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Niklas Kronemeyer, Jens Leker and Moritz Gutsch
Can a Growing Battery Industry Remain Within Planetary Boundaries?

Bernd Selting and Giorgia Carratta
Ethylene Production in the Petrochemical Industry: Competitive Risks and Impacts of the EU Emission Trading Scheme

Tamara Florez and Andrea Kanzler
Corporate Social Responsibility and Sustainable Human Resources Management Practices Among the Millennial Workforce in the Chemical Industry in Ireland

Andreas Dreiling
The Impact of Artificial Intelligence on Innovation Speed in Startups

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Editorial Board

Aim and Scope

The Journal of Business Chemistry (JoBC) focuses on current developments and insights at the intersection of management and chemistry, biotechnology or pharmacy.

The JoBC provides an international forum for researchers and practitioners in companies, research institutes, public authorities, consultancies or NGOs to present and discuss current challenges as well as potential solutions in an interdisciplinary manner. Thus, the JoBC aims to foster the dialog between science and business, to support management practice in the chemical and pharmaceutical industry and to indicate where further research from academia is needed. The JoBC offers high quality publications with academic standards, a fast publishing process and global reach. With this multidisciplinary and boundary-spanning approach, the JoBC intends to become the leading journal for decision makers in the chemical and pharmaceutical industry.

Publisher

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Vol.22, Iss.2, June 2025

Contents

ISSN 1613-9623

JOURNAL OF
BUSINESS CHEMISTRY

Letter from the Editors

Balancing Innovation, Responsibility, and Boundaries: Navigating the Business Chemistry Landscape

After almost two years, it is time to move on to new challenges and say goodbye as Executive Editor of the Journal of Business Chemistry. Looking back on many successful issues, I am very grateful for the support of all authors and reviewers for this and previous issues. I would like to hand over to Friederike Woltmann, who will be the next Executive Editor, and I could not be more confident that the Journal of Business Chemistry will continue to publish excellent articles from the intersection of Chemistry and Business.

As we move through 2025, industries at the intersection of chemistry, management, and innovation are facing unprecedented demands. The need for sustainable transformation, talent retention, competitive resilience, and planetary responsibility continues to shape strategic agendas worldwide. The current issue of the Journal of Business Chemistry reflects these multifaceted challenges through a diverse set of contributions that bridge environmental, technological, and organizational themes.

In this second issue of the year, we begin with the paper by Niklas Kronemeyer, Jens Leker, and Moritz Gutsch, who explore a fundamental question in their article "Can a Growing Battery Industry Remain Within Planetary Boundaries?". Addressing the rising demand for critical raw materials and the environmental impacts of battery production, this study links the development of circular battery value chains to the planetary boundaries framework. Their analysis calls for innovations in battery technologies, recycling, and energy sourcing to align the industry with safe environmental operating limits.

Additionally, the research paper "Ethylene Production in the Petrochemical Industry: Competitive Risks and Impacts of the EU Emission Trading Scheme" by Bernd Selting and Giorgia Carratta presents a comparative cost analysis between EU and US producers. With a focus on ethylene production, it reveals how the EU Emissions Trading Scheme and global overcapacities are creating substantial competitive pressures for European producers. The study underscores the need for policy adjustments and industrial adaptation in the face of rising production costs and regulatory constraints.

Continuing with the innovation management approaches, the research paper "Corporate Social Responsibility and Sustainable Human Resources Management Practices Among the Millennial Workforce in the Chemical Industry in Ireland" by Tamara Florez and Andrea Kanzler examines how CSR and sustainable HRM practices influence employment choices among Millennials in Ireland. Grounded in Social Identity Theory and employer branding, their findings have practical implications for organizations striving to attract and retain talent in an increasingly sustainability-conscious labor market.

Finally, in the Practitioner's Section, Andreas Dreiling investigates how artificial intelligence can influence innovation processes in start-ups. His contribution, "The Impact of Artificial Intelligence on Innovation Speed in Startups", provides a practical framework for integrating AI into innovation management. Highlighting both opportunities and integration challenges, the paper offers guidance for start-ups seeking to increase competitiveness through agile, AI-enhanced innovation strategies.

We hope these thought-provoking contributions will inspire further discussions on the evolving challenges and opportunities within business chemistry. As always, we thank all authors and reviewers for their valuable work and dedication to the journal.

Please enjoy reading the second issue of our journal in 2025. If you have any comments or suggestions, please do not hesitate to contact us at contact@businesschemistry.org. For more updates and insights on management issues in the chemical industry, follow us on LinkedIn: http://www.linkedin.com/company/jobc/ and subscribe to our newsletter.

Warm regards,

Andrea Kanzler
(Executive Editor)

Friederike Woltmann
(Executive Editor)

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Research Paper

Niklas Kronemeyer[a,b], Jens Leker[a,c], Moritz Gutsch[a,*]

Can a growing battery industry remain within planetary boundaries?

The rapid growth of the battery industry leads to a high demand for critical raw materials, an increasing amount of battery waste and environmental impacts along the value-chain. Several life cycle assessments have compared the relative environmental impacts of different battery technologies, production processes, or locations. However, an assessment of the environmental impacts of batteries on a planetary scale is missing. Therefore, we provide a connection between the environmental impacts of the potentially circular battery value chain and the planetary boundaries framework. Transgression of planetary boundaries will lead the Earth down an unstable path, which should be avoided. While the use of batteries in the automotive industry has significant positive impact on the environmental footprint, the battery production will clearly transgress its assigned share of the safe operating space in three planetary boundaries in 2030, 2035 and 2040 on its current trajectory. Consumption of critical raw materials accounts for most of the planetary footprint, encouraging the development of sodium-ion batteries and circular economy strategies. Alongside high recycling rates, the consequent implementation of process innovations, such as dry coating and direct lithium extraction, and the use of renewable energy will reduce the transgression of planetary boundaries. Still, further efforts are required to bring the battery industry in line with its safe operating space for phosphorous cycle and climate change. To avoid the prospect of strict policy interventions, our work encourages the fast-growing battery industry to assess innovations and demand projections through a planetary boundary lens.

1 Introduction

Since the Paris Climate accords were signed in 2015, government and industry have increased their efforts to limit climate change to 2°C compared to pre-industrial levels (The Economist , IPCC 2023). While current global investments in low or negative carbon dioxide (CO2) emission technologies still fall short of the required levels, some ground has been gained (International Energy Agency 2023, The Economist 2023). Electrification of the transport sector, mostly by switching to battery electric vehicles (BEVs), is a strategic aim of major car manufacturers (Kwade et al. 2018,

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Vol.22, Iss.2, June 2025
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Schmuch et al. 2018, Duffner et al. 2021).Government schemes, such as the proposed, even though controversial, ban of internal combustion engine vehicles (ICEVs) from 2035 by the European Union, have created further incentives to increase production of BEVs (European Parliament 2023). Charged with renewable, or other low-carbon electricity, lifecycle CO_2 emissions associated with BEVs are lower than for petrol-fueled cars (Ellingsen et al. 2016). On the other hand, concerns about the high levels of critical raw materials required for battery production or environmental issues associated with mining or disposal of batteries present challenges (Herrington 2021, Du et al. 2022).

Experts estimate that the annual battery production will reach 5,400 to 6,800 GWh per year by 2030, up from 1,800 GWh in 2024 (International Energy Agency 2023, Porsche Consulting GmbH 2023). Innovations in processing technology, such as dry coating, and changes in battery material composition, towards sodium-ion batteries (SIBs), will likely reduce the CO_2 emissions associated with future battery production (Degen et al. 2023). In addition, recycling of end-of-life batteries is expected to reduce the environmental impacts and raw material requirements of the growing battery industry (Baars et al. 2021, Gutsch and Leker 2024). Life cycle assessments (LCAs) have been used to compare the environmental impacts of different battery material choices, production technologies, or end-of-life treatments (Peters et al. 2017). The first LCAs of lithium-ion batteries (LIBs), which currently account for most batteries used in BEVs, were conducted in the early 2000s (Peters et al. 2017). Today, numerous LCAs exist, covering novel material choices, production technologies, and battery recycling (Arshad et al. 2022).

Life cycle assessments are a useful method for comparing the relative environmental strength and weaknesses of different products used for the same function (International Organization for Standardization 2006). But, communication with decision-makers and inferring global strategies from LCAs is challenging (Ryberg et al. 2018). Here, the planetary boundary framework (PB) captures more readily whether a certain activity improves or reduces the chances of staying within Earth´s safe operating space (SOS) (Rockström et al. 2009). Nine planetary boundaries, such as climate change, ocean acidification, and land-system change exist (Steffen et al. 2015). Extended transgression of planetary boundaries will put the Earth out of the relatively stable range (Holocene) that the Earth has been in for the last 11,700 years (Rockström et al. 2009, Steffen et al. 2015).

Application of the planetary boundary method to several industries, for example, the plastic or petrochemical industry have helped to understand which technological shifts and developments are required to align these industries with planetary boundaries (González-Garay et al. 2019, Bachmann et al. 2023). In this context, however, an assessment of the battery industry with the planetary boundary framework is missing. The present paper fills this gap by applying the planetary boundary framework to the battery industry. Using forecasts of technology mixes, production volume and recycling feedstock, we assess the absolute sustainability from a planetary boundary perspective in 2030, 2035 and 2040 for global battery production. We also analyse the impact of battery recycling and further process as well as technology innovations on the sustainability of the battery industry.

2 Background

2.1. Battery value-chain

Current research effort in the battery development is driven by several ambitions. Motivation comes from cost reductions and increased sustainability, as well as diversification by original equipment manufacturer and geopolitical strategies about access to material resources (Wesselkämper et al. 2024). From a technology perspective, batteries can be assigned to one of four broad technology categories, with different properties. The first group utilizes cathode active material (CAM) with lithium, manganese, cobalt, and a comparably low nickel content (low-Ni NMC). A similar yet different CAM with a higher share of nickel, represents the high-Ni NMC cluster. Increasing the nickel content enhances the specific capacity. Reducing the content of cobalt results in lower costs. Batteries with lithium-iron phosphate (LFP) do not use nickel or cobalt as part of the CAM. This lowers the energy density but also brings down costs and environmental impacts. Sodium-ion batteries (SIBs) can reduce the need for critical raw materials alongside lower costs and environmental impacts by replacing lithium with more abundant sodium (Usiskin et al. 2021, Zhang et al. 2024).

Recycling of battery waste is essential to reduce the amount of required virgin raw materials and reduce the risk of supply shortages for critical materials (e.g., Li, Ni, and Co) (Usiskin et al. 2021). Next to environmental benefits, recycling targets in core geographies contribute to a growing battery recycling industry (Neumann et al. 2022). State-of-the-art battery recycling employs pyrometallurgical or hydrometallurgical processes. In the pyrometallurgical process, a slag is

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DOI: 10.17879/43998521709

produced via thermal processes from which materials are extracted (Neumann et al. 2022). In hydrometallurgical processes, batteries are mechanically shredded into a black mass, from which materials are recovered through leaching (Neumann et al. 2022). Material recovery rates of hydrometallurgy generally exceed those of pyrometallurgy (Mohr et al. 2020).

2.2. Production volumes and waste feedstocks

The forecast growth of the battery industry, including the shares of different technologies, is fundamental to the planetary boundary assessment. The ramp-up underlying this study projects a battery demand of 5.4 TWh per year by 2030 (Porsche Consulting GmbH 2023) (see **Fig. 1**) which fits well within the range of current market projections (International Energy Agency 2023, McKinsey & Company 2023). With high-Ni NMC and LFP likely leading the market by 2030, the share of SIBs will increase substantially from 2030 onwards (Degen et al. 2023, Porsche Consulting GmbH 2023).

The ramp-up of the battery industry results in high volumes of battery waste feedstock, consisting of production scrap, batteries from prototypes, test vehicles and end-of-life batteries. The waste feedstock is currently dominated by production scrap due to the high reject rate in the battery factories during ramp-up. Established Gigafactories are expected to reduce reject rates from 18% in ramp-up to 4% (Wesselkämper et al. 2024). From 2030, lower production scrap rates and the fact that batteries produced today will reach their end-of-life will increase the share of end-of-life batteries in the waste feedstock. In addition, the proportion of return batteries due to accidents or technical defects increases with growing BEV fleet.

3 Method

3.1. Planetary boundary framework

A central goal of the planetary boundary framework is to assess whether the Earth remains within its SOS for a set of planetary boundaries (Rockström et al. 2009). To date, no standard characterization model allows to transform life cycle inventory data gathered during an LCA into planetary boundary conditions. As a workaround, we use the individual characterization factors for each elementary flows provided in (Bachmann et al. 2023). Our analysis includes the two core boundaries climate change and biosphere integrity, which have been identified of having the potential to change the Earth ecosystem into a new state on its own if substantially and persistently transgressed (Steffen et al. 2015).

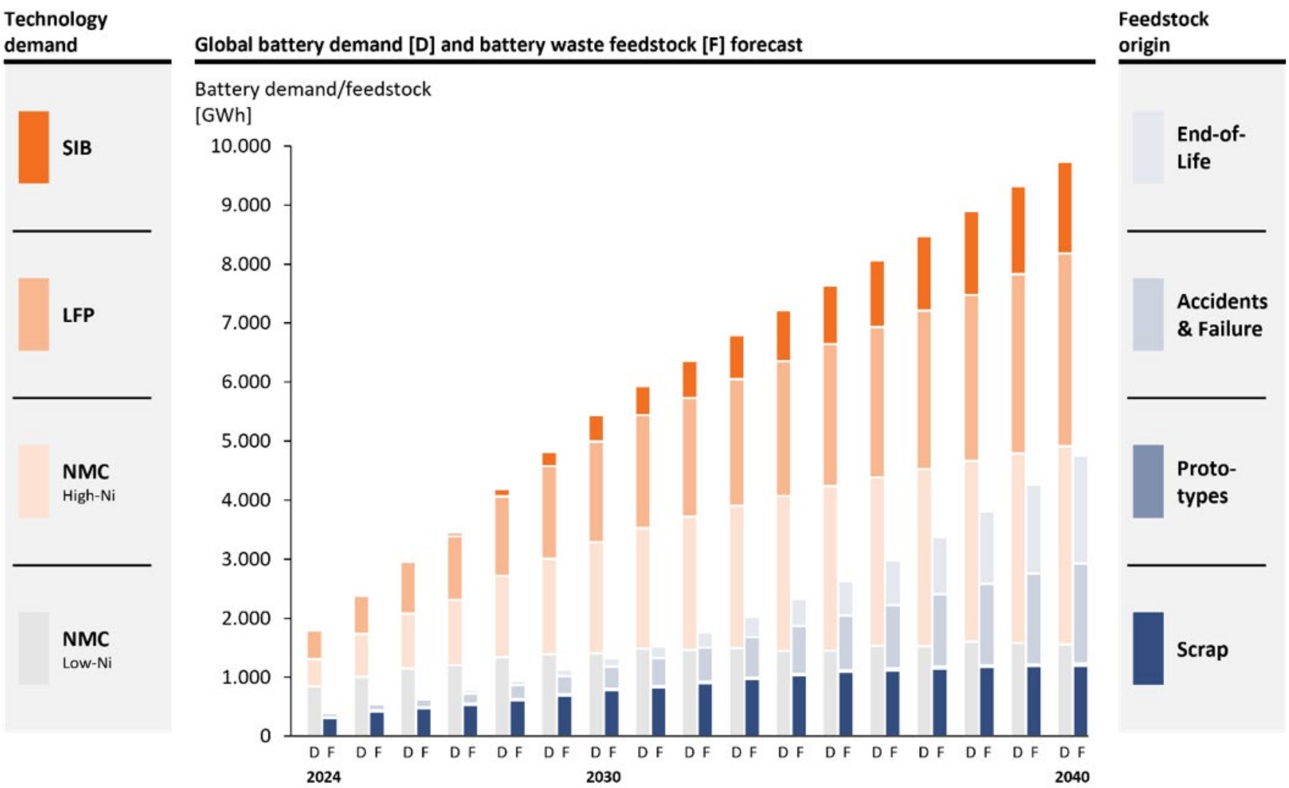

Fig. 1. Battery production and battery waste volume prognosis until 2040, split by battery technology cluster: NMC Low-Ni (NMC111), NMC Hi-Ni (NMC811), LFP and SIB.

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-43998533375
DOI: 10.17879/43998521709

Additionally, we include ocean acidification, phosphorus cycle and stratospheric ozone depletion to our analysis, as these planetary boundaries are directly affected by the two core boundaries (Lade et al. 2020). Each boundary represents a crucial aspect of Earth's system, with potential irreversible consequences for both nature and humanity if transgressed (Steffen et al. 2015).

The present work scales down the share of SOS based on economic approach. Different approach exists to assign a part of the SOS to different activities within the global economy (Ryberg et al. 2018). One popular approach is an assessment based on economic metrics. For this, the total revenue of the battery industry is estimated and divided by global gross domestic product (GDP). For 2022 the global GDP of $100.8 trillion is taken from the World Bank Open Database (World Bank Open Data 2024). For the projection of the global GDP for 2030, 2035, and 2040 an annual growth rate of 2% is assumed. Revenue of the battery industry is calculated by multiplication of global production volumes (in GWh per year) and assumed average battery costs of $153 per kWh on system level.

3.2. Life cycle assessment

Life cycle inventory data for subsequent calculation of planetary boundary impacts is obtained following the ISO14040 standard for life cycle assessments (International Organization for Standardization 2006). Accordingly, we define the functional unit as the yearly global production and recycling of batteries for electric vehicles. Annual production and recycling volumes are estimated until 2040. While multiple production volume forecasts exist, this study is based on prior work from Porsche Consulting GmbH with a predicted production capacity of 5.4 TWh in 2030 (Porsche Consulting GmbH 2023), see **Fig. 1**. Waste flows consist of batteries which have reached end-of-life in the application or are rejected during production due to quality issues.

A cradle-to-grave system boundary is chosen (see **Fig. 2**). Consequently, raw material mining, product manufacturing, and end-of-life treatment are included. To assess the impact of recycling strategies, we assume that recycled materials are integrated in battery supply chain and used as a substitute for virgin materials.

Raw material mining comprises the extraction of materials (e.g. lithium, nickel, cobalt, copper, graphite and aluminium) including concentration and processing into battery grade materials. Ecoinvent 3.9 serves a background source for life cycle inventory data (Wernet et al. 2016).

Cathode and anode active material synthesis is modelled separately due to the comparably high energy demand of 27-31 kWh per kWhbattery (NMC), 4 kWh per kWhbattery (LFP) and 16 kWh per kWhbattery (SIB) (Wernet et al. 2016, Peters et al. 2021).

Cell manufacturing consists of three main parts which are electrode production, cell production and cell conditioning (Duffner et al. 2021). For the baseline scenario, state-of-the-art manufacturing processes (e.g., wet electrode production) have been set (Degen et al. 2023).

