global Warming Potential.

5.4. Assessing circular recovery potential

A major part of the approach was modelling the recovery of acetic acid, generated as a by-product during paracetamol API production. The process generated approximately 397 kg of acetic acid per 1,000 kg batch.
Arcondis assessed a Double Effect Distillation recovery scenario. The model showed that approximately 388 kg of acetic acid could be recovered, corresponding to a 97.74% recovery rate.

Table 4. Acetic Acid Recovery: Mass Carbon Balance per 1,000kg batch

Recovery metric	Result per 1,000 kg batch
Acetic acid by-product generated	397 kg
Acetic acid recovered	388 kg
Recovery rate	97.74%

Avoided-burden credit	-632.90 kg CO2e
Additional electricity burden	67.20 kg CO2e
Net recovery benefit	-565.70 kg CO2e

The recovered acetic acid could potentially displace virgin acetic acid in applications such as industrial solvents, coatings, adhesives, textile processing, wastewater treatment or other chemical processes, depending on purity requirements.

5.5. Evaluating waste and packaging streams

The assessment also quantified solid waste generation. Total solid waste was estimated at 109.4 kg per 1,000 kg batch of paracetamol API. More than 90% of this waste came from packaging-related materials, including mixed packaging, plastics, fibre and cardboard.

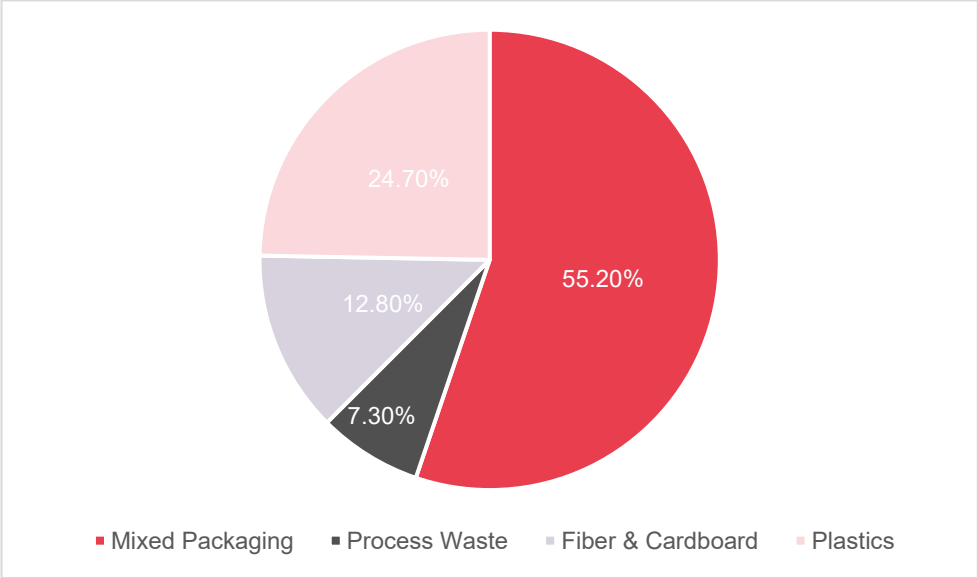

Figure 4: Solid waste generation breakdown by material category.

This showed that packaging was not a secondary issue. It contributed 25.11% of the gross GWP and dominated the solid waste profile. The results pointed to practical improvement opportunities in reusable packaging, supplier take-back systems, recyclable materials and improved segregation.

6. Turning Strategy into Action

The assessment translated sustainability strategy into a set of practical initiatives that could be embedded in pharmaceutical manufacturing operations. Rather than treating LCA as a static report, the findings created a roadmap for targeted process optimization.

6.1. Circular recovery initiatives

The acetic acid recovery scenario showed the strongest potential improvement. Recovering approximately 388 kg of acetic acid per 1,000 kg batch could change the carbon balance of the gate-to-gate process. The gross manufacturing footprint of the core production stages is 446.54 kg CO2e per batch. After including the recovery credit, the final factory account became -119.16 kg CO2e per 1,000 kg batch within the defined boundary.

This does not mean that paracetamol is carbon-negative across its full life cycle. Upstream raw material production and downstream distribution were not fully included in the gate-to-gate boundary. However, it demonstrates that circular recovery can materially transform the environmental profile of internal manufacturing operations.

6.2. Utility and process optimization

The hotspot analysis pointed to filtration, packaging and drying as priority areas. For filtration, the main issue was the energy and thermal demand associated with high-purity water systems such as WFI and PW. For drying, the key driver was thermal energy demand.

Practical initiatives include:

- Improving PW efficiency by reducing unnecessary high-purity water use where quality requirements allow.
- Optimizing filtration operations to reduce energy and thermal demand.
- Improving drying efficiency through better heat integration, process control or equipment optimization.
- Monitoring utilities at process-step level to identify deviations and prioritize investment.

6.3. Packaging and waste reduction

Because packaging contributed 25.11% of gross GWP and more than 90% of solid waste, packaging became a major action area.

