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General Title:
ENEL'S STRATEGIC TRADE-OFFS:
NAVIGATING PROFITABILITY, RELIABILITY, AND SUSTAINABILITY IN THE GLOBAL ENERGY TRANSITION

Individual Part:
THE RECYCLABILITY PARADOX:
A MULTI-CRITERIA ANALYSIS OF END-OF-LIFE PATHWAYS FOR ENEL'S WIND TURBINE BLADES

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Abstract

The common part, consisting of the case and teaching note, explores how Enel navigates the energy trilemma – the fundamental tension between business profitability, grid reliability, and environmental sustainability – through analysis of competitive positioning, regulatory frameworks, capital allocation trade-offs, and infrastructure resilience in the European utility sector. It enables instructor–led discussion of how a large, capital–intensive utility navigates uncertainty in regulation, commodity markets, and infrastructure deployment while shaping long-term investment decisions.

The individual parts examine distinct analytical challenges. The first study applies DCF valuation, financial ratios, and scenario analysis to assess Enel's value drivers and resilience. The individual part evaluates different end-of-life options for wind turbine blades with a Multi-Criteria Decision Making Analysis: landfilling, mechanical recycling, and chemical recycling. By integrating fragmented data weighted to Enel's strategic priorities, the study demonstrates that while mechanical recycling offers immediate viability, solvolysis presents the superior long-term strategic balance.

Keywords

Enel, Competitive Advantage, Corporate Strategy, Trade-Offs, Positioning, Circular Economy

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ENEL'S STRATEGIC TRADE-OFFS: NAVIGATING PROFITABILITY, RELIABILITY, AND SUSTAINABILITY IN THE GLOBAL ENERGY TRANSITION

Part 1:
Case

1. The Energy Trilemma

Rome, November 21, 2024. As the auditorium filled with investors and analysts, Enel's Chief Executive Officer, Flavio Cattaneo, took the stage at Capital Markets Day. Behind him, a large screen displayed the headline: "Strategic Plan 2025–2027." Cattaneo presented a three-year investment plan that he described as Enel's roadmap for what he called "the new energy era."

Cattaneo outlined a commitment of 43 billion EUR in capital expenditure (CAPEX), with a notable emphasis on grid reliability[1] and targeted growth in renewable generation. Out of the 43 billion EUR planned investments, about 26 billion EUR were directed toward the grids business, a 40% increase compared with the previous plan. Roughly 12 billion EUR were allocated to renewables, aiming to add around 12 Gigawatt (GW) of new capacity and to optimize the technological mix with more than 70% derived from onshore wind and dispatchable technologies such as hydropower and storage. This expansion was expected to raise total renewable capacity to about 76 GW and increase electricity generation by over 15% by 2027. About EUR 2.7 billion was allocated to the customer segment, with around 85% directed toward markets where Enel acts as an integrated utility[2], offering combined energy supply and related services (Enel 2024c). This strategic plan unfolded against the backdrop of steadily rising global electricity generation, reflecting the continued growth in demand (Appendix 1).

Cattaneo emphasized that the plan would focus on improving profitability and financial resilience by investing capital only in the most promising areas, while enhancing efficiency through tighter cost control. He added, "Between 2025 and 2027, we will focus on core activities and a flexible

[1] The capacity of the power system to deliver electricity consistently as needed with minimal disruptions (Harvard Electricity Policy Group, n.d.-a).
[2] A utility that owns and controls generation, transmission, and distribution components (Harvard Electricity Policy Group, n.d.-b)

capital allocation, increasing investments mainly on regulated assets[3] with predictable returns that will also support the acceleration of the energy transition." (Enel 2024).

The event brought together investors, analysts, and utility industry experts. Many of them had observed other utilities balancing aging infrastructure with increasingly ambitious decarbonization targets. Cattaneo's plan reflected fundamental tensions that had shaped Enel's evolution and now defined its future: balancing short-term profitability demands from investors, reliability expectations from regulators and customers, and sustainability commitments to governments and civil society. These three imperatives rarely aligned, as pursuing one often undermined the others, thereby encapsulating what could be described as a three-pronged energy dilemma, a "trilemma" faced by Enel. As Cattaneo concluded his remarks, one question loomed over the path ahead: How effectively could Enel navigate business profitability, grid reliability, and environmental sustainability in the years ahead?

2. Enel's Evolution: From Monopoly to Platform

Enel evolved from a state-owned monopoly created to electrify a nation into one of Europe's largest multinational utilities, demonstrating how strategic choices during critical transitions shape decades of corporate trajectory. The company's journey from Rome's corridors of power in 1962 to today's global renewables-and-grids platform illustrates the complex interplay between national industrial policy, market liberalization, and sustainable transformation (see Appendix 2 for a historic timeline).

2.1. Nation-Building Utility (1962–1990s)

In December 1962, the Italian Parliament established Ente Nazionale per l'Energia Elettrica (ENEL), unifying the production, transport, transformation, and distribution of electricity into a

[3] Regulated assets are essential infrastructure investments that provide stable, predictable cash flows because regulators set rates that let companies recover costs in any economic environment (MFG Asset Management 2017).

single state-controlled entity (Enel, n.d.-d). This represented more than regulatory reform; it embodied Italy's post-war ambition to modernize the economy and eliminate disparities between the industrialized north and agricultural south. The new monopoly acquired assets of over 1,300 private electricity companies, creating an integrated national system from previously fragmented local networks (Arena 2019).

Enel's early leadership recognized that network connectivity would drive the country's transformation. The company's grid-first strategy achieved remarkable results: submarine cables linked the mainland to all major islands through sophisticated engineering projects, creating the first truly national electricity system in Italian history. By the early 1970s, 99% of the country gained access to electricity, with over half a million rural homes connected for the first time (Enel, n.d.-d).

In the 1970s, the energy crisis prompted Enel to pioneer renewable energy in Italy, developing the country's largest hydroelectric plant and its first solar and wind power facilities. During the 1980s, growing environmental awareness and the post-Chernobyl phaseout of nuclear power reinforced Enel's commitment to sustainability, with greater emphasis on reducing pollution, protecting local communities, and expanding renewable energy initiatives (Enel, n.d.-d).

2.2. From Monopoly to Markets (1990s–2010)

In the 1990s, the European Union (EU) introduced directives that opened electricity markets to competition and private investments, transforming the industry across Europe. Italy's comprehensive reform arrived with Legislative Decree No. 79/1999, known as the Bersani Decree, which mandated the structural separation of Enel's vertically integrated business model into distinct entities for generation, distribution, and transmission (Fucci and Fucci 1999). Similar reforms unfolded in the United Kingdom, Spain, and Germany, reflecting the EU-wide effort to create an integrated electricity market (Jamasb and Pollitt 2005).

November 1999 marked a watershed moment with Enel's initial public offering (IPO), which became the largest IPO in global history at that time (Goldstein 2003). Through the sale, the Italian Treasury offered 34.5% of Enel's shares, raising approximately USD 19 billion and valuing the company at about USD 54.8 billion. The sale immediately attracted intense interest from investors, with Enel shares expected to represent between 10 and 12% of the Milan Stock Exchange's MIB 30 index (Los Angeles Times 1999). The privatization of Enel exposed management to the discipline of capital markets, while the Italian state retained a controlling interest. This partial privatization fundamentally altered strategic priorities, requiring management to balance public policy objectives with the expectations of private shareholders.

Between 2001 and 2006, Enel executed one of the world's most ambitious smart meter[4] deployments, installing over 30 million units in the first comprehensive national rollout globally and positioning Italy as a global leader in smart grid development (Stagnaro 2024). The 2008 establishment of Enel Green Power (EGP) represented another critical strategic decision, creating a dedicated subsidiary focused exclusively on sustainable energy development (Enel 2018c).

2.3. Platform Leadership & Renewable Expansion (2010–today)

The 2010s saw Enel evolve from a traditional utility into an integrated energy platform. This new operating model combined generation, grids, digital infrastructure, and customer-facing energy services, reflecting management's recognition that the shift toward renewables and customer-centric services required fundamentally different business models (Chesbrough 2020; Helms 2016). Enel's 'Open Power' philosophy supported this shift by promoting external partnerships, stronger research and development (R&D) integration, and organizational changes aimed at scaling renewable and digital services (Chesbrough 2016).

[4] A smart meter provides detailed consumption data that helps reduce electricity bills and improves grid monitoring, performance, and service quality (Iberdrola, n.d.-b).

Enel Green Power's expansion accelerated dramatically during the 2010s, supported by falling technology costs for wind and solar generation and ambitious climate commitments across key markets. The subsidiary's multi-technology approach encompassed wind, solar, hydrogen, hydroelectric, geothermal, marine, battery storage, and hybrid projects, which helped balance fluctuations in renewable output and ensured stable power generation across different conditions (Enel 2018c). By 2018, EGP had established itself as a global leader in renewable energy development, with operations spanning multiple continents and contributing meaningfully to group earnings (Enel 2018c). The company's commitment to net-zero emissions by 2040, with coal phase-out accelerated to 2027, positioned Enel among the most ambitious utilities globally regarding decarbonization (Bompan 2024) (Appendix 3).