Cells that do not meet the quality requirements are discharged from the cell production line. Such waste cells might be fed into a recycling facility to recover valuable materials. Also, cells that have remained in use until their practical end-of-

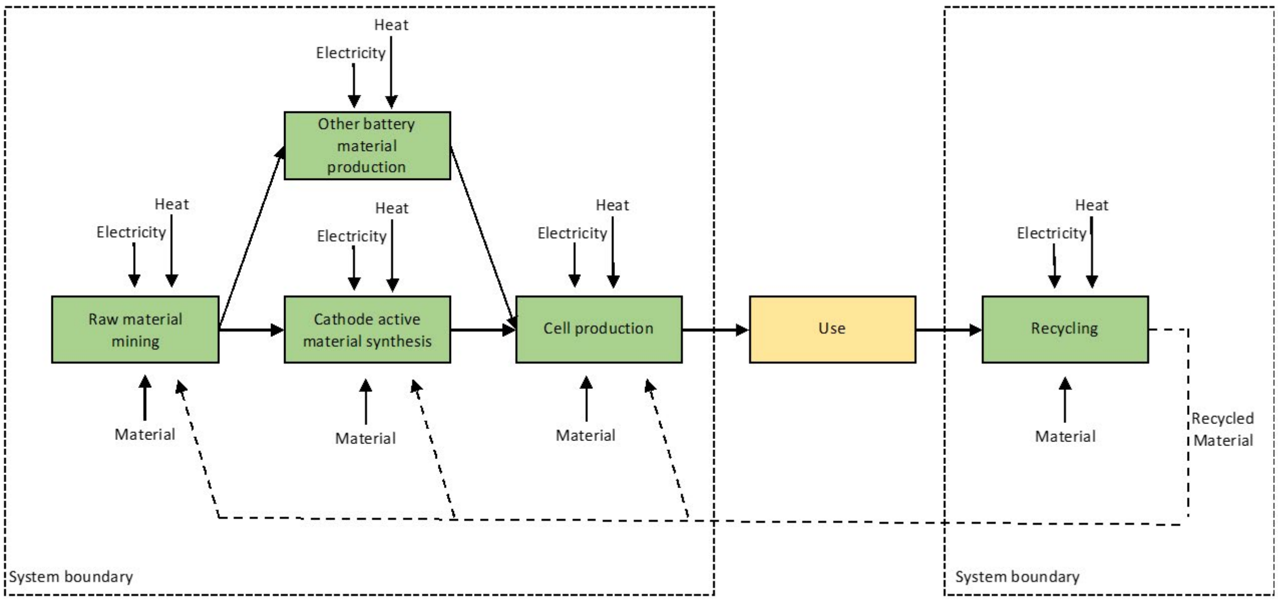

Fig. 2. System boundary of battery value-chain.

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DOI: 10.17879/43998521709

life is reached can be fed into a recycling system. Life cycle inventory data and recovery rates for pyrometallurgical and hydrometallurgical recycling are adapted from (Gutsch and Leker 2024), see also supplementary information.

The focus of this work is on production and recycling of batteries, which battery manufacturer can influence. However, to put results into perspective, we also provide a schematic assessment of the use phase of batteries in vehicle application through a planetary boundary view. Doing so, we compare a BEV fleet of around 115 million vehicles in 2030 with the same number of ICEVs. Three different electricity mixes, based on IEA data, are modelled for battery charging. These are current electricity mix, stated policy mix, and sustainable electricity mix (IEA 2023, Richtie and Rosado 2024). An annual mileage of 15,000 km is used for the average vehicle.

3.3. Scenarios for technology improvement

To analyse the impact of technology innovations on the sustainability we conceive the following set of innovations which are either commonly discussed in the battery community (Harper et al. 2019, Duffner et al. 2021, Degen et al. 2023) (innovations 1-4) or resulting from the planetary boundary analysis (innovation 5):

1. Direct recycling process (for scrap and end-of-life batteries)
2. 100% renewable energy consumption (generated by onshore wind turbines)
3. Reduced energy consumption (data used from Degen et al. (Degen et al. 2023))
4. Direct lithium extraction (lithium sourcing through direct lithium extraction (Vera et al. 2023))
5. Reduced copper use (Reduction of 50% copper consumption)

4 Results

4.1. Planetary boundary results for status-quo battery industry

Fig. 3 shows the percentage of the SOS for each planetary boundary which is occupied by the battery industry in 2030. The SOS defines the limits of each planetary boundary within humankind can safely exists. In this context, the battery industry will occupy 7.6% of Earth´s SOS for climate change, a planetary boundary which is associated with increased extreme weather events and rise of the sea-level. Here, raw material production and energy intensive cell production are problematic. Also, by 2030 the battery industry will need around 2.3% of the SOS for ocean acidification and phosphorous cycle. Transgression of the SOS for ocean acidification implies a reduced pH level of the ocean, posing a threat to coral reefs and maritime food value chains (Rockström et al. 2009). Exceeding the SOS for phosphorous cycle is associated with groundwater contamination, algal blooms and risks for fresh water supply. While both raw material requirements and energy demand for cell manufacturing contribute to ocean acidification, the planetary boundary of the phosphorous cycle is essentially affected only by raw material consumption. For biosphere integrity, which addresses issues around diversity of species in the environment, the battery industry will occupy 0.7% of SOS. The contribution of battery production to stratospheric

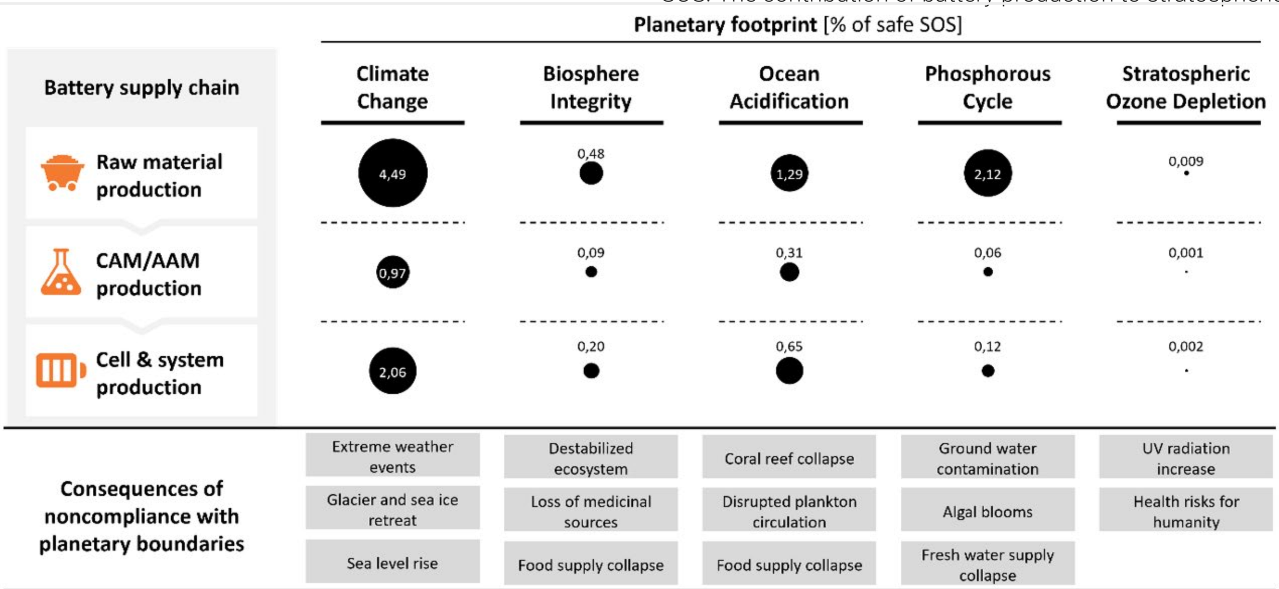

Fig. 3. The battery industries planetary footprint of total safe operating space in 2030.

JOURNAL OF
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Vol.22, Iss.2, June 2025

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DOI: 10.17879/43998521709

ozone depletion, which addresses the negative effect of a shrinking ozone layer on marine and land-based life, is comparably low (0.01%) (Rockström et al. 2009).

For each planetary boundary, the total of SOS should by assigned to different parts of the global economy (Ryberg et al. 2018). With an economic-based approach the total revenue of the battery industry is divided by global GDP. For 2030 we estimate the revenue of the battery industry as $830 billion. This represents 0.7% of global GDP in 2030. Consequently, following the approach of an economics-based assignment of SOS to different industries, the battery industry should be allowed to use 0.7% of the safe operating space ($SOS_{Battery}$).

Comparing the required part of the SOS with its assigned share, the battery industry clearly exceeds its planetary boundary targets for climate change, ocean acidification and phosphorous cycle, see **Fig. 4**. Our results suggest that remaining within $SOS_{Battery}$ is not problematic for stratospheric ozone depletion. For the planetary boundary of biosphere integrity, the assigned $SOS_{Battery}$ is in line with the requirement of the battery industry. The contribution of the battery industry to global GDP will further rise between 2030 and 2040, thus increasing the $SOS_{Battery}$. However, based on current trends, the battery industry will exceed its assigned $SOS_{Battery}$ even further. Although, due to optimization in battery technologies, the battery industry's share of the SOS will increase more slowly than production volumes until 2040, considerable efforts are still required to bring the rapidly growing battery in line with planetary boundaries.

4.2. Impact of recycling and changes in battery chemistry on planetary boundary results

So far, the analysis has not included any recycling of waste feedstock, thus representing a conservative approach. Recycling, however, will play a significant role in bringing the battery industry closer to its $SOS_{Battery}$. Based on the waste-feedstock, we calculate the potential benefit of recycling for planetary boundaries.

Recycling all incoming waste batteries in 2030 with pyrometallurgy can reduce the contribution to global SOS in climate change from 7.6% to 6.8% (see **Fig. 5**). With more efficient hydrometallurgy a reduction to 6.6% is possible. On the other side, 6.6% of global SOS still exceeds the GDP-assigned target of 0.7%. Thus, to reach SOSBattery for climate change the battery industry must reduce its footprint by an additional 79% beyond the 12% reduction achieved through hydrometallurgical recycling. For ocean acidification and phosphorous cycle, recycling reduces the required share of SOS, but it remains higher than the assigned $SOS_{Battery}$. A shift to low-nickel NMC batteries will increase the transgression of $SOS_{Battery}$. Using LFP batteries only would reduce the contribution to planetary boundaries due to fewer required critical raw materials. Despite disadvantages in energy density using SIBs would reduce the contribution to SOS substantially. In fact, for climate change, ocean acidification, and phosphorous cycle, a SIB-dominated battery industry would cut the transgression of $SOS_{Battery}$ by half. While practical implications, such as a lower

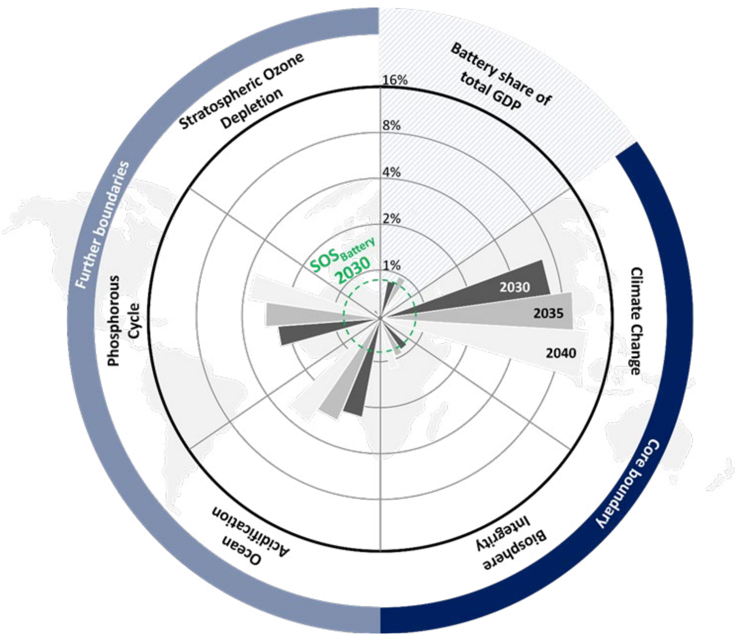

Fig. 4. The planetary and economic footprint of the battery industry in 2030, 2035 and 2040.

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DOI: 10.17879/43998521709

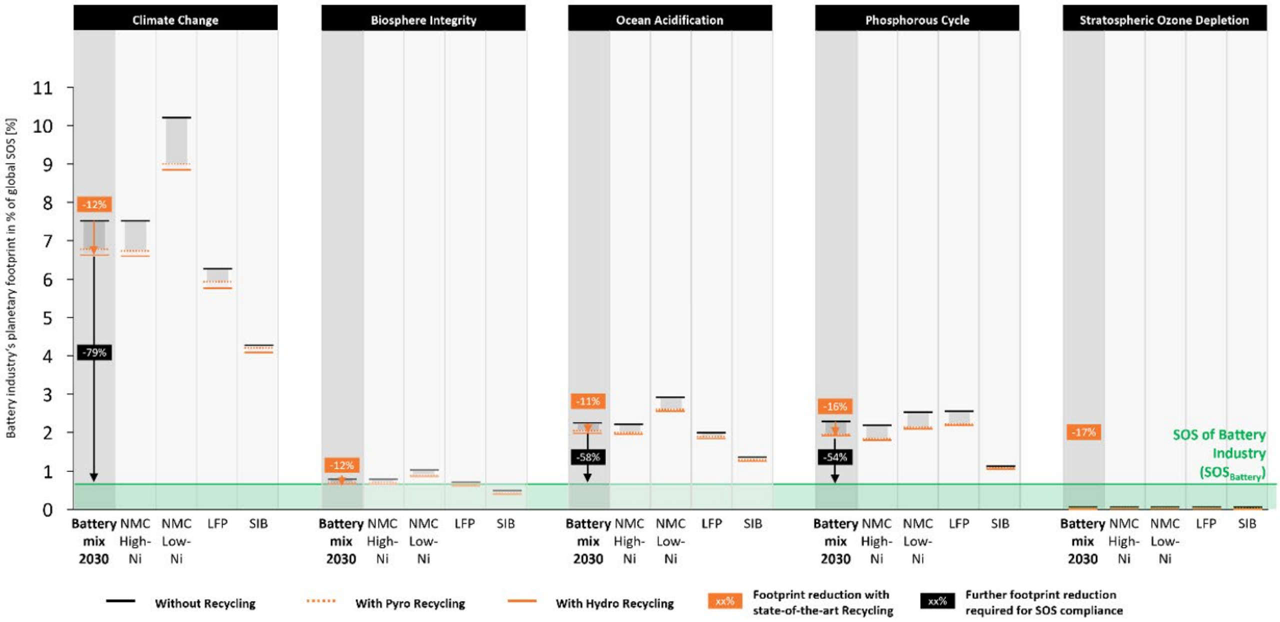

Fig. 5. Impact of battery recycling on planetary footprint of battery industry.

energy density, might limit the wide-spread adoption of SIBs in electric vehicles, results highlight that stra-tegic decisions about the market share of different battery technologies have a high impact on its absolute sustainability.

4.3. Scenario analysis

Further measures are required to bridge the gap between the current path of the battery industry and its SOS$_{Battery}$. Therefore, the impact of technological improvements to both cell manufacturing and recycling are assessed. Assessed innovations within the battery supply chain include direct recycling, direct lithium extraction, increased production energy efficiency, or a switch to 100% renewable energy. With use of copper accounting for more than half of phosphorous cycle impacts for NMC and LFP batteries, another innovation with reduced use of copper is also assessed.

Direct recycling produces CAM directly from spent batteries rather than extracting individual metals. By avoiding the complex separation and subsequent reprocessing of materials into CAM, direct recycling could be a promising alternative to state-of-the-art processes. **Fig. 6** shows that applying direct recycling instead of hydrometallurgy reduces the impact to all planetary boundaries.

The primary extraction of the critical raw material lithium, which occurs in hard rock ores or brines, is associated with considerable environmental impact. Lithium production from brines, which accounts for most of total lithium production, consists of an evaporation process in ponds, consuming a considerable amount of groundwater (Schenker et al. 2022). DLE is a more environmentally friendly method of extracting lithium by pumping concentrated brine to the surface, extracting the lithium and reinjecting the solution underground (Vera et al. 2023). A switch to DLE reduces impacts across all planetary boundaries by 3-4%, which is on par with the use of direct recycling.

Further process innovations such as dry coating, laser drying, and smart dry rooms have been of interest to research and industry. One recent study highlights that these new production technologies can lead to a 66% reduction in energy consumption during cell production (Degen et al. 2023). From a planetary boundary perspective, such measures bring significant improvements for the two core boundaries climate change (-16%) and biosphere integrity (-16%) as well as ocean acidification (-17%).

Next to reduced energy consumption, switching from fossil energy sources to renewable energy is generally seen as a promising way to enhance sustainability. Some battery cell manufacturers already promote the use of 100% renewable energy (The Economist 2023). Using renewable energy during active material synthesis and cell manufacturing brings large benefits for planetary boundaries. The contribution to ocean acidification can be reduced by 50%, allowing the battery industry to operate within the SOS$_{Battery}$ for this boundary. Additionally, this measure promises substantial reductions in climate change impact (-31%) and the phospho-rous cycle (-23%), helping the industry to approach the SOS$_{Battery}$. Reduced consumption of copper results in a focused benefit for the phosphorous cycle (-19%), without substantial benefits for other planetary boundaries.

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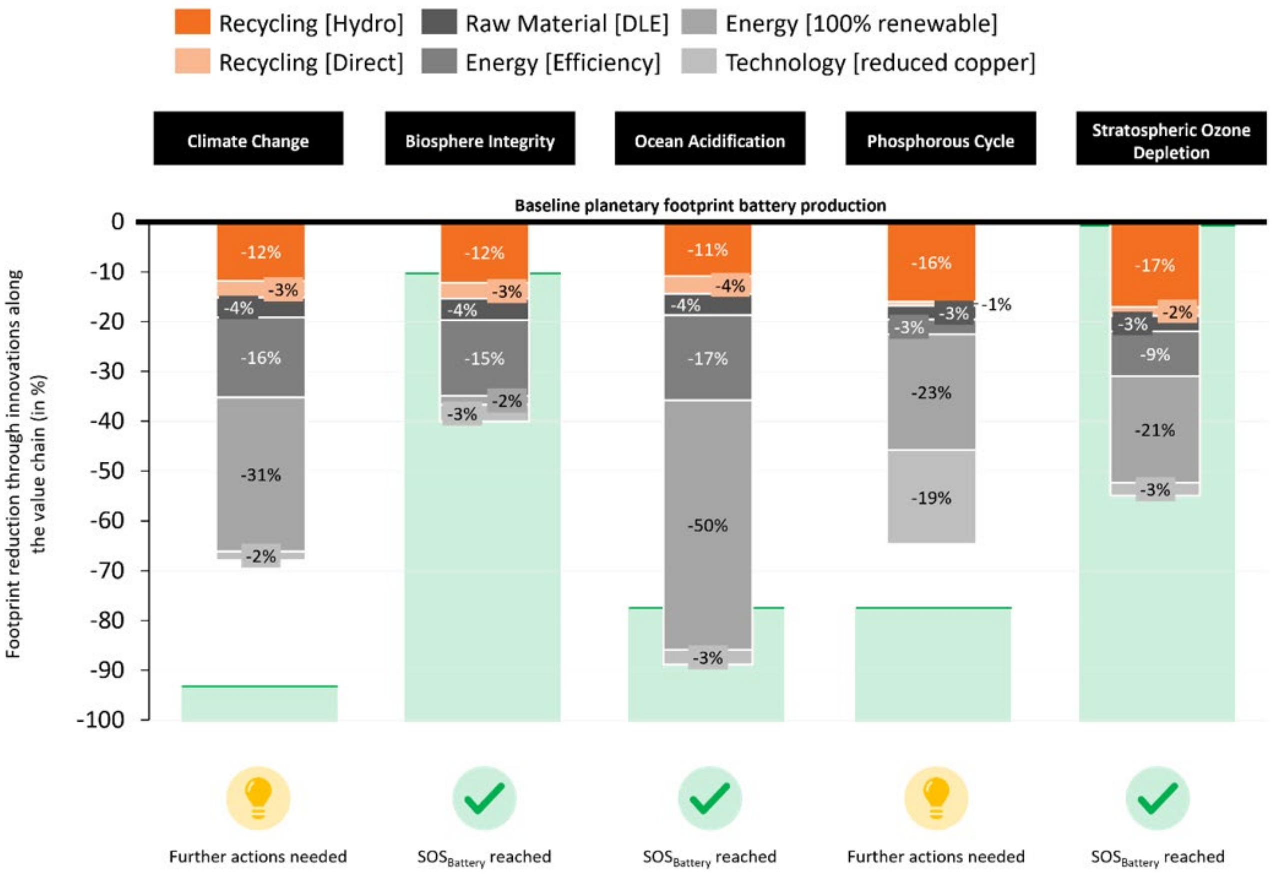

Fig. 6. Impact of future innovations to achieve $SOS_{Battery}$ in 2030.

