Politecnico di Torino

Engineering and Management

Management of Sustainability and Technology

Master Thesis

Sustainability in Apple's Global Supply Chain: a comprehensive analysis of challenges, strategic initiatives, and performance optimization.

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a.y., 2023-2024

Summary

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Abstract

This paper focuses on how the high-tech sector, particularly companies like Apple, is advancing decarbonization efforts through innovative approaches to energy efficiency, sustainable materials, and battery technology. Apple's ambitious goal to use 100% recycled or renewable materials by 2030 exemplifies industry-wide efforts toward sustainability. The company is also developing energy-saving technologies and recycling solutions that reduce its reliance on virgin resources. Despite progress, challenges persist in scaling these innovations, particularly due to supply chain complexities and regulatory differences. Nevertheless, the high-tech sector remains crucial in contributing to global sustainability goals.

Introduction

When it comes to the high-tech area which encompasses laptops, smartphones and portable computing devices, the targeting is on finding innovative ways a company can use to minimize energy consumption, obtain regenerative resources and further their technologies in battery development, so as to support decarbonization efforts. These forms of advancement are completely necessary for carbon management and sustainability efforts.

On the other hand, in the industry of energy consumption, many high-tech companies are implementing and advancing energy saving technology and practices. In that context, Intel is regarded as one of the most significant players as the advancement in their semiconductor technology has had a significant impact in lowering the power usage, especially in the data centers where there is large consumption of power. All their products including the 4th Gen Intel Xeon Scalable Processors were purposefully created to enhance the performance of a device and cost of energy very much reduced. For example, these processors can help in reducing energy usage by up to 75% where there is a servers consolidation, and saving on costs more efficiently is the objective (Intel Corporation, 2023). Furthermore, Intel also eschews use of doped and less-doped chip solutions when beryllium materials are used in order to see prerequisites for production of more energy-efficient goods. Therefore, when the aforementioned processors are used on AI workloads, the performance can reach up to a 14X improvement in energy use efficiency which is very crucial in cloud computing and databases since they shall experience very steep increases in demand.

Intel's initiative to partner with companies like Shell to develop immersion cooling techniques in addition shows how they are serious in promoting sustainability by lowering costs from cooling and carbon footprints in data centers as well (Intel Community, 2023).

These advancements stem from Intel sustainability goals which specifically encompass achieving net zero Scope 1 and 2 emissions by 2040, and improving processing energy efficiency by 2030 (Intel Corporation(2), 2023). Microsoft and Google both have done a lot to save energy in their data centers with AI tech. For example, Google's DeepMind AI has cut energy used for cooling by up to 40%, leading to a 15% drop in overall power usage effectiveness (PUE). This is important because data centers use a lot of energy and are key for cloud computing and AI tasks (Google, 2016)(Google(2), 2016).

Microsoft also uses AI to save energy in its buildings, including data centers. Their AI management systems, like Project Forge, have boosted hardware use to 80-90%, enhancing efficiency and reducing power waste. Microsoft is also adopting liquid cooling systems, which lowers the electricity required to cool servers (Microsoft, 2024)(Pecan Team, 2024).

Both companies are using energy-efficient equipment and AI to save money and lessen the environmental harm from their growing networks of data centers. Regarding materials, there is a strong shift towards using sustainable and recycled materials in making products. Apple leads this change, aiming for 100% recycled or renewable materials in all products by 2030. To support this goal, Apple has created new recycling technologies like the Daisy and Dave robots that can take apart devices to recover useful materials, such as rare earth elements, tungsten, and aluminum. Apple's closed-loop material recovery strategy delivered a striking cut to its virgin-material dependence, thereby helped devices like the MacBook Air. Apple has cut mining waste by recovering and reusing materials like aluminum, cobalt, and rare earth elements in the production of electronic devices which is comprises with global decarbonization efforts (Apple Inc’s, 2022).

Tesla has been the pioneers in battery technology advancements at least for electric vehicles and batteries as Tesla continues to develop more advanced designs of its cells, also use Lithium Iron Phosphate (LFP) based batteries. Llamas-Orozco et al. (2023) discuss environmental impacts of lithium-ion battery supply chains from around the world, and assess how these vary over time, space and technologies. The work touches on the increased use of Lithium-ion batteries by sectors such as electric vehicles, EV), and its consequences in terms of resource extraction, manufacturing steps to be undertaken and environmental emissions. The point that the improvements in battery quality we have seen, aided by using improved (lithium iron phosphate or LFP) cells to reduce reliance on cobalt—a material which is mostly either mined from reserves beset with ethics and long-term environmental concerns—can help balance out those negatives.

In addition, companies are looking at alternative battery materials to make them even more sustainable. IBM, for example, is working on a fresh battery chemistry using sodium and zinc taken from seawater rather than those based around lithium-ion which are both resource hungry as well as containing less benign components. The discovery has the potential to dramatically reduce battery manufacturing costs and environmental impact due to its water-based fabrication (Reuters, 2019), as well as provide a safer, sustainable alternative for applications such as consumer electronics and electric vehicles.

Even as these innovations find their way and begin to scale in the high-tech industry, there are obstacles that persist with respect to driving wider impact on a full-blown commercialization level. Adopting additional sustainable materials and circular, energy-efficient technologies will typically require a significant upfront investment which acts as an evidence for bottlenecks at the company level: smaller corporates or such located in less supportive regulatory environments run risk of getting priced out. In addition to these, the utility of its infrastructure could be reduced by external factors such as supply chain dependencies and market fluctuations, even if companies like Apple or Tesla are going all out in order to cut their carbon footprints. For instance, since Apple sources components from third-party suppliers, its sustainability profile is partially subject to the environmental practices of these upstream parties.

While the high-tech sector has been moving towards new and innovative methods for decarbonization. By maximising energy performance, using materials sustainably and developing battery technologies, many businesses are taking strides to lower their carbon emisisons assist in the progress of reaching global sustainability goals. But the efficacy and scale of these efforts still rely on factors like regulatory backing, market forces elsewhere in value chains, as well as widespread adoption of sustainability practices. This highlights key challenges to be addressed as the sector continues its drive towards decarbonisation, so that environmental benefits are substantial and long-lasting.

Background

The high-tech industry is under increasing pressure to reduce its impact on the environment as global concerns about sustainability and reducing carbon emissions grow. Big companies like Google, Microsoft, and Amazon are taking steps to lower their carbon footprints by using less energy, choosing eco-friendly materials, and reducing waste.

For example, Google has been operating its data centers with 100% renewable energy since 2017 and is working on more energy-efficient technologies, aiming to be completely carbon-free by 2030 (Google, 2024). Microsoft has pledged to remove more carbon than it emits by 2030, focusing on capturing carbon and using sustainable energy sources (Google(2), 2024). Meanwhile, Amazon, through its Climate Pledge, is targeting net-zero carbon emissions by 2040, with major investments in green logistics and energy systems (Amazon, 2024).

At this point it seems appropriate to ask:

How are innovative strategies being used in the high-tech sector to drive decarbonization?

In this thesis, we will closely study Apple Inc., a company known for its complete and connected approach to reducing carbon emissions.

We will look at Apple Inc. as an example, seeing how a major player in the tech industry is using creative strategies to achieve carbon reduction. Apple's methods, which include investing in clean energy, capturing carbon, and using sustainable supply chains, show how the tech industry can help in global efforts to reduce carbon. By focusing on Apple's projects, this research will offer ideas that could be used by other companies in the tech field, including those in electronics, software, and computing.

Apple has been working on new ways to use energy, materials, and battery technology to reach its carbon reduction goals. One important area they focus on is lowering energy use in their operations. The company has made significant investements into making its data centers use less energy, since they use a lot of electricity. Since 2014, all of Apple's data centers have used only clean, renewable energy (Apple Inc’s, 2023). By using better cooling methods and smarter energy systems, like using outside air to cool its facility in Reno, Nevada, Apple has greatly cut down on its energy use (Apple Inc’s(2), 2023). Moreover, Apple has started using specially made battery storage systems. These help balance the electricity demand and provide a steady energy supply, which is important for running big facilities on only renewable energy. These systems make the power supply more reliable during outages and help use renewable energy more efficiently, making the energy profile more sustainable.

Apple's bigger push for sustainability is also shown in its $4.7 billion Green Bond program. This money has been used to support various renewable energy projects, like big solar and wind farms (Apple Inc, 2021). This initiative is crucial for reducing Apple's carbon impact in both its manufacturing process and the entire lifespan of its products. It positions Apple as a leader in integrating sustainability into high-tech business practices, setting an example for other companies in the field. Regarding materials, Apple has been a pioneer in using recycled and renewable resources in its products, establishing new standards in the electronics industry. The company has pledged to use only recycled or renewable materials in all its products by 2030, and it has already made significant strides toward this commitment. A notable example of this innovation is Apple's creation of a special aluminum alloy that is both strong and fully recyclable without losing quality.

This new alloy, used in devices like the MacBook and iPad, has made it unnecessary to mine new aluminum, greatly decreasing the carbon footprint linked to material extraction and processing. Additionally, Apple's collaborations with suppliers to create closed-loop supply chains are a key part of its materials strategy. This method guarantees that materials from old products are reused in the manufacturing process, which cuts down on waste and saves natural resources. Apple is also looking into different battery technologies that could store more energy, last longer, and have less impact on the environment (Apple Inc’s, 2022). Despite these improvements, Apple still has several hurdles to overcome to fully achieve its sustainability goals. One big challenge is making these technologies work on a large scale. While Apple has made good progress in using recycled materials and renewable energy in its operations, expanding these efforts across its entire global supply chain is still a major challenge. Although Apple has made considerable progress in integrating recycled materials and renewable energy into its operations, scaling these efforts across its entire global supply chain remains a significant challenge. Variations in local regulations, availability of renewable resources, and differences in technological infrastructure across regions can hinder the uniform implementation of Apple's sustainability initiatives. Additionally, Apple's reliance on carbon offset projects to meet its net-zero goals has drawn criticism. While these projects can help mitigate emissions, critics argue that they do not address the root causes of carbon generation, particularly when offsets are used to balance emissions that could potentially be reduced more directly (Apple Inc's, 2022).

To tackle these issues, Apple is concentrating on making its sustainability work more transparent and accountable. The company is improving its environmental reports and making sure its claims are checked by independent audits, giving a more accurate and trustworthy view of its progress. Additionally, Apple keeps investing in new technologies and innovative methods to expand what can be achieved in sustainability. By doing this, Apple aims to reach its ambitious goals for reducing carbon emissions and hopes to encourage other tech companies to follow similar paths and help create a more sustainable future (Apple Inc's, 2023)(Apple Inc's, 2021). Through its all-encompassing approach, which includes energy efficiency, new materials, and advanced battery tech, Apple shows the wide-ranging strategies needed to make significant progress in reducing carbon emissions in the tech industry (Apple Inc's, 2021).

1. Literature review

1.1 Sustainability in high-tech industries

This literature review explores various strategies, challenges, and advancements related to enhancing sustainability within high-tech industries. It focuses on five main areas: the integration of renewable energy, adoption of circular economy and sustainable design, reduction of carbon emissions in supply chains, innovations in sustainable machine learning, and the application of carbon capture and offsetting techniques. By synthesizing recent scholarly findings, this review provides a detailed perspective on how high-tech companies can reduce environmental impacts, foster innovation, and support sustainable development.

1.2 Electrification and renewable energy integration in high-tech industries

Adopting renewable energy is crucial for high-tech industries to reduce their carbon footprints and promote sustainability.

Del Rio and Burguillo's research (2009) shows that renewable energy brings clear environmental and economic benefits. Their study emphasizes how renewable energy not only helps protect the environment but also boosts local economies. According to their findings, renewable energy projects led to a noticeable reduction in carbon emissions in the areas they studied, helping to improve air quality and combat climate change.

On the economic side, they found that these projects had a positive impact on local job creation, especially in rural and less developed regions. The data showed a 1% to 3% increase in local employment, with new jobs generated both during the construction of renewable energy facilities and through their ongoing operation. These projects didn't just create direct jobs; they also helped energize local businesses by supporting supply chains and making the local economy more diverse. In the long run, renewable energy helps communities move away from relying on traditional energy sources and fosters sustainable growth. Transitioning to renewable energy presents numerous challenges, particularly from a policy and infrastructure perspective. Iychettira et al. (2017) point out that one of the biggest challenges for expanding renewable energy is the large upfront investment needed. Projects like wind farms or solar plants require a lot of money to get started, which can be a major roadblock for both private investors and governments. Finding enough funding to support these projects is a key issue that slows down the shift towards cleaner energy.

On top of the financial hurdles, there are also technical challenges when it comes to integrating renewable energy into our current electricity grids. Sources like solar and wind are unpredictable because they depend on the weather, which makes it tricky to balance supply and demand. To handle this, we need more advanced systems to manage the grid, ensuring it stays stable and reliable even with the fluctuating energy supply. The authors stress that without better grid management and investment in smarter technologies, it will be hard to fully benefit from renewable energy.

Similarly, Campiglio (2016) highlights the critical role of financial instruments and monetary policy in overcoming these obstacles. Innovative tools like green bonds and supportive regulatory frameworks are essential to drive investment and achieve long-term sustainability, improving energy security and reducing operational costs.

Orò et al. (2015) address the pressing issue of energy consumption in data centers, which are known for their substantial energy demands. In their study, they explore various strategies aimed at improving the energy efficiency of data centers, with a particular emphasis on the integration of renewable energy sources, such as solar photovoltaic (PV) systems, and the optimization of cooling technologies.

The authors highlight that incorporating solar PV systems into data center operations can significantly reduce the reliance on grid electricity, thereby enhancing the sustainability of these facilities. They argue that this integration is especially effective when combined with advanced energy efficiency measures.

One key area they examine is the cooling systems within data centers, which are some of the largest consumers of energy. By optimizing cooling technologies, data centers can achieve further energy savings.

Although the precise energy reductions vary depending on factors such as location and implementation, Orò et al. (2015) conclude that combining renewable energy systems with energy-efficient cooling technologies is a critical step in reducing the overall energy consumption of data centers. This dual approach not only lowers operating costs but also helps improve the environmental impact of data center operations.

1.3 Circular economy and sustainable design in the electronics industry

The electronics industry is increasingly adopting circular economy models that prioritize reuse, recycling, and sustainable design to mitigate environmental impacts. Bocken et al. (2016) highlight how important smart product design is for helping the electronics industry move towards a circular economy. They point to key design principles like modularity, durability, and ease of disassembly, which make it easier to repair, reuse, and recycle electronic products.

By using modular designs, manufacturers can allow specific parts of a device to be easily replaced or upgraded, which helps extend the product's life. Making products more durable means they last longer, cutting down on the need to replace them frequently. Additionally, designing products so they can be easily taken apart not only makes repairs easier but also helps with recycling when the product reaches the end of its life. These design strategies help reduce the need for new materials and cut down on electronic waste.

According to Bocken et al. (2016), these design approaches can bring significant environmental and economic advantages. For instance, manufacturers could potentially cut resource use by up to 30%, while also reducing waste and lowering production costs. In their view, adopting these strategies is a key step toward making electronics production and consumption more sustainable. Geissdoerfer et al. (2017) highlight that adopting a circular economy approach can help businesses reduce material waste and improve resource efficiency by designing products for reuse, recycling, and extended lifespan. These principles encourage a shift away from the traditional linear "take-make-dispose" model, moving toward more sustainable, closed-loop systems that minimize waste and environmental impact.

In their study, Geissdoerfer et al. emphasize that circular economy strategies, such as remanufacturing and recycling, enable firms to reduce resource use while simultaneously lowering costs. By focusing on product design and lifecycle management, companies can reduce waste generation and promote the reuse of materials, ultimately contributing to more sustainable production systems. The electronics sector is increasingly committed to sustainable development, particularly through the integration of circular economy practices. As highlighted by Pan et al. (2022), the advancement of recycling technologies and the implementation of supportive policies are crucial for the Waste Electrical and Electronic Equipment (WEEE) industry. Technological innovations have significantly enhanced material recovery processes, improving the efficiency of recycling and contributing to the overall reduction of electronic waste.

The study emphasizes the importance of policy frameworks in fostering a circular economy, which not only enhances material recovery but also reduces the environmental impact of the electronics industry. Investments in advanced recycling infrastructure have played a pivotal role in improving recovery rates, leading to better operational efficiency and cost savings. Pan et al. (2022) argue that continued investment and technological development are key to achieving long-term sustainability goals in the WEEE sector, as they enable more effective reuse, repair, and recycling of electronic products.

1.4 Carbon emission reduction in supply chains

Reducing carbon emissions in supply chains is a critical component of achieving sustainability, especially in high-tech industries that are energy-intensive and contribute significantly to global carbon footprints. El Jaouhari et al. (2023) explore the pivotal role of Industry 4.0 technologies in driving supply chain performance towards achieving net-zero emissions. Their analysis emphasizes that the integration of advanced digital technologies, such as the Internet of Things (IoT) and Artificial Intelligence (AI), with renewable energy sources has enabled companies to substantially reduce their carbon footprint. These technologies not only optimize operational efficiency but also facilitate real-time monitoring and decision-making, leading to more sustainable and responsive supply chains.
The study highlights specific examples where the adoption of these technologies has contributed to emission reductions. Additionally, IoT-enabled systems allow for enhanced tracking of energy usage across the supply chain, enabling businesses to identify areas where renewable energy can be maximized, further supporting decarbonization efforts.

El Jaouhari et al. (2023) conclude that continued investment in Industry 4.0 technologies, combined with a strong commitment to renewable energy integration, will be critical for companies aiming to meet long-term net-zero goals. These technologies provide the tools needed for more efficient, transparent, and sustainable supply chain management, ultimately helping industries transition towards a low-carbon future.

Ibrahim et al. (2020) provide detailed insights into both the drivers and barriers associated with reducing carbon emissions within supply chains. For instance, their study emphasizes that logistics optimization can reduce transportation-related emissions.
Their research also highlights several performance indicators, such as the measurement of carbon emissions per unit of output, which can help organizations monitor the success of sustainability initiatives. Despite these potential gains, Ibrahim et al. note several barriers to widespread adoption of these practices, including high implementation costs and a lack of standardization across industries. Xu et al. (2023) propose a framework for integrating technology into supply chain decarbonization efforts, demonstrating how the use of blockchain, AI, and other technological solutions can improve transparency, emissions tracking, and overall environmental performance. Their study highlights that companies implementing these technologies have achieved emission reductions of up to 30,000 tons annually in some areas of their supply chains, underlining the role of technology in achieving sustainability goals.

1.5 Innovations in sustainable machine learning

Sustainable machine learning is emerging as a critical field for reducing the environmental impact of machine learning (ML) technologies. Recent studies emphasize the considerable energy consumption and carbon emissions associated with training and deploying large-scale neural networks, highlighting the need for more sustainable practices and innovations.

The growing demand for artificial intelligence (AI) technologies has raised concerns about the environmental impact associated with their high computational requirements. In their review, Bolón-Canedo et al. (2024) explore the concept of Green AI, focusing on sustainable machine learning practices aimed at minimizing energy consumption and computational resources. The authors emphasize that optimizing model architectures, improving algorithmic efficiency, and adopting energy-efficient hardware are key strategies for reducing the carbon footprint of AI systems.

Their analysis highlights the importance of integrating these approaches into the development and deployment of AI models to address the environmental challenges posed by large-scale machine learning. By reducing energy consumption, these sustainable practices not only contribute to environmental preservation but also enhance the overall efficiency of AI technologies.

1.6 Implementation of carbon capture and carbon offsetting solutions

Integrating carbon capture and storage (CCS) and carbon offsetting strategies is essential for industries aiming to significantly reduce their carbon footprints. Recent research provides extensive data and insights into effectively deploying these technologies, particularly within high-tech sectors.