Enel's second-generation smart meter rollout represented a significant advancement beyond the pioneering first-generation system. The second-generation Open Meter enabled quarter-hourly consumption readings, real-time power monitoring, and dedicated communication channels to external devices (Enel, n.d.-a). The expansion of customer-side solutions through the newly founded business line Enel X, established in 2017, introduced a unified suite of energy offerings. Created to lead Enel's diversification beyond traditional generation and distribution, the unit focused on electrifying end uses such as mobility and heating, developing digital energy services, and promoting new consumption models for households, businesses, and cities. Its portfolio included flexible demand management, on-site storage and microgrids, electric-vehicle charging with smart software control, and energy-optimization services. This approach allowed customers to monitor and reduce energy use more effectively while generating savings or revenues by feeding energy back into the grid (Enel X, n.d.).

During the 2020s, Enel restructured its portfolio to concentrate on markets and activities where it held competitive strength, emphasizing core geographies and higher-return businesses while reducing exposure in less strategic territories. Management identified that sustaining aggressive expansion in over 30 countries undermined both financial discipline and operational focus, especially as interest rates and required returns on invested capital increased sharply (Blanco et al. 2021; World Economic Forum 2024). As a result, Enel initiated a corporate simplification process, exiting selected non-core markets such as Argentina, and through the sale of renewable assets in Romania, while adopting lower-capital participation models like joint ventures and stewardship arrangements in non-core regions to maintain a presence without significant capital commitments. Investments were concentrated in core markets, particularly Brazil and Colombia, where the energy transition was more advanced and regulatory frameworks offered stable, predictable growth (Enel 2024e; 2023a; 2024d). Appendix 4 provides an overview of the Group's revenue distribution by business segment and geography, illustrating the relative weight of its grids, generation, and customer solutions businesses as well as the growing concentration in its core markets.

The 2021–2022 energy-price shock, driven by the post-pandemic demand rebound and Russia's invasion of Ukraine, sent European gas and wholesale electricity prices to unprecedented levels, while supply-chain inflation sharply increased the cost of turbines, panels, grid equipment, and construction. Together, these dynamics forced utilities to reassess capital intensity and geographic exposure, reinforcing Enel's decision to prioritize financially stable, regulation-anchored markets (Enel 2023c). Building on these adjustments, the Strategic Plan 2023–2025 set new targets for sustainable electrification: by 2025, roughly 75% of Enel's generation was expected to come from renewable sources concentrated in six core countries: Italy, Spain, Brazil, Chile, Colombia, and the United States (Enel 2022) (see Appendix 5 for Geographic Distribution of Core Markets).

3. Navigating the Energy Trilemma: Strategic Balancing at Enel

Flavio Cattaneo stood at the center of the stage, the Capital Markets Day spotlight highlighting his measured delivery. He detailed Enel's plan, stressing a focus on regulated assets to secure predictable returns while advancing the energy transition. The audience absorbed his words, aware that every choice carried a cost: every euro spent on grid resilience reduced funds for new renewables; every GW of wind or solar added complexity to grid stability; and every pursuit of financial discipline risked slowing progress on decarbonization and reliable electrification. Which tensions emerge between profitability, reliability, and sustainability in Enel's experience? Which conflicting expectations emerge among Enel's key stakeholders? What do these insights reveal about the practical challenges of navigating the energy trilemma and the associated complexities?

3.1. Managing Core Tensions: Business Profitability, Grid Reliability, and Environmental Sustainability

Grid Reliability versus Environmental Sustainability

The relationship between grid reliability and environmental sustainability was characterized by a complex dual dynamic: while they were operationally interdependent, they were financially competitive. The Chile and Argentina study conducted by the Enel Foundation and CESI in 2019 illustrated this operational dependency, showing how the acceleration of renewable investment without corresponding improvements in grid infrastructure created systemic risks. As renewable penetration increased, both countries reached a point where further solar and wind deployment placed significant pressure on balancing reserves and transmission capacity, particularly during periods of low demand and high renewable output. The study showed that the interconnection between Chile and Argentina reduced renewable curtailment by around 180 GWh per year. Crucially, these benefits were only achieved when grid reinforcements and flexible backup generation were developed alongside renewable expansion. This experience demonstrated that the pursuit of sustainability technically relied on infrastructure capable of maintaining system stability. However, it also highlighted the economic constraint: ensuring this reliability required massive investments in dispatchable capacity, storage, and network strengthening, which created a contest for capital between grid reliability and renewable expansion (Enel Foundation 2019).

In response to this zero-sum pressure on capital resources, Enel implemented a notable pivot starting in 2023. Faced with the reality that grid reliability is a prerequisite for sustainable growth, the company sacrificed its near-term renewable energy deployment targets, shifting capital allocation toward regulated grid businesses in its core markets (Enel 2022). This strategic recalibration resulted in a marked reallocation of CAPEX from renewable energy generation to grid infrastructure, representing a fundamental shift from Enel's earlier expansion trajectory. Across successive strategic plans, the Group progressively reduced planned renewable CAPEX from 14.4 billion EUR over the 2020-2022 period (50% of total allocation) to 12 billion EUR over the 2025-2027 period (28%), while planned grid investments nearly doubled from 13.2 billion EUR to 26 billion EUR, rising from 46% to 60% of total CAPEX across the same plan horizons (Enel 2019; 2023b; 2024d) (Appendix 6). Management explicitly characterized this pivot as adopting a "more selective approach towards investments to maximize profitability while minimizing risks" and pursuing a "less capital–intensive and less risky approach in renewables" through partnership-based models (Enel 2023b, 1, 2).

Environmental Sustainability versus Business Profitability

High CAPEX requirements for renewable expansion inherently pressured short-term profitability, yet the dynamic was not a simple trade-off between capital preservation and environmental sustainability. Enel's experience showed that failing to meet environmental targets could also result in tangible financial and reputational costs. After missing its 2023 emission reduction milestone, recording Scope 1 emission[5] intensity of 160 gCO_2eq/kWh[6] compared with a target of 148

[5] Scope 1 emissions are released when a company manufactures a product or delivers a service (McKinsey 2024).
[6] Grams of CO_2 equivalent per kilowatt-hour.

gCO_2eq/kWh, the company incurred a 25-basis–point coupon step-up on several sustainability-linked bonds. This underperformance attracted increased scrutiny from environmental, social, and governance (ESG) investors as well as from the public, underscoring that underperformance on sustainability could directly affect financing costs and market perception (MSCI 2024). In response, Enel sought to reinforce both its environmental and financial credibility. Despite the setback, it achieved a 50% reduction in total absolute greenhouse gas emissions from 190 $MtCO_2eq$[7] in 2017 to 95 $MtCO_2eq$ in 2023, demonstrating meaningful progress even amid coal phase-out pressures, capital constraints, and project delay (Enel 2024b). At the same time, in 2023, the company maintained investment-grade ratings and continued dividend distributions under a revised plan focused on leverage discipline (Fitch Ratings, n.d.; Enel, n.d.-b). By sustaining a disciplined financial stance, Enel strengthened the confidence of lenders and shareholders, ensuring continued access to capital and preserving flexibility to fund its transition strategy.

Grid Reliability versus Business Profitability

Enel's operations have revealed moments where business profitability and grid reliability interacted in complex ways. Periods of network strain and extreme weather have tested the company's ability to maintain service quality while adhering to efficiency and performance targets. In November 2023, a violent storm with winds exceeding 100 kilometers per hour struck the metropolitan area of São Paulo, toppling trees and power lines and leaving around 2 million consumers without electricity. Three days later, roughly half a million customers remained disconnected, prompting criticism from local and federal authorities and calls to review Enel Distribuição São Paulo's concession. The national regulator Agência Nacional de Energia Elétrica (ANEEL) and the state regulator Agência Reguladora de Serviços Públicos do Estado de São Paulo

[7] Million Tonnes of CO_2 equivalent per kilowatt-hour.

(ARSESP) described Enel's response as "much below expectations," noting that only 1,700-1,800 field workers were deployed instead of the 2,500 foreseen in the contingency plan. Both agencies warned that they could recommend allowing the concession to expire (Reuters 2024). Following the event, ANEEL fined Enel 165.8 million reais (≈ 27 million EUR) for delays in restoring service, a penalty later upheld in April 2024 after the company's appeal was rejected. According to ANEEL's technical area, the sanction was applied for the delay in restoration rather than for the storm itself, with criticism directed at the limited number of intervention teams mobilized. Additional blackouts in March 2024 again affected central districts of São Paulo, temporarily disrupting hospital operations and air traffic at the local airport. The consumer-protection agency Procon subsequently fined Enel 12.9 million reais (≈ 2 million EUR) for the prolonged outages. Enel Brazil's management attributed the repeated interruptions to extreme heat and thermal stress on underground equipment, noting that higher loads and illegal connections had increased fault rates. In a later statement, the company announced plans to invest about USD 3 billion between 2024 and 2026 in distribution networks across its three Brazilian concession areas, São Paulo, Rio de Janeiro, and Ceará, to strengthen grid quality, digitalization, and resilience (Mantica 2024). However, such grid upgrades illustrated the difficult financial trade-off utilities face: reliability improvements require large, low-return, and often regulator-constrained CAPEX. These investments protected Enel from future outages and regulatory penalties, but they also consumed significant CAPEX that could otherwise be allocated to higher-return renewable projects or used to bolster financial performance. The São Paulo incidents thus highlighted how maintaining network reliability under cost-efficiency and performance targets can generate both operational pressure and short-term profitability strain. How these pressures interacted, and the extent to which one constrains the other, remained a central question for companies navigating the trilemma in practice.