Measures to reduce copper consumption could include a reduced thickness of the anode current collector foils or the implementation of alternative materials.

Overall, the innovations discussed show great potential for improving sustainability, but full implementation until 2030 is unlikely. For example, the speed of innovation in production processes, regardless of raw material production, recycling or battery production, is limited due to equipment lifetime. Also, a switch to 100% renewable energies is associated with major industrial and political efforts, as a solar park roughly the size of Cuba would be required to power the production of all batteries in 2030 with renewable energy.

4.4. Bringing the use-phase of batteries into perspective

Batteries enable the substitution of fossil-based energy by renewable energy in many applications and contribute to a more sustainable use of these application. The impact on the use phase must also be considered, when discussing batteries' sustainability. However, as battery manufacturers have no direct influence on the use phase, we assess the use of batteries separately from the battery production and recycling.

In the use-phase of batteries, electromobility plays the most significant role. To analyze the effect of the use of batteries from a planetary boundary perspective, **Fig. 7** compares the impact of the use phase of the projected BEV fleet in 2030 (ca. 115 million vehi-cles) with the identical number of internal combustion engine vehicles. The analysis shows that using only ICEVs in 2030 would account for 12% of the global SOS of the planetary boundary climate change. By switching to BEVs, the impact for all planetary boundaries can be significantly reduced. The electricity mix, which is used for charging the batteries has a major influence on absolute sustainability. In sum, electrification of the mobility sector combined with a sustainable electricity mix has potential to improve long-term compatibility with planetary boundaries.

5 Conclusion

The strong increase in demand for batteries has led to large industrial investments along the value chain. The major focus of research innovations in battery production and material development has been on increasing technical properties and reducing costs (Schmuch et al. 2018, Duffner et al. 2021). Recently, however, concerns about the sustainability of the

Vol.22, Iss.2, June 2025
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fast-growing battery industry, especially due to the demand of critical raw materials, have come up. Across industries com-pliance with planetary boundaries has become an overarching challenge to avoid irreversible and problematic changes in the Earth's ecosystem (Rockström et al. 2009, Steffen et al. 2015, Lade et al. 2020). For the first time, the present analysis extends the planetary boundary framework assessment to the battery industry, bringing together an understanding of complex value chains, future technology innovations and sound environmental assessments.

On its current path, the battery industry will exceed its $SOS_{Battery}$ for several planetary boundaries. Without recycling, the production of batteries will exceed the planetary boundary for climate change by a factor of ten in 2030. A similar picture presents itself for ocean acidification and phosphorous cycle. Without sufficient measures, the production of batteries could, by 2040, occupy more than 10% of the global SOS for the planetary boundary of climate change, vastly exceeding its economic value as a share of global GDP. On a positive note, however, changes in battery technology, with an increased use of SIBs wherever possible, could reduce the transgression of planetary boundaries because less critical raw materials are required. Furthermore, consequent recycling of waste batteries brings the industry closer in line with its $SOS_{Battery}$.

Utilizing the planetary boundary approach to assess the absolute sustainability potential of technological innovations shows that improved energy efficiency in cell manufacturing, alongside the use of renewable energy, reduce the transgression of key planetary boundaries by a factor of two. Other assessed innovations, such as direct lithium extraction, bring modest benefits to all planetary boundaries, or high improvements to specific boundaries, such as reduced copper with ultra-thin collector processing, to phosphorous cycle.

Some limitations should be highlighted. First, based on methodological decisions and data availability, only five of the nine planetary boundaries have so far been included in the analysis. Second, uncertainty about the geographic location of battery production capacity led to an assessment of planetary boundaries on a global level, although the effect on some boundaries might better be captured on a detailed regional-level assessment. Future work should thus complement the present findings with a region-specific,

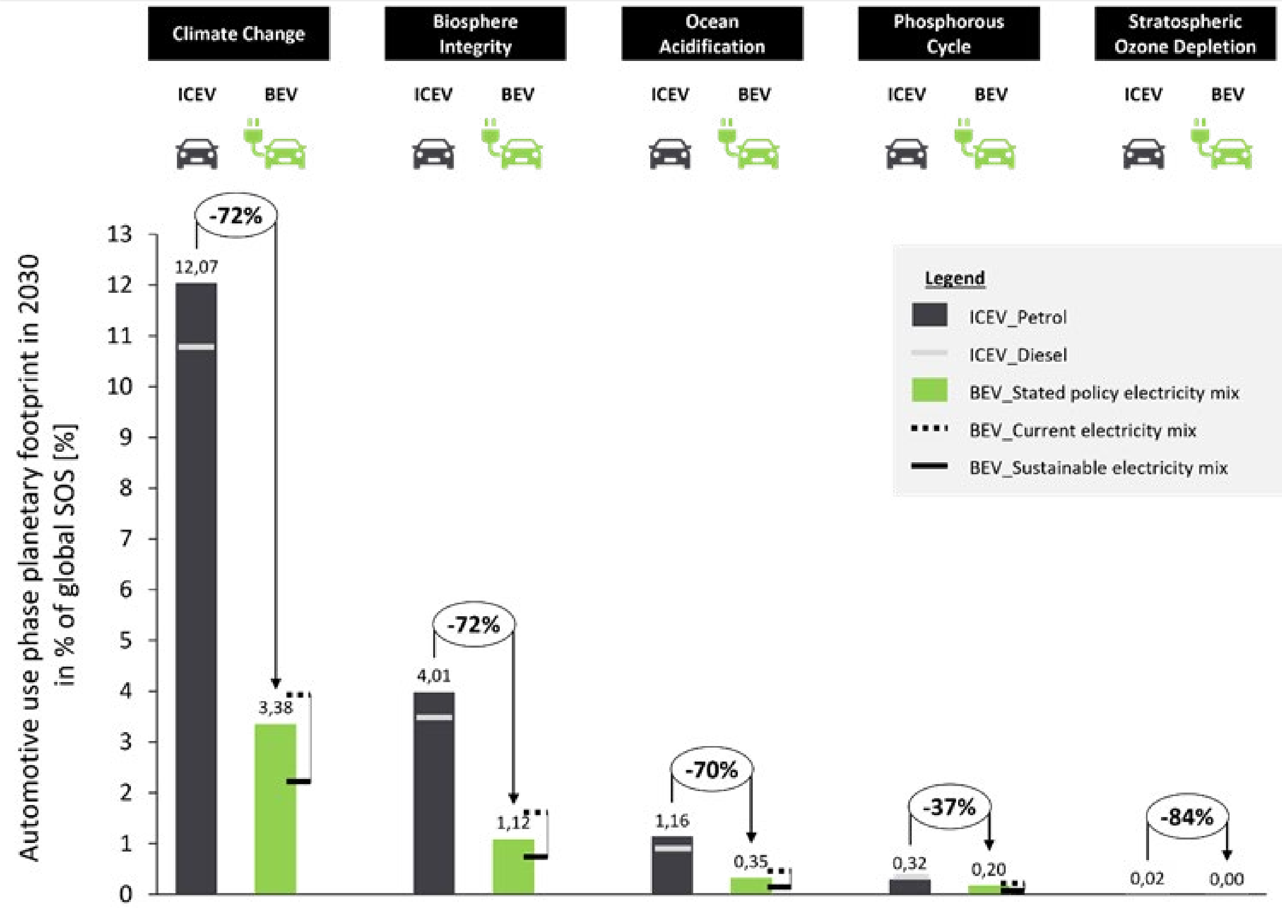

Fig. 7. Impact comparison of automotive use phase in 2030 for ICEVs and BEVs.

Vol.22, Iss.2, June 2025

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rather than global focus. Third, the selected technology clusters for batteries somewhat simplify the diversity of used technologies, and some pathways, for example, a fast uptake of solid-state batteries are not explicitly considered.
Overall, this study shows that even if all innovations were fully implemented, the $SOS_{Battery}$ for climate change and phosphorous cycle would still be exceeded. Therefore, further measures and innovations are required. Although it will be difficult for the battery industry to remain within $SOS_{Battery}$ in all planetary boundaries, it should be recognized that the use of batteries in other industries such as the automotive industry brings benefits compared with the status-quo. In fact, if charged with high shares of renewable electricity, a global fleet of battery electric vehicles requires 2/3 less of the SOS during the use-phase than internal combustion engine vehicles would.
As governmental institutions have recognized the importance of adhering to planetary boundaries, carbon pricing mechanisms have been implemented in many regions. A price for CO_2 emissions monetarily incentivizes industries to reduce their footprint to stay within the core boundary of climate change. It has also been found that additional planetary boundaries, such as phosphorus cycle, biosphere integrity, and ocean acidification benefit from an increased carbon price (Engström et al. 2020). To avoid further price increases, industries should develop an intrinsic interest in complying with sustainability targets. Here, the planetary boundary framework should be used for an analysis about the possible benefit to overall sustainability of a particular innovation. A continuous monitoring of the rapid development and technological breakthroughs of the battery industry through a planetary boundary lens will support the frequent demand from policymakers and society for a more sustainable battery industry.

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CRediT authorship contribution statement

Niklas Kronemeyer: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft. **Jens Leker**: Supervision, Validation. **Moritz Gutsch**: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft.

Data availability

The authors declare that the data used as model inputs supporting the findings of this study are available within the paper and its Supplementary Information files. Additional questions about the data supporting the findings of this study can be directed to the corresponding author.

Declaration of competing interests

Niklas Kronemeyer is employee at Porsche Consulting GmbH. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Vol.22, Iss.2, June 2025
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Research Paper

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Ethylene Production in the Petrochemical Industry: Competitive Risks and Impacts of the EU Emission Trading Scheme

Abstract

The European petrochemical industry is facing significant challenges that threaten its global competitiveness. Key challenges are the rising energy costs and a global increase in overcapacity for critical petrochemical building blocks, including ethylene, propylene, butadiene, benzene, mixed xylol, and toluene (Berry C., 2024). The European Union Emissions Trading Scheme (EU ETS), established with the aim to facilitate the reduction of greenhouse gas emissions in the face of climate change, also imposes further economic burdens on the industry. European emitters must purchase CO_2 allowances (EUAs), while the Carbon Boarder Adjustment Mechanism (CBAM) does not provide full compensation for imports of chemicals from non-EU countries, exacerbating competitive disadvantages. This study conducts a comparative analysis of the competitiveness between the EU and the US in 2023, focusing on naphtha- and ethane-based steam cracking. The calculation of variable production costs for 2023 shows a competitive disadvantage for EU producers, with variable production costs in Europe being $200–$380 higher per ton compared to the US. The situation is further exacerbated by the cost of EUAs, which could increase production costs by up to 11.5% by 2030. The introduction of the EUAs for European CO_2 emitters without cost compensation by considering imports via the CBAM leads to a further deterioration of the competitive situation. EUAs costs could represent up to 11.5% of variable production costs by 2030, depending on the technology and forecast. This study highlights the compounded impact of rising production costs and environmental regulations on the competitiveness of European ethylene production.

Keywords: *Production costs, Cost breakdown, Steam cracking, Ethylene, Competitive analysis, EU ETS*

Introduction

The decision by Versalis, the petrochemical subsidiary of the Italian oil company Eni, to close the steam cracker in Porto Marghera (Italy) in 2021 highlights both an immediate impact on the supply of petrochemicals (e.g., ethylene) and potential long-term structural shifts in the European petrochemical industry (Scafetta P., 2021). This closure, which reduces Italy's ethylene production capacity, signals a broader trend: Italy, once a net exporter of ethylene, is now becoming a net importer (Scafetta P., 2021). The steam cracker, responsible for producing light olefins through the energy-intensive process of thermal cracking, is a critical part of the petrochemical value chain (Ren T., 2006). Steam cracking (thermal cracking) is the most commonly used process for the production of short-chain hydrocarbon

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Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

compounds, including ethylene, propylene and aromatics (Ren T., 2009; Haszeldine R., 1960). Naphtha, derived from crude oil, is the primary feedstock used in steam cracking, with naphtha accounting for 70% of the feedstock used in European steam crackers in 2021, followed by propane, butane, and liquified petroleum gas (LPG) (cefic, 2024; Seifzadeh Haghighi S., 2013; Sedighi M., 2013). In contrast, regions like the USA and the Middle East utilize gaseous hydrocarbons, particularly ethane, as feedstock (Zimmermann H., 2012; Worrell E., 2000).

The European Union (EU), with its limited domestic supply of raw materials, relies heavily on imports for the petrochemical industry. The ongoing decline in crude oil production from European countries like Norway and the UK exacerbates this dependency (Eurostat, 2023). This dependency has historically been a competitive disadvantage for European petrochemicals, from refineries to polymer production. The geopolitical instability caused by the war in Ukraine, coupled with reduced exports of Russian crude oil and natural gas, has further strained the EU's raw material and energy supply chains (McWilliams B., 2023). These disruptions have led to a significant increase in energy costs, which remain elevated more than a year after the conflict began (Alexandros N., 2024). This burden has intensified the challenges faced by energy-intensive industries, including petrochemicals, as high energy costs now directly undermine their global competitiveness (Abhinandan N., 2023).

Another significant challenge is global overcapacity in ethylene production, which reached 218 million tons in 2023 (Richardson J., 2023), and the increasing use of alternative feedstocks, such as gas-based crackers, which offer more competitive cost structures. At the same time, investment in post-consumer plastic recycling and alternative raw materials, such as pyrolysis oil, signals a potential structural shift towards a more circular petrochemical industry (Kusenberg M., 2022; Eni, 2022). While substituting fossil-based feedstock with post-consumer plastic is not yet feasible on a large scale due to technical and capacity constraints (Kusenberg M., 2022; Chang S., 2023; Kabeyi M., 2023), it presents a promising long-term opportunity to enhance European competitiveness. Further reducing CO_2 emissions in the production of ethylene, particularly through the use of electricity for steam generation, is another potential strategy to improve the sustainability and competitiveness of the European petrochemical sector (Mynko O., 2023; Layritz L., 2021). An initial pilot plant for this was commissioned in 2024 at BASF's Verbund site in cooperation with Sabic, a Saudi Arabian petrochemical company, and Linde, an industrial company based in Dublin, Ireland with a focus on industrial gases and process plant development (Nonnast T., 2024).
This move towards innovation is not only driven by technological advancements but also by policy pressures, particularly the EU Emission Trading Scheme (EU ETS). The EU ETS, as the central instrument of the EU's climate policy, has been designed to reduce greenhouse gas (GHG) emissions by setting a cap on the total emissions allowed from key sectors, including petrochemicals. The scheme allocates a limited number of European Union Allowances (EUAs), which are tradable permits that allow companies to emit a certain amount of CO_2. Over time, the cap is reduced, encouraging companies to adopt greener technologies or face increasing costs for non-compliance (EU-Commission, 2024). The EU ETS was introduced under the EU Emissions Trading Directive to ensure that the EU meets its climate targets in a cost-effective manner, and it has been progressively aligned with the objectives of the EU Green Deal and the Paris Agreement. By implementing a carbon pricing system, the EU aims to incentivize companies across industries to reduce their emissions. However, for energy-intensive sectors like petrochemicals, the gradual reduction of EUAs poses a significant challenge. As the projected long-term trend of the carbon price increases, companies within the EU are confronted with rising production costs, which could undermine their global competitiveness, particularly in relation to regions such as the US and Saudi Arabia, where energy costs and regulatory frameworks are more favorable.

The impact of the EU ETS on production costs varies across industries, with the chemical sector facing unique challenges due to its high emissions intensity (Tomás R., 2010). Options for managing these increased costs include passing them on to customers, distributing them along the value chain, or absorbing them through reduced margins (Cooper S., 2024). In this context, the introduction of the Carbon Border Adjustment Mechanism (CBAM) is a critical step in addressing the competitive disadvantages posed by EU carbon pricing. The CBAM aims to prevent carbon leakage by applying a carbon-based tariff to imports from non-EU countries, ensuring that foreign producers face similar emissions-related costs to their European counterparts (European Commission, 2024). Currently, CBAM covers high-emission industries such as cement,

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

steel, aluminum, and fertilizers, but its potential expansion to basic chemicals could provide essential protection for Europe's petrochemical sector against foreign competition (European Commission, 2024).

To sum up, previous studies indicate that the European petrochemical industry faces a competitive disadvantage in feedstock supply compared to regions like the US and Saudi Arabia (Boulamanti A., 2017). Energy disruptions from the war in Ukraine have worsened this situation (Creutzig F., 2022). Additionally, the gradual reduction in available EUAs without sufficient compensation through CBAM for rising costs from foreign competition (European Customs Portal, 2023) may threaten the long-term supply of domestically produced chemicals to Europe. Domestic production of key raw materials like ethylene, propylene and aromatics is important for the production of consumer goods such as tires and packaging, as well as specialized products such as pharmaceuticals and high-performance plastics for the automotive industry (Young, 2022; Zhou, 2021). Guaranteeing the supply of key raw materials through domestic production is important for European industry, as it reduces the effect of geopolitical and logistical disturbances such as tariffs and blocked supply routes. This paper aims to quantify the competitive disadvantage faced by the European petrochemical industry in comparison to major producers like the US, and to assess the impact of the linear reduction of EU allowances (EUAs) on variable production costs. To the best of our knowledge, this is the first study to address this gap by answering the following research questions: How far was this competitive disadvantage aggravated by interruption and resulting increase in energy costs, and what further impact can EU ETS have on this competitive disadvantage without compensation from CBAM. The paper argues that policymakers must urgently consider including basic chemicals in the Carbon Border Adjustment Mechanism (CBAM) as a means of mitigating this competitive disadvantage.

This paper begins by providing an overview of the EU Emission Trading Scheme (ETS), its legal framework within the context of the EU Green Deal, and its economic implications for the petrochemical industry (Section 2). Section 3, titled ‚Methodology,' outlines the research design and approach employed in this study. Section 4, ‚Results,' presents a competitive analysis of the European petrochemical sector, benchmarking it against other key global players such as the US, Saudi Arabia, and China, offering an initial understanding of the industry's position. Following this, the paper compares variable production costs for different types of steam crackers in Europe and the US, investigates the impact of EU allowances (EUAs) on production costs, and provides a cost estimation through 2030. This analysis aims to guide policymakers in considering the inclusion of basic chemicals in the Carbon Border Adjustment Mechanism (CBAM). In Section 5, the paper discusses the key findings, acknowledges the limitations of the analysis, and proposes avenues for future research. Finally, Section 6 provides a summary of the main conclusions drawn from the study.