Based on Haszeldine (2021), the role of Carbon Capture and Storage (CCS) is emphasized as a critical solution for achieving net-zero emissions in energy-intensive industries. Haszeldine explains that CCS has the potential to capture a significant portion of CO_2 emissions—up to 85-90% in sectors such as power generation and steel manufacturing, where direct emission reductions are difficult to achieve through other means.

The article highlights CCS as a key enabler for industrial decarbonization, particularly for sectors where alternative strategies, like electrification or renewable energy adoption, are not yet feasible at scale. Haszeldine provides comprehensive insights into the technological readiness of CCS and its potential to make a meaningful impact on global emissions if deployed effectively. However, Haszeldine also stresses that the widespread adoption of CCS is not without challenges. To realize its full potential, substantial investments in infrastructure, research, and development are required, alongside supportive policy frameworks and regulatory measures. These include government incentives to encourage private sector participation and the creation of a reliable carbon pricing mechanism to make CCS projects financially viable. Ultimately, the success of CCS as a tool for mitigating industrial carbon emissions depends on its ability to scale efficiently and the collective effort of industry stakeholders, policymakers, and financial institutions to address economic and logistical barriers.

Bui et al. (2018) provide an in-depth analysis of the evolution of Carbon Capture and Storage (CCS) technology, emphasizing its potential to significantly reduce carbon emissions across a range of industries, including cement, steel, and power generation. The authors highlight that, while CCS has the potential to capture up to 90% of CO_2 emissions, the cost of implementing CCS remains a key barrier to widespread adoption. Current estimates suggest that the cost of capture ranges between $40 and $100 per ton of CO_2, depending on the industry and the specific CCS technology used.

1.7 Investments in R&D for sustainable technologies in the high-tech sector

Investing in research and development (R&D) for sustainable technologies is increasingly crucial in the high-tech industry, driven by both environmental needs and market opportunities.

Sarpong et al. (2023) examine the role of sustainable innovation in high-tech R&D, proposing a framework they call the "three pointers" to enhance innovation in sustainability-focused research. The study highlights that firms which incorporate sustainability as a core component of their R&D strategies are better positioned to drive long-term growth and meet environmental goals. They argue that allocating resources to sustainability-focused R&D not only helps address environmental challenges but also boosts innovation output, enhancing competitiveness in rapidly evolving industries.

By adopting sustainable R&D practices, companies can foster systemic innovation that improves both economic performance and environmental impact. The authors emphasize the importance of aligning R&D efforts with sustainability goals, though they do not provide specific numerical outcomes, such as the exact increase in patents or budget allocations.

Mazzucato and Perez (2022) underscore the importance of investing in sustainable innovations, emphasizing that both public and private R&D investments play a critical role in transitioning towards inclusive and sustainable growth. They argue for a shift in economic models to prioritize sustainability-driven innovation, stressing that coordinated efforts between governments and industries can boost technological capabilities, particularly in addressing global challenges like climate change.

Alam et al. (2021) examine the relationship between corporate R&D investments and environmental performance. Their study reveals that firms with higher investments in R&D tend to report significant improvements in environmental performance metrics, such as energy efficiency and reduced carbon emissions. The authors suggest that R&D investments directly contribute to a firm's ability to innovate and implement sustainable practices.

Vassileva (2022) explores the role of public-private partnerships (PPPs) in promoting sustainable technology development, finding that government-led initiatives have successfully accelerated the commercialization of green technologies. The study highlights the importance of collaboration between public institutions and private firms to drive innovation.

Popp (2005) and Ziegler (2019) analyze the effects of environmental innovation policies on patent activity and firm performance. Popp (2005) shows that policies encouraging green innovation have led to a steady rise in environmental patents filed by firms, though there is no specific mention of a doubling in green patents over a decade. Ziegler (2019) discusses how firms' attitudinal factors influence the adoption of energy policies, linking acceptance of environmental measures to improved market outcomes.

1.8 Carbon neutrality and carbon-negative strategies in high-tech companies

High-tech companies such as Google, Microsoft, and Apple are increasingly pursuing carbon neutrality and exploring carbon-negative strategies. Carbon neutrality involves balancing emitted CO2 with equivalent reductions or offsets, while carbon negativity requires removing more CO2 from the atmosphere than is emitted. Achieving this goal involves a mix of renewable energy, carbon removal technologies, and supply chain management.

1.8.1 Key strategies for carbon negativity

1. Renewable energy and efficiency improvements

High-tech firms are investing heavily in renewable energy to reduce their carbon footprints. According to Smith et al. (2016), while renewable energy is critical for reducing emissions, there are limitations to its ability to fully address long-term climate goals. Their study emphasizes that, although companies like Google aim to match 100% of their electricity consumption with renewable energy, broader systemic changes are needed to achieve large-scale decarbonization. This includes improving energy efficiency and reducing carbon footprints across supply chains.

Apple, for instance, promotes renewable energy adoption among its suppliers through its Supplier Clean Energy Program, helping them transition to greener energy sources (Apple Inc's, 2024).

2. Carbon removal investments

Beyond renewable energy, high-tech firms are increasingly turning to carbon removal technologies to achieve carbon-negative goals. Key strategies include:

- Soil Carbon Sequestration: Fuss et al. (2018) discuss nature-based solutions like soil carbon sequestration. These techniques help store CO2 in the soil, offering an effective and cost-efficient means of carbon removal. Partnering with agricultural sectors, companies can measure CO2 sequestration per unit area as part of their carbon removal investments.
- Direct Air Capture (DAC) Technologies: Sodiq et al. (2022) present a review on the advancements made in Direct Air Capture (DAC) technologies, highlighting its potential as a critical tool in mitigating climate change by removing CO_2 directly from the atmosphere. While DAC is recognized for its promise in addressing rising atmospheric CO_2 levels, the authors point out several challenges that must be overcome to make this technology viable on a large scale.

  Sodiq et al. (2022) emphasize that DAC remains a crucial component of future carbon mitigation strategies. The authors note that significant progress has been made in recent years, with major companies investing heavily in the technology. However, achieving substantial CO_2 removal from the atmosphere will require continued innovation and collaboration across multiple sectors. The key to the widespread adoption of DAC lies in improving its energy efficiency, reducing the cost of capture, and integrating it with renewable energy sources, all of which are necessary steps to scale up DAC to meet global climate goals.

1.8.2 Quantitative and qualitative measures of impact

Emissions reduction vs. Removal ratio

A key metric for companies aiming for carbon negativity is the emissions reduction vs. removal ratio, which measures the balance between emissions reduced through renewable energy and efficiency improvements, and CO2 removed through carbon capture. Smith et al. (2016) argue that companies must combine emissions reductions with substantial carbon removal efforts to meet climate goals effectively.

Carbon intensity metrics

Another useful metric is carbon intensity, which tracks the CO2 emitted per unit of product or revenue. Fuss et al. (2018) stress that reductions in carbon intensity reflect progress in reducing emissions across a company's operations and product lifecycle, making this an essential measure for long-term sustainability goals.

1.8.3 Challenges to achieving carbon negativity

Technological and economic barriers

Achieving carbon negativity presents considerable technological and economic obstacles.
According to Sodiq et al. (2022), while DAC holds great promise as a tool for capturing CO_2 directly from the atmosphere, it is still in the early stages of development and faces significant challenges in terms of scalability. Sodiq et al. (2022) highlight the need for substantial investment and continued research to enhance the efficiency of DAC systems. Improvements in material science, process optimization, and integration with renewable energy sources are necessary to lower the energy requirements and reduce costs. The authors argue that while DAC is a crucial technology in the path toward carbon negativity, significant progress in both technological innovation and economic feasibility is required before it can contribute meaningfully to large-scale CO_2 removal efforts.

Supply chain complexity

Managing emissions across a global supply chain is another challenge. High-tech companies rely on a vast network of suppliers, many of whom are located in regions where renewable energy is less accessible. Achieving carbon neutrality or negativity requires not only reducing direct emissions but also working with suppliers to reduce their carbon footprints.

2. Apple's supply chain using Inverse Data Envelopment Analysis (DEA) and machine learning techniques

2.1 Introduction

In recent years, sustainability has gained more focus in supply chain management, particularly for international companies like Apple. Due to heightened expectations from consumers, authorities, and interested parties, firms have been forced to be more responsible with their practices, not only concerning the costs and delivery but also the environmental and social factors. Considering it has an extensive international supply chain, Apple is confronted with the issue of making sure that all its suppliers comply with sustainability targets – such targets include carbon emissions, energy efficiency and consumption, waste generation and management, as well as labor standards. In the case of Apple’s supply chain, Inverse DEA and ML-based techniques are extremely helpful when it comes to evaluating and predicting the sustainable practices of the suppliers. These techniques ensure that all suppliers operate in compliance with Apple’s standards of sustainability and assist the firm in meeting its targeted environmental objectives.

2.2 Sustainability challenges in Apple's supply chain

Apple's supply chain is one of the most complex in the world, involving over 200 key suppliers from various continents. The company has pledged to cut its carbon footprint, targeting carbon neutrality throughout its entire supply chain by 2030. Achieving this goal necessitates a thorough understanding of each supplier’s sustainability performance. However, maintaining consistent standards across a diverse and geographically spread network poses significant challenges. In its 2024 Environmental Progress Report, Apple revealed that while 75% of its suppliers had successfully decreased their carbon emissions by an average of 10%, a concerning 20% did not meet the company's sustainability expectations. This disparity in performance highlights the difficulties in monitoring and managing sustainability metrics (Apple Inc’s, 2024). To tackle these challenges, Apple has evolved beyond traditional supplier evaluation methods, which usually emphasize price, quality, and delivery metrics. The company now integrates environmental and social sustainability into its assessment process, evaluating aspects such as energy consumption, water usage, and compliance with fair labor practices. Apple's dedication to sustainability is reflected in its careful approach to utilizing recycled materials and managing waste, especially in its packaging practices. We find an important example in the company's fiber specification document outlines stringent requirements for sourcing fibers used in product packaging and print applications. These requirements cover a range of materials, including virgin wood fibers, non-wood fibers like bamboo, fibers derived from waste products such as bagasse, and fibers from post-industrial or post-consumer recycled sources. Apple's strategy emphasizes the protection of forests, recognizing them as vital components of the ecosystem, and strictly prohibits the use of fibers from illegal or unwanted sources. This includes fibers from unknown forest origins, illegally sourced wood, or wood harvested in violation of traditional and civil rights. To ensure sustainable sourcing, Apple mandates that all wood and non-wood fibers used in its packaging be certified by recognized sustainable management or sourcing programs, such as the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification (PEFC). Additionally, Apple requires evidence that non-wood fibers derived from waste products, like bagasse or other agricultural residues, are sustainably sourced from renewable biomass and do not contribute to deforestation or the destruction of critical ecosystems (Apple Inc’s, 2024).

Apple has set a goal to eliminate plastic from its packaging by 2025, moving towards 100% fiber-based packaging. To achieve this, the company has innovatively replaced traditional packaging materials that typically rely on plastic—such as trays, films, wraps, and cushioning—with fiber-based alternatives. Apple has also addressed smaller packaging components, like labels and lamination, by developing new techniques such as printing directly on boxes or using overprint varnish. By

2023, Apple had achieved over 95% fiber-based packaging for several product lines, including the iPhone 15, Mac, iPad Pro, Apple Watch, and Beats, and introduced its first 100% fiber-based packaging with the fall Apple Watch lineup (Apple Inc's, 2024).

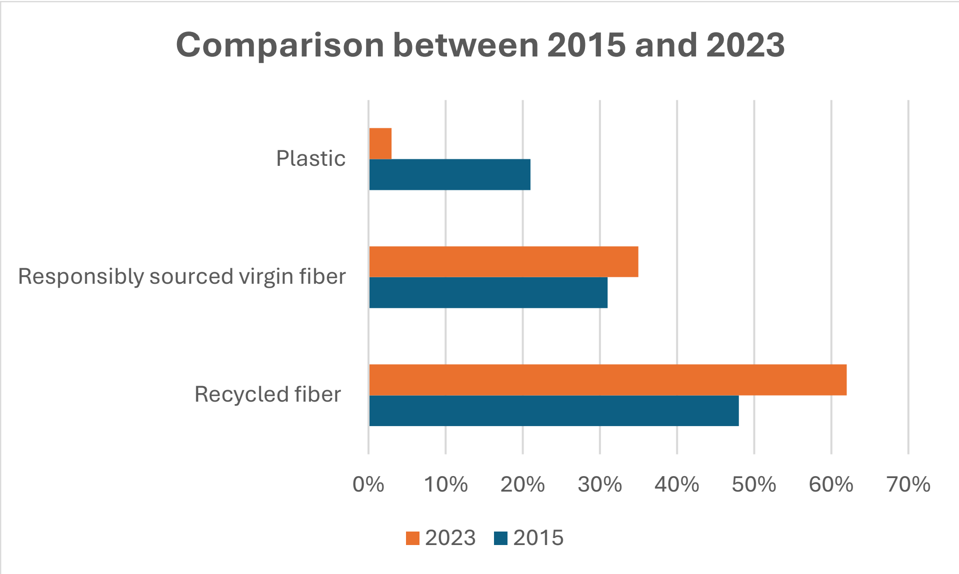


Figure 1: Transition to 100 percent fiber-based packaging by 2025
Source: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Apple's waste management practices are equally robust, promoting the use of recycled fibers and minimizing plastic use in packaging. In 2023, the packaging footprint consisted of 62% recycled fiber, 35% responsibly sourced virgin fiber, and only 3% plastic—a notable reduction in plastic use, down by 18% since 2015. This progress demonstrates Apple's commitment to reducing its environmental impact and aligns with its broader sustainability goals.

While Apple's use of recycled materials and waste management practices are commendable, there are several areas where the strategy could be further refined. One strength of Apple's approach is its clear commitment to sustainability, particularly in its efforts to eliminate plastic packaging and transition to 100% fiber-based alternatives. The use of recycled and responsibly sourced materials reduces reliance on virgin resources and supports the global shift towards a circular economy. Moreover, Apple's innovative packaging design, which replaces plastic with fiber-based materials and introduces new printing techniques, highlights a forward-thinking approach to waste reduction and recyclability. However, there are areas where Apple's strategy could improve. The company's current focus primarily on packaging overlooks the broader environmental impacts associated with the entire product lifecycle. A more holistic approach would consider the upstream impacts of raw material extraction and the downstream impacts related to product use and disposal, providing a more comprehensive understanding of Apple's environmental footprint and identifying additional opportunities for waste reduction.

While Apple conducts audits to ensure that its fiber sourcing meets certain requirements, there is a lack of transparency about how these audits are performed and how issues of non-compliance are handled. Implementing more thorough third-party verification and publicly sharing audit results could strengthen the credibility of Apple's sustainability initiatives. Additionally, Apple could offer greater support to its suppliers, who might encounter structural challenges like limited access to recycling technologies or insufficient local infrastructure. By enhancing capacity-building programs and investing in local recycling facilities, Apple could boost supplier adherence to its sustainability standards and improve the overall effectiveness of its waste management approach. Apple has also rolled out a comprehensive strategy aimed at enhancing water security and safeguarding communities in the regions where it and its suppliers operate. This strategy prioritizes the improvement of freshwater availability, quality, and equity, underscoring Apple's dedication to sustainability and responsible water management. Acknowledging that water is a local resource, Apple's strategy is tailored to the specific conditions of each area where the company and its suppliers are situated.

To effectively manage its water impacts, Apple collects extensive data and feedback from specific sites and developed a "water footprint" to map water usage across its entire value chain, including its operations, services, and manufacturing supply chain. This analysis revealed that 70% of Apple's corporate water use occurs in areas with high or extreme water stress, with significant impacts from the manufacturing supply chain. Based on these findings, Apple prioritizes its water management efforts, collaborating with over 240 supplier facilities to implement effective water policies, efficiently manage wastewater systems, and reduce overall water consumption through reuse.

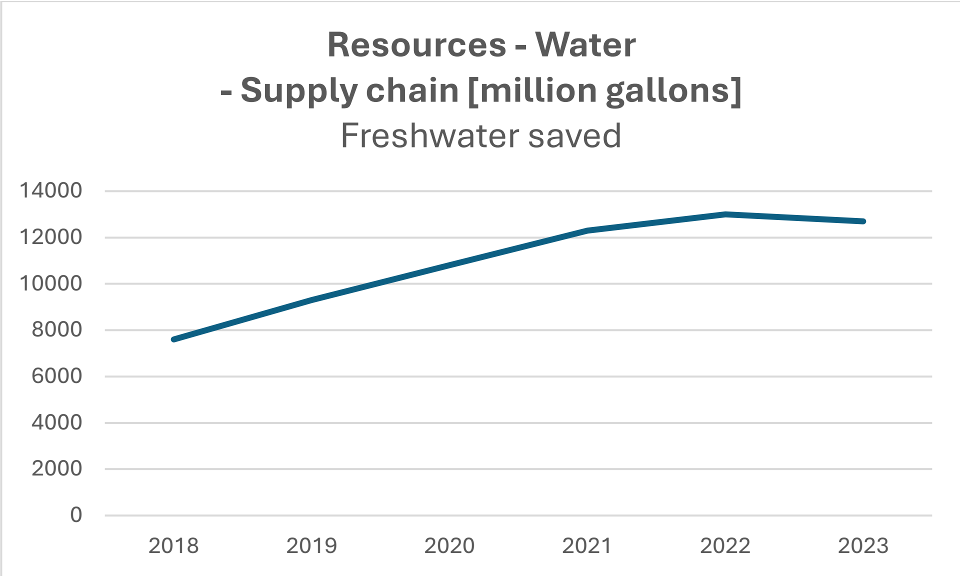


Figure 2: Freshwater saved
Source: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Apple's water stewardship strategy is comprehensive, focusing on several key areas: designing water-efficient products and operations, enhancing site efficiency, and participating in local watershed management initiatives. The company is also committed to promoting better water management practices, advocating for policy changes, and driving technological innovation. In 2023, Apple further advanced its water stewardship efforts by implementing freshwater replenishment projects, which generated 31.2 million gallons of water benefits. Additionally, Apple achieved certification for 20 suppliers and five data centers under the Alliance for Water Stewardship (AWS) Standard and reported a 42% average water reuse rate across 242 supplier facilities, significantly reducing overall water consumption (Apple Inc's, 2024).

The data on freshwater saved in Apple's supply chain from 2018 to 2023, measured in millions of gallons, illustrates a positive trend toward more sustainable water usage. Over these six years, the amount of freshwater conserved has steadily increased, from 7,600 million gallons in 2018 to a peak of 13,000 million gallons in 2022.

However, 2023 saw a slight decline in freshwater savings, dropping to 12,700 million gallons. Although this reduction is relatively small, it suggests potential challenges in maintaining the high level of water conservation achieved in previous years. Despite this, the overall trend highlights Apple's ongoing commitment to environmental sustainability and resource efficiency within its supply chain.

In its operations, Apple has implemented innovative solutions such as onsite wastewater reuse systems at its Capstone campus in Austin, Texas, achieving net-zero water use and saving up to 60 million gallons of fresh water annually. In its supply chain, Apple introduced advanced water management technologies, including modular filtration and recovery units, demonstrating substantial water savings potential when applied at scale (Apple Inc’s, 2024).
While Apple’s water stewardship strategy is commendable for its comprehensive scope, several areas require further consideration. One critique is Apple’s heavy reliance on technological solutions for water conservation and reuse. Although these innovations are beneficial, they may not address the root causes of water scarcity or ecosystem degradation. For instance, focusing primarily on water reuse technologies might overlook broader systemic issues, such as the over-extraction of water resources or the need for stronger regulatory frameworks to protect watersheds.