Table 5. Practical Initiatives identified during the case study

Initiative	Practical action
Returnable transport packaging	Replace single-use cardboard and plastic layers with reusable pallets, crates or bulk containers where contamination risk is low.
Supplier take-back schemes	Ask suppliers of p-aminophenol, acetic anhydride, solvents and auxiliary materials to take back empty drums, IBCs, pallets, liners and secondary packaging.
Reusable or reconditioned containers	Use certified reconditioned or closed-loop drums and IBCs for non-sterile input materials where GMP and safety rules allow.
Secondary packaging reduction	Review whether plastic wrapping, outer cartons, fibreboard and intermediate layers are necessary for each material stream.
Mono-material packaging	Replace mixed or laminated materials with clearly separable cardboard, HDPE or PP streams.
Recycled-content materials	Specify recycled-content cardboard and plastic for secondary and tertiary packaging.
Improved segregation	Set up separate streams for cardboard, plastic film and liners, drums and IBCs.

6.4. Governance and stakeholder engagement

Turning the findings into action would require cross-functional ownership. Sustainability improvements in pharmaceutical manufacturing cannot sit with one function alone; they involve quality, engineering, procurement, EHS, manufacturing, supply chain and finance.

Table 6. Stakeholder groups and their role in implementation in the governance model

Stakeholder group	Role in implementation
Manufacturing and engineering	Optimize filtration, drying, utilities and recovery systems.
Quality and GMP teams	Assess where reusable packaging or recovered materials are compatible with compliance requirements.
Procurement	Engage suppliers on take-back schemes, packaging specifications and circular material options.
EHS and sustainability	Track environmental indicators and validate improvement impact.
Finance and leadership	Evaluate investment cases for recovery technology and operational upgrades.
Digital and data teams	Connect LCA insights with manufacturing data, ERP systems and sustainability platforms.

The long-term opportunity is to make LCA a living operational tool. By linking environmental modelling with manufacturing data, ERP systems and sustainability platforms, companies can identify emissions hotspots continuously, prioritize interventions and justify circular manufacturing investments with stronger evidence.

7. How Arcondis Made a Difference

Arcondis helped shift the discussion from broad sustainability ambition to operational evidence. The case study showed that the environmental footprint of reshored pharmaceutical production cannot be understood through assumptions or generic averages alone. It requires process-level data, practical manufacturing knowledge and a circularity lens.
The distinctive contribution was the ability to connect LCA with strategic reshoring decisions. Instead of treating reshoring as a purely supply-chain or geopolitical issue, Arcondis framed it as an opportunity to redesign pharmaceutical manufacturing for resilience and sustainability at the same time.

Table 7. Ways in which Arcondis made a difference

Differentiator	Value delivered
Process-level insight	Identified the true hotspots in filtration, packaging and drying rather than focusing only on synthesis.
Circular manufacturing perspective	Demonstrated the value of acetic acid recovery and quantified its potential to transform the gate-to-gate carbon balance.
Actionable improvement roadmap	Translated LCA findings into practical initiatives for utilities, recovery, packaging and waste reduction.
Strategic relevance	Connected technical findings to Europe's broader pharmaceutical reshoring and resilience agenda.

The paracetamol API case shows that sustainable pharmaceutical manufacturing is measurable and actionable. The greatest opportunities are often found in the details: a filtration step, a drying unit, a packaging decision or a recovery loop.
The conclusion is clear: reshoring is necessary, but not sufficient. The future of European pharmaceutical manufacturing must be local, circular and data-driven. Anything less risks solving one crisis while deepening another.

7.1. Acknowledgements

We express our gratitude to Mr. Luis Aquino Velasquez from Institute for Technology and Innovation Management in RWTH Aachen University. This study was conducted as part of his Master thesis "Product Lifecycle Assessment of a Common Healthcare Product: From Raw Materials to Manufacturing: A Case Study on Paracetamol API".

Arcondis

info@arcondis.com
www.arcondis.com

Basel (Headquarters)

Arcondis AG
Hegenheimermattweg 167b,
4123 Allschwil, Switzerland

T +41 61 717 82 00

Boston

Arcondis Corporation
90 Canal Street
Boston, Massachusetts
02114 USA

T +1 857 4444 515

Frankfurt

Arcondis GmbH
Mergenthalerallee 79 – 81
65760 Eschborn
Germany

T +49 6196 76 99980

Košice

Arcondis Solutions s.r.o.
Štúrova 27
040 01 Košice
Slovakia

T +421 915 577 685

Kuala Lumpur

Arcondis Solutions Sdn Bhd
Tower 8, Avenue 5, Horizon 2
Bangsar South City
Kuala Lumpur
Malaysia

Munich

Arcondis GmbH
Landshuter Allee 8
80637 München
Germany

T +49 89 54 55 83 24

San Diego

Arcondis Corporation
Emerald Plaza 402 West
Broadway Suite 400, San Diego,
CA 92101

T +1 857 4444 515

Singapore

Arcondis PTE LTD
20A Tanjong Pagar Road
088443
Singapore

T +65 6983 5659