The EU ETS: Challenges and Opportunities

The EU Emissions Trading System (EU ETS) is a cornerstone of the European Union's climate policy, introduced in 2003 and launched in 2005 with the aim of reducing GHG emissions in a cost-effective way (EU Commission, 2003). It forms an essential part of the EU's broader strategy to meet its climate targets under the European Green Deal, with the overarching goal of achieving net-zero emissions by 2050 (EU Commission, 2019). By putting a price on carbon, the EU ETS incentivizes industries to reduce emissions by either investing in cleaner technologies or purchasing emissions allowances (EUAs) to cover their carbon output. Indeed, The EU ETS Directive operates on a ‚cap-and-trade' mechanism, which (a) sets a limit on GHG emissions from major emitters by distributing emission allowances and (b) enables the trading of these allowances to facilitate cost-effective emission reductions (Woerdman, 2015). The cap is progressively lowered each year to align with the EU's climate goals, ensuring a steady decline in overall EU emissions. By 2023, the EU ETS contributed to a reduction of approximately 47% in emissions from European power and industrial plants compared to 2005 levels (EU-Commission, 2024).

The EU ETS is not without its challenges, particularly for energy-intensive sectors such as petrochemicals. While the scheme provides incentives for decarbonization, it also places a financial burden on industries that rely heavily on carbon-intensive processes. The gradual reduction of the available EUAs over time, without immediate compensation for rising production costs, has led to concerns over the competitiveness of European industries. European companies are at a distinct disadvantage when compared to

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

their counterparts in regions with more favorable regulatory environments, such as the US and the Middle East. The US, for instance, has adopted a more flexible regulatory approach, and its relatively lower energy prices give American petrochemical companies a price advantage. Similarly, in the Middle East, energy costs are often subsidized, and environmental regulations are less stringent, which allows companies to produce petrochemical products at a lower cost.

While European industries are bound by some of the world's most stringent carbon pricing mechanisms, their competitors in regions like the US and the Middle East operate under less restrictive conditions. This disparity has led to concerns about carbon leakage. Where compensation measures are not put in place, companies may decide to relocate their operations to countries with less stringent emissions regulations, thus negating the environmental benefits achieved by the EU (Chen Y., 2024; Martin R., 2022; Cozma I., 2022). In sectors like petrochemicals, which are heavily integrated into global supply chains, the risk of carbon leakage is especially pertinent, as EU companies face rising costs that are not shared by foreign competitors.

Recognizing these challenges, the EU has introduced the Carbon Border Adjustment Mechanism (CBAM), designed to level the playing field by imposing a carbon price on imports from countries that do not have comparable carbon pricing systems (EU Commission, 2023). Starting in 2026, CBAM will gradually replace the current free allowance system for sectors such as cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen, with the transition taking place over a ten-year period (Ambec, 2024). While this shift marks a step forward in addressing carbon leakage, its effectiveness in mitigating competitive disadvantages faced by European petrochemical companies remains uncertain. Currently, the CBAM focuses on imported goods and does not fully address the internal cost disparities between European producers and those operating under less stringent environmental regulations. Moreover, the eventual success of the mechanism will depend on the scope and design of its implementation, as well as the rigor of its enforcement. As CBAM phases in, careful calibration will be critical to ensure it effectively supports EU climate goals while safeguarding industrial competitiveness.

In conclusion, while the EU ETS and the introduction of the CBAM represent significant advancements in addressing emissions and preventing carbon leakage, they may not suffice to ensure a truly level playing field for European industries. A broader and more integrated strategy is essential to balance the EU's ambitious climate goals with the economic viability of critical sectors, which are vital to the European economy. This is not just a matter of economic competitiveness. If production shifts abroad to regions with weaker environmental regulations, the emissions avoided within the EU may simply occur elsewhere, undermining global climate efforts. By carefully implementing and enforcing the CBAM, the EU can not only support its industry but also incentivize cleaner production methods internationally, contributing to global environmental sustainability.

Methodology

In order to reassess the competitiveness of the European petrochemical industry regarding the changes occurred in 2022 following the Russian Invasion of the Ukraine, the development of ethylene production capacities in the USA, Saudi Arabia and China was first compared with the European one. In addition to the comparison of capacity developments to produce light olefins and the calculation of production costs (Boulamanti A., 2017), the import trend into the EU and the effect of the EU ETS on the production costs were both considered in this study.

The change of the capacities of one of the main building blocks, namely ethylene, in the petrochemical industry was analyzed here in order to examine the development of the total capacity of the countries considered over the last 10 years. Among the nations considered are these with the highest capacity of ethylene production including the USA, Saudi Arabia, and China as well as the community of nations of the EU (Bielicki J., 2014). Information on capacity developments was provided by Chemical Market Analytics, a Dow Jones company (OPIS, Dow Jones, 2023).

Import trends into the EU was determined using the Eurostat database (Eurostat, 2024) and analyzed for ethylene and the main thermoplastic polymers of ethylene. The focus on the polymers was on polyethylene (PE) in the three forms of high-density PE (HDPE), low-density PE (LDPE) and linear low-density PE (LLDPE). Imports from Saudi Arabia and the USA were analyzed as major net exporters of thermoplastics, as well as China, which has built up large capacities over the last 10 years. The following HS codes (Harmonized Commodity Description and Coding System for International Trade) for polymers were used for HDPE "390120" and for LDPE and LLDPE "390110" (European Customs Portal, 2023). The

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

HS code "390120" represents polyethylene with a specific density of >= 0.94, in primary form (HDPE). The HS code "390110" indicates all imports of polyethylene with a specific density of < 0.94 (LDPE & LLDPE).

The single largest source of price information was the Chemical Market Analytics price database (OPIS, Chemical Market Analytics, 2023), other sources were Our World in Data, Intratec, Eurostat and the US Department of Energy.

The consumption factors of the publication of Aikaterini Boulamanti were used to calculate the variable production costs (Boulamanti A., 2017).

3.1 Variable production cost calculation

An assessment of the competitive situation of steam crackers in Europe was made on the basis of an overview of capacity expansions in the USA, Saudi Arabia, and China with developments in the EU. In addition to the capacity developments, the imports from these countries into the EU were also considered, both of the monomer ethylene and of the polymers (here HDPE, LDPE and LLDPE). By calculating the variable production costs in the USA and the EU for 2023, the competitive disadvantage, which has been significantly exacerbated by the energy crisis, was determined. Additionally, the impact of the EU ETS with the linear decrease of EUAs on European production costs has also been calculated and a forecast till 2030 with stable variable production costs has also been considered.

The paper of Boulamanti et al. already compared the production costs between the EU and the USA for basic chemicals (including ethylene) in order to determine the competitive situation between the countries in the year 2016. The variable production costs in the USA and Europe were calculated using the consumption factors and the average annual prices of the individual cost items for 2023. The production of ethylene based on a steam cracker with ethane feed and a steam cracker with naphtha feed were compared. The variable production costs were calculated by multiplying the consumption factor with the respective price (OPIS, Chemical Market Analytics, 2023).

$$Variable\ production\ cost = Consumption\ factor * Price$$

As labor costs in the production of ethylene are not a large cost position and do not differ significantly between the two regions (USA and the EU), this cost item was not included in the calculation of variable production costs.

To calculate the impact of EUAs in the production costs for European Steam Cracking including the development in the CO_2 emissions, the production forecast for ethylene and the reduction of EUAs till 2030 the compound annual growth rate (CAGR%) was used. The CAGR% is calculated by dividing the end value after the period ($V(t_n)$) by the start value ($V(t_0)$) and then square-rooting this fraction by the factor 1 divided by the period ($1/t_n$-t_0). The result is then subtracted by 1 to obtain the decimal number for the growth. The following formula was used for this:

$$CAGR(t_0, t_n) = \left(\frac{V(t_n)}{V(t_0)}\right)^{\frac{1}{t_n - t_0}} - 1$$

The additional costs of EUAs in the EU ETS are calculated assuming constant variable production costs over the period up to 2030. For the calculation of the share of EUA costs, both the increase in ethylene production based on the forecast of OPIS/Dow Jones (OPIS, Dow Jones, 2023) ($CAGR_{C2}$) and the development of CO_2 emissions based on the OECD database for the manufacturing industry in the EU are considered ($CAGR_{CO2}$). The development of CO_2 emissions in the manufacturing industry in the EU fell by 1.79% per year from 2005 to 2021, while in the USA they rose by 0.35% per year over the same period. These trends of CO_2 emissions in the EU have been used as a forecast for the calculation of the emissions with the same decline over the years till 2030. The development of the costs without a further reduction in CO_2 emissions was also calculated. The amount of EUAs (L_{ETS}) will be reduced linearly by 2.2% from 2021 to 2030 according to the new EU directive of 2021 (EU-Commission, 2024). The reduction in certificates was included in the total costs, considering the CO_2 emissions for the production of one ton of ethylene (C^0_{CO2}) in the respective production process.

$$C^t_{CO_2} = C^0_{CO_2} + \left(C^0_{CO_2} * CAGR_{CO_2}\right) + \left(C^0_{CO_2} * CAGR_{C_2}\right) + \left(C^0_{CO_2} * L_{ETS}\right)$$

Results

4.1 Ethylene capacities

The trend over the last decade shows a sharp rise in the number of installations in China, while the number of installations in other countries/regions has changed at a much slower rate (see Figure 1).

In China, the number of installations was three times higher than in 2012, once again a reflection of the country's investment activity. An increase at a higher pace can be

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

seen in the USA since 2017, while there has been a decline in the number of installations in Europe. The number of installations in Saudi Arabia has remained almost constant.

The development of ethylene capacity is characterized by solid growth in China and the USA. In China, ethylene production capacity has increased three times in the last 11 years. Capacity in the USA has also increased by 70%. Capacity in Saudi Arabia has increased by 14%. Only the capacity to produce ethylene in Europe has fallen by 7% over the last 11 years. Extraordinary capacity increases in China have already overtaken European capacity in 2015 and the US in 2021. The US now has the second highest capacity among the countries and regions compared.

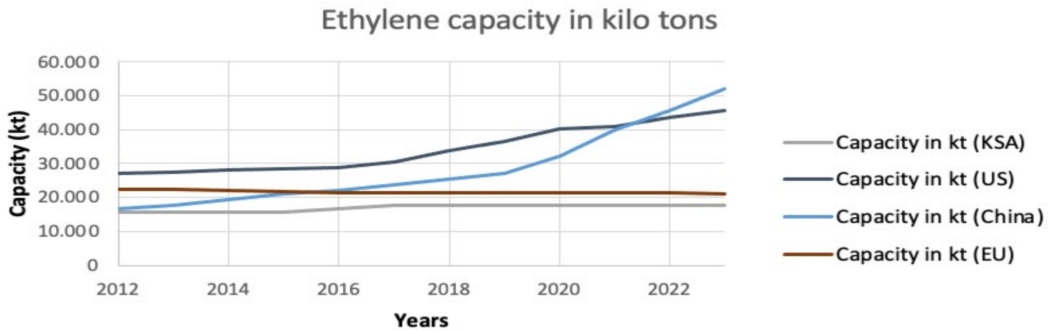

Figure 1: Capacity for the production of ethylene in the US, China, Saudi Arabia, and the EU (OPIS, Dow Jones, 2023)

4.2 Import development

In addition to the developments in ethylene production capacities, the trend in imports of derivatives into the EU from the previously compared countries was also examined (see Figure 2). The years from 2012 to 2023 were presented here as the time horizon. Firstly, the olefins were analyzed in order to examine the development of monomers for the EU. Secondly, the derivatives (polymers) of ethylene were considered, as the transport of polymers has a cost advantage over monomers - ethylene is a gas, while the polymers are solid under normal conditions.

The following HS code was used for the development of imports of ethylene “2901210”. The increased capacities, particularly in ethylene production, are also reflected in the increased imports of ethylene into the EU. Imports of ethylene from the USA have risen sharply in the last two years, putting additional pressure on the European value chain. The volume of imports from the USA has multiplied in the last two years, while the share from the other two countries analyzed (Saudi Arabia and China) has remained constant or fallen slightly. The import volumes of ethylene from the USA fell again modestly in 2023, though they remain above pre-energy crisis levels.

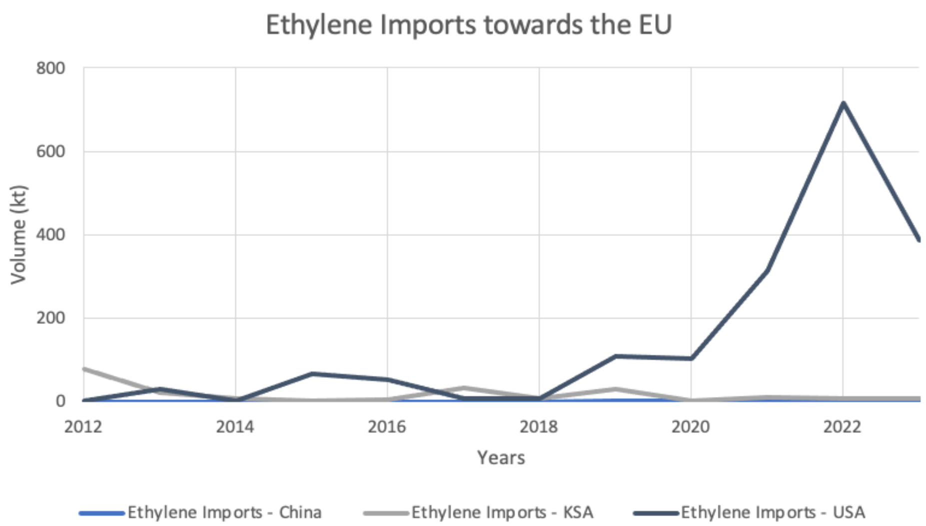

Figure 2: Ethylene imports into the EU based on eurostat data for the last decade (Eurostat, 2024)

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

A decrease in imports from Saudi Arabia can be seen in HDPE since 2018 and in LDPE and LLDPE since 2017 (see Figure 3). Imports from the USA have increased significantly over the same period (see Figure 3). As with LDPE and LLDPE, the volume of HDPE imported from the USA has doubled. The quantities of HDPE from Saudi Arabia have fallen by a third since 2018 and by two-thirds for LDPE and LLDPE.
In the cumulative analysis of PE imports, the decrease in imports with the simultaneous increase in imports from the USA is even more striking (see Figure 3). Imports from China have also increased but on a much lower level. The largest exporters to the EU in this analysis are the USA and Saudi Arabia. The increase in the USA, now the largest exporter of PE to the EU, is directly related to the capacity increases in the USA since 2017.

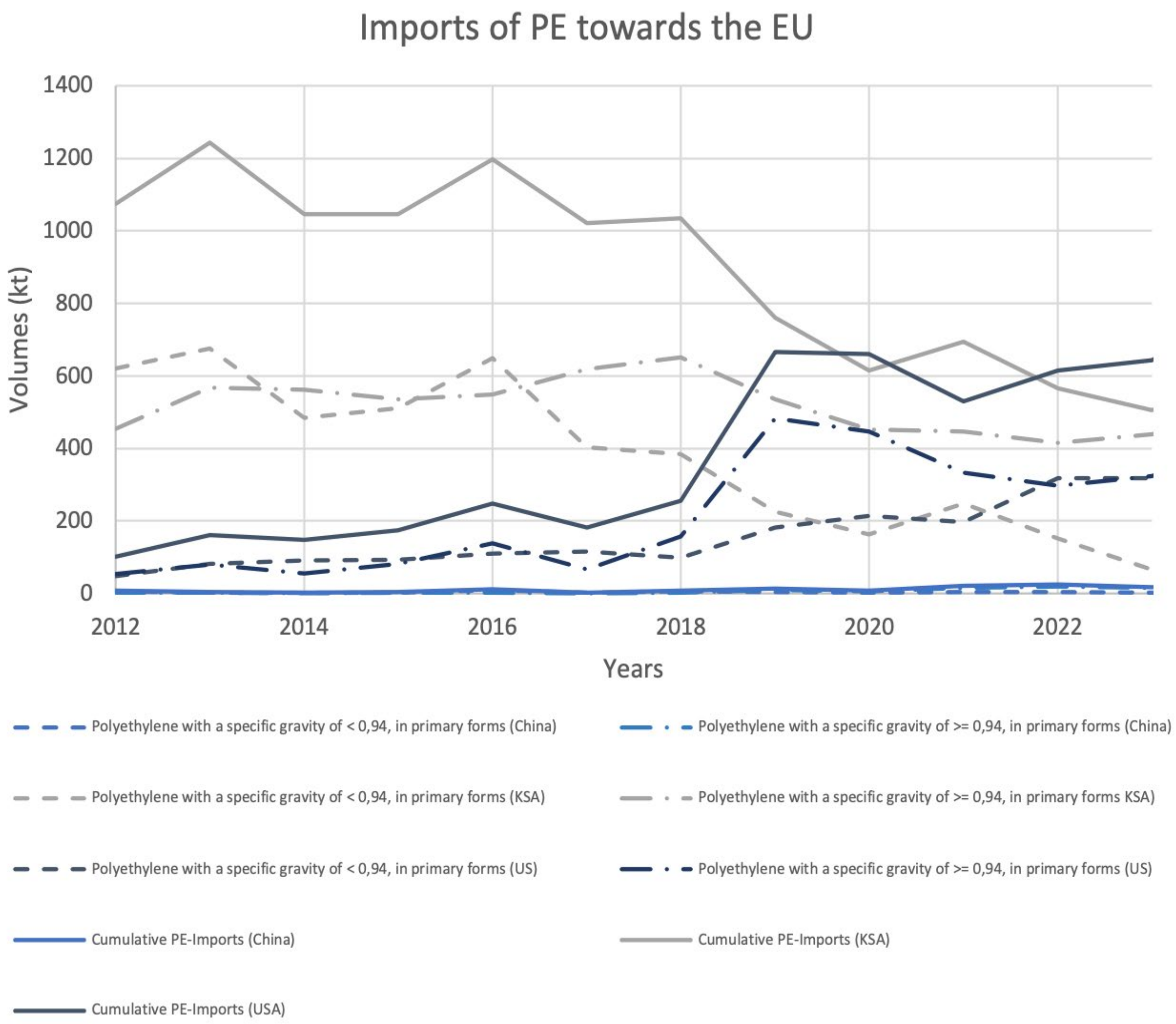

Figure 3: PE imports into the EU from the US, Saudi Arabia, and China by type (Eurostat, 2024)

JOURNAL OF
BUSINESS CHEMISTRY

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

4.3 Steam cracking

The USA has expanded ethylene capacities in the last 10 years by 70%, and import trends show an increase in ethylene and ethylene derivatives from the USA to the EU. The shale gas boom in the USA has also ensured that American steam cracker operators have another source of feedstock (ethane) at their disposal (Stangland E., 2018; Chang H., 2014). The share of gas-based steam crackers in the USA is around 57%, while in Europe, it is only 21%. Naphtha-based steam crackers are by far the most common in Europe (70%) and can be explained by the historical development of the European petrochemical industry and the limited supply of gaseous hydrocarbons in the European petrochemical value chain (Boulamanti A., 2017). In the USA, naphtha-based steam crackers account for 43% of total capacity. For this reason, both technologies were used to calculate the variable production costs in the USA and Europe. The comparison and choice of technology serve to illustrate the actual competitive situation between the USA and the European petrochemical industry in 2023.