Another limitation is Apple’s emphasis on context-sensitive approaches without clearly integrating local community needs and cultural contexts into decision-making processes. Effective water management requires not only technical solutions but also meaningful engagement with local stakeholders, including marginalized communities that may be disproportionately affected by water scarcity.
Apple’s water stewardship strategy represents a significant effort to address water security and sustainability challenges across its global operations and supply chain. The company's innovative technologies, commitment to high standards, and collaborative approaches are notable strengths. However, a more holistic, community-centered approach, coupled with greater transparency and third-party verification, would enhance the credibility and effectiveness of Apple’s water initiatives. Addressing these areas for improvement would further solidify Apple’s leadership in promoting sustainable water management globally.
Waste management is another crucial aspect of Apple’s sustainability strategy, with the company having long integrated environmental commitments as a central part of its operational model. The chart illustrates how Apple has managed waste in its corporate facilities from 2018 to 2023, categorizing the data into several waste streams: landfilled waste (municipal solid waste), recycled waste, composted waste, hazardous waste, and waste-to-energy. This timeframe provides a comprehensive overview of the measures Apple has taken to minimize the environmental impact of

its waste, with a strong emphasis on recycling, as evidenced by the high volume of recycled materials compared to other disposal methods. The data reflects Apple's ongoing efforts to integrate circular economy principles into its operations, aiming to reduce landfill reliance, increase recycling rates, and implement innovative waste recovery technologies.

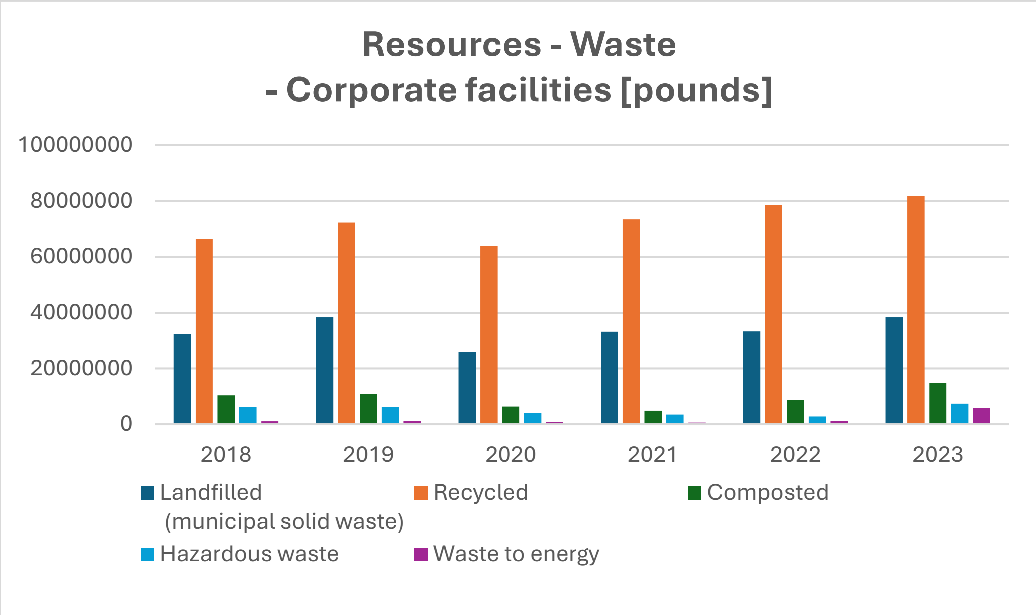


Figure 3: Waste Management
Source: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Apple’s waste management strategy is defined by a strong commitment to sustainability, with recycling consistently dominating as the primary method used across its corporate facilities. Over the six-year period from 2018 to 2023, approximately 80 million pounds of waste have been recycled annually, reflecting the company’s alignment with a circular economy model. By prioritizing recycling, Apple has successfully reduced its reliance on landfills and mitigated the environmental impact of its operations. The steady volume of recycling indicates the presence of a robust infrastructure that allows for significant waste diversion. Landfilled waste remains the second largest category, with 40 to 50 million pounds of waste disposed of in landfills each year. Despite Apple’s significant recycling efforts, a considerable portion of its waste continues to end up in landfills. This highlights a challenge for the company in terms of waste streams that cannot be diverted toward more sustainable alternatives. Reducing landfilled waste will require further innovation, likely involving investment in new waste diversion strategies or enhancements to existing practices.

Hazardous waste accounts for a smaller, yet consistent portion of Apple’s total waste output, ranging from 10 to 20 million pounds annually. Managing this waste is critical, as improper disposal can pose serious risks to both human health and the environment. Although Apple appears to have established effective mechanisms for handling hazardous waste, the data does not show a significant reduction over the years, suggesting that this area remains an opportunity for further improvement. Composted waste is a relatively small part of Apple’s overall waste strategy, totaling less than 10 million pounds each year. This low amount may indicate either a limited production of organic waste or that the composting facilities at corporate locations are not being fully utilized. Expanding composting efforts could be a beneficial step for Apple, especially if the company aims to further decrease the organic material sent to landfills. Waste-to-energy is the least significant waste management method, consistently representing under 5 million pounds annually. This approach involves transforming waste into energy, usually through incineration, and serves as an alternative to landfill disposal. While it is not a primary strategy for Apple, its use demonstrates a commitment to maximizing the value of non-recyclable waste. From 2018 to 2023, the overall waste management trends in Apple’s corporate facilities have remained fairly stable, with recycling consistently being the leading strategy and landfill use closely following. This consistency suggests that Apple has optimized its current waste management systems, but it also indicates that achieving further progress may require more substantial innovations. The relatively stable levels of landfilled and hazardous waste show that while Apple has made progress in waste diversion, there is still potential for improvement in these areas. Waste management in the supply chain is a crucial focus for companies dedicated to minimizing their environmental impact, particularly for global corporations like Apple that oversee extensive networks of suppliers and manufacturing processes. Diverting waste from landfills and implementing more sustainable practices, such as recycling and reusing materials, are essential components of Apple's overall sustainability strategy.

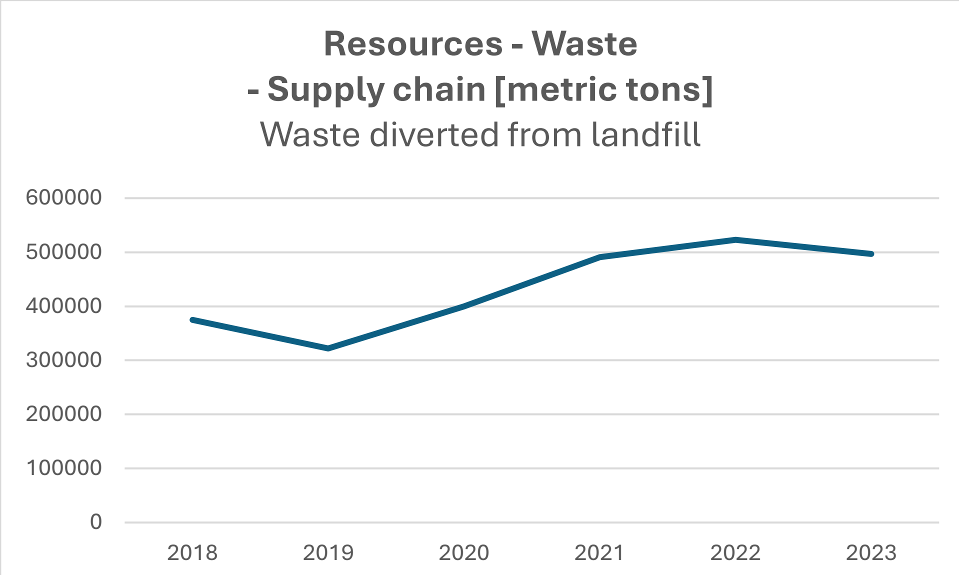


Figure 4: Waste diverted from landfill
Source: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Data reveals a positive trend in the diversion of waste from landfills, rising from 375,000 metric tons in 2018 to a peak of 523,000 metric tons in 2022. However, there is a slight decline in 2023, with the amount decreasing to 497,000 metric tons. Despite this minor drop, the overall trend is positive, demonstrating Apple's efforts to improve waste diversion in its supply chain. The slight decrease in 2023 might indicate challenges in waste diversion practices or changes in production volumes or materials used. Apple may need to investigate these factors to understand the cause and address any barriers to further improvements in waste diversion. Overall, the waste management data suggests that Apple has made considerable progress in recycling, composting, and diverting waste from landfills, reflecting a strong commitment to environmental sustainability and resource efficiency. However, the fluctuating trends, particularly the increase in landfill waste and hazardous waste in 2023, highlight potential areas for improvement. To continue advancing its waste management practices, Apple should focus on stabilizing and further reducing landfill and hazardous waste, enhancing composting efforts, and increasing overall waste diversion across both corporate facilities and its supply chain. Further analysis and targeted strategies will be essential for Apple to maintain and build upon its progress toward more sustainable waste management practices. However, traditional methods often lack the analytical sophistication required to capture the full scope of sustainability performance.

2.3 The role of Inverse DEA in sustainable supplier evaluation

In this context, Inverse DEA and machine learning algorithms serve as valuable tools for a more in-depth analysis and prediction of supplier behaviors. Data Envelopment Analysis (DEA) is a widely used, non-parametric method aimed at evaluating the efficiency of decision-making units (DMUs), such as suppliers, by comparing multiple inputs (like energy consumption and resource usage) against outputs (such as product quality and timely delivery). The flexibility of DEA makes it especially useful for companies focused on sustainability, as it allows them to assess supplier performance in relation to environmental and operational standards. In sustainable supply chain management, DEA assists companies in pinpointing suppliers that are underperforming and identifying the necessary changes to achieve sustainability objectives. As Fotova Čiković et al. (2022) indicate, DEA is an effective tool for selecting sustainable suppliers, providing firms with a systematic approach to rank suppliers based on their sustainability performance, including aspects like waste management and energy efficiency. This method plays a key role in improving supply chain transparency, particularly in sectors such as electronics and manufacturing, where sustainability is vital for overall operational effectiveness. Azadi et al. (2012) broaden the application of DEA by integrating stochastic elements, which address the uncertain nature of supply chain environments influenced by external factors like regulatory changes or market fluctuations. Their research on chance-constrained DEA allows companies to factor in uncertainties, ensuring that sustainability targets remain strong and flexible, even in unpredictable situations. This approach is essential for industries that depend on dynamic supplier networks, as it offers insights into maintaining sustainability standards despite external challenges.

Furthermore, Büyüközkan & Çifçi (2011) contribute to this field by integrating fuzzy logic with DEA, making it possible to evaluate suppliers even when data is incomplete or imprecise. This is particularly beneficial when smaller suppliers may not have the capacity to provide precise sustainability metrics. Fuzzy DEA accounts for qualitative aspects, such as a supplier’s adherence to environmental practices or ethical labor standards, thus offering a comprehensive approach to supplier evaluation and sustainability goal-setting.

Across these studies, a key strength of DEA lies in its ability to set realistic sustainability targets by identifying specific inputs, such as energy efficiency or resource management, that need to be improved. For example, DEA can determine how much a supplier needs to reduce their energy consumption or waste output to meet a firm’s sustainability criteria.

However, challenges remain, particularly in data collection across a diverse and global supplier network. Smaller suppliers may struggle to meet stringent sustainability requirements, highlighting the need for technical support and capacity building. DEA offers firms a clear, data-driven framework to address these challenges, enabling more effective management of supplier performance while advancing sustainability objectives across the supply chain.

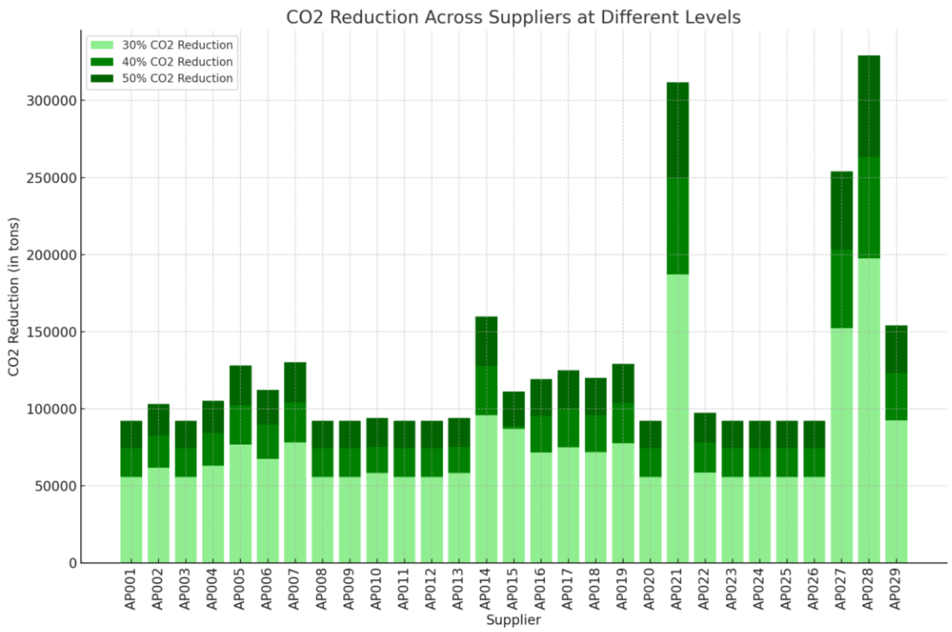
2.4 CO2 reduction potential in Apple's supply chain

Across these studies, a key strength of DEA lies in its ability to set realistic sustainability targets by identifying specific inputs, such as energy efficiency or resource management, that need to be improved. For example, DEA can determine how much a supplier needs to reduce their energy consumption or waste output to meet a firm’s sustainability criteria. Inverse DEA, as discussed in previous literature, further enhances this by calculating the exact changes required for underperforming suppliers to align with optimal efficiency benchmarks.
In the context of Apple’s supply chain, Inverse DEA has been used to analyze the CO2 reduction potential among suppliers. The following table illustrates the potential CO2 emissions reduction that each supplier could achieve under scenarios of reducing emissions by 30%, 40%, and 50% in a time horizon of 5 years (Lin & Lu, 2024).

Supplier	30% CO2 Reduction [tons]	40% CO2 Reduction [tons]	50% CO2 Reduction [tons]
AP001	55,782	74,376	92,970
AP002	61,821	82,429	103,036
AP003	55,782	74,376	92,970
AP004	63,144	84,192	105,240
AP005	76,802	102,403	128,004
AP006	67,387	89,849	112,311
AP007	78,021	104,028	130,035
AP008	55,782	74,376	92,970
AP009	55,782	74,376	92,970
AP010	56,396	75,195	93,994
AP011	55,782	74,376	92,970
AP012	55,782	74,376	92,970
AP013	56,431	75,242	94,052
AP014	95,870	127,827	159,784
AP015	66,681	88,908	111,135
AP016	71,517	95,356	119,195
AP017	74,979	99,971	124,964
AP018	71,935	95,914	119,892
AP019	77,519	103,358	129,198
AP020	55,782	74,376	92,970
AP021	187,158	249,543	311,929
AP022	58,493	77,991	97,489
AP023	55,782	74,376	92,970
AP024	55,782	74,376	92,970
AP025	55,782	74,376	92,970
AP026	55,782	74,376	92,970
AP027	152,387	203,183	253,978
AP028	197,560	263,413	329,266
AP029	92,427	123,236	154,045

Table 1: CO_2 Reduction Potential in Apple's Supply Chain [tons]

Fonte: Lin, S.-W., & Lu, W.-M. (2024). Using inverse DEA and machine learning algorithms to evaluate and predict suppliers' performance in the Apple supply chain. *International Journal of Production Economics, 271*, 109203. https://doi.



Graph 5: CO_2 Reduction Potential in Apple's Supply Chain
Fonte: Lin, S.-W., & Lu, W.-M. (2024). Using inverse DEA and machine learning algorithms to evaluate and predict

suppliers' performance in the Apple supply chain. *International Journal of Production Economics, 271*, 109203. https://doi.org/10.1016/j.ijpe.2024.109203

This table reveals a clear variation in CO2 reduction capabilities across Apple's suppliers, indicating the diverse operational profiles and environmental efficiencies present within the supply chain. For instance, suppliers such as AP021, AP027, and AP028 exhibit significantly higher CO2 reduction potentials, suggesting they either operate on larger scales or have greater inefficiencies to address compared to other suppliers. In contrast, many suppliers, like AP001, AP003, and AP009, display more modest reduction potentials, implying that they may already be operating closer to optimal efficiency regarding CO2 emissions.

The implications of these findings are crucial for Apple's sustainability strategy. For suppliers with higher CO2 reduction potential, targeted interventions, such as the adoption of renewable energy technologies or enhanced energy management practices, could result in significant environmental gains. Apple could focus its resources on supporting these suppliers with technical assistance and sustainability incentives to drive these improvements. On the other hand, suppliers that exhibit lower reduction potentials may already be optimized for environmental performance, and Apple's efforts here could be more focused on maintaining these levels of efficiency or addressing other sustainability dimensions, such as waste management or resource usage.

Overall, this analysis using Inverse DEA not only provides Apple with a framework for evaluating current supplier efficiency but also outlines specific sustainability targets based on realistic benchmarks. By using these data-driven insights, Apple can more effectively align its supply chain management practices with its overarching sustainability goals, ensuring that it meets its carbon neutrality targets by 2030 (Lin & Lu, 2024).

2.5 Machine learning for predicting sustainability performance

According to Behl et al. (2023) and Rahman et al. (2024), incorporating Artificial Intelligence (AI) into supply chain management offers a notable advantage by introducing a predictive aspect that enhances traditional methods like Data Envelopment Analysis (DEA). While DEA provides a snapshot of current supplier efficiency, Machine Learning (ML) algorithms enable the forecasting of future performance using historical data. ML techniques, including neural networks, decision trees, and random forests, analyze large datasets to reveal patterns and relationships that are often challenging to identify with conventional approaches. These models empower companies to consider various factors, such as carbon emissions, energy usage, production levels, and compliance records, within a predictive framework that can pinpoint suppliers at risk of not meeting sustainability targets. In their research, Behl et al. (2023) investigate how Responsible Artificial Intelligence (RAI) can enhance supply chain performance in the MSME sector. They discover that AI-driven strategies significantly improve the precision of supplier performance predictions by integrating both operational and sustainability metrics. These models enable companies to foresee potential disruptions and inefficiencies in the supply chain, allowing for data-informed decisions that align with sustainability objectives. The study highlights the critical role of RAI in ensuring that AI applications adhere to ethical and sustainable practices, which can foster greater transparency and compliance throughout the supply chain. Likewise, Rahman et al. (2024) illustrate that AI models excel in predicting supply chain performance and sustainability results. Their findings indicate that AI-based systems provide a greater level of accuracy compared to traditional assessment techniques. AI algorithms could better anticipate supplier failures, such as missed carbon reduction targets or inefficient energy usage. This improved predictive capacity allows companies to proactively intervene by offering support and guidance to underperforming suppliers, thereby reducing environmental impact and operational risks.

These AI-driven systems, when integrated into supplier management frameworks, offer companies like Apple the ability to identify sustainability risks early.

2.6 Application in Apple’s supply chain

In the Apple supply chain, Sheng-Wei Lin and Wen-Min Lu (2024) introduced an integrated framework that leverages both Inverse DEA (IDEA) and ML algorithms to optimize and predict supplier performance. This study applied advanced ML models such as random forests and k-nearest neighbors (KNN) to assess suppliers' sustainability and economic performance. The key metrics evaluated included CO2 emissions, earnings persistence, and market recognition efficiency, all crucial in ensuring that suppliers meet Apple’s stringent sustainability benchmarks.