3.2. Managing Stakeholder Expectations

Operating in over 30 countries, Enel's management confronted a complex web of stakeholder expectations that spanned governments and regulators, shareholders and bondholders, and local communities. Enel had been proactive in collaborating with governments and regulators. For example, it delivered its coal phase-out in Chile ahead of regulatory deadlines, accelerating decarbonization but giving rise to financial write-downs on aging power plants and significant workforce transitions (Enel 2020a).

With shareholders and bondholders, Enel faced expectations for reliable financial performance and prudent capital management. Investors sought consistent dividend growth and strong credit metrics, prompting Enel to uphold cash-flow discipline and maintain investment-grade ratings. To meet these demands, Enel had focused on optimizing its portfolio through selective renewables investments with predictable returns and rigorous cost control, reinforcing stakeholder confidence in its profitability and long-term value creation (Enel 2018a).

Local communities and civil society had expected reliable energy supply alongside sustainable local development, prompting landmark initiatives such as the "Futur-e programme", which transformed decommissioned Italian thermal-power sites into new commercial, cultural, and green hubs through transparent engagement with local authorities and community groups (Enel 2016b).

Balancing these potentially conflicting demands underscored the strategic complexity and tight maneuvering that Enel's management had to undertake to satisfy all stakeholders simultaneously (see Appendix 7 for an overview of Enel's main stakeholder groups).

Enel's practical experience demonstrated that the trilemma was not an abstract strategic concept but rather a lived reality played out in boardrooms, government negotiations, and investor communications. The company's strategic adjustments illustrated an ongoing process of adaptation and communication in response to evolving market, regulatory, and technological conditions. Similar challenges were faced by many utilities across the industry.

4. Competing Strategies in European Utilities

As applause faded in the auditorium, the atmosphere during Enel's Capital Markets Day shifted from optimism to reflection. Flavio Cattaneo's remarks on disciplined growth and system resilience echoed across an industry struggling with the same unsolved puzzle. From Portugal to France, every European executive overseeing a grid, a turbine, or a balance sheet faced the same pressures: maintaining reliable power systems, accelerating decarbonization, and protecting investor returns. The contradiction was universal. Each utility promised progress on all three fronts, yet advancing one goal inevitably strained the others. In that moment, Enel's challenge seemed to mirror the entire industry's condition, a collective balancing act where no company had yet discovered the perfect equilibrium.

4.1. Competitors' Distinct Responses to the Energy Trilemma

Despite facing the same underlying tensions, major European utilities have adopted different strategic responses, reflected in contrasting organizational capabilities and investment priorities (Appendix 8).

EDP: Renewable Expansion as Primary Growth Engine

EDP pursued an aggressive renewable growth strategy, positioning sustainability and energy transition leadership as its core competitive advantage. In 2023, the company deployed EUR 5.4 billion in consolidated CAPEX, with 89% directed to renewable energy projects, including offshore wind, onshore wind, and distributed solar capacity. By contrast, grid-related CAPEX remained relatively low at close to EUR 1 billion, a level that is modest both in absolute terms and compared with the grid investment intensity reported by many other European utilities (EDP 2024). The 2023–2026 strategic plan targeted EUR 25 billion in total investment, with EUR 21 billion focused on renewable deployment at 4.5 GW per year, and EUR 4 billion on grid infrastructure (EDP 2024).

On shareholder returns, EDP maintained a stable dividend policy with a 2023 payout ratio of 63% of recurring net profit, proposing EUR 0.195 per share, a 3% increase versus 2022, corresponding to a dividend yield of 4.2% (EDP 2024; Morningstar 2025a). Net debt stood at EUR 18.5 billion, reflecting disciplined financial management. EDP's sustainability positioning was reinforced by S&P Global Sustainability Yearbook recognition as the world's most sustainable electric utility (EDP 2023b). The company aims to achieve 100% renewable energy generation by 2030 and reach net-zero emissions by 2040 (EDP 2023a). EDP’s strategy thus reflected an aggressive renewable expansion approach, deploying substantial capital into high-growth renewable segments and reinforcing its strong sustainability credentials.

EDF: State–Backed Operator Prioritizing Decarbonization through Nuclear Generation

Électricité de France (EDF) confronted the trilemma as a state majority–owned, nuclear–anchored operator whose overarching priority was managing capital structure while decarbonizing generation. The majority of its energy portfolio comprised nuclear generation, which accounted for approximately 78% of total generation in 2023. The company deployed EUR 21 billion in total CAPEX in 2023, with approximately EUR 5 billion directed to grids including Enedis, a subsidiary of EDF responsible for operating and maintaining France’s electricity distribution network, and only around EUR 1.8 billion allocated to renewable generation capacity (EDF 2024a). This represents an 11% increase to the year before driven largely by connections to renewable generation and electric-vehicle charging infrastructure (EDF 2024b).

Over 4 GW of renewable generation were connected to the distribution network in 2023, up from 2 GW in 2019, representing a 120% increase in renewable connections (EDF 2024b).

On the dividend side, EDF prioritized balance sheet strengthening and capital strength. In 2023, the company paid no dividend, reflecting the suspension of shareholder payouts since 2021 following EDF's transition to full state ownership (EDF, n.d.-b; n.d.-a). Net financial debt was reduced by EUR 10.1 billion during 2023 to EUR 54.4 billion, with the net debt to EBITDA ratio falling to 1.36 times, reflecting strategic emphasis on equity strengthening and rating maintenance rather than maximizing near-term cash distributions (European Commission 2024; EDF 2024b). EDF's 2023 generation was 93% decarbonized, and the company positioned itself as the world's leading producer of low–carbon electricity. However, renewable energy accounted for only 15% of total generation (EDF 2024a). The company's strategy thus reflected a fundamentally different mandate: as a state–backed operator, EDF subordinated near-term shareholder cash returns to the imperatives of system resilience, balance sheet stability, and large–scale decarbonization.

Iberdrola: Renewable Growth and Grid Strengthening with Stable Returns

Iberdrola pursued an expansionist strategy combining substantial renewable capacity additions and large-scale grid investment. In 2023, the company deployed a record EUR 11.4 billion in gross investments, representing a 6% increase, with renewables and grids accounting for 93% of total CAPEX. The renewables business alone received EUR 5.4 billion, equivalent to 47.5% of total investment. Critically, Iberdrola installed more than 3.3 GW of renewable energy in 2023, bringing total installed renewable capacity to 42.2 GW worldwide, a 5.3% increase from 2022 (Iberdrola 2024c). According to Ignacio Galán, Executive Chairman of Iberdrola, "For every euro invested in renewables, one euro must be invested in electricity grids." (Iberdrola 2023). Consequently, the company deployed approximately EUR 5.2 billion in grid infrastructure (Iberdrola 2023).

On shareholder returns, Iberdrola increased its annual dividend by 10.8% to EUR 0.55 per share, corresponding to a dividend yield of 4.2%. Funds from operations grew 8% to EUR 11.1 billion, demonstrating the cash generation capacity to sustain both substantial investment and shareholder returns (Iberdrola 2024a; 2024b; Morningstar 2025b). Iberdrola's strategy thus represented a calculated effort to balance all three dimensions of the trilemma: deploying record CAPEX volumes in both renewables and grids while delivering visible shareholder remuneration. The company bet that efficient capital allocation and strong operating cash flows would permit simultaneous expansion in renewables and grids while maintaining shareholder returns.

Viewed together, these peer strategies underscored that similar trilemma pressures can lead to materially different capital allocation outcomes. EDF's nuclear-centered, state-backed model reflected a fundamentally different mandate and capital allocation logic than its Western European peers. EDP's concentrated focus on renewable expansion was enabled by a narrower asset scope and organizational scale, allowing for sharper strategic specialization. Iberdrola's simultaneous expansion of grids and renewables, while sustaining shareholder remuneration, rested on a large, regulated asset base and strong operating cash flows. Each company thus confronted the same tensions, but from distinct structural starting points shaped by asset composition, ownership structure, and regulatory exposure.