The Calculation of the European ethane costs has been done by using the American prices and adding the transportation costs for ethane towards Europe (Nguyen D., 2021). Looking at the calculation of variable production costs, it can be seen that variable production costs are lower for ethane-based steam cracking than for naphtha-based steam cracking. Ethane-based steam crackers are significantly more cost-effective in terms of variable production costs in the USA than in Europe. Ethane as a feedstock for the production of ethylene in steam crackers has a cost advantage over naphtha-based steam crackers in Europe, but utility costs are still uncompetitive compared to the US. Feedstock costs comprise the largest share of variable production costs (see Figure 4). By-product credits are high in both regions but are $100-300/tons higher in Europe (see Figure 4). The utility costs are smaller, especially in the US. The utility costs in Europe are conspicuous, as they are significantly higher than in the USA at around $240-250/tons (see Figure 4). In the USA, utilities costs are around $60-70/ton.

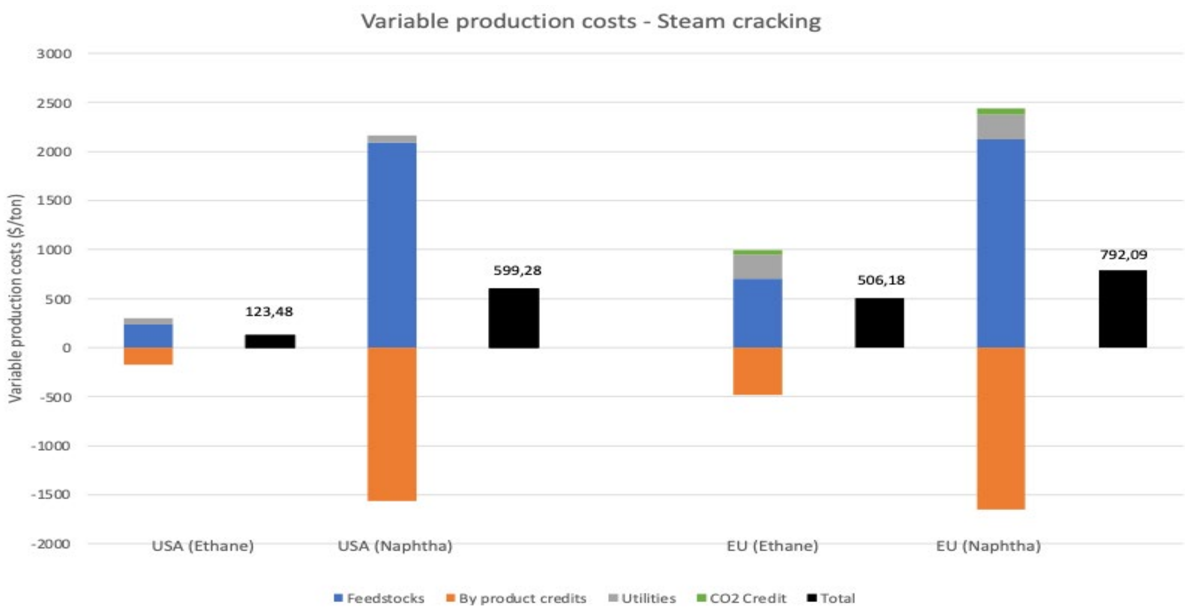

Figure 4: Overview of the cost positions for the production of ethylene by type and region (USA and EU) in 2023 (Boulamanti A., 2017), (OPIS, Chemical Market Analytics, 2023)

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

Considering by-product credits, a comparison of the total variable production costs between the US and Europe shows that the US ethane-based ethylene production is significantly lower than the naphtha-based ethylene production in the US and Europe (see Figure 4). Naphtha-based ethylene production costs are $599/ton in the USA and as much as $792/ton (without CO_2 credit: $730/ton) in Europe. In contrast, ethane-based ethylene production costs are $123/ton in the USA and $506/ton (without CO_2 credit: $460/ton) in Europe. Accordingly, the European naphtha-based steam cracking process will have variable production costs in 2023 that are almost six times as high as the American ethane-based steam cracking process. The production costs of ethylene via ethane-based steam cracking in Saudi Arabia has an even higher cost advantage than production in the USA (Boulamanti A., 2017). The steam crackers in China, like the steam crackers in Europe, are primarily naphtha-based and have cost disadvantages in the production of ethylene compared to ethane-based steam crackers. However, the steam crackers in China are younger and therefore less susceptible to maintenance and breakdowns than the older European steam crackers (Beacham W., 2024).

4.4 CO_2 emissions and effect of missing CBAM consideration of HVC

The introduction of the EU ETS leads to a further cost factor in the production of ethylene and its derivatives (HDPE, LDPE, and LLDPE) compared to the global competition, which does not implement this trading system. The production of both the precursor (naphtha) from the crude oil refineries and the production of ethylene (energy-intensive industry) falls under the trading system and thus leads to an increase in the variable production costs of ethylene from the steam cracker (European Commission, 2024). The introduction of the fourth phase of the EU ETS with a faster decline in the supply of EUAs, combined with a change in energy supply towards emission-intensive coal-fired power generation due to the limitation of fossil energy sources (natural gas and crude oil), led to a tripling of EU ETS spots prices for one ton of CO_2 in 2023 (Goldthau A., 2023).

In the publication by Ghanta et al., the GHG emissions were calculated in kg CO_2-eq on the basis of the three feedstocks naphtha, ethane, and ethanol for the production of ethylene. For standardization, the production of 400 kilotons was considered in each case (Ghanta M., 2013). The energy source in all cases was natural gas (Ghanta M., 2013). The GaBi® database was used for the calculation in the publication (Ghanta M., 2013). As ethylene production based on steam cracking was compared in this publication, only the GHG emissions of these two processes are relevant here. The production of one metric ton of ethylene on the basis of naphtha leads to a cumulative GHG emission of 1.135 kg (CO_2-eq), while the conversion of ethane produces 840 kg (CO_2-eq) of GHG emissions (Ghanta M., 2013). The average spot price for a EUA in 2023 was $49.81 (€47.3) per ton of CO_2 (Tiseo I., 2024). According to the calculation of the costs for the production of one ton of ethylene in the two processes under review, the EU ETS results in additional costs of $56.53 in naphtha-based and $41.84 in ethane-based steam cracking for the European petrochemical industry (see Figure 4).

Imports of ethylene and downstream derivatives are not yet included in the CBAM (European Commission, 2023). The EU ETS benchmark values for basic organic chemicals, including ethylene and its derivatives, cannot currently be used to determine GHG emissions due to technical problems (European Commission, 2023). Considering the additional pressure for steam cracker operators and polymer producers due to the introduction and gradual reduction of the total number of EUAs in the EU ETS with the increased variable production costs and the resulting increase in imports of ethylene and derivatives from non-EU countries, the result is a business environment with significant competitive disadvantages for the European petrochemical industry. Steam cracking for ethylene production even had considerably higher production costs compared to the USA in 2017, even before the upheavals in energy costs in Europe due to the Ukraine-Russia war and the associated sanctions against Russian raw material supplies (Boulamanti A., 2017). Competitive disadvantages in production costs will be intensified by the prolonged exclusion of petrochemicals in the CBAM.

Additional costs of EUAs on production costs in Europe are 8,7% in ethane-based Steam Cracking and 7,5% in naphtha-based Steam Cracking for 2023 (see Figure 5). The linear decrease in EUAs and the development of ethylene production forecast by OPIS/Dow Jones were considered here.

JOURNAL OF BUSINESS CHEMISTRY

Vol.22, Iss.2, June 2025
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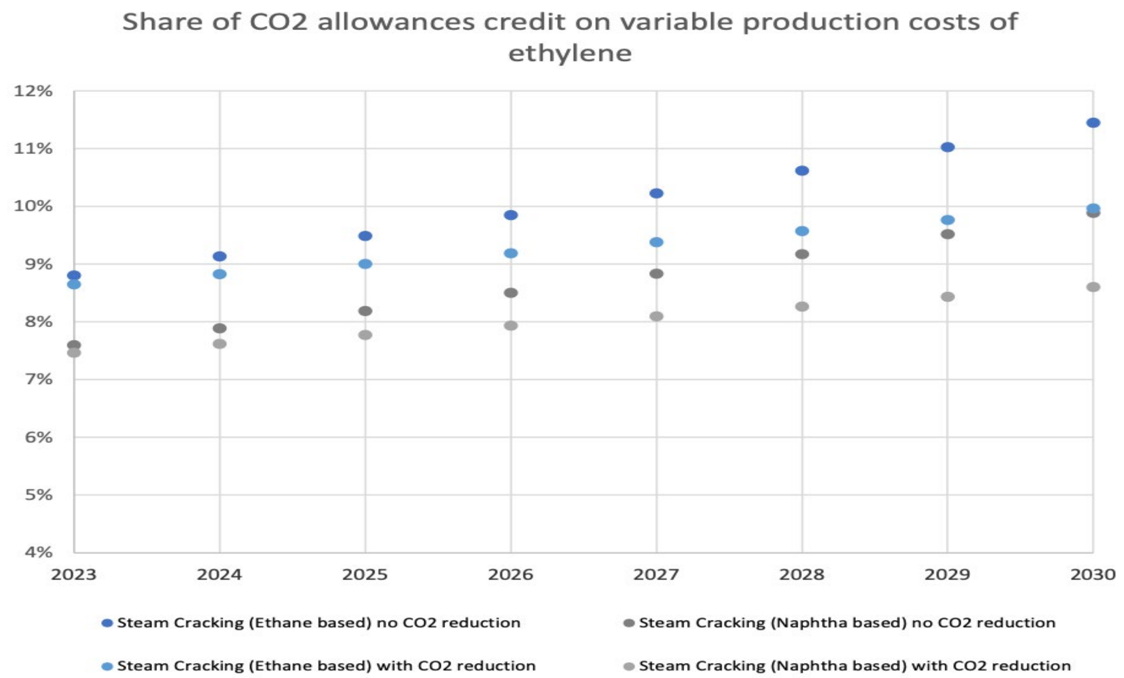

Figure 5: Development of the additional costs of EUAs on the production costs with actual energy costs depending on the consideration with and without CO2 reduction for ethane and naphtha-based Steam Cracking

The advantage of American steam crackers stems from the high proportion of ethane-based crackers, which, in addition to the lower production costs for ethylene, also have lower CO2 emissions than naphtha-based steam crackers (Ren T., 2008).

An ethane-based steam cracker in Europe would have some competitive advantages in ethylene production compared to the naphtha-based steam crackers. The decision of INEOS to build an ethane-based steam cracker in Belgium (INEOS, 2023) thus proves to be a further risk for the established steam cracker landscape in Europe.

Discussion

The findings on import trends and capacity expansions in ethylene production through steam cracking highlight the significant competitive pressures faced by European producers. A cost comparison reveals that European steam crackers incur substantially higher variable production costs than their U.S. counterparts, primarily due to differences in feedstock availability and pricing. Additionally, the older infrastructure of European steam crackers increases susceptibility to production losses and repair costs, further exacerbating their competitive disadvantage.

Capacity expansions have been concentrated in regions with favorable economic and regulatory conditions for ethylene production. The Middle East and the U.S., benefiting from abundant, low-cost feedstocks like ethane, and China, with its rapidly growing market demand and strategic investments, have attracted the bulk of global investments. Even for ethylene production via ethane steam cracking—recognized as a cost-effective alternative—European costs exceed U.S. costs by approximately $300 per ton. Notably, ethylene production costs via ethane in Europe align with those of naphtha-based production in the U.S., underscoring Europe's unfavorable cost position.

The introduction of the EU ETS compounds this disparity by increasing production costs for European ethylene producers, as steam cracking is a significant source of CO_2 emissions. The linear reduction of allowances under the EU ETS will likely intensify these cost pressures. Without adequate compensation mechanisms under the CBAM, European producers risk carbon leakage, where production shifts to regions with less stringent environmental regulations, undermining the EU's climate goals and industrial competitiveness. Notably, the CBAM's gradual implementation from 2026 and its eventual replacement of free allowances for certain sectors highlight the urgency of its careful calibration to prevent unintended market distortions.

From a geopolitical perspective, maintaining a certain level of domestic feedstock production is critical to ensuring

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

resilience against, for instance, potential supply chain disruptions and trade embargoes. The reliance on imports for key raw materials would leave the European petrochemical sector vulnerable to external shocks, weakening its long-term stability and sustainability. Policies supporting domestic feedstock diversification and investments in advanced production technologies could mitigate such vulnerabilities. Europe's competitive disadvantages, rooted in higher raw material and energy costs for fossil fuels, have been amplified by global market dynamics. Increased production capacities in regions like Saudi Arabia and the U.S. have enabled these producers to export surpluses to higher-cost regions like Europe, further straining local markets. Concurrently, countries such as China, previously net importers, are becoming increasingly self-sufficient, altering the global supply-demand balance.

The pressure on Europe's petrochemical sector underscores the importance of aligning industrial strategy with environmental objectives. Investments in carbon capture, utilization, and storage (CCUS) technologies, as well as advancements in green hydrogen for steam cracking, could reduce the carbon intensity of production while enhancing competitiveness (Layritz L., 2021). However, such transitions require robust policy support, including funding mechanisms under the EU Green Deal and collaboration between public and private stakeholders.

To safeguard the resilience and sustainability of Europe's ethylene production, it is imperative to include basic chemicals like ethylene under the CBAM. This inclusion would help prevent carbon leakage, support domestic industries, and ensure alignment with the EU's broader climate objectives. Without such measures, Europe risks not only losing industrial competitiveness but also failing to achieve its environmental and strategic goals. Furthermore, the integration of circular economy principles—such as chemical recycling of plastics—into ethylene production chains could offer a dual benefit: reducing reliance on virgin fossil feedstocks and lowering overall emissions.

Conclusion

As the heart of the petrochemical industry, the steam cracker is an energy-intensive process essential for producing downstream products used in various markets such as automotive, pharmaceuticals, packaging, and construction, due to the polymers derived from its monomers (Young B., 2022; Zhou X., 2021). However, the energy-intensive nature of steam cracking significantly contributes to variable production costs, while the process remains a major source of CO_2 emissions (Amghizar I., 2020). Efforts to reduce these emissions are underway, with the EU Emission Trading System (EU ETS) serving as a key driver, although it also increases production costs for European producers.

The last decade has seen significant increases in polyethylene (PE) imports to the EU, a trend likely to persist due to rising raw material and energy costs, exacerbated by post-COVID-19 market dynamics (Chen Y., 2023). Meanwhile, capacity expansions in major producing countries such as China, Saudi Arabia, and the USA have intensified competition, with the USA notably increasing its exports of both monomers and polymers. This expansion highlights structural risks for Europe's petrochemical sector, which faces cost disadvantages even under normalized conditions for raw material and energy prices.

The EU ETS's linear reduction of free allowances further compounds these challenges. By 2030, emissions trading costs are projected to reach over 10% of production costs for naphtha-based and 11.5% for ethane-based steam cracking. Unless imports are subjected to equivalent costs through the Carbon Border Adjustment Mechanism (CBAM), European producers will remain at a disadvantage, further widening the competitive gap. Petrochemicals, such as ethylene, and their polymers are currently excluded from the CBAM, intensifying economic pressures on domestic producers. Including the six building blocks of the petrochemical industry and key downstream products in the CBAM would provide a level playing field for European producers. While production costs in Europe have historically exceeded those in regions with abundant, low-cost feedstocks (e.g., the USA and the Middle East), excluding these products from CBAM could also allow naphtha-based production in Asia to gain a competitive edge. Incorporating petrochemicals into the CBAM could mitigate the risk of further plant closures, ensuring the resilience of Europe's petrochemical value chains. The downstream products of basic chemicals must also be considered in CBAM, otherwise the competitive disadvantage of European producers would be shifted backwards along the value chain.

Resilient petrochemical production is vital for safeguarding the EU's broader supply chain and meeting industrial policy objectives. Petrochemicals are indispensable feedstocks for various end-use applications, including critical sectors such as healthcare and infrastructure. From a geopolitical perspective, maintaining a certain level of domestic feedstock production is critical to ensuring resilience against, for instance, potential supply chain disruptions and trade

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
DOI: 10.17879/22998693375

embargoes. The reliance on imports for key raw materials would leave the European petrochemical sector vulnerable to external shocks, weakening its long-term stability and sustainability. Policies supporting domestic feedstock diversification and investments in advanced production technologies could mitigate such vulnerabilities. However, as CO_2 emissions from petrochemical production are currently challenging to calculate (European Commission, 2023) standardized methodologies are urgently required to ensure these products can be effectively integrated into the CBAM. Failure to do so risks imposing a persistent cost burden exclusively on EU producers, undermining both industrial competitiveness and climate objectives.

The alignment of industrial policy with climate goals will require not only adjustments to the CBAM but also investments in sustainable technologies, such as low-carbon feedstocks and advanced recycling methods. These measures, coupled with robust policy support, can help secure the long-term viability and sustainability of Europe's petrochemical industry.

Further research could consider the impact of regulatory or geopolitical events on the variable production costs of the European petrochemical industry beyond the scope of the EUAs and CBAM. Technological developments towards more sustainable production processes, such as the use of pyrolysis oil or electricity as a furnace heating source, could also be reviewed. As previously mentioned, the production of basic chemicals in the petrochemical industry is crucial for securing the value chain in many industries (Young B., 2022; Zhou X., 2021) thereby increasing the resilience of the European industry.