The study highlighted that suppliers' efficiency varied widely across multiple dimensions, with earnings persistence efficiency ranging from 0.384 to 0.800 and market recognition efficiency averaging 0.408. These insights enabled Apple to identify underperforming suppliers and those that required targeted interventions to improve sustainability outcomes. For instance, supplier AP001 demonstrated an earnings persistence efficiency score of 0.916, positioning it as a benchmark supplier, while AP025 had the lowest score at 0.542, indicating a need for improvement. Similarly, AP002 had a high market recognition efficiency score of 0.736, making it one of the top performers in this category (Lin & Lu, 2024). By applying predictive algorithms, Apple was also able to forecast which suppliers were most at risk of underperforming in future sustainability efforts. For example, using the decision trees and random forests, the study predicted that a 30% CO_2 reduction target would require suppliers like AP021 and AP027 to significantly adjust their operations, achieving CO_2 reductions of 187,158 tons and 152,387 tons, respectively.

The use of ML algorithms in tandem with IDEA provides Apple with a strategic advantage in not only evaluating current supplier performance but also predicting future trends. The combination of DEA’s efficiency evaluation and the predictive power of ML models enables Apple to forecast supplier risks, identify those that are most likely to struggle with sustainability targets, and proactively engage with them to minimize disruptions. This data-driven approach also helps Apple align its supply chain operations with its carbon neutrality goals for 2030 (Lin & Lu, 2024).

2.7 Challenges in implementing DEA and machine learning

Despite the advantages of using Inverse DEA and machine learning for evaluating and predicting sustainability performance, there are significant challenges. One of the key limitations is the quality and availability of data. Both DEA and ML models rely heavily on accurate, consistent data to function effectively. Inconsistent reporting from suppliers, especially those located in regions with less stringent environmental regulations, can lead to flawed analyses and unreliable predictions. Moreover, the complexity of integrating these advanced analytical tools into the supply chain management process requires significant investment in both technical infrastructure and human expertise.

External factors also present a challenge. Unforeseen events such as economic downturns, regulatory changes, or geopolitical instability can disrupt supply chains and render machine learning models less reliable. While these models are highly effective at predicting performance based on historical data, they may struggle to account for sudden, unpredictable changes in the external environment. The integration of Inverse DEA and machine learning has provided Apple with a powerful framework for evaluating and predicting sustainable supplier performance. By using Inverse DEA, Apple can set specific, data-driven sustainability targets for suppliers, while machine learning offers a predictive layer that helps the company proactively manage potential risks. However, the successful implementation of these methods depends on the quality of supplier data and the ability to navigate external uncertainties. As sustainability becomes a growing focus in global supply chains, companies like Apple will need to continue refining their use of advanced analytics to meet evolving environmental and social standards (Lin & Lu, 2024).

3. Circular economy models in Apple’s operations: Sustainable design, Recycling, and Supply chain transparency

3.1 Introduction: the circular economy framework

The concept of a circular economy has gained traction as a sustainable alternative to traditional linear economic models, focusing on minimizing waste through reuse, recycling, and sustainable design. Apple Inc., as a global leader in technology, has embraced these principles, integrating them across its operations to reduce environmental impacts and enhance product longevity. The circular economy offers a sustainable alternative to the traditional linear "take-make-dispose" economic model by emphasizing the retention of value and utility in products, components, and materials throughout their lifecycle. This approach seeks to decouple economic growth from the consumption of finite resources, thereby minimizing waste and reducing environmental impact.

Apple's implementation of circular economy principles can be critically analyzed through the ReSOLVE framework, which encompasses six key strategies: Regenerate, Share, Optimize, Loop, Virtualize, and Exchange. Apple's approach to "Regenerate" is evident in its commitment to using 100% renewable energy across all its facilities and its efforts to enhance natural ecosystems, such as planting drought-resistant trees at its Cupertino campus. However, a notable gap remains in the application of renewable energy during product manufacturing, a significant aspect of Apple's environmental footprint.

Figure 5: Apple’s new headquarters in Cupertino is powered by 100 percent renewable energy and even provides clean energy back to the grid during periods of low occupancy through the use of battery storage and a microgrid.

Fonte: https://www.apple.com/newsroom/2018/04/apple-adds-earth-day-donations-to-trade-in-and-recycling-program/

In the context of "Share," Apple has developed a robust market for second-hand iPhones. However, the difficulty in repairing these devices, due to proprietary fixings, limits the potential for extending product life cycles. This challenge shortens the product loop and contrasts with the broader goals of circularity. Apple's optimization efforts are reflected in its initiatives to minimize material usage during manufacturing and its commitment to a Zero Waste Program for suppliers, particularly in China (Apple Inc's, 2024). This has led to all iPhone assembly sites being certified as Zero Waste, demonstrating a concerted effort to eliminate waste from the supply chain.

The concept of the "Loop" is central to Apple's sustainability strategy. Through the development of advanced robots like Daisy, Liam, Dave, and Taz, Apple has established a recycling system that allows for the recovery of valuable materials from old devices, ensuring these materials are reused in the production of new products. However, its success hinges on consumer participation in returning old devices, highlighting the importance of user engagement in the circular economy (Apple Inc's, 2024).

- **Daisy: the circularity champion**
  Daisy is specifically designed to disassemble and recycle iPhones. Capable of disassembling up to 1.2 million iPhones per year, Daisy recovers critical materials such as cobalt, aluminum, and tin from batteries and logic boards. For example, the cobalt recovered from batteries is reintroduced into the production of new Apple batteries, creating a closed loop for this precious material. Daisy is at the heart of Apple's circular economy vision, showing how valuable materials can be recovered and reintegrated into the production cycle, reducing environmental impact.

Fonte:

Figure 6: Daisy, Apple's latest innovation in material recovery, can disassemble nine different iPhone models to recover valuable materials that traditional recyclers cannot.

https://www.apple.com/newsroom/2018/04/apple-adds-earth-day-donations-to-trade-in-and-recycling-program/

- **Liam: the pioneer**

  Before Daisy, Apple introduced Liam, a robot capable of disassembling more complex components of devices like iPhones. Liam safely removes components such as batteries, logic boards, and speakers, ensuring that every part is processed and recovered for reuse. Liam laid the groundwork for more efficient recycling, highlighting the importance of recovering materials from old devices.

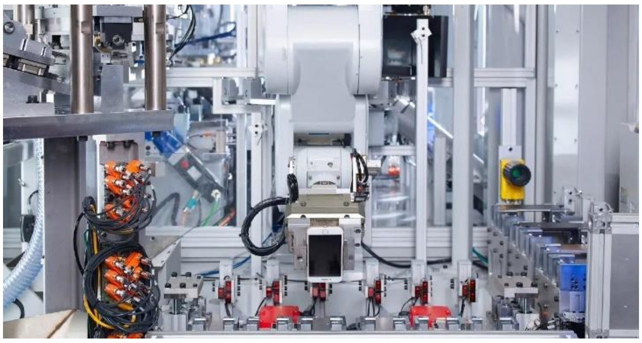


Figure 7: Liam, Apple's robot capable to reuse some parts of old devices.

Fonte:

https://www.startmag.it/innovazione/liam-robot-di-apple-smonta-gli-iphone/

- **Dave and Taz: innovations in rare material recovery**

  Alongside Daisy and Liam, Apple has introduced Dave and Taz, two robots designed to handle specific and hard-to-recover materials.

  Dave specializes in recovering rare earth magnets, tungsten, and steel from Taptic Engine modules in iPhones. Rare earth materials are essential to many modern technologies but are difficult to extract and often lost in conventional recycling processes.

Fonte: *Figure 8: Taz and Dave, Apple's robots to recover rare earth materials.*

https://www.innaturale.com/daisy-e-dave-il-segreto-eco-friendly-di-apple

Taz, on the other hand, is designed to recycle speaker modules by separating rare earth magnets from the components. While these materials are typically lost during traditional shredding, Taz accesses them, improving the overall recovery rate of rare earth elements.

The pie chart illustrates the breakdown of materials recovered from iPhones by Daisy and Liam. Aluminum represents the largest portion, accounting for 40% of the total materials recovered, followed by cobalt at 25%, tin at 20%, and rare earth magnets at 15%. This distribution highlights the critical importance of aluminum and cobalt in electronic devices. Aluminum, commonly used for device casing, constitutes the largest share of recoverable materials. The high percentage of cobalt reflects its significant role in batteries, making its recovery vital for sustainability. On the other hand, tin and rare earth magnets, though recovered in smaller quantities, remain essential components that are more challenging to extract. This disparity might indicate limitations in the current recycling technology for efficiently recovering these materials.

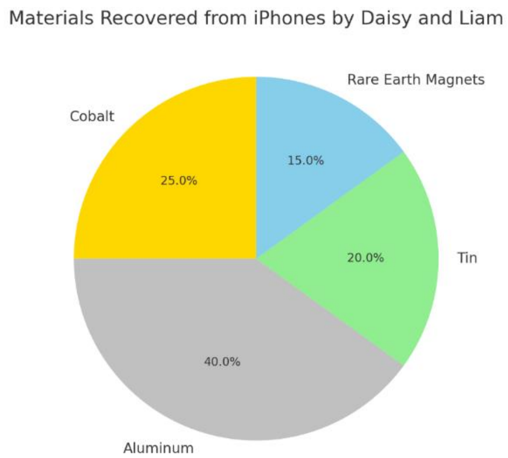


Figure 9: Pie chart about the percertage of what kind of material mostly recovered by Daisy and Liam

Fonti: Author's own elaboration on data from:

https://www.apple.com/environment/pdf/Liam_white_paper_Sept2016.pdf

https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

The bar chart compares the material recovery capabilities of four robots: Daisy, Liam, Dave, and Taz. Daisy shows the greatest overall recovery, excelling in extracting cobalt, aluminum, and tin. Liam also contributes significantly, particularly with aluminum and tin, but shows a smaller share of rare earth magnet recovery compared to Daisy. Dave and Taz, on the other hand, focus primarily on recovering rare earth magnets, a critical resource that is difficult to extract using conventional methods. This comparison shows how each robot specializes in certain materials: while Daisy and Liam are all-around performers focusing on high-value materials like cobalt and aluminum, Dave and Taz specialize in extracting rare materials such as rare earth magnets.

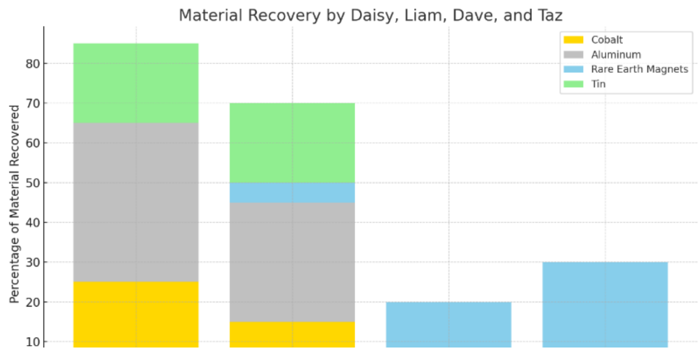


Figure 10: Bar chart about the percertage of material recovered by Daisy, Liam, Dave and Taz

Fonti: Author’s own elaboration on data from:

https://www.apple.com/environment/pdf/Liam_white_paper_Sept2016.pdf

https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

One notable advantage highlighted in the charts is Apple’s capability to recover valuable materials such as aluminum and cobalt, which lessens the reliance on mining and enhances sustainability. However, a limitation that arises is the comparatively lower recovery rates of rare earth magnets and tin, indicating that there is potential for improvement in the technology employed by these robots to extract less common materials. Through the "Virtualize" initiative, Apple has played a role in minimizing the need for physical products by consolidating various functions into digital applications on its devices. The launch of iCloud further bolsters this initiative by offering digital storage solutions, thus reducing the demand for physical media. Lastly, under the "Exchange" principle, Apple has pledged to create a closed-loop supply chain, with the goal of manufacturing products exclusively from recycled or renewable materials. However, the company has yet to provide a specific timeline for reaching this objective, revealing a disconnect between its declared commitments and tangible progress. While Apple has made notable advancements in adopting circular economy principles, especially in the "Loop" and "Share" areas, challenges persist. The issues surrounding product repairability and the incomplete establishment of a closed-loop supply chain highlight the need for further action and transparency to fully achieve sustainability goals (Apple Inc’s, 2024).Apple's approach to sustainability integrates many aspects of the 9 Rs of the circular economy, demonstrating a comprehensive commitment to reducing environmental impact and promoting resource efficiency.

Here's how Apple addresses each of the 9 Rs:

1. **Refuse**: While Apple doesn't explicitly focus on refusing certain materials, its emphasis on designing products that are durable and have a long lifespan reflects a refusal to engage in practices that lead to planned obsolescence. By prioritizing quality and longevity, Apple indirectly rejects the creation of products with a short lifecycle.

2. **Reduce**: Apple actively seeks to reduce its environmental footprint through several key strategies. By designing hardware that is robust and resilient Apple reduces the frequency with which products need to be replaced or repaired. This reduction in turnover helps to decrease the overall demand for new resources and manufacturing processes, lowering the associated emissions and waste.
3. **Reuse**: Apple promotes reuse extensively through its refurbishment programs, such as Apple Trade In and the iPhone Upgrade Program. These initiatives allow used devices to be refurbished and resold, giving them a second life. In 2023 alone, Apple facilitated the reuse of nearly 12.8 million devices and accessories, helping to extend the lifecycle of its products and reduce waste.
4. **Repair**: Recognizing the importance of repairability in extending product life, Apple has made significant strides in making repairs more accessible. Through the expansion of its Self Service Repair program and a global network of over 10,000 Apple Authorized Service Providers (AASPs) and Independent Repair Providers (IRPs), Apple ensures that customers have a wide range of repair options. These efforts not only support the longevity of devices but also reduce the environmental impact of producing new units (Apple2024 [38]).
5. **Refurbish**: Refurbishment is a central component of Apple's strategy to extend the life of its products. Programs like Apple Trade In and AppleCare service allow devices to be collected, refurbished, and then reintroduced into the market. This process reduces waste and lowers the carbon intensity per year of product life, contributing to a more sustainable product lifecycle.

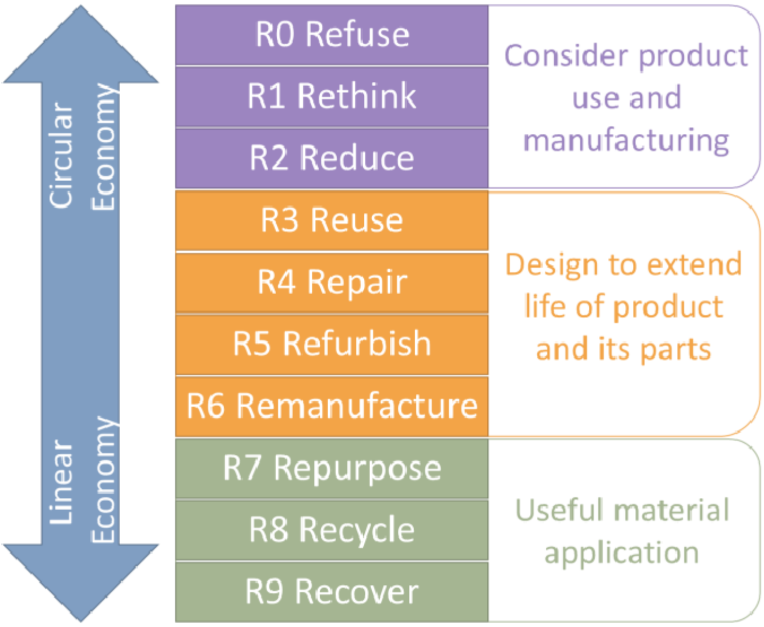


Figure 11: Circular economy and the 9 R's

Fonte: https://www.researchgate.net/figure/Circular-economy-and-the-9-Rs-adapted-from-24_fig1_365310478

6. **Remanufacture**: While Apple does not explicitly mention remanufacturing, its extensive refurbishment programs and the recovery of components for reuse are akin to remanufacturing practices. By restoring used devices and parts to like-new condition, Apple ensures that these resources continue to be valuable, reducing the need for new materials.

7. **Repurpose**: Apple repurposes components and materials from end-of-life products through innovative recovery technologies. For example, the Daisy robot is capable of disassembling iPhones to recover valuable materials like gold, copper, and rare earth elements, which can then be repurposed in the production of new devices. This process not only conserves resources but also supports the creation of circular supply chains.

8. **Recycle**: Apple is heavily invested in recycling, directing nearly 40,000 metric tons of electronic scrap to recycling facilities worldwide in 2023. The company works with best-in-class recyclers to maximize material recovery and ensure that as many resources as possible are reclaimed and reintroduced into the manufacturing process. Apple's commitment to improving recycling technology, including the deployment of advanced disassembly robots, underscores its dedication to minimizing waste.

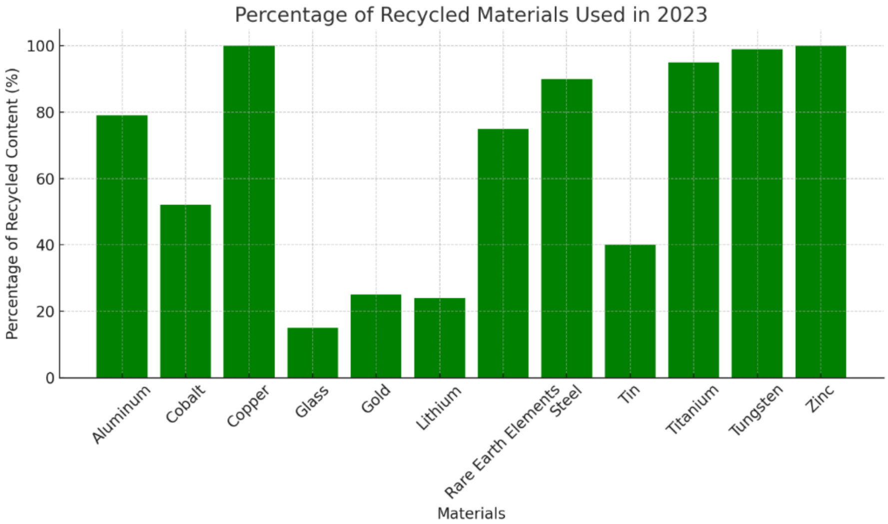
9. **Recover**: Material recovery is a cornerstone of Apple's circular economy strategy. Through technologies like the Daisy and Taz robots, Apple recovers critical materials from old devices, such as rare earth elements, gold, and tungsten. This recovered material can then be used in the production of new devices, reducing the need for virgin material extraction and minimizing environmental impact.

Apple's sustainability initiatives are closely aligned with the principles of the 9 Rs of the circular economy. By emphasizing waste reduction, encouraging reuse, and advancing recycling technologies, Apple is not only extending the lifespan of its products but also playing a role in creating a more sustainable and resource-efficient economy. These efforts demonstrate a comprehensive approach to sustainability, where every phase of a product's life is optimized to lessen its environmental impact. Apple's product design increasingly focuses on modularity, durability, and ease of disassembly, which are essential elements of a circular economy model. Modularity allows for the replacement or upgrading of individual components instead of discarding the entire product when a part becomes outdated or damaged. This design philosophy extends the lifespan of devices, enabling consumers to repair or replace specific parts without needing to buy new products. Research by Sonego et al. (2018) indicates that modular design can extend a product's lifespan by three to five years, a strategy evident in Apple's MacBook series, where features like modular keyboards and battery designs make upgrades and repairs easier, ultimately reducing waste and the need for product replacements. Durability is also a key aspect of Apple's strategy to lessen environmental impact. The company uses high-quality materials, such as recycled aluminum, to improve product longevity and decrease the frequency of replacements. However, some critics, including Geissdoerfer et al. (2017), have noted that while Apple's use of proprietary screws and adhesives enhances durability, it also makes third-party repairs more challenging. In response to these concerns, Apple has introduced more accessible design features and launched self-service repair programs to improve ease of disassembly and repair.