4.2. Persistence of Trade-Offs

As the applause faded and the lights brightened, Cattaneo stepped away from the podium, leaving the auditorium in thoughtful silence. Investors exchanged glances, recalling his words about a roadmap of disciplined growth and flexible capital allocation. The true scale of the challenge became clear: Enel's challenge was not merely its own; it echoed the entire industry's struggle to juggle three imperatives at once.

Across the room, portfolio managers revisited their models. The questions Cattaneo had posed about balancing large–scale grid investments with financial discipline, matching renewables growth to market realities, and harmonizing digital platforms with legacy operations were the ones they also needed to answer for EDP, EDF, and Iberdrola. Each peer's capital allocation strategy thus reflected an explicit choice about which dimensions of the trilemma to prioritize.

In that charged atmosphere, it was evident that no utility held a perfect solution. The industry's collective reflection underscored a shared truth: success would hinge not on any single strategic play but on each company's ability to navigate the trilemma through disciplined execution, adaptive priorities, and the careful sequencing of investments as market, regulatory, and technological conditions evolved.

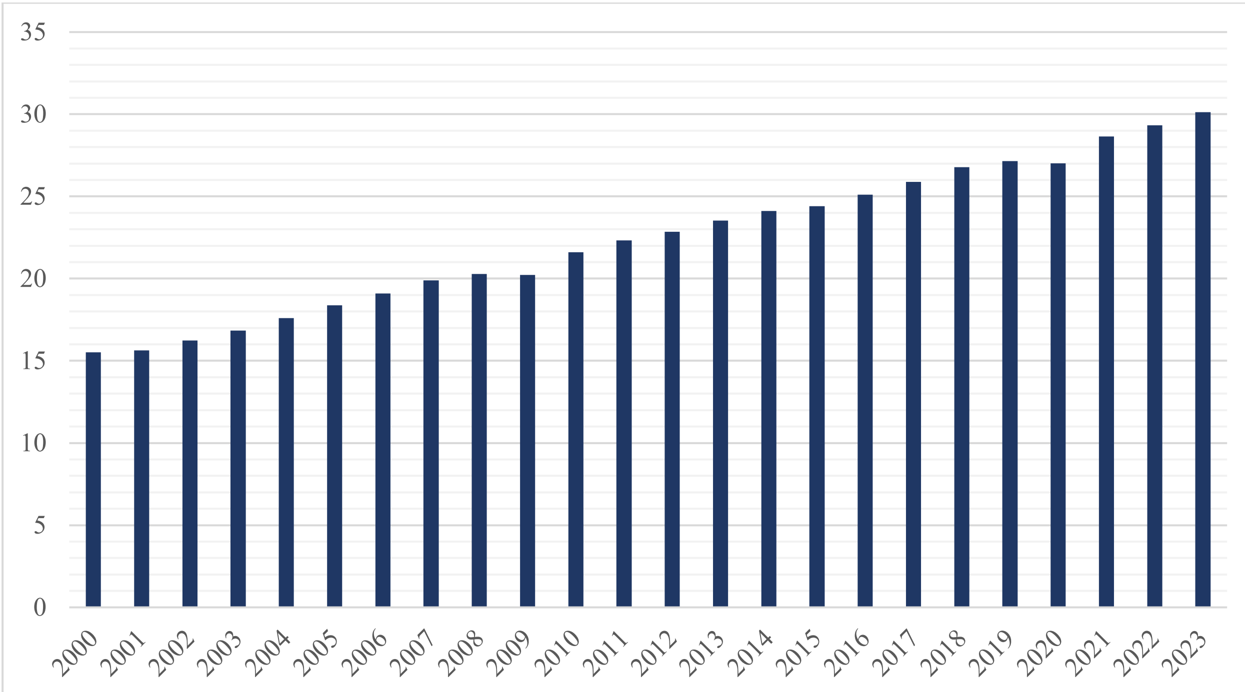
5. The Crossroads Ahead

Throughout the discussions at Capital Markets Day, Flavio Cattaneo maintained a measured optimism about Enel’s capacity to navigate the competing demands of profitability, reliability, and sustainability. Like his industry peers, Cattaneo knew that the energy trilemma would continue to shape every strategic decision. Stakeholder concerns were raised over missed emission reduction milestones and execution delays on renewable projects, yet Cattaneo and his team emphasized the resilience of Enel’s financial position and the company’s ability to adapt its capital allocation strategy as market realities evolved.

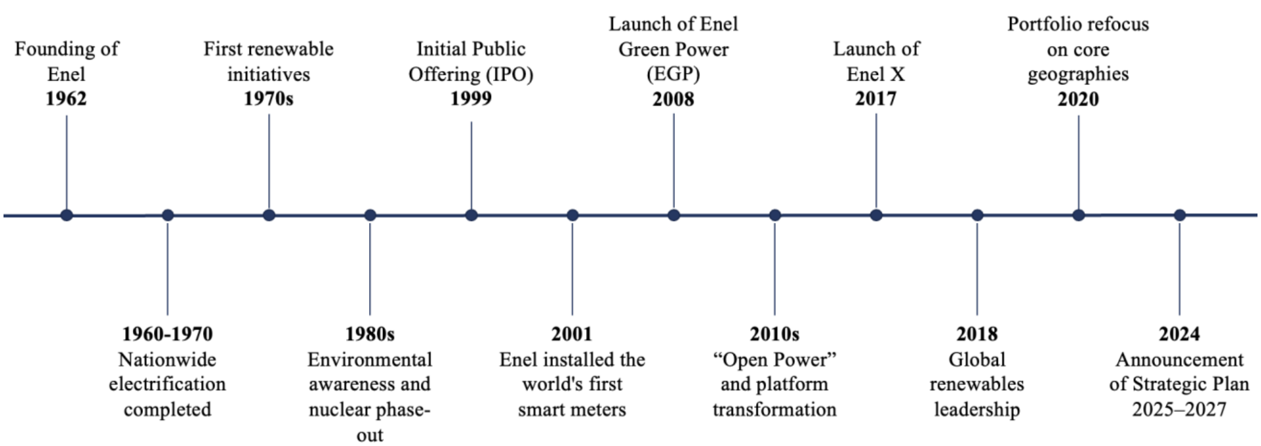
As he left the auditorium that afternoon, Cattaneo faced lingering questions about the years ahead. Could Enel sustain its momentum amid tightening CAPEX constraints and growing stakeholder pressure? Would renewed investment in regulated assets and flexible planning truly support the acceleration of the energy transition, or would new bottlenecks emerge? He hoped so, but only the future could tell.

Case Appendix

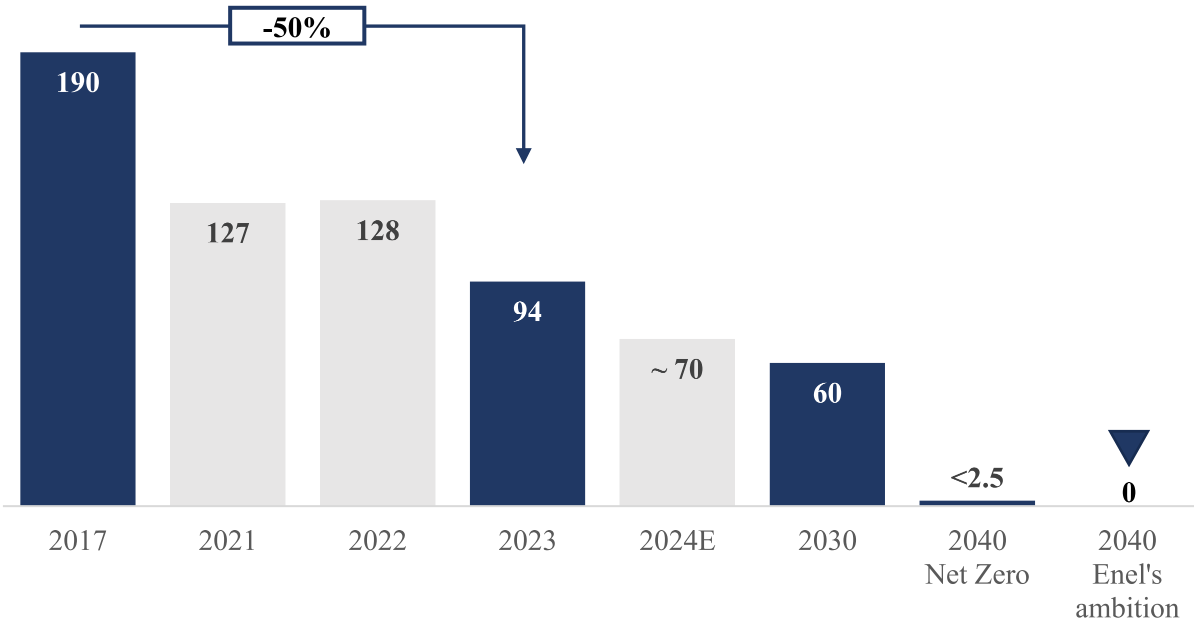
Appendix 1: Total Global Electricity Generation (million GW), Adopted from (IEA 2025b)