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Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:6-22998695342
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Appendix

Table 1: Number of facilities for the production of ethylene - data based on OPIS a Dow Jones Company

Number of Facilities	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Saudi Arabia	15	15	15	15	16	16	16	16	17	16	16	16
US	47	45	45	45	45	56	49	62	56	57	58	58
China	45	51	61	70	76	83	85	94	103	110	116	126
Europe	55	53	52	54	51	55	51	55	51	51	51	54

Table 2: Capacity overview for the production of ethylene – data based on OPIS a Dow Jones Company

Total Capacity (kt)	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Saudi Arabia	15.589	15.790	15.790	15.790	16.566	17.683	17.750	17.750	17.750	17.750	17.750	17.750
US	27.015	27.608	28.041	28.581	28.853	30.493	33.914	36.580	40.338	40.947	43.783	45.827
China	16.524	17.678	19.336	21.050	22.189	23.901	25.554	27.013	32.177	39.829	45.709	52.048
Europe	22.519	22.311	21.994	21.853	21.554	21.554	21.554	21.554	21.554	21.554	21.280	21.094

Table 3: Consumption factors including the three cost blocks of feedstocks, by-product credits and utilities for the production of one metric ton of ethylene – overview from the following publication (Boulamanti A., 2017)

Cost analysis model Steam cracking	Units	Consumption	
		Ethane	Naphtha
Feedstocks			
Naphtha	t/t		3,3
Light Naphtha	t/t		
Distillate, fuel oil	t/t		
n-Butane	t/t		
Propane	t/t		
Ethane	t/t	1,29	
Refinery gas	t/t		
Co-products			
C1 fuel	t/t	0,11	0,5
C3s crude	t/t	0,04	
C4s crude	t/t	0,04	0,34
Resiual fuel oil	t/t		0,13
Hydrogen	t/t	0,08	0,05
Propylene	t/t		0,53
Pygas	t/t	0,02	0,75
Utilites			
Electricity	kWh/t	140	44
Cooling water	t/t	206	400
Fuel	Gj/t	21	22,3
Other materials			
Catalyst	$/t	0,16	5,49
Chemicals	$/t	3,16	

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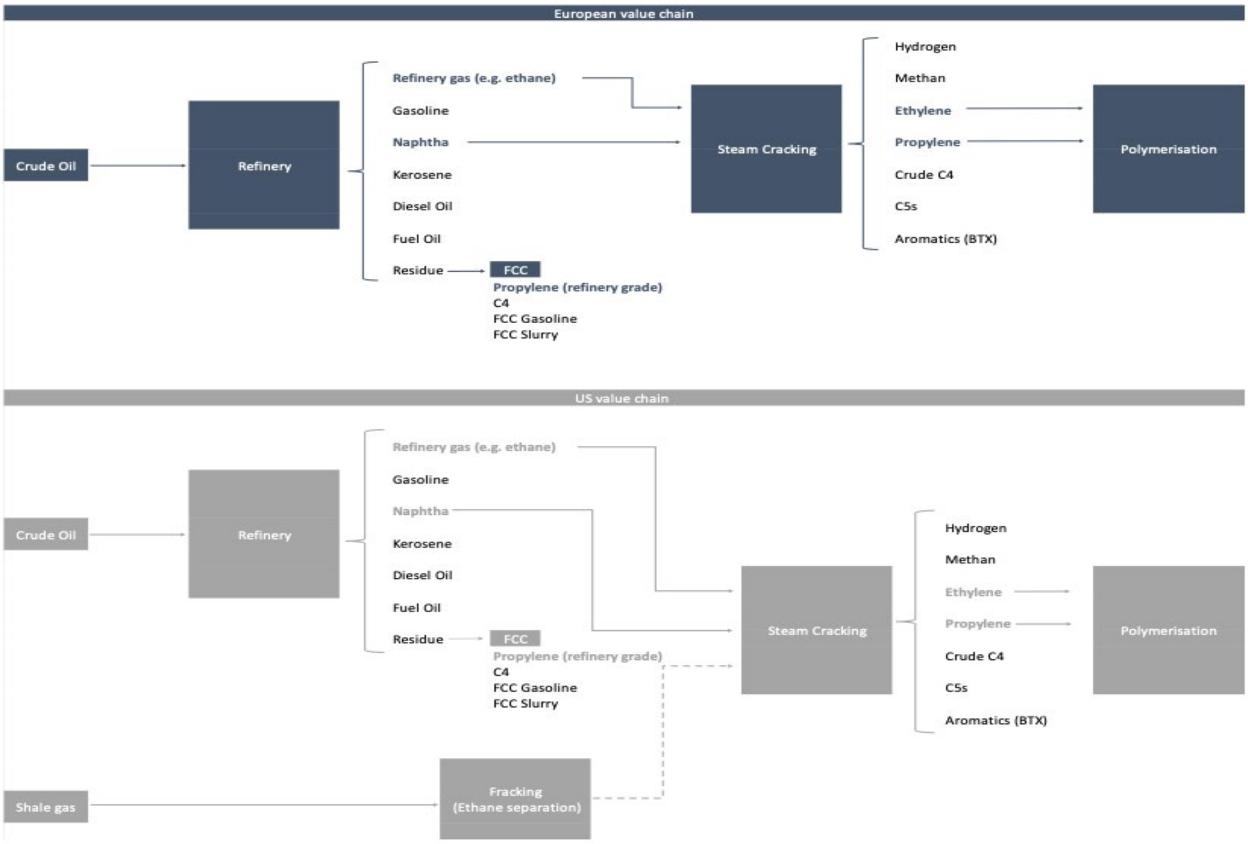

Figure 6: Simplified overview of the European and US petrochemical value chain - Fracking and the subsequent processing of the shale gas with the separation of high-purity ethane provides the US steam crackers with another source of raw materials

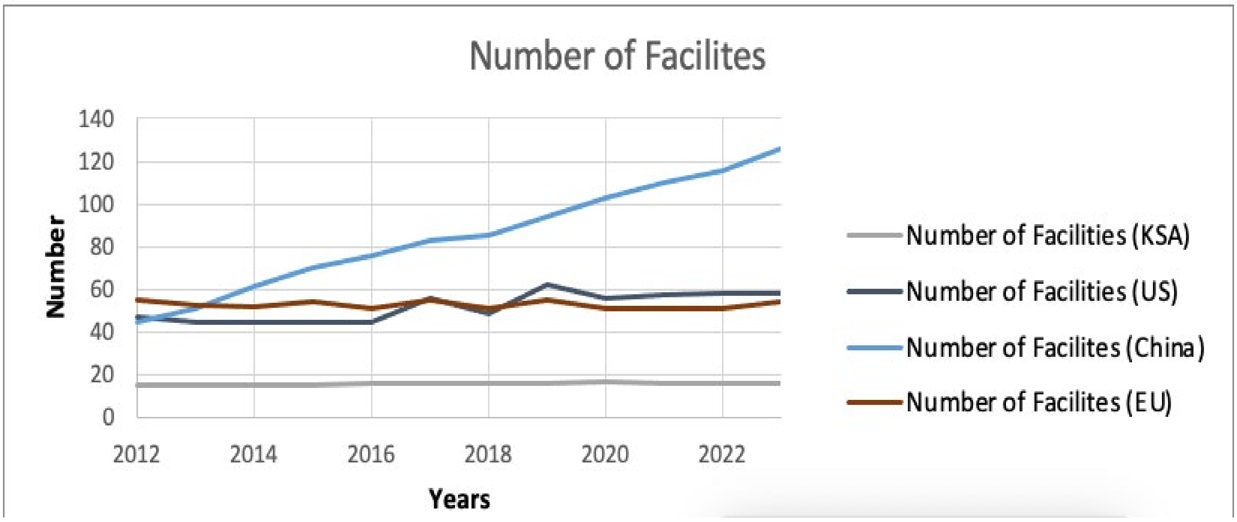

Figure 7: Number of ethylene facilities in the US, China, Saudi Arabia and the EU-Data - based on OPIS a Dow Jones Company

JOURNAL OF
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Research Paper

Tamara Florez*, Andrea Kanzler**

Corporate Social Responsibility and Sustainable Human Resources Management Practices Among the Millennial Workforce in the Chemical Industry in Ireland

Abstract

Companies around the globe are struggling to find the right talent. Therefore, the concepts of talent attraction and talent retention are central. Millennials are the most significant generational group in the current labor market in Ireland and worldwide. This study connects the Millennial workforce with Corporate Social Responsibility (CSR) and Sustainable Human Resource Management (SHRM) practices through the lens of a green employer brand, using the framework of Social Identity Theory (SIT). Consequently, this study poses the question: What relevance does the Millennial workforce in Ireland place on CSR and SHRM when considering employment with a company? A survey was conducted using non-probability and snowball sampling techniques. Data were collected from 100 individuals who were part of the job market in Ireland. The data were analyzed using SPSS 26 for both descriptive and inferential statistical analysis. Two simple t-tests were conducted to analyze the relationship between the variables, which provided several practical implications.

Keywords: *Corporate Social Responsibility, Sustainable Human Resources Management practices, Millennials, Employer attraction, Employer retention, Green employer brand, Employer Branding, Irish organizations, Corporate Sustainability Reporting Directive.*

1 Introduction

Since 2013[1], businesses across the globe have been grappling with a growing shortage of qualified professionals, as evidenced by data from ManpowerGroup (2023). It is projected that by 2030, the global talent shortage will reach approximately 85 million individuals, resulting in estimated revenue losses of 8.5 trillion US dollars (Francino et al., 2024). Employers must be mindful of the necessity to attract, engage, and retain talent (Chaudary, 2018), particularly in sectors of the economy where demand is intense (Bharadwaj & Yameen, 2021). This situation also applies to the chemical industry, where organizations are confronted with a shortage of skilled workers. As a result, they are required to anticipate and proactively engage in strategies to attract, retain, and develop these individuals from the outset of their careers, particularly during their training or academic pursuits (Evonik, 2024). The challenges that organizations face in attracting, engaging, and retaining

1 Four out of five employeers manifest to have difficulty to find skilled talent, which represents 77% in the global current market, more than double than reported in 2015. The most affected countries are Taiwan (90%), Germany (86%), and Hong Kong (85%) respectively. Ireland reports a high skilled demand percentage with 81% (Manpower, 2023).

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Vol.22, Iss.2, June 2025
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DOI: 10.17879/43998522519

top talent are numerous and multifaceted (CIPD, 2021a; CIPD, 2019; Chaudary, 2018; Chambers et al., 1998).

First, the global economy is complex and interdependent, with multinational organizations and states operating in a demanding market. This environment requires talent with keen judgment, cultural awareness, IT literacy, and outstanding managerial skills (Henkel, 2024; RTE, 2022b; The Irish Times, 2022; IrishJobs.ie, 2021). Secondly, large corporations are competing with small and medium-sized enterprises (SMEs) to attract high-quality talent (Chambers, E. et al., 1998). Third, the current global market, which is characterized by a high level of interconnectedness, provides talented workers with the opportunity to relocate to different geographical areas and contexts (Alrazehi, H. and Noor Aina Amirah, 2020; Luna-Arocas, R. et al., 2020; Chambers, E. et al., 1998). Fourth, basic demographics (Chaudhary, 2018) indicate that in many European countries, the birth rates had been low for decades. A similar phenomenon is occurring in Japan and the United States. By 2030, the majority of the baby boomer generation will have retired from the workforce (Francino, et al., 2024; Chambers, E. et al., 1998).

Demographic data indicate that the current generation of leaders is the Millennial cohort (Chaudhary, 2018; Sengupta, D. 2017). The Millennials represent the most significant generational cohort in the contemporary labor market in Ireland and globally (Fry, R. 2022; TeamStage, 2022; Chaudhary, 2018; Sengupta, D. 2017). As of 2023, the population of Ireland reached 5.3 million, according to data from the Central Statistics Office (CSO, 2024). Of the aforementioned population, over 1.46 million individuals were between the ages of 25 and 44 (Clark, D. 2024). The Millennial cohort represents the largest segment of the population in Ireland and is of paramount importance for the workforce. It is estimated that by 2025, Millennials will constitute 75% of the global workforce (TeamStage, 2022; Sengupta, D. 2017).

The subject of the correlation between the relevance that Millennials show towards certain constructs, such as Corporate Social Responsibility (CSR) and Sustainable Human Resources Management (SHRM) practices[2], is of significant importance. The present study focuses on the relevance that the Millennial workforce gives to CSR and SHRM practices when deciding to work for an organization in the Republic of Ireland.

Prior research has been conducted among students (Wang & Chen, 2022; Chaudhary, 2019; Chaudhary, 2018; Klimkiewicz & Oltra, 2017; Guerci et al., 2016; Highhouse et al., 2003). In those studies, the samples consisted of students with minimal or no previous employment experience. The present study is particularly relevant as it empirically expands the existing body of research examining the relationship between Corporate Social Responsibility (CSR), Sustainable Human Resource Management (SHRM) practices, and the Millennial generation. It offers a novel contribution to the field by providing insights from the perspective of current employees in Ireland, regardless of the economic sector in which they are employed.

Furthermore, the studies in this field have been conducted in emerging economy nations, including Brazil, India, Turkey, and South Africa. In this context, this study is distinctive in that it proposes the implementation of a pilot measuring scale for CSR and SHRM practices in a developed economy[3], specifically in the EU, which is regarded as one of the countries with the highest Gross Domestic Product (GDP) per capita after Luxembourg (Honohan, 2021).

In order to gain insight into the relationship between CSR, SHRM practices, and the preference of Millennials to work for organizations in Ireland, the present study develops a scale to measure these factors.

This subject is of interest to people, practitioners, and leaders of organizations of all sizes because it has the potential to contribute to the body of knowledge that tends to improve the SHRM practices, identify methods for attracting talent, and ascertain how to retain it.

Aim and Objectives

This research employs the tenets of Social Identity Theory (SIT) to advance the existing literature on the nexus between CSR and SHRM practices. The objective is to construct a

2 The authors of the present study agree with Renwick et al., 2013 in their suggestion that the notion of sustainability applies to HRM itself. That is why instead of GHRM, is Sustainable Human Resources Management (SHRM) practices one of the constructs that is under analysis in the present paper. However, for the purpose of this paper, Green Human Resources Management (GHRM) and Sustainable Human Resources Management (SHRM) are going to be consider as equivalent.

3 The need to contribute to the discussion and conceptual development of SHRM practices in a national context, in a developed country, and from the individual perspective, was highlighted by Yong et al. (2020) in their review of the extent literature of green HRM practices (Yong et al., 2020).

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

scale for gauging the significance attributed to CSR and SHRM by the Millennial workforce in the Republic of Ireland. To this end, the following research question is posed:
What is the perceived relevance of CSR and SHRM practices among the Millennial workforce in Ireland?

Research Objectives

- *To examine the relevance of CSR for the Millennial workforce in Ireland. This study seeks to address the perceived need for HR professionals in Ireland to gain a deeper understanding of the importance of CSR for the Millennial workforce. By gaining this understanding, organizations in Ireland can enhance their strategies for attracting, engaging, and retaining key talent.*
- *To ascertain whether the Millennial workforce in Ireland exhibits a preference for SHRM practices. The findings of this study could potentially indicate the necessity for the implementation of SHRM practices in the future, with the aim of attracting, engaging, and retaining high-skilled talent.*

2 Theoretical Background & Hypotheses

Attracting Key Talent: Millennials

Global pressures regarding the environment have prompted organizations to implement environmental management initiatives by adopting policies and practices that are environmentally friendly. Human Resource Management (HRM) has garnered attention in the academic literature concerning the integration of traditional HRM practices with environmental concerns or green practices (Chaudhary, 2019). Prior research has indicated that the Millennial demographic exhibits concern about environmental issues (Powell, 2021; Robinson, 2019; Chaudhary, 2018; Sengupta, 2017). It has been posited that individuals in the Millennial demographic are inclined to leave their organizations if they perceive a lack of alignment between the values espoused in their work and their personal values (Rigoni & Adkins, 2016; Alrazehi & Noor Aina Amirah, 2020; Luna-Arocas et al., 2020; Chaudhary, 2018).

The concept of "prestige" has been employed to elucidate the phenomenon of organizational identification among employees within the framework of Social Identity Theory (SIT).

Prospective employees tend to gravitate toward organizations that adhere to CSR principles, and the identification relationship is mediated by anticipated pride and employer reputation (Wang & Chen, 2022; Chaudhary, 2018).

Social Identity Theory (SIT), Employer Brand, and CSR

Social Identity Theory (SIT) (Tajfel & Turner, 1997) was developed to elucidate the phenomenon of intergroup prejudice, with a particular focus on ethnocentrism. In SIT, group conflict can be instigated by awareness and affiliation with different groups. The theory introduces the concepts of an ingroup (i.e., the self) and an outgroup (i.e., the other). It posits that there is a tendency for members of the ingroup to perceive their ingroup more positively than they perceive the outgroup. According to SIT, the outcome of social comparison and the drive to compete with others is prestige (Worley, 2021). In alignment with SIT, individuals tend to affiliate with groups that can enhance their self-concept and self-esteem, thereby reinforcing their social identity (Tajfel & Turner, 1997).

The influence of employer brand attributes, such as organizational support, on employee commitment and talent retention has been demonstrated (Arasanmi & Krishna, 2019). An organization that conducts its business ethically instills pride, motivation, and purpose in its employees (Tanwar & Prasad, 2017). This research posits that the implementation of CSR and SHRM practices by an organization can enhance its prestige, which in turn can be conveyed through its employer brand. When employees develop an affinity for an organization through its employer brand, they may experience feelings of pride, motivation, and leadership, and may also be less likely to consider leaving their jobs.

Therefore, it can be inferred that the Millennial workforce would likely prefer to work for organizations that apply CSR and SHRM practices over those that do not. In alignment with SIT, individuals who exhibit a high level of identification with their employer may be prone to experience positive emotions derived from the organization (Wang & Chen, 2022). SIT has also been employed to elucidate how implemented CSR components can impact employee conduct within organizational contexts (Bharadwaj & Yameen, 2021).

Additionally, it has been utilized to examine the preferences of job seekers regarding organizations that adhere to SHRM practices (Wang & Chen, 2022; Sulich, 2021; Chaudhary, 2018; Renwick et al., 2013).

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

In particular sectors of the industry, such as the chemical sector, corporations require a substantial number of highly qualified employees to maintain a competitive advantage and remain at the forefront of the market (Evonik, 2024; Henkel, 2024). These organizations are beginning to implement SHRM practices at all stages of their HR process, utilizing employer branding to attract and retain high-skilled talent.

The theoretical framework of SIT is relevant for examining the phenomenon of employer branding and the role of CSR in shaping organizational identity. In the case of Evonik, the organization deliberately utilizes its employer brand to position itself as an employer of choice among target groups (Evonik, 2024).

CSR and SHRM

The activities undertaken by organizations as part of their inherent business processes may result in environmental degradation, thereby rendering them accountable for such consequences. In response to these environmental concerns, a developing Green Human Resource Management (GHRM) model or Sustainable Human Resource Management (SHRM) practices suggests a green approach to people management within organizations. The development of literature and research in SHRM is still ongoing (Yong et al., 2020; Shen et al., 2018; Renwick et al., 2013). There is a need to gain a deeper understanding of the underlying processes through which SHRM influences employee attitudes and outcomes (Yong et al., 2020; Chaudhary, 2018; Shen et al., 2018).

Consequently, there has been a notable surge in interest surrounding the nexus of CSR and SHRM, as evidenced by the growing body of literature on the subject (CIPD, 2021b; Yong et al., 2020; Shen et al., 2018). Research related to these constructs has seen a significant increase in recent years, with new studies emerging in 2007, a notable peak in 2016, and continuing to the present (Yong et al., 2020). The implementation of the EU's Corporate Sustainability Reporting Directive (CSRD) has resulted in an increased demand for sustainability information (The European Council, 2022). In the chemical industry, for instance, some organizations recognize their human capital as a key determinant of their business success (Evonik, 2024; Henkel, 2024). Furthermore, it has been affirmed that the chemical industry is under substantial pressure due to environmental concerns (Schneider, 2024).

Other organizations have acknowledged the importance of disclosing sustainability-related information, recognizing that doing so can enhance investor confidence, support financial market stability, and foster trust among customers, business partners, employees, and other stakeholders, as well as the general public (BASF SE, 2024).

However, as is the case with any nascent field of study, current research in SHRM practices is primarily concerned with delineating its theoretical underpinnings. Nevertheless, the authors posit that SHRM confers a competitive advantage upon organizations and can be utilized as a tool to attract key talent (Bharadwaj & Yameen, 2021; Chaudhary, 2021; Kivinda et al., 2021; Sulich, 2021; Yong et al., 2020; Renwick et al., 2013). It is crucial to highlight the lack of clarity surrounding the distinction between CSR and SHRM practices in the corporate realm (Sulich, 2021).