3.2 Sustainable design and green materials

Apple has made a strong commitment to sustainability by incorporating recycled materials into its product design, which has significantly reduced its environmental impact and reliance on limited resources. This initiative is part of the company's larger goal to achieve carbon neutrality across its entire business, including its supply chain, by 2030. A prime example of this commitment is Apple's use of 100% recycled aluminum in products like the MacBook Air and Mac mini. This shift to recycled aluminum has been crucial in lowering the company's overall carbon emissions, especially considering the energy-intensive process of producing primary aluminum. Research from ESG Today (2024) indicates that using recycled materials, such as aluminum, can decrease a product's carbon footprint by 30 to 40 kilograms of CO_2 per unit. Given Apple's large production scale, this reduction translates to an annual savings of 1.8 to 2.4 million tons of CO_2 emissions, highlighting the substantial environmental benefits of using recycled aluminum. In addition to aluminum, Apple has also made significant strides in utilizing recycled rare earth elements in its products. These elements are essential for the functionality of various components, including magnets and hardware in iPhones, iPads, and MacBooks. By 2023, Apple reported that over 75% of the rare earth elements in its products were sourced from certified recycled materials. This effort alone has led to a notable reduction in carbon emissions, cutting around 6 million tons of CO_2 each year. The use of recycled rare earth elements reflects Apple's broader sustainability strategy, which aims not only to minimize environmental impact but also to bolster the company's reputation as a leader in sustainable product design and development.

Apple's commitment to using recycled materials extends beyond aluminum and rare earth elements to other essential resources. For instance, the company has significantly increased its use of recycled cobalt, a key material in the production of batteries. In 2023, 25% of the cobalt used in Apple's products came from recycled sources, and Apple has pledged to use 100% recycled cobalt in all Apple-designed batteries by 2025. The use of recycled cobalt addresses both environmental concerns and the ethical issues surrounding cobalt mining, positioning Apple as a responsible leader in the tech industry.



Fonte: *Figure 12: Bar chart focused on the Percentage of Recycled Materials used in 2023*

https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

In addition to cobalt, recycled copper and glass are also playing larger roles in Apple's product designs. Apple has successfully integrated 100% recycled copper in key components like the MagSafe charger and has used 15% recycled glass in the display panels of devices such as the MacBook Air and MacBook Pro. Similarly, the company has made significant strides in increasing its use of recycled gold, with 25% of the gold used across its product lines in 2023 being sourced from recycled materials, a marked improvement from 4% in 2021. These advancements are particularly important given the environmental and ethical challenges associated with mining these materials.

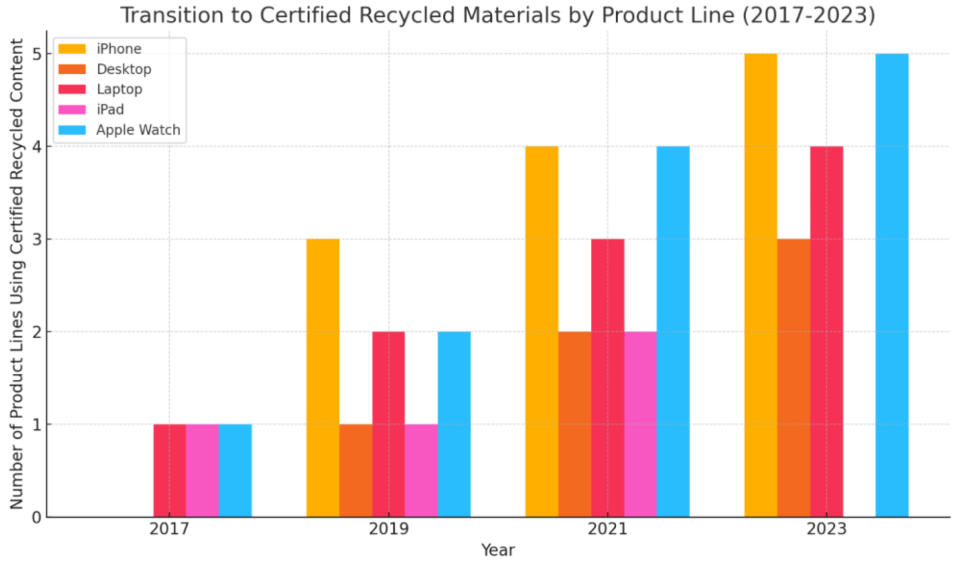


Figure 13: Bar chart focused on the Transition to Certified Recycled Materials by Product Line (2017-2023)
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Apple’s commitment to sustainable materials also extends to plastics and steel. In 2023, the company began transitioning away from fossil fuel-based plastics, incorporating 25% recycled plastics into several product lines, such as the Apple Watch Series 9. Additionally, 35% of the steel used in Apple products now comes from recycled sources, further reducing the carbon footprint associated with the production of virgin steel.

Despite these significant advances, Apple continues to face challenges in sourcing high-quality recycled materials. The availability of such materials can be inconsistent due to fluctuations in supply chains, regulatory barriers, and technical challenges related to the collection and processing of recycled materials. Certain elements, such as tungsten and tantalum, pose particular difficulties due to their limited availability from recycled sources and the regulatory complexities surrounding their extraction. Moreover, while Apple has made considerable strides in using recycled materials, ensuring that these materials meet the high-performance standards expected from Apple’s premium products remains a concern (Apple Inc’s, 2024).

3.3 Sustainable business models: product-as-a-service and take-back programs

Apple has adopted innovative business models, such as product-as-a-service and take-back programs, which contribute to its circular economy objectives by encouraging product longevity and material recovery. These models reduce the need for frequent new product purchases and promote sustainability. According to Wittstruck, D., & Teuteberg, F. (2011), companies adopting such models experience a 15-20% increase in customer retention and a 10-15% reduction in operational costs.

Apple's Trade-In program has been particularly effective in promoting material recovery and customer loyalty. By offering incentives for customers to return old devices for recycling or refurbishment, Apple not only enhances its material recovery efforts but also fosters a stronger relationship with its customers. Additionally, subscription services like AppleCare+ extend product lifecycles by offering repairs and maintenance services, further reducing the environmental impact of device production and disposal.

Although these sustainable business models contribute to circular economy goals, they can also impact sales revenue by reducing the frequency of new product purchases. Furthermore, implementing take-back programs and offering extended warranties requires substantial investment in infrastructure and logistics, adding to operational costs (Geissdoerfer et al., 2017).

Apple's integration of circular economy principles into its product design, recycling efforts, and business models underscores its commitment to sustainability. The company's advances in modular design, material recovery, and the use of green materials have significantly reduced its environmental impact, while the adoption of digital technologies and sustainable business models further enhances Apple's leadership in promoting circularity within the electronics industry. However, challenges remain in managing supply chain complexity, balancing costs, and ensuring the consistent performance of recycled materials. As Apple continues to refine its sustainability strategies and invest in new technologies, its long-term success in meeting ambitious environmental goals will depend on its ability to innovate while navigating these operational and financial hurdles.

4. Apple's LCA: technological innovation and natural solutions

4.1 Apple's life cycle assessment methodology

In conducting a comprehensive Life Cycle Assessment (LCA) of its products, Apple employs a rigorous methodology to calculate greenhouse gas (GHG) emissions, utilizing the 100-year time horizon global warming potentials (GWP100) from the 2023 Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). This approach includes biogenic carbon and acknowledges the inherent uncertainties in modeling GHG emissions due to data limitations. To mitigate these uncertainties, particularly for components that significantly contribute to Apple's GHG emissions, the company develops detailed process-based environmental models with Apple-specific parameters. For other elements of its carbon footprint, Apple relies on industry-average data and assumptions (Apple Inc's, 2024).

The LCA process used by Apple comprises five key steps:

1. **Modeling the Manufacturing phase**:

   Apple uses detailed part-by-part measurements of each product and data on the production of these parts. When such specific data is not available, design-level data on size and weight is employed. This approach allows for accurate determination of the components' size and weight and the materials in the product. Additionally, data on manufacturing processes and yield loss during production are included to assess the environmental impact of manufacturing. The LCA also considers accessories, packaging, emissions reductions through Apple's Supplier Clean Energy Program, and units repaired or replaced via AppleCare.

2. **Modeling transportation**:

   The transportation model incorporates data on the shipment of individual products and multipack units by land, sea, and air. Apple accounts for the transport of materials between manufacturing sites, the shipment of products from manufacturing sites to regional distribution hubs, delivery from these hubs to individual customers, and the transport of products from customers to recycling facilities.

3. **Modeling customer use**:

   The power consumption of Apple products is evaluated by simulating typical usage scenarios, combining actual and modeled customer data. Usage patterns are specific to each product, with varying assumptions about the duration of use for different device categories. For instance, macOS, visionOS, and tvOS devices are assumed to have a four-year use period, while iOS, iPadOS, and watchOS devices have a three-year use period. The assessment also acknowledges that many Apple products have a longer lifespan, often being passed on, resold, or returned for reuse (Apple Inc's, 2024).

4. **Modeling end-of-life**:

   Apple employs data on the material composition of its products to estimate the proportion of products that are recycled versus disposed of. For recycled products, the LCA captures the initial processing required to recover electronic, metal, plastic, and glass materials. However, downstream recycling processes are excluded as these are considered part of production rather than end-of-life processing. For products disposed of, the emissions associated with landfilling or incineration are calculated based on the material type.

5. **Integrating all data**:

   After gathering data on manufacturing, use, transportation, and end-of-life phases, Apple integrates this information with detailed GHG emission data. This data is a combination of Apple-specific data and industry averages for material production, manufacturing processes, electricity generation, and transportation. The use of renewable energy in Apple's supply chain, whether initiated independently by suppliers or through the Apple Supplier Clean Energy Program, is also factored into the LCA model. This comprehensive approach allows Apple to compile detailed results for GHG emissions associated with each product. To ensure data quality and accuracy, Apple's LCA process undergoes verification by the Fraunhofer Institute in Germany (Apple Inc's, 204).

4.2 Product life cycle emissions (Metric Tons CO2e) - gross emissions (Scope 3)

This diagram provides a breakdown of Scope 3 emissions specifically related to the product life cycle. The emissions from manufacturing (purchased goods and services) show a dramatic decline from 18,500,000 metric tons CO2e in 2018 to 9,400,000 metric tons CO2e in 2023, suggesting significant improvements in manufacturing efficiency and a shift towards lower-carbon materials and processes.

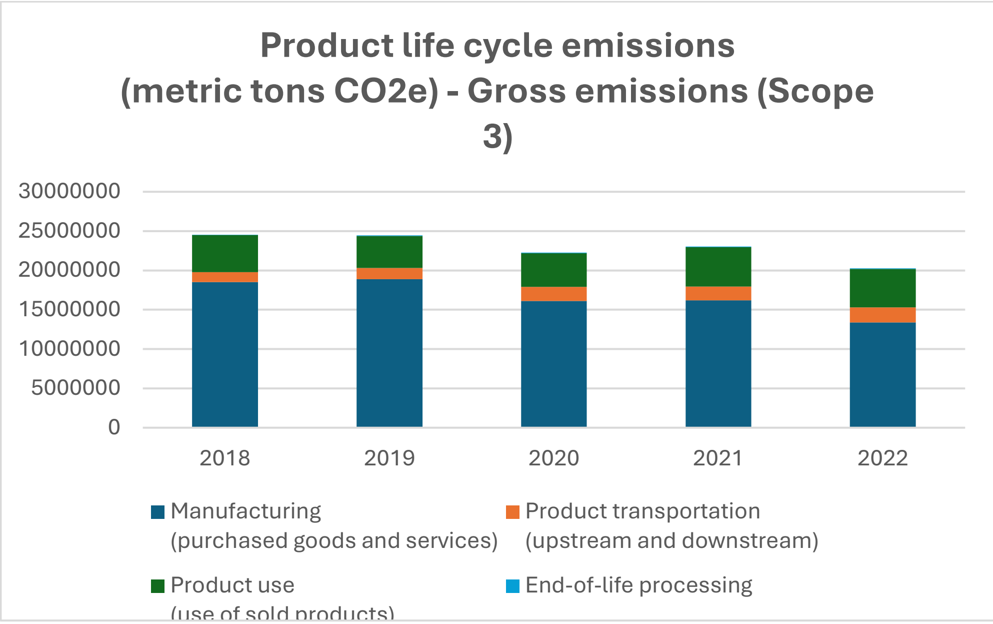


Figure 14: Apple's Product life cycle emissions
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Product transportation emissions have been relatively stable, with minor fluctuations, but there is a decrease in 2023, possibly due to more efficient logistics and a shift from air to ocean shipping. Product use emissions have seen less variation, maintaining around 4,600,000 to 4,900,000 metric tons CO2e from 2018 to 2023, reflecting consistent use-phase emissions for Apple products. The emissions associated with end-of-life processing are low but have slightly increased, indicating that there is room for improvement in recycling and disposal processes. While Apple's LCA methodology demonstrates a commendable commitment to transparency and environmental responsibility, there are several areas where a critical perspective might be warranted:

1. **Reliance on industry averages**:

   Although Apple uses detailed process-based models for significant GHG contributors, it still relies on industry average data for other elements of its carbon footprint. This reliance could lead to inaccuracies in assessing the true environmental impact, as industry averages might not reflect Apple's specific supply chain characteristics or product compositions. A more granular approach, using Apple specific data across all elements, would enhance the precision of their LCA.

2. **Exclusion of downstream recycling processes**:

   The exclusion of downstream recycling processes from the end-of-life modeling raises questions about the comprehensiveness of Apple's LCA. While it is noted that these processes are considered part of production rather than end-of-life, excluding them may overlook the full environmental impact of a product's lifecycle. Incorporating these downstream processes would provide a more complete picture of the environmental footprint.

3. **Uncertainty in customer use modeling**:

   The LCA uses modeled customer data to estimate product usage patterns, assuming specific lifespans for different categories of devices. However, the actual usage and disposal behavior of consumers can vary widely. For example, some products may be used significantly longer or shorter than the modeled averages, impacting the accuracy of the energy consumption and emissions data. Incorporating more dynamic, real-world usage data could improve the accuracy of this aspect of the LCA.

4. **Third-Party verification limitations:**
   The verification of Apple's LCA by the Fraunhofer Institute lends credibility to the process; however, the scope of this verification is not fully detailed. Understanding whether this verification extends to all aspects of the LCA, including the assumptions and methodologies used, would be crucial for assessing the robustness and reliability of Apple's environmental claims.

Apple's ambitious goal of achieving carbon neutrality by 2030 requires a diverse set of strategies aimed at reducing and offsetting emissions across its entire global operations. The company's approach is multifaceted, incorporating cutting-edge technological innovations alongside natural, more traditional solutions. By combining efforts like Carbon Capture and Storage (CCS), Direct Air Capture (DAC), reforestation, and soil carbon sequestration, Apple aims to mitigate the emissions produced not just by its direct operations but also throughout its supply chain. This chapter will explore how Apple is leveraging both technological and natural strategies to tackle its carbon footprint, highlighting both the strengths and the challenges inherent in these approaches.

4.3 Carbon offsetting and renewable energy projects

In addition to directly reducing emissions through technologies like carbon capture and storage (CCS), Apple has embraced carbon offsetting to address its remaining emissions. This approach involves substantial investments in renewable energy and large-scale environmental initiatives that help counterbalance the carbon emissions Apple is unable to eliminate through its operations. Alongside its renewable energy efforts, Apple is actively engaged in ecosystem restoration, particularly through its Restore Fund. With a $200 million commitment to reforestation, Apple is facilitating the planting of millions of trees in areas such as Colombia and Kenya. These initiatives aim not only to sequester carbon—potentially up to 1 million tons each year—but also to deliver additional environmental advantages, including the restoration of biodiversity and enhancement of water quality. By employing advanced technologies like satellite imagery and artificial intelligence, Apple monitors and verifies the effectiveness of these reforestation projects, ensuring that the carbon offsets are both genuine and enduring (Apple Inc's, 2024).

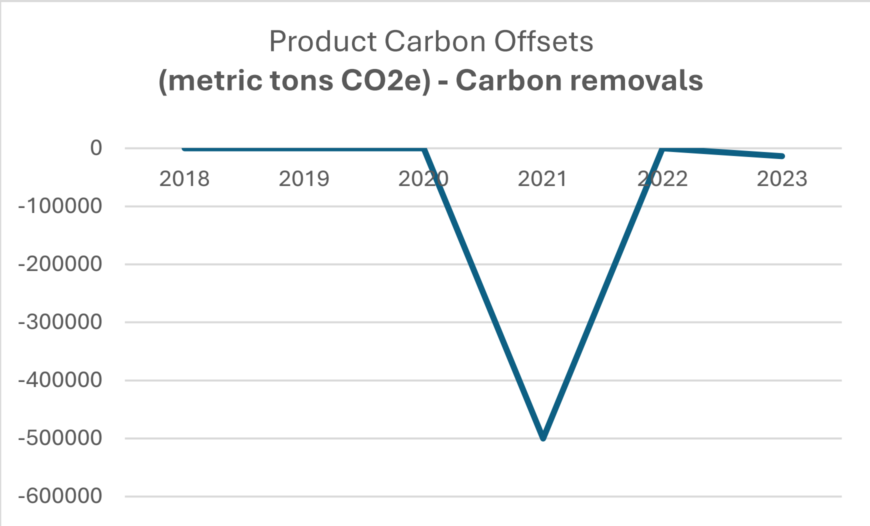


Figure 15: Apple's Product Carbonb Offsets
(metric tons CO2e) - Carbon removals Product Carbon Offsets
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

This graph shows the use of carbon offsets specifically related to Apple's product carbon offsets. A notable entry in 2021 reflects the offset of approximately 500,000 metric tons of CO_2e, as explained by Apple's participation in projects such as the Chyulu Hills project in Kenya and additional carbon credit purchases from two other initiatives. These projects were critical in offsetting a significant portion of Apple's direct emissions across its supply chain (Apple Inc's, 2024).

The drop in carbon offsets in the subsequent years, reaching around -13,500 metric tons CO_2e by 2023, suggests variability in the scale of offsets. This could be due to changes in Apple's offset strategy or challenges in high-quality offsets. The 2021 offsets were part of broader reforestation and conservation efforts in Kenya, Guatemala, and China, focusing on high-standard certified projects. While carbon offsetting through renewable energy and reforestation is an essential part of Apple's strategy, it is not without its complexities. Moreover, while offsetting helps mitigate emissions, it is a compensatory measure, meaning it does not directly reduce the emissions produced by Apple's operations or supply chain. This limitation suggests that while offsets are useful, they are not a long-term substitute for reducing emissions at the source (Abanades et al., 2021).

4.4 Exploring direct air capture (DAC) for long-term carbon management

Direct Air Capture (DAC) is becoming an essential technology in long-term strategies for managing carbon emissions, as highlighted by Sodiq et al. (2022). Unlike traditional Carbon Capture and Storage (CCS) systems that capture CO_2 at the source of emissions, DAC extracts CO_2 directly from the surrounding air. This makes it particularly valuable for tackling residual emissions that are challenging to eliminate through other methods. This unique capability positions DAC as a potential solution for companies like Apple, which are looking for ways to achieve ambitious carbon neutrality goals. According to Sodiq et al. (2022), while DAC technology has made significant strides in recent years, it still encounters substantial challenges. High costs and energy consumption are the main obstacles to scalability, which can vary based on the technology and location. Nevertheless, research is concentrating on enhancing the energy efficiency and cost-effectiveness of DAC through innovations such as advanced sorbent materials, process optimization, and integration with renewable energy sources. Apple's interest in DAC includes collaborations with industry leaders like Climeworks and Carbon Engineering, who are leading the way in DAC development. These partnerships allow Apple to evaluate the feasibility of scaling DAC technologies within its sustainability framework. Although the technology shows promise, Sodiq et al. (2022) emphasize that significant technological advancements are still needed to make DAC a fundamental part of broader carbon reduction initiatives.