Appendix 2: Historic Timeline of Enel´s Key Milestones, Own Illustration



Appendix 3: Enel's Total Absolute Emissions ($MtCO2_{eq}$), Adapted from (Enel 2024f)



Appendix 4: Revenue by Business Segment and Geographic Region, Adapted from (Enel 2024a)

	Conventional Generation & Global Trading		Enel Grids		EGP		Enel X Global Retail [2]		Services & Other		Total	
In million EUR[1]	FY 2023	FY 2022	FY 2023	FY 2022	FY 2023	FY 2022	FY 2023	FY 2022	FY 2023	FY 2022	FY 2023	FY 2022
Italy	**26,178**	**55,389**	**7,610**	**6,963**	**3,248**	**2,149**	**28,717**	**33,351**	**(16,426)**	**(14,344)**	**49,327**	**83,508**
Iberia	**11,348**	**17,488**	**2,379**	**2,258**	**1,217**	**935**	**20,747**	**28,114**	**(10,263)**	**(15,962)**	**25,428**	**32,833**
Rest of World	**2,809**	**4,090**	**10,228**	**12,948**	**7,127**	**6,095**	**2,644**	**2,522**	**(1,527)**	**(1,781)**	**21,281**	**23,874**
Latin America	2,548	3,858	10,227	12,956	5,109	4,164	2,157	2,071	(1,465)	(1,715)	18,576	21,334
Argentina	7	145	560	1,000	28	35	5	13	(1)	(1)	599	1,192
Brazil	656	959	6,321	7,762	846	739	545	543	(529)	(783)	7,839	9,220
Chile	1,335	2,268	1,590	2,562	2,570	2,076	197	192	(694)	(671)	4,998	6,427
Colombia	317	218	823	753	1,108	822	1,040	1,002	(5)	(43)	3,283	2,752
Peru	233	268	933	879	258	201	370	321	(217)	(205)	1,577	1,464
Other	-	-	-	-	299	291	-	-	(19)	(12)	280	279
Rest of Europe	-	14	1	(8)	161	40	76	89	1	(48)	239	87
North America	261	218	-	-	1,612	1,702	331	312	(62)	(18)	2,142	2,214
Africa, Asia & Oceania	-	-	-	-	255	196	84	70	(1)	-	338	266
Row elisions	-	-	-	-	(10)	(7)	(4)	(20)	-	-	(14)	(27)
Other	**(145)**	**(632)**	**42**	**863**	**28**	**(12)**	**11**	**363**	**(407)**	**(280)**	**(471)**	**302**
Total	**40,190**	**76,335**	**20,259**	**23,032**	**11,620**	**9,167**	**52,119**	**64,350**	**(28,623)**	**(32,367)**	**95,565**	**140,517**

1. Rounded figures, FY 2022 restated figure
2. Enel X Global Retail includes Enel X Way

Appendix 5: Geographic Distribution of Enel´s Core Markets, Own Illustration

Appendix 6: Enel's CAPEX Mix by Business Segment and Geographic Region, Adapted from (Enel 2024a)

	Conventional Generation & Global Trading		Enel Grids		EGP		Enel X Global Retail [2]		Services & Other		Total	
In million EUR[1]	FY 2023	FY 2022	FY 2023	FY 2022	FY 2023	FY 2022	FY 2023	FY 2022	FY 2023	FY 2022	FY 2023	FY 2022
Italy	**393**	**408**	**3,084**	**2,714**	**1,982**	**821**	**565**	**582**	**74**	**115**	**6,098**	**4,641**
Iberia	**306**	**271**	**885**	**860**	**782**	**833**	**311**	**323**	**21**	**28**	**2,305**	**2,315**
Rest of World	**75**	**312**	**1,520**	**2,043**	**3,127**	**4,756**	**199**	**189**	**11**	**5**	**4,931**	**7,305**
Latin America	71	289	1,378	1,903	1,917	2,106	105	80	11	5	3,482	4,384
Argentina	2	81	103	164	-	1	-	-	-	-	105	246
Brazil	1	1	813	1,235	945	772	50	23	1	1	1,810	2,032
Chile	38	83	111	153	581	817	7	4	7	3	744	1,061
Colombia	9	11	238	220	302	286	23	25	-	-	571	542
Peru	20	17	112	132	56	201	26	28	3	-	217	377
Other	-	95	-	-	34	29	-	-	-	-	34	125
Rest of Europe	-	17	142	140	55	53	15	19	0	0	212	228
North America	4	7	-	-	1,024	2,408	69	75	-	-	1,097	2,490
Africa, Asia & Oceania	-	-	-	-	131	189	9	15	-	-	141	203
Other	**-**	**-**	**24**	**40**	**19**	**18**	**97**	**112**	**87**	**72**	**228**	**242**
Total	**775**	**992**	**5,512**	**5,657**	**5,910**	**6,428**	**1,172**	**1,206**	**193**	**219**	**13,563**	**14,503**

1. Rounded figures, it includes capex related to asset classified as HFS for 849 €mn in 2023 and 156 €mn in 2022.
2. Enel X Global Retail includes Enel X Way

Appendix 7: Enel's Key Stakeholders and How They Interact, Own Illustration

Stakeholder	How they work with Enel
Governments and Regulators	Governments and regulators set decarbonization timelines and energy policy frameworks. Enel collaborates through formal regulatory compliance, tariff negotiations, and environmental policy alignment. Enel commits to meeting or exceeding government climate targets and regulatory requirements for grid reliability and renewable energy penetration. (Enel 2020b)
Shareholders and Bondholders	Shareholders and bondholders engage with Enel through quarterly earnings reports, annual shareholder meetings, and investor presentations. Enel maintains regular communication on dividend policy, capital allocation strategy, and credit ratings. The company pursues disciplined capital management and selective investments with predictable returns to sustain investor confidence in profitability and financial stability. (Enel 2018d; 2018b)
Local Communities and Civil Society	Local communities and civil society engage with Enel through participatory consultation processes, particularly in community site redevelopment projects. Enel solicits input on repurposing decommissioned facilities and addresses community expectations for local employment, environmental protection, and sustainable development through transparent stakeholder dialogue and collaborative planning. (Enel 2016a)

Appendix 8: Key Metrics 2023 of Enel, EDP, EDF, and Iberdrola Own Illustration

	Enel	EDP	EDF	Iberdrola
Financials (in million)				
Revenue	€ 92,882	€ 16,202	€ 139,715	€ 49,335
EBITDA	€ 21,833	€ 4,359	€ 39,927	€ 13,799
EBIT	€ 13,376	€ 2,168	€ 13,200	€ 8,973
Net Income	€ 3,438	€ 952	€ 10,016	€ 4,803
Total CAPEX	€ 12,768	€ 5,406	€ 21,021	€ 11,382
Grid CAPEX	€ 5,512	€ 997	€ 5,025	€ 5,178
Renewable CAPEX	€ 5,911	€ 4,771	€ 1,759	€ 5,403
Operational Cashflow	€ 14,620	€ 1,552	€ 29,808	€ 12,130
Net Debt	€ 67,618	€ 18,527	€ 54,400	€ 58,827
Ratios				
Net Debt / EBITDA	3.10	4.25	1.36	4.26
ROCE	9.8%	5.0%	4.9%	7.4%
Dividend yield	5.9%	4.2%	0.0%	4.2%
Capacity				
Total installed capacity	81.4 GW	28.2 GW	117.3 GW	62.9 GW
Renewable capacity	63 GW	24.4 GW	32.8 GW	42.2 GW

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THE RECYCLABILITY PARADOX:
A MULTI-CRITERIA ANALYSIS OF END-OF-LIFE PATHWAYS FOR ENEL'S WIND TURBINE BLADES

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1. Introduction

The energy transition involves a notable contradiction: the technologies engineered to generate renewable energy are producing waste streams that present significant challenges for existing waste management systems. Wind turbine blades (WTBs) exemplify this paradox. Despite their vital role in decarbonization, blades are engineered as durable composite materials designed to withstand decades of high loading, rendering them resistant to conventional recycling processes. This durability enables operational performance but becomes an environmental liability at end-of-life, the stage when blades finish their service life and require decommissioning. Nevertheless, in 2021, the European wind industry already committed to reuse, recover, or recycle 100% of decommissioned blades (WindEurope 2021). For Enel, Europe's largest renewable energy operator, wind turbine blade end-of-life management represents both a pressing operational challenge and a strategic opportunity. Enel has recognized this issue and initiated pilot programs to develop viable recycling pathways for decommissioned blades, yet the company still lacks a large-scale, commercially viable solution for blade end-of-life management (Enel 2020b).

This analysis answers the research question: Which end-of-life management alternative for WTBs optimally balances environmental sustainability, financial viability, and technical feasibility within Enel’s strategic context? A review of current literature identifies three primary pathways for evaluation: landfilling, mechanical recycling (grinding), and chemical recycling (solvolysis). Multi-Criteria Decision Making (MCDM) is employed as the evaluation framework to simultaneously assess these alternatives across diverse environmental, financial, and technical dimensions. By integrating fragmented data through an MCDM framework weighted to Enel's strategic priorities, this study demonstrates that while mechanical recycling offers immediate viability, solvolysis presents the superior long-term strategic balance.