In this context, the objective of the present study is to ascertain the significance attributed by the Millennial workforce in Ireland to CSR and SHRM practices. To this end, the two constructs will be subjected to a joint analysis, leading to the formulation of the following hypotheses:

Research Hypotheses

H1 There is a positive correlation between CSR and the Millennial workforce in Ireland.

H2 There is a positive correlation between SHRM practices and the Millennial workforce in Ireland.

3 Methodology

Research Paradigm

A paradigm represents a philosophical and theoretical framework of a scientific school or discipline. Within this framework, theories, laws, and generalizations are formulated, and experiments are conducted to support the body of knowledge. In essence, a paradigm represents a perspective that is widely accepted by theorists as the fundamental basis for their research approach (Armstrong, 2012).

To facilitate the formulation of generalizations and enhance the credibility of research, it is essential that studies of human behavior adopt a research paradigm. The specific paradigm adopted by a researcher may vary depending on the nature of the phenomenon under study and the researcher's individual preferences. This decision plays a pivotal role in shaping the investigative approach and defining the researcher's identity (Kankam, 2019). The four most widely researched

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

paradigms are pragmatism, interpretivism, positivism, and post-positivism. The appropriate application of a research paradigm allows researchers to approach a phenomenon of interest in a clear and systematic manner (Kankam, 2019).

The positivism paradigm maintains that researchers should direct their attention toward the observation of empirical phenomena, as outlined by Armstrong (2012). In interpretivism, the focus is on the meaning of phenomena, with qualitative methods typically employed for data collection (Armstrong, 2012). Despite the use of diverse instruments to examine a phenomenon in close detail, post-positivism asserts that no universal truth can be identified (Panhwar et al., 2017). Given that social phenomena are subject to change over time and exhibit considerable variation across geographical locations, the utilization of a post-positivist paradigm is advised, as it permits the investigation of a phenomenon from multiple perspectives, employing a variety of methods and contextual frameworks (Panhwar et al., 2017).

The authors of this study adhere to a post-positivist paradigm, recognizing that this research approach enables the researchers to circumvent the limitations of both positivism and interpretivism. Post-positivism is situated at the midpoint of the research paradigm continuum (Chui, 2015), offering a "pluralistic approach" that balances the tenets of both positivism and interpretivism (Panhwar et al., 2017). Additionally, it facilitates a more reflexive analysis that incorporates the researchers' values and the contextual factors inherent to the research setting.

Type of Study and Sample procedures

This study employs a quantitative methodology with a cross-sectional design, utilizing primary data collection. Its cross-sectional nature enables an examination of the extent to which Corporate Social Responsibility (CSR) and Sustainable Human Resource Management (SHRM) practices correlate with one another within the generational cohort of Millennials in Ireland.

The present study focuses on Millennials, a demographic cohort born between 1981 and 1996 (TeamStage, 2022), who were either currently employed or seeking employment in the Republic of Ireland at the time of the study.

The study employed a non-probability sampling strategy. Data were collected from individuals residing and working in the Republic of Ireland based on their availability (convenience sampling) and snowball sampling techniques. The researchers identified a number of participants and requested that they identify other potential participants, inform them about the study, and encourage them to complete the survey.

The instrument was administered via self-report. A QR code and a direct link to a questionnaire containing the scales were disseminated via various social media platforms, including LinkedIn, WhatsApp, Telegram, phone text messages, and emails, to individuals residing and working in the Republic of Ireland, who were invited to participate in the study on a voluntary basis. The survey was accessible for a period of 10 days. Once the 10-day period had elapsed, the link and QR code ceased to accept further responses. The data were anonymized prior to analysis. A sample of 100 individuals was successfully reached within the specified timeframe during which the survey was still active. Of the 100 individuals surveyed, two were not residing or employed in Ireland. The remaining 13 respondents were identified as belonging to Generation Z (ages 16-24), while the remaining 17 respondents were classified as Generation X (ages 42-55). As these 30 individuals represent distinct generational groups apart from Millennials, they were excluded from the present study.

A sample of 68 Millennials (ages 25-41) was selected and surveyed. The respondents completed the survey successfully and were residing in Ireland and participating in the labor market at the time of the study. For details, please refer to Figures 1 and 2.

Millennial Sample	Individuals	Percentage
Male	30	44,12%
Female	38	55,88%
Total sample	68	100%

Figure 1. Millennial sample disaggregated by gender

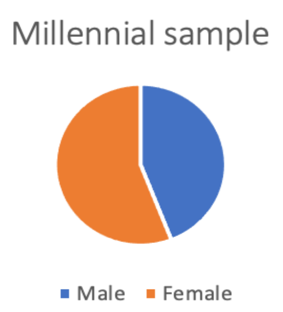

Figure 2. Graphic of the sample distribution according to gender

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

Scholarity level of the Sample	% Female	% Male	Total Percentage of Both
High-school	1,47	5,88	7,35
Post-Secondary School	4,41	2,94	7,35
Undergraduate	2,94	1,47	4,41
Bachelor Degree	11,76	22,05	33,81
Graduate Studies	5,88	1,47	7,35
Master Degree	27,94	10,29	38,23
Doctorate	1,47		1,47

Figure 3. Scholarity level of the sample discriminated by gender

The questionnaire was used to collect basic demographic data, including current location, gender, educational level, and job status. Non-personal or identify data were not collected; see Figure 3 for details.
The inquiries pertaining to the employment status of the participants were as follows:

a. I am currently employed and I am not looking for a job ____
b. I am currently employed and I am actively looking for a new job ____
c. I am currently unemployed and I am not looking for a job ____
d. I am currently unemployed and I am actively looking for a job ____
e. Others. _____ Please specify:______________

Furthermore, the questionnaire included an item inquiring about the tenure of respondents within their respective organizations. As participation in the study and completion of the survey were both optional, no IP addresses or other identifying information was collected.

Scale Development Methodology

The development of scales is a challenging undertaking that necessitates a significant investment of time and patience. The reliability and accuracy with which the construct can be operationalized, as well as the extent to which true covariance between the variables of interest can be observed, are key factors influencing the success of scale development (Hinkin, 1995). As stated by the American Psychological Association (cited in Hinkin, 1995), psychometric scales should possess proven content validity, criterion-related validity, construct validity, and internal consistency.
Content validity is defined as the quality of a scale in accurately measuring the intended construct (Talavera, 2004; Hinkin, 1995).
Criterion validity pertains to the relationship between the scale and another established scale. Construct validity concerns the underlying attributes of the construct and their relationship with the scale itself. Finally, internal consistency refers to the homogeneity of items within a scale, indicating the extent to which each item's partial score correlates with the total score obtained after the scale is applied (Hinkin, 1995).
The extent to which the scale items reflect the conceptualization of the construct under investigation is referred to as content validity (Talavera, 2004). This can be regarded as the fundamental psychometric requirement for the creation of a new scale, which must be developed through the item generation process (Hinkin, 1995). An inductive or deductive approach may be employed in the development of items for a psychometric scale. In the deductive approach, a typology of the construct is utilized as a preliminary step, followed by data collection (Hinkin, 1995).
In the present study, a deductive approach was utilized. At the outset of the item creation process, a comprehensive understanding of the theoretical foundations of the construct was achieved. Following the completion of the literature review on CSR and SHRM, the authors of this study developed two new scales to measure CSR importance and SHRM relevance.

Vol.22, Iss.2, June 2025
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CSR Importance_ Éire _Scale
SHRM Importance_Éire_ Scale

The items, CSRImportance Éire6 and CSRImportance Éire7, were self-developed items and were derived from the existing literature on the subject matter.

Furthermore, it is essential to emphasize that the content validity of the present study was ensured by the preceding studies on which it was based (Esen and Süral 2020; Chaudhary, 2019; Chaudhary, 2018; Klimkiewicz and Oltra; 2017). The authors of this present study have confidence in the content validity analyses conducted by the authors who developed the previous items; that were used to create the new simplified scale applied in the present research. The questionnaire was comprised of two sections, with a total of 22 items. The initial section, comprising six items, pertained to the demographic characteristics of the participants. The items that collected data pertaining to the participants' demographics employed straightforward, unambiguous, and closed-ended questions. The second section of the questionnaire, comprising 16 items, was designed to assess constructs related to CSR and SHRM. All items in this section employed a five-point Likert scale, with responses ranging from 1 (strongly disagree) to 5 (strongly agree). The use of a five-point Likert scale has been demonstrated to enhance the reliability coefficient alpha (Hinkin, 1995).

Research Instrument

CSR Importance_ Éire _Scale

In order to ascertain the relative importance of CSR, items from the scale developed by Klimkiewicz and V. Oltra (2017) were employed in conjunction with two items that had been specifically devised for this purpose. The items "CSRImportance Éire6" and "CSRImportance Éire7" were developed by the authors of this study. The two items were created with the intention of simplifying the scale by substituting the two final items proposed by Klimkiewicz and V. Oltra's scale. These items were designed to elicit respondents' perceptions following exposure to study cases. As no study cases were utilized in the present research, only the aforementioned questionnaire was employed. Consequently, the two items were removed, as illustrated in Figure 4.
Prior research in this field has employed case studies to provide participants with illustrative examples of organizational practices pertaining to CSR. These examples have been presented in the context of two distinct organizational approaches: one that adheres to CSR principles and another that does not. Notable examples of research that employed study cases or two scenarios in which subjects participated prior to answering the questionnaires include those of Wang H-y and Chen Z-X (2022), Chaudhary R. (2019), Chaudhary R. (2018), and Klimkiewicz and V. Oltra (2017).
In their study, Klimkiewicz and V. Oltra (2017) proposed investigating the measurement of employer branding policies and the attraction of Millennials. Tanwar and Prasad (2017) proposed that studies related to employer branding in developed countries be conducted in a cross-industry context and using cross-sectional data. Bharadwaj and Yameen (2021) proposed that future research should investigate the impact of CSR on employee attraction and retention in sectors other than information technology (IT).

SHRM Importance_Éire_ Scale

Four items were adapted from the second phase of the study conducted by Esen and Süral Özer (2020) regarding the development of an instrument to measure SHRM. The items of SHRM explored the following areas: working conditions, development, and happiness (items 11, 13, and 14) and sustainable employment policies (item 12). Given that studies of this nature rely on voluntary participation, the objective of the item adaptation was to devise a more straightforward and expedient scale for administration, namely the SHRM ÉIRE Scale.

The SHRM ÉIRE Scale is concerned with a number of key areas, including working conditions, the development and well-being of employees, and employment policies.
The pursuit of meaning and purpose in the workplace, the search for effective leadership, and the desire for professional growth and opportunities for personal fulfillment are the primary reasons why Millennials tend to leave their jobs (Gallup, 2016; Rigoni, B. and Adkins, A. 2016; TeamStage, 2022). Millennials seek organizations that demonstrate social responsibility, possess a clearly articulated mission, and exhibit exemplary leadership (Gallup, 2016; Rigoni, B. and Adkins, A. 2016; TeamStage, 2022). Furthermore, an item was included to explore sustainable employment policies, as recommended by Klimkiewicz and V. Oltra (2017). Consequently, the process yielded two streamlined new scales for gauging the significance of CSR and the relevance of SHRM practices.

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

Item	Taken from
I am skeptical toward organisations that define themselves as socially responsible*Reversed scale	P_3 $CSR_{Positiv}$,Klimkiewicz and Oltra
Including social and environmental issues in corporate policies enhances company competitiveness.	P_6 $CSR_{Positiv}$, CSR-Based employer Klimkiewicz and Oltra
Socially responsible companies operate both in their own interest and in the interest of the whole society	P1 $CSR_{Positiv}$, CSR-Based employer Klimkiewicz and Oltra
When I want to get some more information about a concrete employer, it happens that I read social reports or analyse CRS rankings.	I_3. $CRS_{Importance}$ Klimkiewicz and Oltra
If I would have to decide whether to work for a company or another, I would base my decision on corporate values, the way the organisation treats its employees, and how ethical and sustainable the organisation is.	Self- developed item, $CSR_{Importance\ Éire6}$
I look to work for organisations that care about reducing their environmental impact.	Self- developed item, $CSR_{Importance\ Éire7}$
While reviewing job offers, I pay attention to whether the company is socially responsible.	I_2 $CSR_{Importance,}$ CSR-Based employer Attractiveness Klimkiewicz and Oltra
It is important for me to find a job in a company that I consider socially responsible.	I_1.$CSR_{Importance}$, CSR-Based employer Attractiveness Klimkiewicz and Oltra
CSR brings profits for organisations.	P_2 $CSR_{Positiv}$, Klimkiewicz and Oltra
Generally, socially responsible companies, compared to other employers, offer more attractive working conditions.	I_4. CSRImportance, CSR-Based employer Klimkiewicz and Oltra
Employees should be encouraged to take part in social responsibility projects	I_{24} Taken from Freitas et al., 2012:152
Elderly employees, female employees, disabled employees and employees of different nationalities should be employed at an adequate level	I_{25} Taken from Jepsen & Grob, 2015:166-168; Freitas et al., 2012:152
Material and non-material awards (salaried leave, leave, gifts, cash, points, promotion) should be given to employees due to their voluntary services that contribute to the environment or society	I_{13} Taken from Masri & Jaaron, 2017:487; Jensen et al., 2013:1719
Employees should be trained on sustainability	I_8 Freitas et al., 2012:152; Masri & Jaaron, 2017:487
Socially responsible companies, in comparison with other firms, are more reliable employers.	I_5. $CSR_{Importance}$, Klimkiewicz and Oltra
Companies should not engage in solving social problems, as it is a state matter. *Reversed scale	$CSR_{Positiv}$ Klimkiewicz and Oltra

Figure 4. Scale items and sources

JOURNAL OF
BUSINESS CHEMISTRY

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

Data Analysis Method

The following section outlines the methodology employed in the data analysis. The data were analyzed using the statistical software package SPSS 26, with the aim of conducting descriptive and inferential statistics. In order to analyze the relationship among the variables, two simple T-tests were conducted.

4 Results

In regard to the reliability of a scale, two crucial concerns emerge: the internal consistency of the items within the scale and the stability of the results produced by the scale over time (Hinkin, 1995). The most commonly employed criterion for evaluating the reliability of a scale is internal consistency, as measured by Cronbach's Alpha (Ooi et al., 2007; Hinkin, 1995).

To evaluate the internal consistency of the newly developed scales, CSRImportance Éire and SHRM Éire, a Cronbach's Alpha analysis was conducted. Out of the total number of participants, 68 individuals were selected based on the targeted demographic criteria. These 68 subjects were identified as belonging to the Millennial demographic and provided complete and valid responses to the two scale items. The results of the reliability analysis for each scale are presented below:

CSR _Importance_Éire_Scale

Reliability

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	67	98.5
	Excluded[a]	1	1.5
	Total	68	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.810	7

Figure 5. Reliability CSR _Importance_Éire_Scale.

SHRM ÉIRE_ Scale

Reliability

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	66	97.1
	Excluded[a]	2	2.9
	Total	68	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.803	4

Figure 6. Reliability SHRM _Éire_Scale

As illustrated in the Cronbach's Alpha analysis, both scales exhibit satisfactory levels of reliability, as evidenced by Figures 5 and 6.

JOURNAL OF
BUSINESS CHEMISTRY

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

For CSRImportance Éire

As evidenced by the mean score of 3.61, the majority of respondents demonstrated a high level of relevance regarding the importance of CSR.

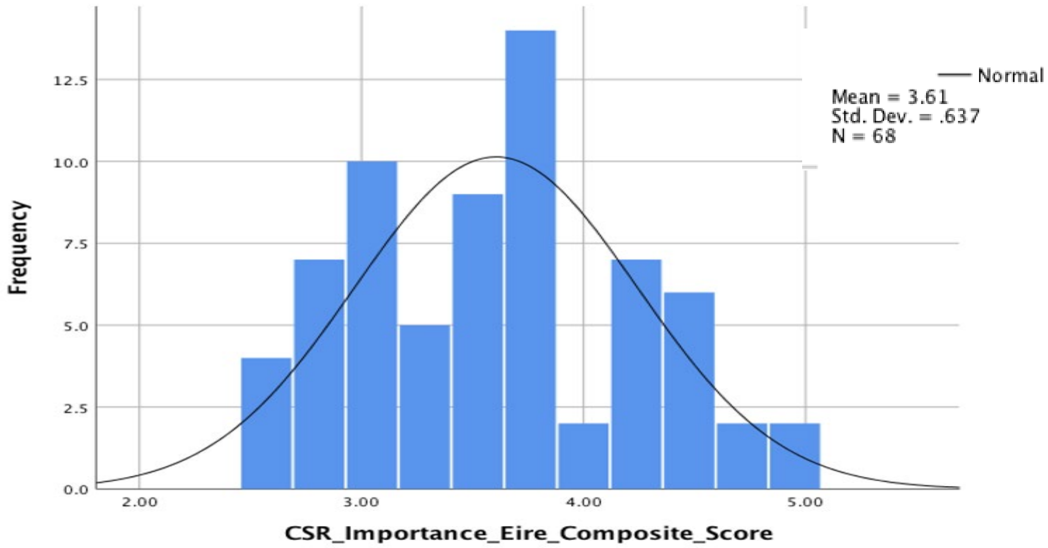

Figure 7. CRS _Importance_Éire_Scale_ Composite Score

H1 There is a positive correlation between CSR and the Millennial workforce in Ireland.

In order to ascertain whether there was evidence to suggest that there was a significant relationship between the importance of CSR among the Millennial workforce in Ireland, a single sample t-test was conducted.

The results of the single sample t-test indicated that the observed difference was statistically significant. Therefore, H1 is accepted. The sample size was 68, with a mean of 3.60, standard deviation of 0.07, and a p-value of less than 0.05, which was considered statistically significant.

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
CSR_Importance_Eire_Composite_Score	68	3.6057	.63717	.07727

One-Sample Test

	Test Value = 4.3					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
CSR_Importance_Eire_Composite_Score	-8.985	67	.000	-.69426	-.8485	-.5400

Figure 8. CSR_Importance_Éire_Scale_ T-Test

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

For SHRM Éire

As evidenced by the mean score of 4.10, the majority of Millennial respondents demonstrated a high level of relevance toward SHRM practices. This construct was rated higher than CSRImportance Éire.

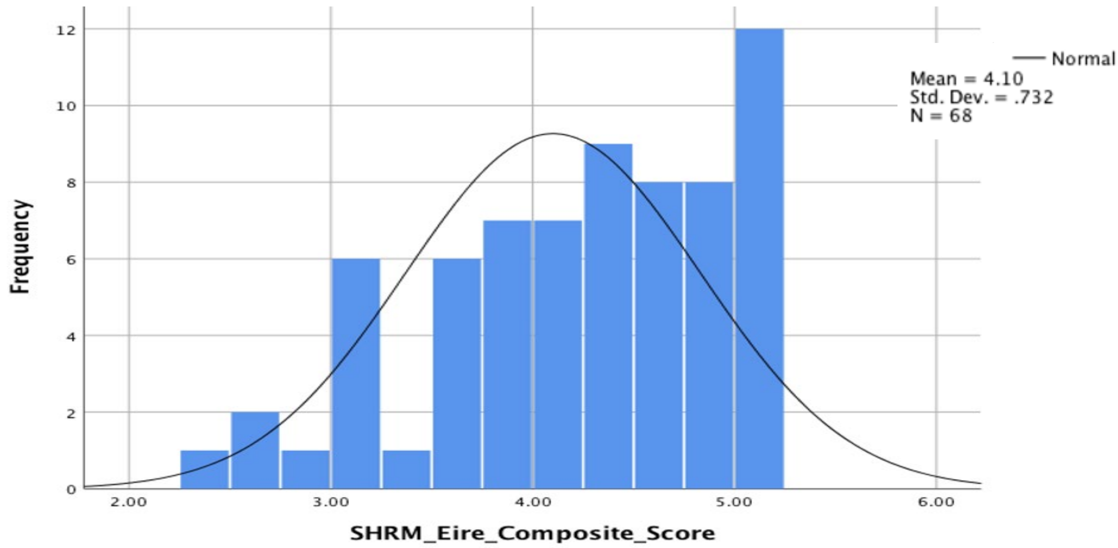

Figure 9. SHRM _ Éire_Scale Composite Score

H2 There is a positive correlation between SHRM practices and the Millennial workforce in Ireland.