4.5 Natural carbon sequestration: Reforestation and Soil management

In addition to exploring technological solutions like DAC, Apple has committed to nature-based carbon sequestration methods, such as reforestation and sustainable agricultural practices. Sodiq et al. (2022) highlight the complementary role that nature-based solutions play alongside advanced technologies like DAC in the broader carbon management landscape. Reforestation and soil management practices offer a more cost-effective means of carbon sequestration while providing additional environmental benefits, such as biodiversity conservation and improved soil health.

Apple’s reforestation initiatives, such as the mangrove restoration project in Colombia, are designed to sequester significant amounts of CO_2 while simultaneously restoring ecosystems and benefiting local wildlife (Apple Inc’s, 2024). Similarly, Apple’s support for sustainable agricultural practices, including no-till farming and agroforestry, helps sequester carbon in soils while promoting healthier and more resilient agricultural systems. Sodiq et al. (2022) emphasize that these natural solutions, while effective, also face limitations related to the finite carbon storage capacity of soils and forests and the potential risks posed by natural disturbances like wildfires or pests.

5. Analyzing Scope 1, 2, and 3 emissions and corporate strategies for sustainable development

5.1. Scope 1, Scope 2, and Scope 3 emissions: progress and challenges

Apple Inc. has positioned itself as a leading advocate for corporate sustainability, setting an ambitious goal to achieve carbon neutrality across its entire value chain by 2030. This commitment covers all three scopes of greenhouse gas emissions, Scope 1, Scope 2, and Scope 3, demonstrating a comprehensive and multi-faceted approach to tackling climate change. The company's strategy encompasses substantial investments in carbon removal technologies, alongside efforts to align with the Intergovernmental Panel on Climate Change (IPCC) recommendations to limit global warming to 1.5°C.

This analysis delves into Apple’s progress toward its climate objectives, evaluates the effectiveness of its strategies, and discusses the key challenges and opportunities in its pursuit of carbon neutrality.
Apple’s path to carbon neutrality involves addressing emissions across three distinct scopes, each with its own set of challenges and strategies (Apple Inc’s, 2024).

5.1.1 Scope 1 emissions: direct emissions from Apple's operations

Scope 1 emissions are direct emissions from sources that Apple owns or controls, such as fuel combustion in company facilities and vehicles. According to the data provided:

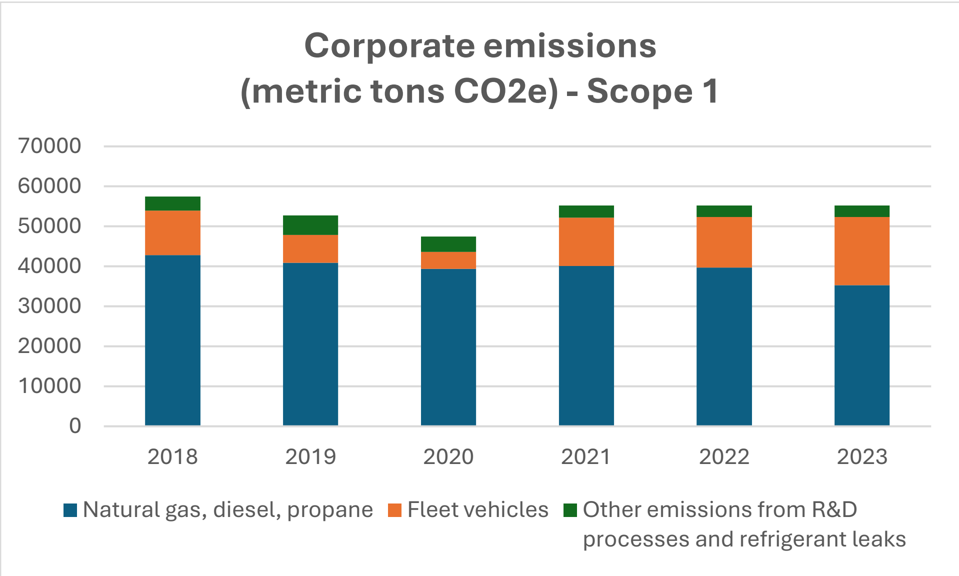


Figure 16: Apple's Corporate emissions (metric tons CO2e) - Scope 1
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Natural gas, diesel, and propane emissions have shown a slight downward trend from 42,840 metric tons CO2e in 2018 to 35,300 metric tons CO2e in 2023. This decrease reflects Apple's ongoing efforts to optimize its energy use and reduce dependence on fossil fuels.

Fleet vehicles emissions initially dropped from 11,110 metric tons CO2e in 2018 to 4,270 metric tons CO2e in 2020, followed by an increase to 17,000 metric tons of CO2e in 2023. This rise could be attributed to a rebound in company operations and travel following pandemic-related restrictions.

Other emissions from R&D processes and refrigerant leaks have remained relatively stable, fluctuating slightly around 3,000 to 4,870 metric tons CO2e over the five years. This stability suggests ongoing but manageable challenges in controlling emissions from specialized operations and processes.
Apple has made significant progress in reducing these emissions by investing in low-carbon technologies and optimizing manufacturing processes. One notable area of advancement is the reduction of fluorinated greenhouse gases (F-GHGs),

which are potent climate pollutants prevalent in electronics manufacturing. Through collaboration with suppliers to implement advanced gas abatement technologies and transitioning to alternative, less harmful gases, Apple has managed to significantly cut down on these emissions. However, the effectiveness of these measures is contingent on the pace of technological advancements and the broader industry's adoption of low-carbon technologies.

5.1.2 Scope 2 emissions: indirect emissions from purchased electricity

Scope 2 emissions refer to indirect emissions from the generation of purchased electricity. Apple has achieved a notable milestone by securing 100% clean electricity for its global operations since 2020. This commitment is evident in the emissions data:

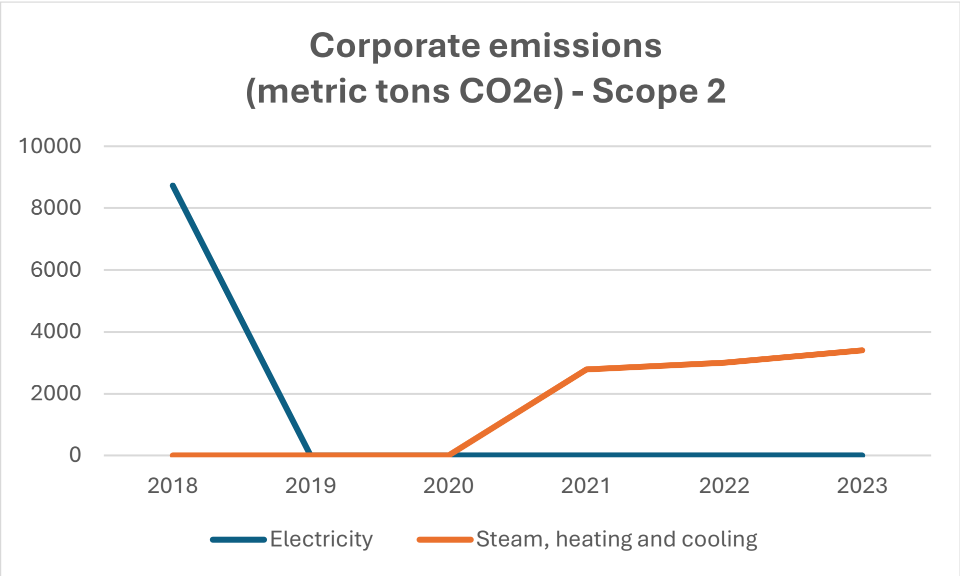


Figure 17: Apple's Corporate emissions (metric tons CO2e) - Scope 2
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Electricity emissions fell dramatically from 8,730 metric tons of CO_2e in 2018 to zero from 2019 onwards, reflecting the successful transition to renewable energy sources. This achievement is a testament to Apple's effective strategy in managing and reducing its Scope 2 emissions through the adoption of renewable energy. On the other hand, emissions from steam, heating, and cooling have risen from zero before 2021 to 3,400 metric tons CO_2e in 2023. This increase indicates an emerging challenge in managing the energy needs for heating and cooling, especially in regions where clean energy solutions for these utilities are not yet fully developed or deployed.

While Apple has successfully reduced its Scope 2 emissions from electricity to zero, extending this commitment across its supply chain poses significant challenges. Apple's Supplier Clean Energy Program has made substantial progress, with over 320 suppliers transitioning to renewable electricity, covering 95% of Apple's direct manufacturing spend. Despite these efforts, certain regions with limited renewable energy infrastructure pose ongoing challenges. The company's reliance on renewable energy certificates (RECs) as a transitional measure has been effective in the short term but may not always directly reduce fossil fuel consumption. This underscores the need for more robust solutions, such as direct power purchase agreements (PPAs) and significant investments in renewable energy infrastructure, to ensure a genuine and sustainable reduction in emissions (Apple Inc's, 2024).

5.1.3 Scope 3 emissions: indirect emissions across Apple's value chain

Scope 3 emissions represent the largest share of Apple's carbon footprint and include indirect emissions across the entire value chain. These emissions stem from various activities, including product manufacturing, transportation, business travel, and end-of-life product disposal. The Scope 3 emissions data highlights key trends and challenges:

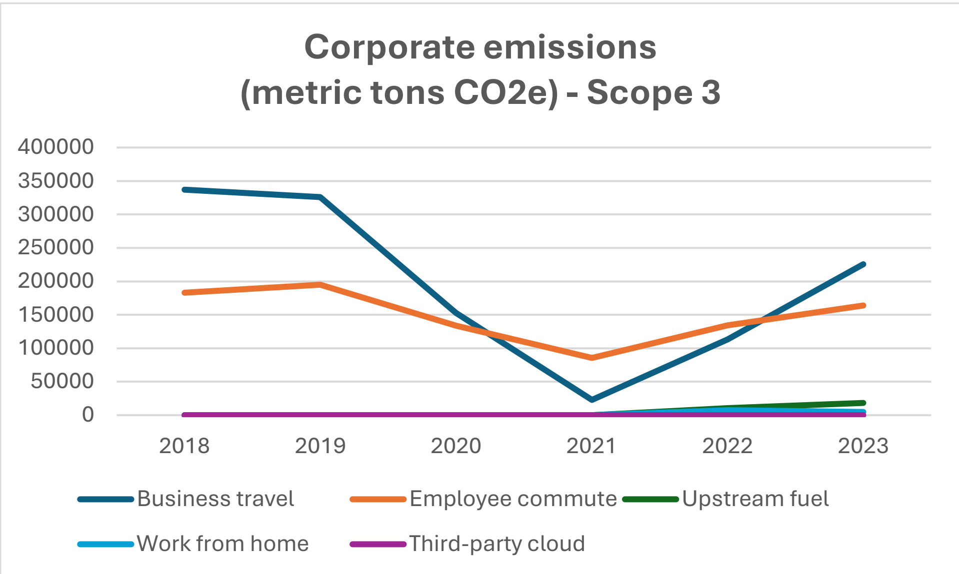


Figure 18: Apple's Corporate emissions (metric tons CO2e) - Scope 3
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Business travel emissions have seen substantial fluctuations, declining from 337,000 metric tons CO2e in 2018 to a low of 22,850 metric tons CO2e in 2021, likely due to travel restrictions during the COVID-19 pandemic. However, as restrictions eased, emissions rebounded to 225,700 metric tons CO2e in 2023, suggesting that business travel remains a significant contributor to Apple's carbon footprint.

Employee commute emissions also show variability, dropping from 183,000 metric tons CO2e in 2018 to 85,570 metric tons CO2e in 2021, before rising again to 164,100 metric tons CO2e in 2023. This trend mirrors changes in commuting patterns as remote work became more common during the pandemic but suggests a return to pre-pandemic commuting behaviors.

Upstream fuel and work from home emissions, which were not reported prior to 2021, have emerged as new areas of focus, with emissions rising from zero to 18,300 metric tons CO2e and 4,700 metric tons CO2e, respectively, by 2023. This reflects a growing recognition of the environmental impact of remote working arrangements and supply chain logistics.

Addressing Scope 3 emissions is particularly challenging due to the extensive and complex nature of Apple’s supply chain. To mitigate these emissions, Apple has implemented several initiatives. For example, the company has shifted from air to more carbon-efficient ocean shipping, resulting in a 20% reduction in transportation emissions in 2023. Additionally, Apple’s increased use of recycled aluminum and other materials has significantly reduced the carbon footprint associated with its products. Nevertheless, achieving a truly circular supply chain and ensuring the responsible sourcing and quality of recycled materials remain significant challenges. The goal is not only to reduce emissions but also to maintain high-quality standards and sustainable practices across all suppliers and partners.

6. Strategic R&D and open innovation: sustainable technologies for competitive advantage

6.1 Investments in R&D for sustainable technologies

Apple's investment in research and development (R&D) has become a cornerstone of its strategy to foster sustainability and maintain a competitive edge in a market increasingly focused on environmental responsibility. The company's R&D spending underscores its commitment to innovation that reduces environmental impact, aligning with broader trends in the tech industry where sustainability is becoming a critical factor for long-term growth. Apple has consistently allocated around 25-30% of its annual R&D budget, amounting to approximately $22 billion, to projects that focus on reducing the environmental footprint of its products and operations (Apple Inc's, 2024). This significant investment reflects the importance of sustainability-focused innovation, a trend supported by academic research. Sarpong et al. (2023) note that companies dedicating substantial portions of their R&D budgets to sustainability projects see higher innovation output and long-term competitive advantages.

One of the key areas of focus for Apple's sustainable R&D is the development of new materials.

The graphs below provide an in-depth look at Apple's carbon footprint across various product categories, including iPhones, iPads, Apple Watches, laptops, and desktops. By examining the carbon emissions (measured in kilograms of CO2 equivalent, kgCO2e) associated with each product model and storage configuration, we can assess Apple's progress and challenges in reducing the environmental impact of its products.

6.1.1 Carbon footprint analysis by product category

6.1.1.1 iPhone

The carbon footprint of iPhone varies significantly across models and storage capacities:

iPhone 15 Series: The iPhone 15 and iPhone 15 Plus show lower carbon footprints for lower storage models (56 kgCO2e for the 64GB iPhone 15) and an increase as storage capacity rises (up to 79 kgCO2e for the 256GB iPhone 15 Plus). Notably, there is no data for the 512GB model for the iPhone 15 and iPhone 15 Plus, which might suggest limited production or availability of these models. The iPhone 15 Pro and Pro Max models have higher footprints, reflecting the more advanced technology and materials used. The iPhone 15 Pro Max, with a 1TB storage option, has the highest carbon footprint at 110 kgCO2e, indicating a significant impact from increased storage and likely more energy-intensive production processes. Comparative Trend: The trend across generations (iPhone 13, 14, and 15) shows incremental improvements in reducing the carbon footprint, particularly in lower storage configurations. The iPhone SE (3rd generation) has the lowest footprint at 46 kgCO2e for the 64GB model, indicating Apple's success in producing a more environmentally friendly option.

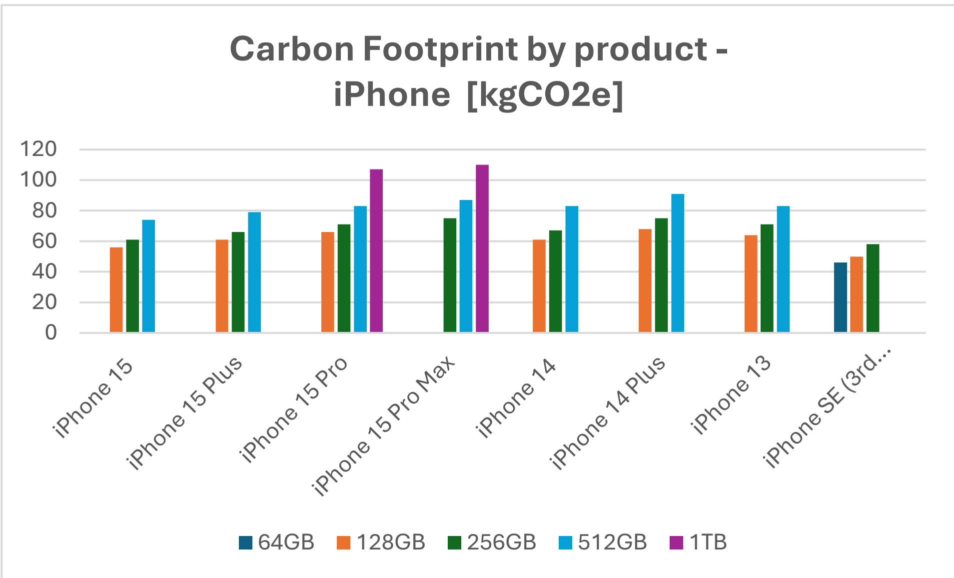


Figure 19: Apple's Carbon Footprint by product - iPhone [kgCO2e]

Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

6.1.1.2 iPad

The carbon footprint for iPad also varies widely depending on the model and storage capacity:

iPad Pro Models: The 12.9-inch iPad Pro shows the highest carbon footprint across all iPad models, especially in the 1TB configuration (183 kgCO2e), which suggests a significant environmental impact due to the large size and high-performance capabilities. The 11-inch model has a lower footprint, reflecting its smaller size and potentially less energy-intensive components.

Other iPad Models: The iPad Air and other non-Pro models generally have lower carbon footprints, ranging from 68 kgCO2e for the iPad mini (64GB) to 90 kgCO2e for the iPad mini (512GB). The variation in carbon footprints across storage capacities indicates that higher storage configurations typically lead to greater carbon emissions.

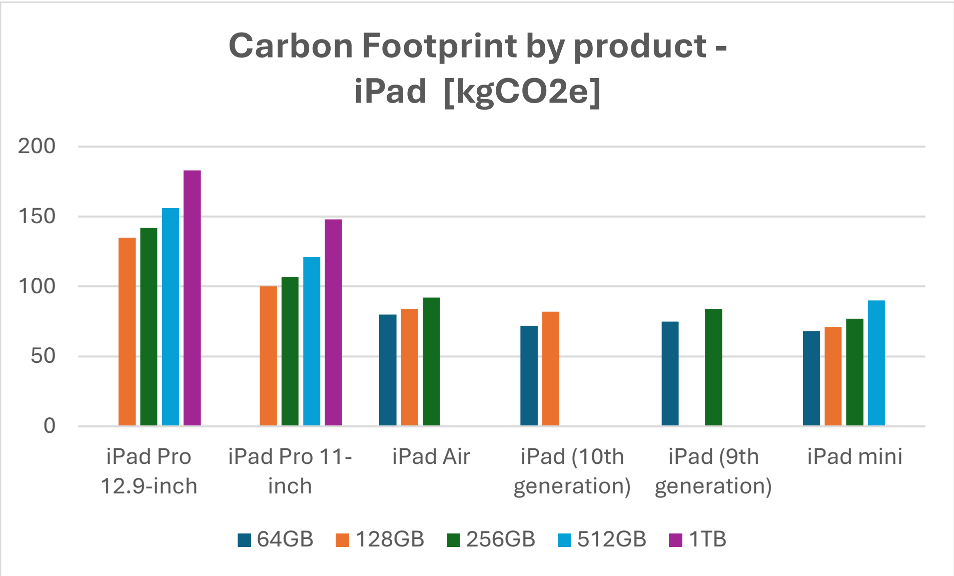


Figure 20: Apple's Carbon Footprint by product - iPad [kgCO2e]
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

6.1.1.3 Apple Watch

The carbon footprint data for Apple Watch shows interesting trends: Apple Watch Ultra 2: This model, particularly in its titanium case configurations (with Alpine or Trail Loop), has relatively low carbon footprints (12 kgCO2e and 11 kgCO2e, respectively). This suggests that despite being a more premium model, the materials and design considerations keep its environmental impact relatively low.