2. Overview of Wind Turbine Blade Waste and Current Waste Management Approaches

2.1 Material Composition Challenge and its Scale

A typical material bill for a 50 MW onshore wind plant is detailed in Appendix 1. Most parts of a wind turbine are already recyclable and are processed as such. Blades, however, remain challenging to recycle due to their materials and their complex composition (Jensen and Skelton 2018). WTBs consist of two major composite materials: glass fiber (GF) or carbon fiber (CF) and thermosetting resin[1] (Liu et al. 2022). These materials are engineered for extreme durability and mechanical strength, which makes conventional recycling difficult (Paulsen and Enevoldsen 2021). By 2050, global volumes of blade waste will reach 43 million tons, with 25% coming from Europe (Liu and Barlow 2017). The average lifetime of a wind turbine is around 20 years (Dolan and Heath 2012). Turbines installed during the industry's expansion in the early 2000s are now approaching decommissioning. Out of the 290 Gigawatt (GW) of wind energy capacity currently installed in Europe, roughly 80 GW will reach end-of-life by 2030 (WindEurope 2025). Research shows each kilowatt of wind power requires about ten kilograms of blade material (Liu and Barlow 2017). Given Enel's wind capacity of approximately 15.7 GW, this equates to roughly 157,000 tons of blade material (Enel 2025b). This volume of retiring blades poses a major strategic challenge.

2.2 Current End-of-Life Management Practices

The wind energy industry faces a divergent set of pathways for managing decommissioned blades. While the literature identifies a wide spectrum of technologies, this analysis focuses on the three alternatives most representative of the strategic landscape, which include landfilling, mechanical recycling, and chemical recycling.

[1] Thermosetting resins harden permanently when heated, forming a strong, crosslinked structure (Cheng et al. 2025).

Landfilling: Landfilling is the baseline linear economy approach currently used for most retired European blades (Paulsen and Enevoldsen 2021). About 60% of waste fiber-reinforced plastics[2] end up in landfills (Bennet et al. 2021). The method involves segmentation of blades into 7 to 10 meter sections, followed by transport to regional landfills (Sproul et al. 2025). In response to the environmental implications of this practice, the association WindEurope called in 2021 for an EU-wide ban on the landfilling of WTBs to be embedded in legislation (WindEurope 2021).

Mechanical Recycling: Mechanical recycling entails grinding and shredding of blades to recover material for secondary applications or repurposing (Fonte and Xydis 2021). This methodology achieves full commercial status with established operations at meaningful scale (Paulsen and Enevoldsen 2021). Enel has focused its pilot initiatives on mechanical recycling approaches, transforming decommissioned blade materials into construction products such as bricks and fiberglass pellets (Enel 2020a). Enel's competitor, Iberdrola, has operationalized mechanical recycling through a partnership employing shredding and classification technologies to process decommissioned blades into materials for reuse across multiple industries (Iberdrola 2025).

Chemical Recycling through Solvolysis: Solvolysis is the most common method of chemical recycling. It uses chemical solvents to break down the resin structure, recovering both fibers and resin components in separate forms (Paulsen and Enevoldsen 2021). Unlike mechanical recycling, solvolysis preserves fiber length and quality, making recovered materials suitable for high-value applications rather than downcycling. However, this process currently operates predominantly at pilot and demonstration scale (Diez-Cañamero and Mendoza 2023; Mishnaevsky Jr. 2023).

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[2] Fiber-reinforced plastics (FRPs) are a combination of plastic resins, glass, carbon and other fibers (Bennet et al. 2021).

3. Methodology: Multi-Criteria Decision Making Framework

3.1 MCDM Theoretical Justification and Approach Selection Rationale

Strategic decisions on complex technological options such as recycling require systematic evaluation frameworks (Alamerew and Brissaud 2019). WTB management represents a MCDM problem: multiple alternatives must be evaluated against conflicting criteria that resist single-dimensional optimization (Triantaphyllou et al. 1998). Environmental performance, financial costs and benefits, and technical maturity cannot be ranked against a single metric. Instead, they demand a structured methodology that makes trade-offs explicit and defensible.

This analysis applies the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) combined with weighted aggregation to navigate these trade-offs (Hwang and Yoon 1981). TOPSIS identifies the alternative closest to the positive ideal solution while simultaneously maximizing distance from the negative ideal solution, providing an intuitive interpretation of relative alternative performance. Finally, the analysis applies sensitivity analysis to test whether the ranking holds when weighting assumptions change.

3.2 Decision Criteria Definition and Weighting

This analysis selects, organizes, and synthesizes four decision criteria into three sustainability pillars, providing a coherent strategic assessment based on prior studies. Environmental criteria are based on the circularity assessment framework developed by Diez-Cañamero and Mendoza (2023), the financial criterion is grounded in the financial performance analysis conducted by Liu et al. (2022), and the technical criterion reflects the multidisciplinary technology readiness assessments conducted by Paulsen and Enevoldsen (2021) and Fonte and Xydis (2021).

The continuous and ordinal metrics associated with the criteria identified in the literature are converted into standardized 1–5 scores to enable TOPSIS aggregation. Each criterion's range is divided into five bands using a threshold-based approach. Finally, all alternatives are scored based on their band placement. This ensures reproducible, evidence-based scoring. Appendix 2 and Appendix 3 summarize all criteria and scoring rubrics.

Environmental Pillar (35% combined weight): Two criteria emerge from the analysis of Diez-Cañamero and Mendoza (2023): the Product Circularity Indicator (PCI) developed by Bracquené et al. (2020) and a Global Warming (GW) indicator. Furthermore, the analysis reveals a positive correlation between the two metrics (Appendix 4). While standardized product-level circularity metrics are debated (Linder et al. 2017), the PCI measures how effectively circular strategies maintain material value and quality, ranging from 0 (fully linear disposal) to 1 (fully circular recovery) (Bracquené et al. 2020). The Global Warming Indicator (GW) measures the tons of CO_2 equivalent emissions associated with the life cycle of WTBs. These two criteria receive 35% combined weight (distributed equally at 17.5% each), reflecting three strategic imperatives specific to Enel's organizational context. First, Enel's 2040 net-zero target makes lifecycle emissions material for performance measurement and investor expectations (Enel 2025a). Second, European regulations including the European Green Deal, Circular Economy Action Plan, Waste Framework Directive, and anticipated critical materials regulations push mandatory circularity (European Commission 2008; 2015; 2019). Third, around 23% of Enel's shareholder base consists of Socially Responsible Investors, with 43.2% of capital from UN Principles for Responsible Investment signatories, linking circular performance indirectly to cost of capital (Enel 2025b).

Financial Pillar (40% weight): Net Value, as assessed in the analysis of Liu et al. (2022), covers operational costs associated with different end-of-life processes and includes revenue from recyclates. This criterion receives 40% weight, reflecting three fundamental business model constraints. First, Enel has fiduciary obligations to shareholders that require economic sustainability in its operational decisions. Second, recovered material markets are volatile, subject to price cycles, regulatory changes, technology shifts, and market saturation (Moore et al. 2022). Third, advanced recycling infrastructure, such as solvolysis, requires substantial upfront investment for Enel, necessitating an evaluation of whether operational value can offset these costs (Liu et al. 2022).

Technical Pillar (25% weight): Technology Readiness Level (TRL), as assessed in the analyses of Paulsen and Enevoldsen (2021) and Fonte and Xydis (2021), evaluates the maturity of blade recycling technologies, from lab development to pilot and commercial scale. It receives 25% combined weight, positioned as an enabling constraint rather than a primary optimization objective. This weighting reflects that technical readiness is necessary but not sufficient for strategic success. Pilot-scale technologies (TRL 5-6) offer limited operational history but remain valid strategic options. Commercial technologies (TRL 8-9) enable predictable deployment with established cost structures and supplier relationships (Fonte and Xydis 2021; Paulsen and Enevoldsen 2021).

4. Application of MCDM Analysis

4.1 Scoring of Alternatives on the Environmental Criteria

Product Circularity Indicator (PCI): Diez-Cañamero and Mendoza (2023) report the following PCI performance across three alternatives. *Landfilling* achieves a PCI of 0.22, reflecting complete material exit from productive economic cycles and the absence of material recovery mechanisms. All blade material enters final waste streams with no potential for functional reuse or value reintegration. *Mechanical recycling* achieves a PCI of 0.54, reflecting moderate circularity constrained by significant downcycling into progressively lower value applications. Material recovery rates of 42 to 60% are limited by the mechanical grinding process. Recovered glass fiber fragments are primarily directed toward construction materials or composite fillers rather than structural reuse, reducing the economic value of recovered material and limiting closed-loop recovery potential (Menna et al. 2025). *Solvolysis* achieves a PCI of 0.77, reflecting superior material value retention through recovery rates of 90 to 100%. This superior material quality enables incorporation into structural applications including aerospace composite manufacturing, structural repairs, and high-performance composites, rather than downcycling into lower-value applications.