Apple Watch Series 9 and SE: The Series 9 shows a notable increase in carbon footprint with the stainless steel case (29 kgCO2e), likely due to the manufacturing processes and materials involved. The Apple Watch SE, with only one available footprint (7 kgCO2e for the aluminum case with Sport Loop), indicates a more environmentally friendly option, potentially targeting a more budget-conscious and eco-aware market.

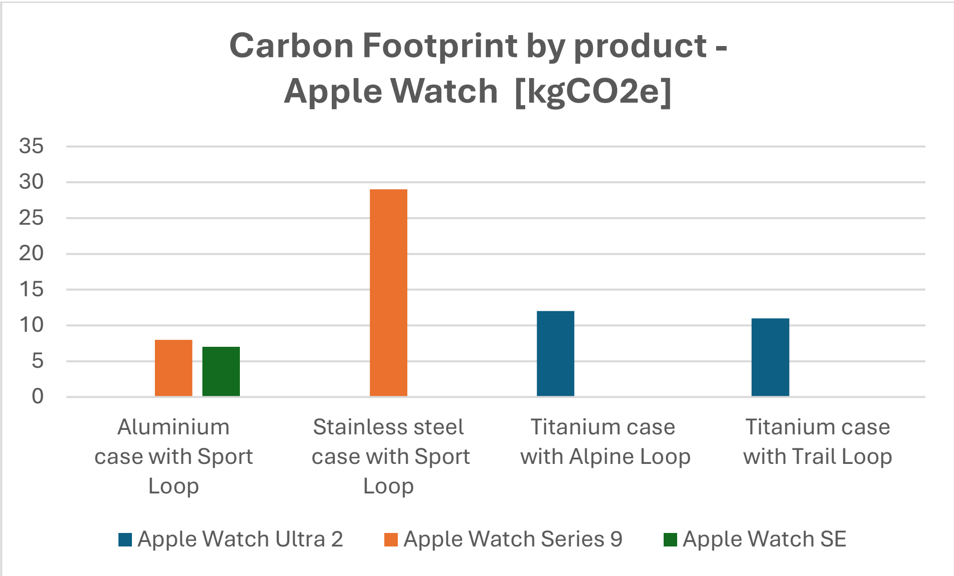


Figure 21: Apple's Carbon Footprint by product - Apple Watch [kgCO2e]
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

6.1.1.4 Laptop

Apple's laptop exhibit a broad range of carbon footprints: MacBook Pro and Air: The carbon footprint for MacBook models varies significantly based on size and configuration. The 16-inch MacBook Pro with the M3 Max chip has the highest footprint (348 kgCO2e for 1TB), reflecting the high-performance components and larger form factor. Comparatively, the 13-inch MacBook Air models have lower carbon footprints, particularly the 2024 model with the M3 chip at 135 kgCO2e (256GB), showcasing Apple's advances in designing more efficient, lightweight laptops.

Model Differences: The MacBook Air generally has a lower footprint than the MacBook Pro models, indicating the efficiency gains from using less powerful components and a focus on lighter, thinner designs. The newer M3 chip models appear to demonstrate improved energy efficiency compared to previous generations.

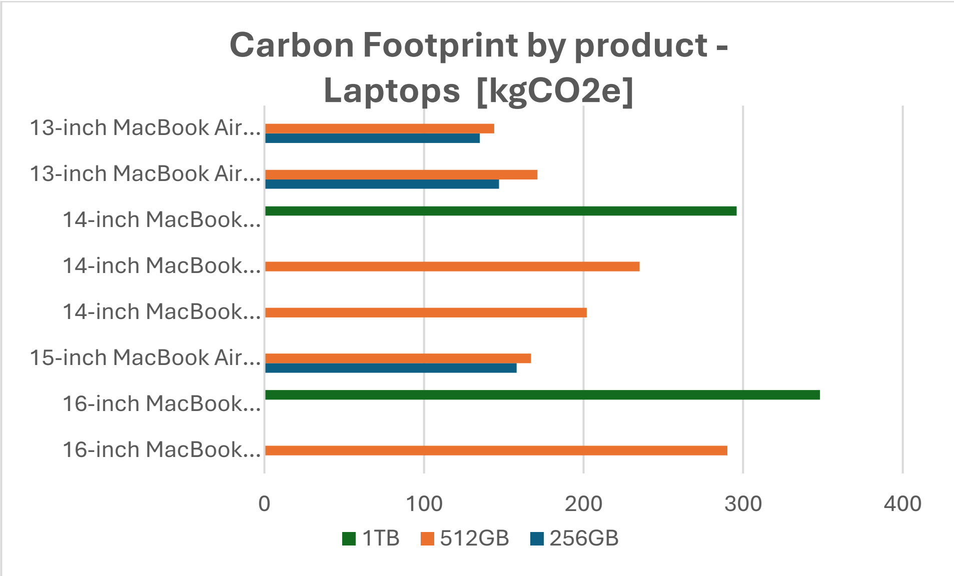


Figure 22: Apple's Carbon Footprint by product - Laptops [kgCO2e]
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

6.1.1.5 Desktop

Apple's desktop models show the highest carbon footprints across all product categories:

Mac Pro (2023): The carbon footprint of the Mac Pro (2023) is exceptionally high (1572 kgCO2e for the 1TB configuration), which is by far the largest footprint among all Apple products listed. This is likely due to the high-performance requirements, extensive material use, and energy-intensive manufacturing processes required for this professional-grade computer.

Other Desktop Models: The iMac and Mac Studio models have more moderate carbon footprints, ranging from 112 kgCO2e for the Mac mini (256GB, M2 chip) to 346 kgCO2e for the Mac Studio (M2 Ultra). The variation in these footprints highlights the impact of different configurations and chips on overall emissions.

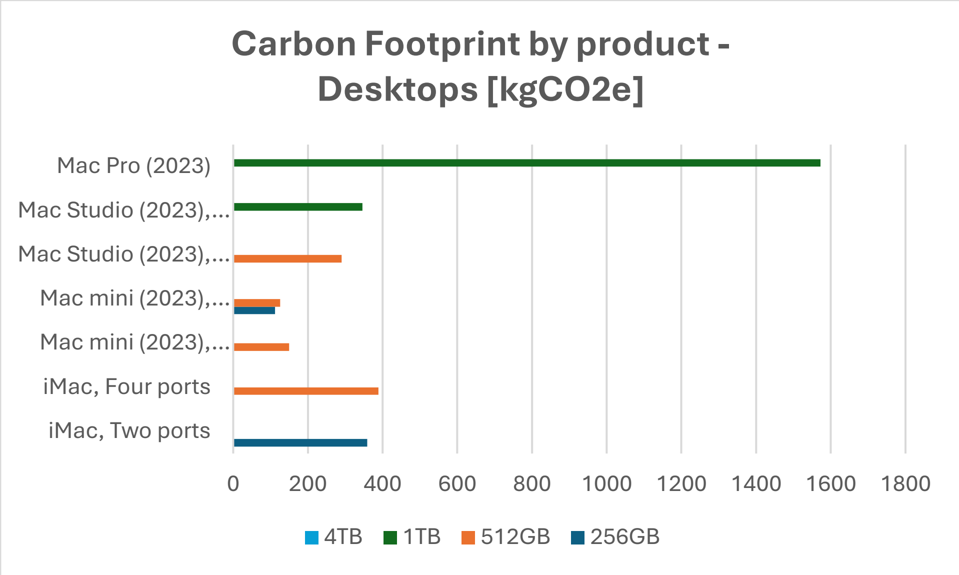


Figure 23: Apple's Carbon Footprint by product - Desktops [kgCO2e]
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

The data reflects Apple's ongoing efforts to reduce the carbon footprint of its products through improved design, materials, and energy efficiency. The table illustrates the carbon footprint (measured in kgCO2e) of various MacBook models released in 2023 and 2024, differentiated by chip type (M3, M3 Pro, M3 Max, and M2) and storage capacities (256GB, 512GB, and 1TB). Notably, the 16-inch MacBook Pro (2023) with the M3 Max chip has the highest carbon footprint at 348 kgCO2e for the 1TB model. The 14-inch MacBook Pro (2023) shows varying carbon footprints across chip types, with the M3 Max chip also having a higher footprint. Conversely, the 13-inch MacBook Air (2024) has lower footprints, ranging from 135 to 144 kgCO2e across storage capacities. This suggests that larger models and higher-performance chips contribute more significantly to overall carbon emissions. Apple's continuous efforts to improve energy efficiency and sustainable design likely contribute to these variations, but the carbon footprint still depends on the model's performance and storage configuration.

The absence of data for some storage configurations, such as the 1TB models for certain MacBook Air versions, highlights potential gaps in emissions reporting or the unavailability of specific configurations at the time of analysis. Overall, this table underscores the need for ongoing efforts to reduce the environmental impact of high-performance models, which tend to have higher carbon footprints due to the resources required for their production.

6.2 Strategic R&D for sustainable competitive advantage

Apple's R&D investments are not just about meeting environmental goals—they are also a critical component of the company's strategy for maintaining competitive advantage. By focusing on sustainability, Apple aligns its products with evolving global environmental standards and consumer expectations, ensuring that it remains a leader in the tech industry. Strategic investments in low-impact manufacturing, product longevity, and regulatory compliance are key pillars of this approach.

Product longevity and repairability have also become central to Apple's sustainability strategy. Through modular product designs and self-service repair programs, Apple has extended the lifespan of its devices by up to five years. This not only reduces electronic waste but also strengthens customer loyalty, as consumers are more likely to invest in products that last longer and are easier to maintain. The emphasis on durability and repairability aligns Apple with global sustainability trends and enhances its brand reputation as a company committed to environmental responsibility.

Furthermore, Apple's strategic R&D investments ensure compliance with international environmental regulations, such as the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive and the Restriction of Hazardous Substances (RoHS) Directive. By meeting or exceeding these regulatory standards, Apple mitigates its exposure to legal risks and enhances its access to key global markets. This compliance is essential for maintaining long-term business stability and growth, particularly as environmental regulations become more stringent worldwide.

However, strategic R&D for sustainability is not without its challenges. The capital investment required for these initiatives is substantial, and there is always the risk that continued investment in sustainable technologies could yield diminishing returns over time. As initial gains in environmental performance become harder to achieve, Apple must balance its commitment to sustainability with the need to maintain profitability and shareholder value (Mazzucato & Perez, 2022).

6.3 The role of R&D in Apple's sustainability leadership

Apple's commitment to sustainability through strategic R&D and open innovation underscores its leadership in the tech industry's transition to a greener future. By investing in sustainable materials, energy efficiency, and renewable energy, Apple not only reduces its environmental footprint but also enhances its competitive advantage. Open innovation practices further amplify these efforts, allowing Apple to collaborate with external partners, accelerate the adoption of new technologies, and share the financial risks associated with sustainability-focused R&D. While the costs and risks of investing in sustainable technologies are significant, Apple's long-term strategy positions it to reap substantial benefits. From enhanced market differentiation to compliance with global environmental standards, Apple's approach to sustainability is a model for how tech companies can innovate to meet the growing demands of consumers and regulators alike. By continuing to prioritize sustainability in its R&D efforts, Apple is not only driving technological progress but also contributing to a more sustainable future for the entire industry.

7. Apple's sustainable investments and economic return

In recent years, Apple Inc. has made significant commitments to integrating sustainability into its production processes. These commitments have been actualized through substantial investments in renewable energy, energy efficiency, and the use of recycled materials.

7.1 Apple's sustainable investments

Since 2016, Apple has issued green bonds worth USD 4.7 billion in total, of which USD 3.4 billion has been granted to projects on sustainability. The greater share of the investment is being utilized in projects that are contributing to mitigation against carbon emissions and achieving the goal of carbon neutrality by 2030. The funds obtained from the issuance of green bonds are being utilized in projects related to the development of renewable energy, improvement of energy efficiency, capturing of carbon, and research and development in low-carbon production of products (Apple Inc. GreenBond, 2023).

According to Apple's 2023 Green Bond Impact Report, the proceeds from the green bonds have been dispersed into a number of various projects, including the 320 MW IP Radian Solar project in Texas and various solar projects across Michigan, which all combine to account for the electricity usage by

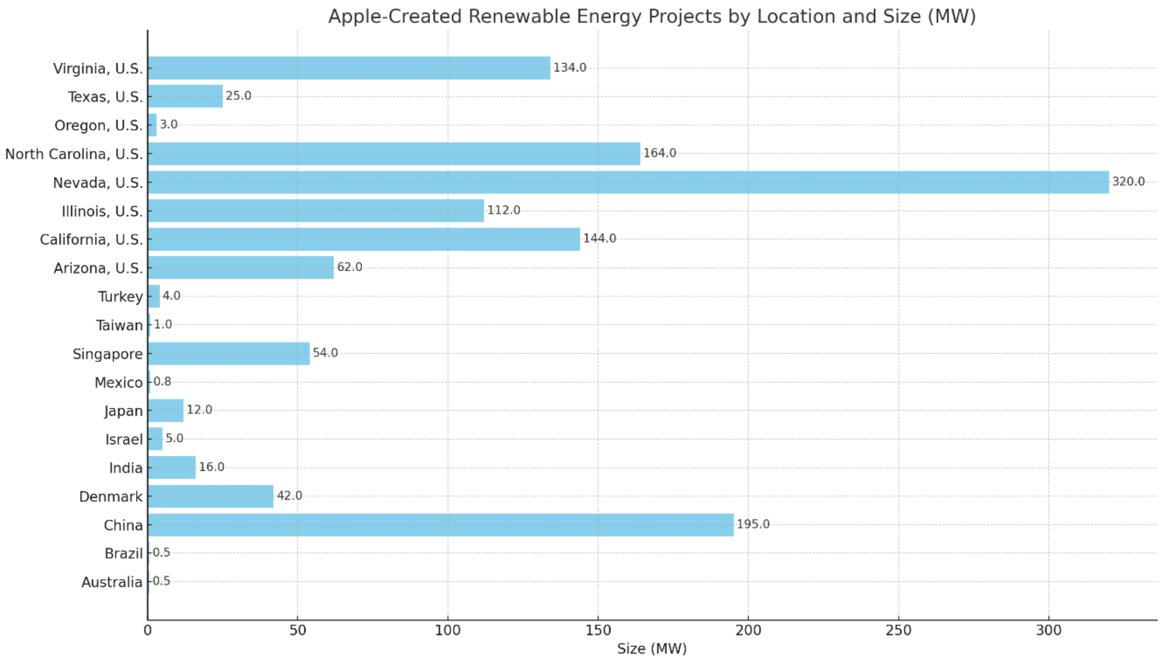


Figure 24: Bar Chart of Apple-Created Renewable Energy Projects by Location and Size (MW)

Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

all of Apple's products worldwide. Other projects installed by Apple around the globe have brought them to 1,647 MW of installed renewable energy. These include a number of solar, wind, microidro and biogas fuel cell technologies in several countries around the globe including China, Denmark, Japan, and the United States. All of the largest projects are in the United States, including a 320 MW solar project in Nevada and a 195 MW solar project in China. Overview: Graph 21 provides the various Apple renewable energy projects developed by location and size, hence showing the scattering by geography. Specifically, Apple has developed its creation of renewable energy projects on different continents, with relevant installed capacity in states such as Nevada, California, and North Carolina. These investments also contribute to the growth of cleaner energy grids worldwide, besides supporting Apple's commitment to 100% renewable energy. Also, Apple has pursued a broad combination of renewable energy technologies that will enable it to meet its sustainability goals.

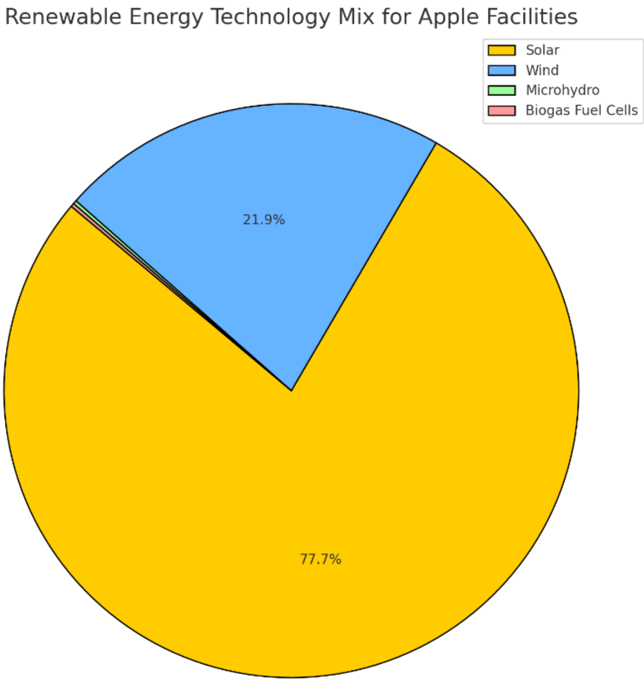


Figure 25: Pie Char of Renewable Energy Technology Mix for Apple Facilities

Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Solar energy contributes about 78% of the total renewable energy capacity, wind energy contributes 22%, while Microidro and biogas fuel cells each contribute less than 1%. This is what Graph 22 shows that by far and away, Apple relies on solar energy as the major driver of all the concerns with regard to powering its facilities. These are further steps in Apple's ambitious commitment to carbon neutral operations by 2030 and further demonstrate Apple's commitment to clean energy transition. Apple works on low-carbon product design, where the company increases the usage of recycled materials within its products. Product design that incorporates recovered materials reduced their products' carbon footprint by massive amounts. Nevertheless, further investments in research and development are necessary to improve the purity and quality of recycled materials so that they may be effectively harnessed in the making of new products (Apple Inc. GreenBond, 2023).

7.2 Reputational and competitive benefits

Green bonds have also brought a number of economic benefits for Apple while financing projects of sustainability, complementing the environmental impacts. According to Ehlers and Packer (2017), green bonds are intended for "internalizing environmental externalities and adjusting risk perceptions" through market mechanisms and are one of the essential parts of sustainable finance. Through the issuance of green bonds, Apple has been able to make available considerable capital to fund projects that will be associated with greenhouse gas emission reduction, energy cost reduction, and the ability to further improve operational efficiencies.

Another factor that might be at play, which would improve the appeal of green bonds to issuers such as Apple, is what has been described as the "green premium" or "greenium." As MacAskill et al. (2021) observed, green bonds have frequently been issued at lower yields than their conventional counterparts-a function of strong investor demand for environmentally responsible investments. This allows Apple to increase the funds at a better price, therefore reducing the financing costs. As MacAskill et al. add, this phenomenon reflects the rising importance of sustainability to investors and provides an economic benefit for issuing green bonds. Green bond issuance has increased Apple's stakeholder reputation, which includes investors, customers, and regulators. Green bonds are often viewed as a pledge for environmental care; thus, this can be an effective way to build up a better image of the company and raise brand value accordingly. In addition, as environmentally aware consumers are continuously increasing, Apple's commitment to sustainability gives them further competitiveness. Recycling materials in the manufacturing of these products such as the iPhone and Mac enables Apple to market these gadgets as green products. This is very appealing to an increasing number of environment-sensitivity aware consumers.

Although there are clear stated merits in green finance, such benefits also have their own limits. According to Gilchrist et al., "the rapid growth of the market in recent years has been accompanied by concerns of potential greenwashing and a lack of consistent standards." Greenwashing involves a situation in which firms make unsubstantiated claims about the environmental benefits of either their products or their investments, thereby giving a misleading appearance of environmental responsibility. This, on one hand, undermines the credibility of green finance instruments and may erode investor confidence.
Apple has taken some measures to reduce the green washing of this project. Third-party verification and certification of the green bond projects are some of the measures taken by Apple.

7.3 Economic returns on investments

The economic returns on these sustainable investments by Apple are evidently captured in the form of operational cost savings, most of which come from renewable energy and energy efficiency investments. By integrating renewable energy into business operations, Apple has managed not only to reduce carbon emissions drastically but also decreased dependency on fossil fuels, thus saving money considerably over a period of time (Apple Inc. GreenBond, 2023). Hence, according to the global estimates of average cost, investments in renewable energy ultimately will lead to a cost saving of about 20 to 25 percent over conventional energy sources in a period of 10 to 20 years (Irena, 2022). For Apple, with several hundred million dollar-equivalent investments in renewable energy, this can translate into a potential cost saving of USD 200 mln to USD 250 mln over a decade. Moreover, the Supplier Clean Energy Program has reduced the emission rate throughout the supply chain by ensuring that suppliers are committed to using 100%

renewable electricity and supporting Apple in achieving its sustainability goals, which also contributes to a reduction in supply chain costs.

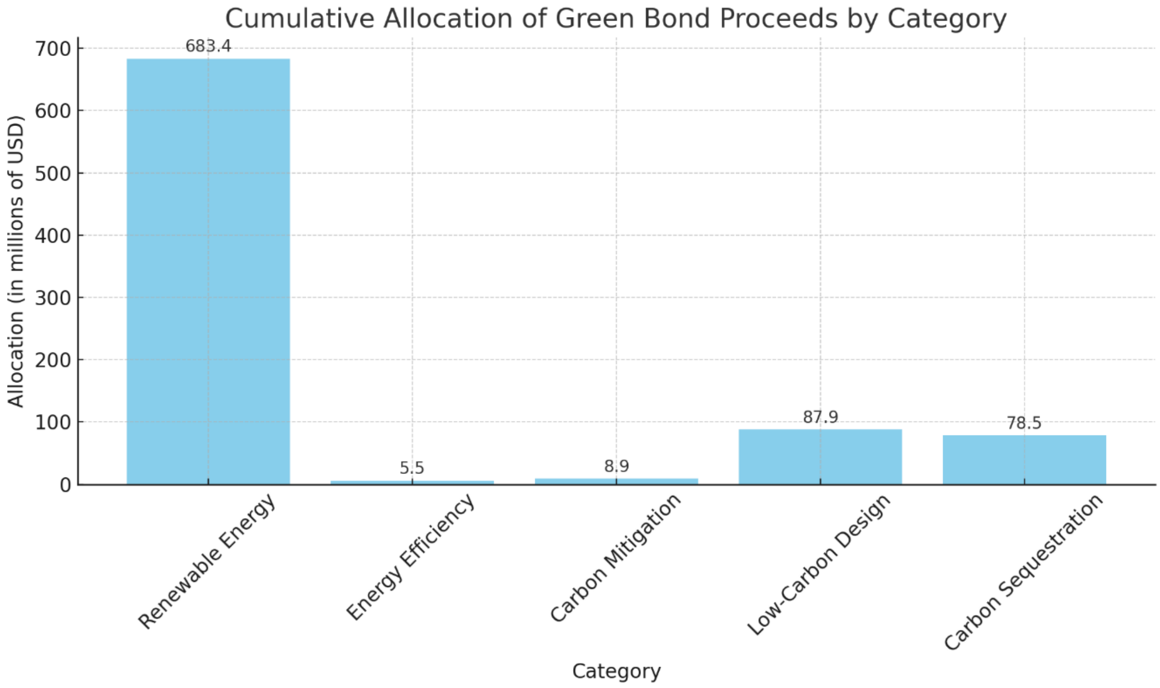


Figure 26: Bar Chart of Cumulative Allocation of Green Bond Proceeds by Category

Fonte: https://s2.q4cdn.com/470004039/files/doc_downloads/additional_reports/2023/apple_greenbond_report_fy2023.pdf

Estimates put the general cost reduction due to enhanced energy efficiency along the supply chain at about 10-15% (IRENA, 2022), which, for Apple, could mean saving millions annually because of a reduction in energy use and enhancement in operations efficiency. Besides, the strategic deployment of reclaimed materials enables Apple to cut costs on raw materials while managing to keep the quality of its products maintained. (Apple Inc's, 2024). Apple produces several million devices each year; the savings in material costs could be consequential, possibly contributing toward an overall lower cost of production that would push profit margins even higher.

This can be analyzed as, through the issuance of green bonds, Apple's sustainable investments prove that environmental strategy is not only a matter of ethics duty but also a key determinant of competitive advantage and profitability. Using green bonds for financing of renewable energy projects, enhancing energy efficiency, and embedding recycled materials in products, Apple has been able to reduce operational costs and enhance brand value, attracting environmentally sensitive investors. These initiatives have served to imbed not only Apple's sustainability credential but also to create substantial economic returns, hence placing Apple on the front line for corporate sustainability.

8. Environmental compliance and innovation: Apple’s sustainable policies

Apple’s environmental strategy blends regulatory compliance, material innovation, supplier engagement, and global advocacy to address global sustainability goals. The timeline shown in the image highlights Apple’s climate policy advocacy efforts from 2015 to 2023, demonstrating its role in shaping environmental policy and its proactive leadership in renewable energy and carbon neutrality. Through this timeline, Apple’s increasing involvement in global climate efforts becomes clear, ranging from its early support for the American Business Act on Climate Pledge in 2015 to its active push for global decarbonization policies and the Paris Agreement goals in later years. This continuous engagement showcases how Apple’s strategies align with key international agreements and its role as an advocate for strong climate policies.

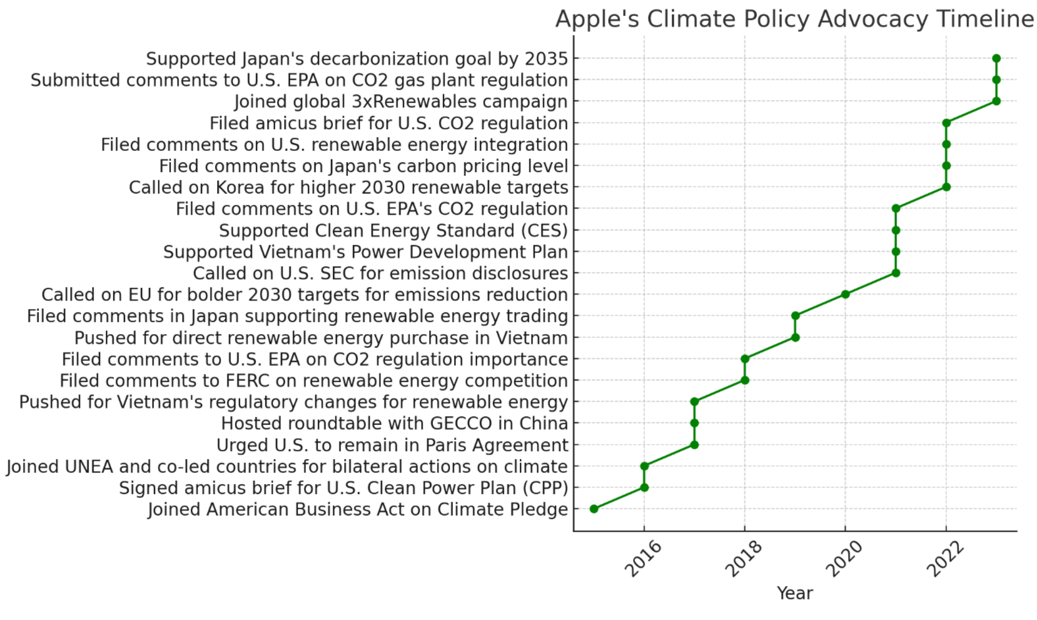


Figure 27: Timeline of Apple’s Climate Initiatives
Fonte: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2024.pdf

Apple's timeline of climate policy advocacy illustrates how the company has transitioned from supporting foundational initiatives to actively shaping policy at national and international levels. The timeline begins in 2015, when Apple joined the American Business Act on Climate Pledge and publicly committed to the principles of the Paris Agreement. This initial action reflects Apple’s understanding of the need for corporate responsibility in addressing climate change. The timeline then shows Apple's involvement in broader international frameworks, such as its participation in the UN Environment Assembly (UNEA) in 2016, where it led efforts for bilateral actions on climate.

As the timeline progresses, Apple's advocacy grows more strategic and focused on renewable energy deployment. In 2017, Apple began hosting roundtables, such as with the Green Electricity Consumption Cooperative Organization (GECCO) in China, and pushed for regulatory changes in countries like Vietnam to allow businesses to directly purchase renewable energy. This marks a significant evolution in Apple's climate policy advocacy, shifting from corporate commitments to direct policy interventions aimed at transforming energy markets globally. Apple's efforts to influence energy policies continue in 2018, where the company filed comments with the U.S. Federal Energy Regulatory Commission (FERC) and the U.S. Environmental Protection Agency (EPA), highlighting the importance of renewable energy integration into national grids. The timeline shows how Apple not only supports government regulations but also advocates for stronger emission controls. This is particularly important as Apple begins aligning its corporate policies with science-based emission reduction targets set by the Paris Agreement. As a result, the timeline marks a shift from purely corporate sustainability toward a more activist role in climate governance.

By 2021, Apple had become a key voice in the global climate dialogue, as evidenced by its support for the Clean Energy Standard (CES) in the U.S. and similar renewable energy targets in South Korea and Japan. This phase of the timeline indicates Apple's increasing influence in shaping national energy policies to support renewable energy and decarbonization. Moreover, Apple's advocacy efforts expanded beyond just policy frameworks to include financial and technical support for suppliers through public-private partnerships (PPPs), facilitating the global shift towards renewable infrastructure.

In 2023, Apple's timeline underscores its continued commitment to global renewable energy goals through its participation in the 3xRenewables campaign, which aims to triple global renewable energy capacity by 2030. This final point in the timeline highlights Apple's sustained leadership in advocating for bold decarbonization targets, both at the corporate and governmental levels. Apple's global advocacy now encompasses strong policy engagement, public-private collaboration, and supplier support, making it a key player in driving the global energy transition (Apple Inc’s, 2024).

8.1 Compliance with RoHS II, REACH, and the WEEE directive

Apple’s commitment to environmental sustainability extends to regulatory compliance with standards such as RoHS II and REACH, which regulate hazardous substances and chemicals in products. This compliance is also reflected in Apple’s broader global advocacy efforts, as shown in the timeline. For instance, Apple’s push for regulatory reforms in Vietnam to allow direct renewable energy purchases in 2017 underscores its focus on complying with international and local environmental standards, while also actively working to shape the regulatory environment for renewable energy adoption.

In alignment with Happaerts’ (2012) discussion on subnational governance, the timeline demonstrates Apple’s recognition of the importance of multi-level collaboration to advance sustainability goals. As seen in its advocacy across countries like the U.S., Vietnam, and Japan, Apple actively supports government efforts to create more transparent and ambitious renewable energy policies. This reflects how Apple’s regulatory compliance is not merely a reactive stance but an integrated approach that leverages policy advocacy to further its environmental objectives.

8.2 Paris agreement alignment and carbon neutrality goals

The timeline also serves as a testament to Apple’s alignment with the Paris Agreement and its goal of achieving carbon neutrality by 2030. Through strategic interventions, such as supporting the Clean Energy Standard in the U.S. and pushing for South Korea’s higher 2030 renewable energy targets, Apple positions itself as a global advocate for policy reforms that facilitate the transition to renewable energy. Apple’s support for science-based emission reduction targets, seen throughout the timeline, mirrors the company’s corporate strategy of encouraging its supply chain to adopt renewable energy and reduce greenhouse gas emissions.

This proactive engagement aligns with Mazzucato & Perez (2022), who argue that corporate strategy must include green innovation to achieve long-term sustainable growth. Apple's advocacy for stronger carbon pricing in Japan and its continued pressure on the EPA for emissions regulations demonstrate how the company’s advocacy is not only focused on internal sustainability but also on external systemic change.

8.3 Energy Star and product efficiency

Apple’s focus on energy-efficient product design is another integral part of its sustainability strategy, as outlined in the timeline. In addition to advocating for renewable energy, Apple promotes energy efficiency standards globally. For example, Apple’s energy-efficient products, such as the MacBook Air and iMac, are a result of both internal innovation and external policy alignment. In 2022, Apple submitted comments to encourage the expansion of renewable energy in the U.S., a reflection of the company’s commitment to product efficiency and broader energy infrastructure improvements.

As Happaerts (2012) explains, the success of corporate sustainability initiatives often depends on subnational governance and local policy alignment with global sustainability frameworks. The timeline illustrates how Apple’s advocacy efforts span multiple levels of government, from national policies in the U.S. to international partnerships. These collaborations are essential for Apple to achieve its product efficiency goals, reduce emissions, and meet its carbon neutrality target.

9. Promoting sustainability among employees and stakeholders in high-tech firms

In the high-tech industry, sustainability is increasingly a powerful driver for innovation and long-term success. By engaging employees and stakeholders on issues of sustainability, companies can continue to improve corporate reputation but also achieve better operational efficiencies and improved environmental outcomes. Studies have highlighted that integrating sustainability into the organizational framework is essential to leverage employee engagement and stakeholder involvement in making meaningful progress.

9.1 Employee engagement and sustainability

Employee engagement is one of the most critical aspects in promoting sustainability initiatives. Casey and Sieber (2016) noted that employee motivation and engagement are increased when an organization addresses sustainability and corporate social responsibility. A case study of one such firm reported that the active provision of sustainability and CSR programs by companies leads to a 25% higher motivation level among employees and decreasing rates of turnover by as much as 20%. Employees will feel more attached to, or in other words, committed to sustainability and CSR initiatives, if they can see how their everyday tasks fit in with wider objectives. Engagement at this level not only encourages job satisfaction but also leads to improved organizational performance. A company willing to take CSR and sustainability seriously will get employees who are more concerned with practices aiming to reduce waste and save resources and will directly benefit the company through its performance in sustainability. Similar programs are replicated in the partnering Apple does at higher learning institutions and Impact Accelerator, which amplifies opportunities for underrepresented communities to drive innovation, improve environmental outcomes, and realize clean energy solutions at scale (Apple Inc's, 2024).

9.2 Stakeholder engagement and environmental policy

The external stakeholders will, therefore, be influential in shaping the corporate sustainability strategies.

Le Van et al. (2019) examine the role that stakeholder involvement has in popularizing green products, especially in the emerging markets such as Vietnam. The findings from their work are that active participation of the stakeholders in corporate sustainability operations not only enhances corporate reputation but promotes innovation in the green products. With the engagement of customers, suppliers, and other relevant stakeholders, companies have the potential to reduce negative impacts on the environment while developing more sustainable business models. Le Van et al. further add that through stakeholder strategies, companies experience a reduction in inefficiencies, while operational outcomes are developed for long-term sustainability. For instance, the Global partnerships, like RE100 and Exponential Roadmap Initiative, of Apple are some of the ways through which energy efficiency along the supply chain is improved and renewable energy consumed (Apple Inc's, 2024).

9.3 Circular economy and social indicators

The shift towards a circular economy has further reinforced the role of sustainability in high-tech industries. Scarpellini (2021) examines the use of social indicators, such as employment and resource efficiency, as key metrics in sustainability reporting. The integration of circular economy principles enables companies to better manage waste, reduce resource consumption, and create employment opportunities. By focusing on circular economy practices, companies are able to align their sustainability efforts with broader social and environmental goals, contributing to long-term economic growth and resource sustainability.

Apple has focused on recycling initiatives with Carnegie Mellon University and MIT, advancing robotic recycling technologies to process disassembly and material sorting mechanisms (Apple Inc’s, 2024).

9.4 From awareness to action

Finally, awareness must be translated into concrete steps for sustainability. According to Ditlev-Simonsen (2010), structured programs on sustainability are what take businesses beyond general awareness into concrete commitment and involvement by employees and stakeholders in tangible measurable efforts. Companies with such programs enjoy significant quantifiable waste and resource use reductions each year. The actions further improve the sustainability performance of the company and thus contribute toward overall environmental objectives.

Apple, through the Supplier Code of Conduct and other environmental programs, makes the suppliers liable to a certain extent for the proper use of resources (Apple Inc’s, 2024).

Conclusions

This thesis has explored the innovative approaches being taken within the high technology industry, focusing particularly on Apple Inc., when it comes to issues of sustainability and decarbonization. Apple is remarkable in this regard as well due to its ambitious aim of reaching carbon neutrality for its entire supply chain by 2030 alongside its goal of incorporating 100% recycled or renewable materials in all of its products by 2030. However, despite considerable strides, there are a number of significant concerns that have to still be resolved in order for these sustainability goals to be fully accomplished.

The intricacy of Apple's supply chain is perhaps one key challenge. The company is working toward its suppliers to cut carbon emissions and implement clean technologies, however, still there are wide gaps in the environmental performance of suppliers because of the local laws, availability of resources and technological capability. Third party suppliers who are based in regions with weak environmental laws are used and this makes it difficult to successfully implement sustainable strategies in a global supply chain.

Another area where concerns could be highlighted is the scalability of these new recycling technologies and their material recovery innovations at Apple. While Daisy, Liam, Dave and Taz robots have increased the efficiency of recovery of such materials as rare earth elements or aluminum from end of life products, the application of these technologies is still limited by the rate of consumer engagement in recycling programs and the diffusion of these technologies around the globe. Additionally, the potential of these systems to recover materials that are used in lesser quantities, such as rare earth magnets, is also limited, which means that there is an opportunity for technology improvement to maximize material recovery potential.

Apple has also been using operational carbon offsetting projects within the framework of its net zero policy which has also raised some concerns with respect to addressing the causes of emissions rather than the causes. Such offsets, while they provide to shrink some of the negative effects, do not obviate the need for supply chain level emission reductions in the first instance within the context of the areas with less prevalent renewable energy infrastructure.

However, the company’s commitment to also relying on circular economy models such as the use of closed-loop supply chain and recycled material content including aluminum and rare earth elements also reflects its resolve to reduce resource extraction and waste generation.

Nevertheless, the issues like the repairability of devices or the nondisclosure in some areas of the sustainability reports indicate that there is still room for improvement to achieve the circular economy model of production and consumption. Take, for instance, the case of Apple, whose increased availability of certain products for self-repairs is limited by a set of proprietary elements and design options that prevent the widespread adoption of repairs and therefore the prolongation of product life.

Moreover, while Apple's expenditures on the development of renewable energy and energy-efficient technologies such as battery storage have significantly lowered the company’s operational carbon footprint, a decarbonised supply chain is still not fully materialised. A considerable number of the companies in the supply chain still depend on conventional energy sources, and the uptake of clean energy options is uneven particularly in the developing regions.

The company’s initiatives for promoting sustainability by developing new technologies, circular economy, and the use of renewable energy sources leave no doubt that Apple is one of the leaders in the decarbonization processes of the high-tech industry. On the other hand, the company has several number of significant issues to resolve, for example, enhancing visibility of the supply chain, expanding material resource recovery technologies and standardization of noise abatement practice across all territories. If those challenges are managed, then the envisaged sustainability outcomes may become a reality and the company can be a best practice to other organizations within this industry. These efforts however will need to be complemented by continuous innovation, increased stakeholder engagement, and stronger regulatory frameworks.

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