Per Appendix 3, landfilling's PCI of 0.22 falls in the 0.20–0.40 band (Score 2). Mechanical recycling's PCI of 0.54 exceeds the 0.40 threshold (Score 3). Solvolysis's PCI of 0.77 exceeds the 0.60 threshold (Score 4).

Global Warming Indicator (GW): The GW impact assessment quantifies the lifecycle carbon footprint by incorporating manufacturing emissions, transportation, end-of-life processing energy, and environmental credits derived from material substitution. Diez-Cañamero and Mendoza (2023) report the following GW performance measured in tons of CO_2 equivalent (per three-blade wind turbine unit). *Landfilling* generates 623 tons CO_2 equivalent, representing the highest emissions baseline reflecting the energy intensity of ongoing landfill operations and complete absence of material substitution credits. Transportation from collection points to regional landfill facilities contributes approximately 39 tons CO_2 equivalent, while operational landfill emissions dominate the remaining impact through methane generation and site management activities. *Mechanical recycling* generates 562 tons CO_2 equivalent, reflecting the trade-off between processing energy intensity and material substitution benefits from recovered glass fiber and resin components. This observed intermediate performance reflects variability in assumptions regarding recovered material quality and end-application scenarios. While grinding processes demand relatively low energy overall (0.27 Megajoules (MJ)/kg), recovered material value is limited by quality degradation, yielding environmental credits that offset only approximately 12% of lifecycle GW impacts. *Solvolysis* generates 467 tons CO_2 equivalent, indicating improved performance but with potential for further environmental impact reduction. Although solvolysis is energy-intensive at 19.2 MJ/kg, recovery of 90–100% material combined with superior fiber quality generates substantial environmental credits from material substitution, offsetting 40–73% of lifecycle GW impacts (Diez-Cañamero and Mendoza 2023).

Per Appendix 3, landfilling's 623 tons CO_2 exceed the 550-ton threshold (Score 2), mechanical recycling's 562 also fall in this band (Score 2), while solvolysis's 467 falls below it (Score 3).

4.2 Scoring of Alternatives on the Financial Criterion

Net Value: Liu et al. (2022) report a comprehensive financial analysis comparing all end-of-life pathways. *Landfilling* generates a net value of -62 USD for GF and -57 USD for CF per ton of recycled material, reflecting pure disposal expenses with no recovered material value. Although landfilling is a mature technology that requires minimal capital investment, financial viability erodes through emerging landfill restrictions and escalating disposal fees. Among immediately deployable recycling technologies, *mechanical recycling* is the only viable option, achieving a net value of 284 USD for GF and 3,011 USD for CF per ton of recycled material through a balance of moderate processing costs and recovered material value from fiber-rich and resin-rich fractions. Mechanical recycling demonstrates established commercial viability at industrial scale, providing reliable near-term options though with lower profit margins. *Solvolysis* achieves a superior net value of 606 USD for GF and 13,090 USD for CF per ton of recycled material, driven by high-yield resin recovery. Unlike mechanical recycling, where the resin fraction has limited worth, solvolysis recovers valuable resin components that offset higher processing costs. While near-term deployment is constrained by capital intensity and limited infrastructure, Liu et al. (2022) identify this high-value recovery as the mechanism ensuring medium-term financial viability once markets mature (Liu et al. 2022). However, the net value for solvolysis represents future potential unit economics. Early-stage CAPEX is a barrier not fully captured in the operational value.

Per Appendix 3, landfilling's net value of -62 USD (GF) falls in the negative band (Score 1). Mechanical recycling's net value of 284 USD (GF) exceeds the 150 USD threshold (Score 3). Solvolysis's net value of 606 USD (GF) exceeds the 600 USD threshold (Score 5).

4.3 Scoring of Alternatives on the Technical Criterion

Technology Readiness Level: According to Paulsen and Enevoldsen’s (2021) and Fonte and Xydis (2021) analyses, *landfilling* represents TRL 9 (fully commercial technology) and is universally deployed across industrialized nations with established regulatory frameworks, standardized operational procedures, mature cost structures, and mature supplier ecosystems, requiring no further technological innovation or development. *Mechanical recycling* represents TRL 8 to 9 (fully commercial technology) with several established commercial operators demonstrating sustained operations. Mechanical grinding and material sizing constitute routine industrial operations with fully established cost structures and multiple commercial suppliers. *Solvolysis* represents TRL 4 to 6 (pilot/demonstration phase) reflecting limited large-scale operational examples and absence of permanent commercial facilities currently processing WTB materials (Bennet et al. 2021). Pilot facilities indicate technical viability but have not achieved sustained large-scale commercial operation, leaving significant engineering challenges and commercial scaling uncertainty (Fonte and Xydis 2021; Paulsen and Enevoldsen 2021).

Per Appendix 3, landfilling’s TRL of 9 falls within the highest band (Score 5). Mechanical recycling’s TRL of 8–9 also meets this highest threshold (Score 5). Solvolysis (TRL 4–6) spans the Score 2 and Score 3 thresholds but is assigned to the TRL 5–6 band (Score 3).

4.4 TOPSIS Results and Discussion

The TOPSIS provides a structured mathematical framework for aggregating heterogeneous criteria and identifying the alternative achieving superior balance across multiple dimensions. Following Hwang and Yoon (1981) methodology, criterion scores are normalized across alternatives on standardized scales, weighted according to specified pillar weights, and evaluated against the positive ideal solution (maximum weighted score on each criterion) and the negative ideal solution (minimum weighted score on each criterion). The relative closeness coefficient is calculated as the ratio of the distance from the negative ideal to the total distance from both ideals, yielding scores between 0 and 1 where higher values indicate superior overall performance. Applying environmental weight of 35%, financial weight of 40%, and technical weight of 25% to normalized criterion scores yields the following quantitative results: Solvolysis achieves a relative closeness score of 0.81, mechanical recycling achieves 0.51, and landfilling achieves 0.19. Solvolysis ranks first because its superior environmental and financial performance outweighs its technical-maturity constraints in the base case. The substantial scoring margin (0.30) indicates that incremental efficiency improvements in mechanical recycling would be insufficient to overcome the deficit relative to solvolysis. All formulas and calculations are provided in Appendix 5.

Sensitivity analysis confirms solvolysis maintains the first ranking position across reasonable weighting variations. Even when the financial weight is raised to 45% and the environmental weight reduced to 30%, or vice versa, solvolysis still ranks highest. Only when the technical criterion is weighted at 45% does mechanical recycling rank nearly equal to solvolysis (Appendix 6). This scenario requires prioritizing technical maturity as a primary optimization objective rather than as an enabling constraint. This implies that unless Enel prioritizes immediate operational certainty above all other factors, Solvolysis remains the dominant strategy.

5. Strategic Recommendations for Enel's Blade End-of-Life Management

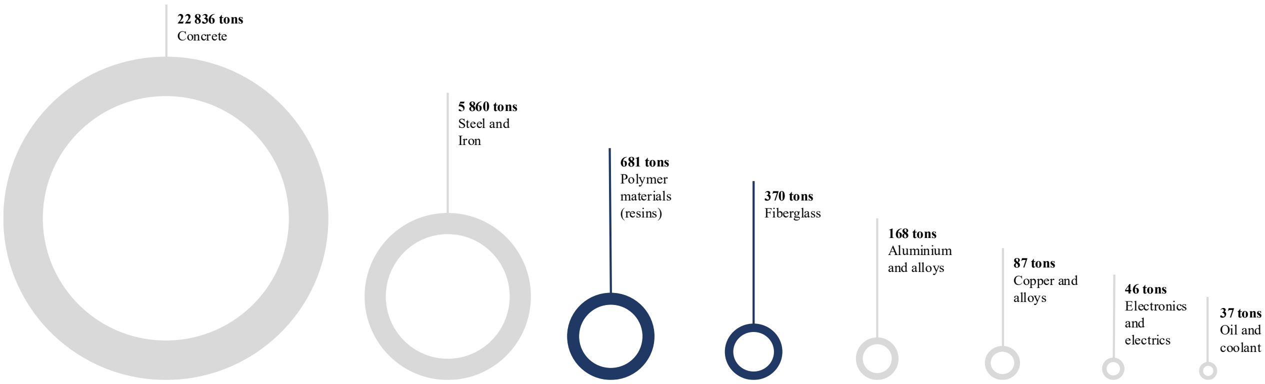
The analysis identifies solvolysis as the optimal long-term alternative driven by its superior unit economics, despite its current technical immaturity and high upfront capital expenditures. Consequently, Enel should adopt a phased implementation approach. In the immediate term, Enel should build upon its existing mechanical recycling pilots to maintain economic viability and operational compliance. However, in the long term, to capture the high financial returns of solvolysis without bearing the full burden of initial investment, Enel should pivot toward joint ventures with technology partners rather than full vertical integration. This strategy creates a distinctive opportunity to differentiate Enel from rivals such as Iberdrola, which have committed to mechanical recycling. By securing priority access to high-quality recovered fibers through these partnerships, Enel establishes first-mover advantages in industry standards and technical expertise that persist as the technology scales.

6. Conclusion

This analysis applies MCDM methodology to demonstrate that solvolysis represents the strategically superior long-term pathway for Enel's WTB end-of-life management, balancing environmental performance, financial viability, and technical feasibility. A key limitation of this analysis is the exclusion of exact CAPEX, which likely overstates the financial viability of pre-commercial solvolysis. The finding is robust across reasonable weighting variations. The base case MCDM weighting reflects Enel's specific organizational priorities. Alternative organizational priorities or regulatory contexts may yield different weightings and potentially different rankings. Future research should extend this analysis by incorporating circular design principles that reduce material volumes, evaluating how design-stage interventions such as modular architecture or lighter composites affect the environmental and financial performance rankings.

Appendix

Appendix 1: Material Bill for a 50 MW Onshore Wind Plant, Adapted from (IRENA 2019)



Appendix 2: Results of the Prior Analyses

Criterion	Source	Pillar	Landfilling	Mechanical Recycling	Solvolysis (Chemical)
Product Circularity Indicator (PCI)	Diez-Cañamero & Mendoza 2023	Environmental	0.22	0.54	0.77
Global Warming (GW) in tons CO2 eq.	Diez-Cañamero & Mendoza 2023	Environmental	623	562	467
Net Value (USD/ton) for GF/CF	Liu et al. 2022	Financial	-62/-57	284/3,011	606/13,090
Technology Readiness Level (TRL)	Paulsen & Enevoldsen 2021 and Fonte and Xydis (2021)	Technical	9	8-9	4-6

Appendix 3: Scoring Rubric and Criterion Scoring Matrix

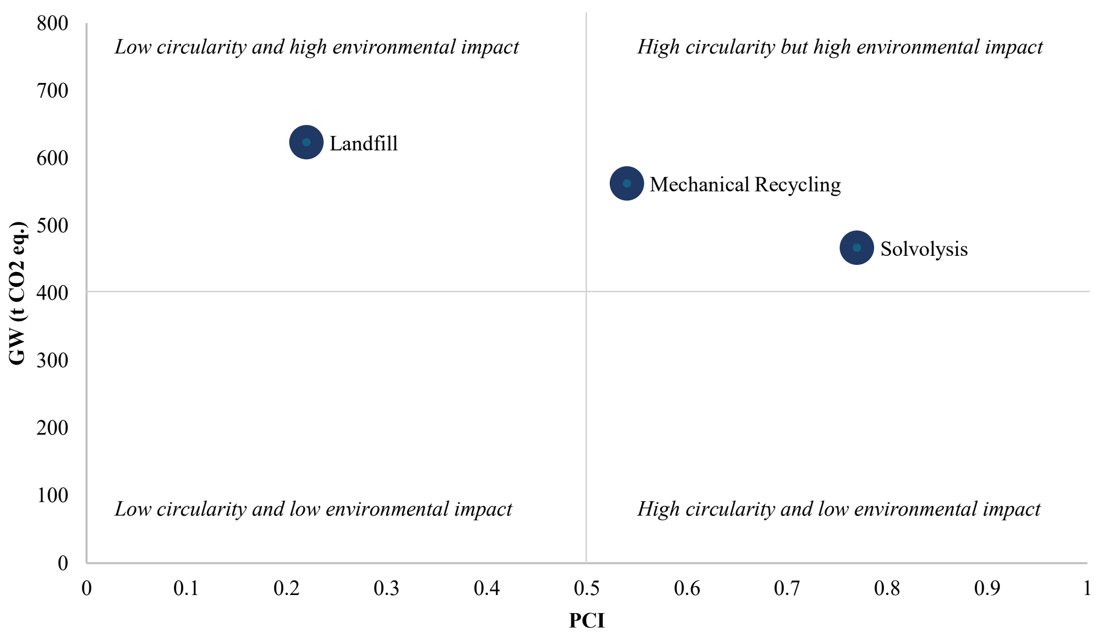
Score	PCI	GW (tons CO_2)[1]	Net Value (USD/ton)[2]	TRL
5	0.80–1.00	<350	$600+	TRL 9
4	0.60–0.80	350–450	$400–600	TRL 7–8
3	0.40–0.60	450–550	$150–400	TRL 5–6
2	0.20–0.40	550–650	$0–150	TRL 3–4
1	0.00–0.20	650–750	Negative	TRL 1–2

[1] The GW scoring bands were defined using threshold-based methodology rather than equal intervals, reflecting the natural clustering of end-of-life pathways in the lifecycle assessment literature. Diez-Cañamero and Mendoza (2023) report GW values ranging from 225 t CO2-eq (solvolysis best-case) to 744 t CO2-eq (pyrolysis worst-case). The threshold values of 350, 450, 550, and 650 t CO2-eq were established as critical boundaries distinguishing performance across technology alternatives: Score 5 captures optimal chemical recycling scenarios; Score 4 captures good solvolysis and mechanical recycling performance; Score 3 captures typical mechanical recycling and acceptable solvolysis; Score 2 captures poor mechanical recycling and comparable landfill emissions; Score 1 captures worst-case scenarios. This approach ensures that band assignments reflect substantive technological differences rather than arbitrary numerical divisions, enhancing the interpretability of the MCDM results.

[2] Net Value scoring bands were defined using a threshold-based approach calibrated exclusively to glass fiber (GF) compositions from Liu et al. (2022) for standardized comparison. The threshold values of $0, $150, $400, and $600/ton were established as critical boundaries distinguishing substantive economic differences: Score 5 captures solvolysis-level profitability ($600+); Score 4 captures strong mechanical recycling ($400–$600); Score 3 captures acceptable mechanical recycling ($150–$400); Score 2 captures marginal profitability ($0–$150); Score 1 captures cost-negative pathways (negative values). This threshold-based approach reflects substantive financial distinctions rather than arbitrary numerical divisions, enhancing the interpretability of the MCDM results.

Criterion	Weight	Landfilling	Mechanical Recycling	Solvolysis
Environmental Pillar	**35%**			
PCI	17.5%	2/5	3/5	4/5
GW	17.5%	2/5	2/5	3/5
Financial Pillar	**40%**			
Net Value	40%	1/5	3/5	5/5
Technical Pillar	**25%**			
TRL	25%	5/5	5/5	3/5

Appendix 4: PCI and GW Correlation, Adapted from (Diez-Cañamero and Mendoza 2023)



Appendix 5: TOPSIS Calculation and Relative Closeness Coefficients

The following formulas are adapted from (Madanchian and Taherdoost 2023).

Step 1: Vector Normalized Scores

$$r_{ij} = \frac{x_{ij}}{\sqrt{(\sum_{i=1}^{m} x_{ij}^2)}}$$

Criterion	Landfilling	Mechanical Recycling	Solvolysis	Sum of Squares	√Squares
PCI	0.37	0.56	0.74	29.00	5.39
GW	0.49	0.49	0.73	17.00	4.12
Net Value	0.17	0.51	0.85	35.00	5.92
TRL	0.65	0.65	0.39	59.00	7.68

Step 2: Weighted Normalized Scores

$$v_{ij} = r_{ij} \times w_j$$

Criterion	Landfilling	Mechanical Recycling	Solvolysis
PCI (17.5%)	0.06	0.10	0.13
GW (17.5%)	0.08	0.08	0.13
Net Value (40%)	0.07	0.20	0.34
TRL (25%)	0.16	0.16	0.10

Step 3: Ideal Best and Ideal Worst Solutions

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\} = \{(^{\max}{}_j v_{ij} \mid i \in I'), (^{\min}{}_j v_{ij} \mid i \in I'')\}$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} = \{(^{\min}{}_j v_{ij} \mid i \in I'), (^{\max}{}_j v_{ij} \mid i \in I'')\}$$

Criterion	A^+	A^-
PCI	0.13	0.06
GW	0.13	0.08
Net Value	0.34	0.07
TRL	0.16	0.10

Steps 4 and 5: Distances (D) and Relative Closeness (C)

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \qquad D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \qquad C_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

Alternative	D^+	D^-	Relative Closeness (C)	Ranking
Landfilling	0.28	0.07	**0.19**	**3**
Mechanical Recycling	0.15	0.15	**0.51**	**2**
Solvolysis	0.07	0.28	**0.81**	**1**

Appendix 6: Sensitivity Analysis

Case	Environmental Weight	Financial Weight	Technical Weight	Landfilling Relative Closeness	Mechanical Recycling Relative Closeness	Solvolysis Relative Closeness
Base Case	35%	40%	25%	0.19	0.51	0.81
Financial-Weighted	30%	45%	25%	0.17	0.51	0.83
Environmental-Weighted	45%	30%	25%	0.22	0.51	0.78
Technical-Weighted	25%	30%	45%	0.36	0.59	0.64

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