In order to ascertain whether there was evidence to suggest that there was a significant relationship between the perceived importance of SHRM among the Millennial workforce in Ireland, a single sample t-test was conducted. The results of the single sample t-test indicated that the observed difference was statistically significant.

Therefore, hypothesis H2 is accepted. The sample size was 68, with a mean of 4.10 and a standard deviation of 0.73. The p-value was less than 0.05, which was considered statistically significant.

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
SHRM_Eire_Composite_Score	68	4.1005	.73182	.08875

One-Sample Test

	Test Value = 4.3					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
SHRM_Eire_Composite_Score	-2.248	67	.028	-.19951	-.3766	-.0224

Figure 10. SHRM _Importance_Éire_Scale_ T-Test

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

In light of these findings, it can be argued that the relevance that Millennials ascribe to CSR is positively correlated with three key outcomes: job applicant attraction (Wang H-y and Chen Z-X, 2022), employee engagement (Shen et al. 2018; Renwick et al., 2013) and improved job retention (Wang H-y and Chen Z-X, 2022; Bharadwaj and Yameen, 2021; Shen et al. 2018). Prospective employees indicate a preference for organizations that implement CSR (Wang H-y and Chen Z-X, 2022). Additionally, SHRM practices have been demonstrated to influence employee workplace outcomes, including organizational identification, task performance, and the intention to quit (Shen et al.,2018).

5 Discussion

The objective of this study was to determine if CSR and SHRM practices are of relevance for the Millennial workforce residing and working in Ireland. In order to achieve this objective, the present study employed the scale proposed by Klimkiewicz and Oltra (2017) and proposed two new scales to measure CSR importance and SHRM relevance:
The CSR Importance_ Éire _Scale and the SHRM Importance_ Éire_ Scale for Ireland were developed for the purposes of this study.

The results of the present study support the assumptions of this research. With the theoretical background of Social Identity Theory (SIT) (Tajfel & Turner, 1979), it can be asserted that Corporate Social Responsibility (CSR) and Sustainable Human Resource Management (SHRM) practices are highly relevant for the Millennial workforce in Ireland. It can be inferred that these constructs are expressed through the employer brand within organizations, and the Millennial workforce in Ireland recognizes these constructs and practices environmental concerns and values through the psychological process of identification within their organizations (Wang & Chen, 2022; Arasanmi & Krishna, 2019; Tanwar & Prasad, 2017). The study also demonstrates that SHRM practices are perceived as extremely important for Millennials in Ireland.
This suggests that organizations should focus on SHRM to improve the attraction of high-skilled talent and enhance employee retention and engagement. Prior studies of this nature have been conducted on prospective employees, the majority of whom were college students with minimal or no prior workforce experience (Wang & Chen, 2022; Chaudhary, 2019; Chaudhary, 2018; Klimkiewicz & Oltra, 2017; Guerci et al., 2016; Highhouse et al., 2003). In contrast, the present study was conducted among individuals belonging to the Millennial generation who were actively employed and residing in the Republic of Ireland.
Moreover, other research of this nature (Wang & Chen, 2022; Chaudhary, 2019; Chaudhary, 2018; Klimkiewicz & Oltra, 2017) employed hypothetical organizations to assess CSR and SHRM practices. In contrast, this study utilized data from the organizations with which the target audience was affiliated at the time of the study, ensuring the confidentiality of both the organizations and the respondents.
It is notable that other studies conducted in the field of employer branding, CSR, and SHRM practices have been performed in various geographical regions, particularly in emerging economies such as Brazil, India, Malaysia, Ghana, Turkey, and South Africa. This is the inaugural study of its kind conducted in a developed country that is also a member of the European Union.
The authors of the present study assert that this is the first study of its kind conducted in the Republic of Ireland. No prior studies have elucidated the interrelationship between the constructs of CSR, SHRM practices, and the Millennial workforce. This represents a significant issue for HR practitioners, organizations, and employees alike, as it lays the groundwork for further research in this field. It has the potential to foster a more robust stance from various entities within Irish organizations regarding sustainability, climate change concerns, and the necessity to address national indicators such as actual individual consumption (AIC). This would occur regardless of the economic sector, the size of the organization, and whether it is private or public.

Contribution of the Study

The present study has developed a novel scale for measuring Corporate Social Responsibility (CSR) and Sustainable Human Resource Management (SHRM) practices with the objective of elucidating the motivational factors that attract key talent to organizations in Ireland. A paucity of studies has been conducted in this field among employees, and there is a dearth of research examining the factors influencing SHRM practices at the individual level (Yong et al., 2020).

Building on the existing research in this field, the present study aimed to make a significant contribution to the development of theory and methodology while addressing a considerable gap in knowledge. To this end, the study proposed an integrative model of CSR and SHRM practices

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

with the objective of enhancing employer attractiveness and employee retention within sectors that are experiencing difficulties in recruiting talent, such as the chemical industry. The findings of this study align with the conclusions drawn by several prominent researchers in the field, including Bharadwaj and Yameen (2021), Sulich (2021), Wang & Chen (2022), Chaudhary (2018), Shen et al. (2018), Klimkiewicz & Oltra (2017), Sengupta (2017), Tanwar & Prasad (2017), Renwick et al. (2013), and Chambers et al. (1998). These researchers have highlighted the crucial role of CSR and SHRM practices in contemporary business.

Therefore, the findings of the present study support the assertion that CSR and SHRM practices are of significant importance for the Millennial workforce in the Republic of Ireland. Furthermore, it can be proposed that organizations should invest in SHRM practices to attract and retain skilled personnel, given that the SHRM Éire Scale was rated as more relevant than the CSR Importance Éire Scale.

The scale may be utilized by practitioners and scholars to assess the relevance of CSR and SHRM practices within organizations, thereby identifying the need for further training and development, designing and identifying policies and practices pertaining to CSR and SHRM, diagnosing requirements for the reinforcement of the employer brand, and generating programs to attract and retain key talent within organizations. Moreover, government bodies may utilize this scale as a preliminary framework for future research in the field, thereby facilitating the development of public policies that contribute to a more homogeneous indicator of the development of the Irish economy in the EU.

Managerial Implications

The recent scale demonstrates sufficient psychometric attributes and can be utilized as a valuable tool for HR professionals, business practitioners, policymakers, and scholars to assess the relevance of Corporate Social Responsibility (CSR) and Sustainable Human Resource Management (SHRM) practices among the Millennial workforce in the Republic of Ireland.

It is incumbent upon managers to recognize the value of CSR in fostering positive relations with internal stakeholders (i.e., employees). Moreover, they should prioritize investment in SHRM practices, as evidenced by their relevance for the Millennial workforce in Ireland. The results demonstrate the value of a sustainable approach to people management.

It is recommended that organizations implement CSR and SHRM practices, as well as a green employer brand, as part of a long-term strategic effort. This approach will enable them to create greater value for all stakeholders.

Costs

The financial implications of integrating Corporate Social Responsibility (CSR) and Sustainable Human Resource Management (SHRM) practices are considerable for organizations in Ireland, irrespective of their size or business sector. The implementation of both CSR and SHRM practices often necessitates structural changes in existing procedures. In some cases, this may result in increased costs associated with the development of specialized programs for internal stakeholders or the surrounding community. Nevertheless, these costs should be regarded as an investment, as organizations would otherwise incur expenses related to recruiting and training new talent or attempting to retain their best employees.

Furthermore, it is crucial to emphasize the immeasurable loss that organizations experience when they lose talent that cannot be replaced, taking with it invaluable tacit knowledge. Additionally, the implementation of CSR and SHRM practices provides a competitive advantage in a dynamic market (Yong et al., 2020).

Limitations

Previous studies that have sought to ascertain the relationship between Corporate Social Responsibility (CSR) and job attraction or intention among Millennials have employed methodologies that incorporate case studies in addition to the items included in the survey. Respondents were presented with two organizations: one that demonstrated CSR practices and another that exhibited a disregard for such practices. Subsequently, the items from the questionnaires were applied.

In the analysis of the results, the authors identified the necessity of providing definitions for CSR and SHRM practices prior to the survey. The authors presumed that the concepts of CSR and SHRM were already familiar to the Millennial workforce in Ireland, given that previous research has indicated that Millennials tend to prioritize environmental concerns (Powell, 2021; Robinson, 2019; Sengupta, 2017).

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

It is crucial to highlight that an enlarged sample size would enhance the potential for further generalization of the study. Given that Ireland has a population of approximately 5.3 million, it can be reasonably concluded that a sample size of 68 individuals represents a sufficiently robust sample for the purposes of this study.

Future studies would benefit from broadening the demographic section of the survey. It is recommended to include a question regarding the sector of employment of the respondents. Conducting further studies to ascertain whether there are notable discrepancies in the perceptions of respondents from a diverse range of sectors—including technology, chemicals and pharmaceuticals, healthcare, hospitality, and others—would be beneficial. Additionally, it would be valuable for policymakers and government leaders to explore whether there are significant differences in the perceptions of CSR and SHRM practices among public officers and those in the private sector.

It would also be interesting to ascertain whether there are significant changes in the level of importance that employees ascribe to CSR and SHRM practices compared to contractors and other categories of workers, such as temporary staff. Finally, a study could be conducted to determine whether there are differences in the perceptions of talent in small and medium-sized enterprises (SMEs) compared to those in large companies.

6 Conclusion

The findings of this study demonstrate that the implementation of Corporate Social Responsibility (CSR) and Sustainable Human Resource Management (SHRM) practices is crucial for organizations seeking to attract and retain the Millennial workforce. The existing literature on CSR and SHRM is limited. This study establishes a link between the Millennial workforce and CSR and SHRM through the lens of a green employer brand, drawing upon the tenets of Social Identity Theory.
Furthermore, it can be stated that few studies have been conducted in the field of CSR and SHRM practices from the perspective of current employees. To investigate the relationship between CSR, SHRM, and the preferences of Millennials to work for organizations in Ireland, this study develops a scale to measure these factors.

It is imperative that all industry sectors, at all levels of organizations, and in all corners of the world give due consideration to the importance of CSR and SHRM practices. The scope of the new EU Corporate Sustainability Reporting Directive (CSRD) is more expansive than that of its predecessor, the Non-Financial Reporting Directive (NFRD). The CSRD is legally binding for Member States, employs hard law, and introduces fines and other penalties. Conversely, the necessity for organizations to disclose sustainable data is paramount at this juncture. Not only must large organizations comply, but SMEs and, in select instances, other organizations outside the EU—subject to certain financial and branching criteria—are also obliged to report (Gilbert-d'Halluin, 2024; The European Council, 2022).

Organizations must provide both forward-looking information and retrospective data. In accordance with the European Sustainability Reporting Standards (ESRS), s1 relates to the social dimension of working conditions, equal treatment for all, and the organization of the workforce. These aspects serve to measure the proposed scale.
It is imperative that leaders in all industries and sectors comprehend the underlying causes of the increasing resignation rates within their organizations and devise effective responses to workers' needs (Cook, 2021; Fuller & Kerr, 2022; TeamStage, 2022). The solution lies in the implementation of SHRM practices and CSR as long-term organizational strategies.

In light of the growing demand for skilled professionals in various economic sectors, an increasing number of organizations are turning to SHRM practices to recognize their human capital as a cornerstone for success in a globalized economy. Prominent examples include BASF (2024), Evonik (2024), and Henkel (2024).

The advent of the global pandemic has brought to light a long-standing issue that requires urgent attention: the significance of human capital in organizations extends beyond mere financial considerations. Furthermore, the pandemic highlighted the vulnerabilities of workers and the interconnectivity of value chains within organizations (European Council, 2022). It is imperative that organizations consider the mental health of their employees and the work-life balance of their staff at a strategic level, and that this consideration be ongoing.

JOURNAL OF
BUSINESS CHEMISTRY

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
DOI: 10.17879/43998522519

The implementation of SHRM practices within organizational frameworks offers a multitude of advantages. Firstly, this approach aligns with four of the ten disclosure requirements outlined by the CSRD. Secondly, it enhances awareness among organizations and stakeholders regarding pertinent aspects of sustainability. Thirdly, it responds to the growing demand for corporate sustainability information, particularly from the investment community. Fourthly, other stakeholders, such as business partners and internal clients, may utilize the implementation of SHRM practices and this information to analyze and foster comparisons within organizations and market segments. A fifth advantage is that policymakers and environmental agencies could use this information to maintain close observation of the needs of staff and workers, thereby gaining a more comprehensive understanding of them and better anticipating social and environmental trends.

It is worth noting that organizations are beginning to integrate AI into their operations with the dual objective of maintaining competitiveness and reducing costs. Notwithstanding the aforementioned factors and the accelerated expansion of generative AI, one conclusion remains indisputable: organizations continue to rely on human input. It could be argued that enterprises, businesses, services, and products are contingent upon the planet's continued existence. The findings of the present study demonstrated that the Millennial workforce in Ireland attaches significance to CSR and SHRM practices when evaluating potential employers and determining their long-term commitment to an organization. The results indicate that it would be advantageous for leaders and policymakers to implement these practices within their organizations to retain their key talent.

It is also noteworthy that, despite the general population's lack of perception of CSR and SHRM practices as important, sustainability remains a significant concern. The reality of climate change is indisputable, and the necessity for enhanced efficiency in consumption levels is a matter of survival for all.

Vol.22, Iss.2, June 2025
URN: urn:nbn:de:hbz:643998533884
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JOURNAL OF
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Practitioner's Section

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The Impact of Artificial Intelligence on Innovation Speed in Startups

Innovation is a crucial factor for the success of companies, particularly start-ups, in maintaining their position in the market. Consequently, these companies must be prepared to incorporate new technologies into their business activities. One such technology is artificial intelligence (AI). AI is undergoing rapid technological development, yet the integration of AI into innovation management is still barely researched.
This paper examines the traditional "one-size-fits-all" approach to innovation processes and presents novel and versatile innovation processes. It considers the remaining commonalities of these processes and their potential for optimization through AI.
The importance of innovation as a success factor for startups is discussed. It emphasizes how innovation can help to overcome uncertainties and increase competitiveness. In the following, a framework is presented that deals with an AI-augmented innovation process and the potential obstacles during integration. It utilizes the ability of AI to improve the innovation process itself.

1 Introduction

One of the most discussed topics in media, political discourses and academia is artificial intelligence (AI). AI is the capacity of a system to interpret data fed into it and assist humans in decision-making and problem-solving.(Haenlein & Kaplan, 2019) It also has the potential to facilitate positive economic change. Current research indicates that AI can enhance productivity, innovation processes, international trade and economic growth. Despite the considerable public interest, the development of AI technologies is still relatively unknown. As interest in AI continues to grow, the lack of data makes it difficult to eveluate the development and integration of AI technologies and their economic impact (Buarque et al., 2020).
The objective of this paper is to examine the influence of AI on the innovation speed in start-ups. This topic is of significant interest to scientists, entrepreneurs, investors and those engaged in innovation management. For start-ups, innovation represents a crucial factor for success, enabling them to thrive in a market characterized by uncertainty and intense competition.
This research analyzes the current literature to identify the gaps within the research for the integration of AI into innovation processes. Subsequently, a framework for an AI-augmented innovation process is developed. This framework clarifies how a successful implementation can work.
The initial chapters provide an overview of current research on innovation in start-ups and exhibit why innovation is a critical success factor to them. To understand how AI can assist humans within the innovation process, it is essential to comprehend how these systems operate. Consequently, the fundamental core elements that facilitate collaboration are discussed.

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JOURNAL OF
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Subsequently, the traditional view of innovation processes is presented and it is discussed how variable these processes are due to their dependency on their environment. Despite this variability, several commonalities are still identifiable. Furthermore, two frameworks are introduced. Combining commonalities, frameworks and AI results in an AI-augmented innovation process. Finally, a conclusion about the framework's influence on the speed of innovation and a hypothesis for future investigations is presented.

2 Main Part

2.1 Start-Ups

According to Aulet & Murray (2013), the characteristics of a start-up can be described as follows. A start-up is characterized by a high degree of innovation, which relates to technology, internal processes or business models, among other things. In addition, start-ups strive for rapid growth and have a strong will to enter global markets. These types of companies often lose money first and are therefore dependent on investments. If the business model is subsequently successful, exponential growth is to be expected. These characteristics distinguish start-ups from small and medium-sized enterprises, which tend to focus on addressing a local market. They are not dependent on innovation to survive or grow on the market. In comparison to start ups these companies typically grow linearly (Aulet & Murray, 2013).

After founding, most start-ups are exposed to a so-called „Death Valley" phase. This is the phase in which young companies must establish themselves and their products to realize regular profits and sustain themselves (Hudson & Khazragui, 2013). This phase is characterized by a low survival rate (Hyytinen et al., 2015). For this reason, it is important to look at the possible success factors. One of these factors, which is discussed in this paper, is the power and speed of innovation.

2.1.1 Innovation as Success Factor

Previous research indicates that certain entrepreneurial factors and activities are more likely to result in a successful business start-up than others (Kim et al., 2018),(Tomy & Pardede, 2018). While in general the ability and willingness to persevere in these activities may be necessary for a successful start-up, it is not sufficient on its own. Because persistence may lead to a focus on the wrong activities (Fritsch et al., 2006).

The extent to which innovation is a success factor for young companies has not been widely studied in the literature. However, there are some industry-specific studies and a few general statements that innovation is a success factor for start-ups.

In their research, Kim et al. (2018) were able to identify critical success factors for design start-ups. Entrepreneurship, technology, economics and innovation were identified as success factors and each was assigned five further attributes. Of these, the five attributes of innovation are particularly relevant for this work. The first is entrepreneurial motivation and the resulting philosophy and goals of the company. Secondly, progressive thinking is mentioned which is based on a flexible corporate culture and open-minded employees. Another important point is the self-development of employees. Here, employees engage in activities designed to enhance their own learning and development, thereby contributing to the overall success of the business. The commercialization of ideas is of particular importance to develop new business ideas and integrate them successfully into the market. Finally, a „marked-oriented opportunity switch" is mentioned, which states that companies must adopt a flexible business model and must continuously develop their products or services and adapt them to the market (Kim et al., 2018). These attributes are crucial for establishing an innovative atmosphere that fosters the entrepreneurial success of design start-ups by stimulating innovation processes.

In their work, Tomy and Pardede (2018) identified uncertainties that must be considered when predicting the success of a technology start-up. These competitive uncertainties result from the lack of knowledge about the actions and behavior of the competition. They arise from the inability to recognize the competitive strategies for the competitors' product and service offerings.

The origins of these uncertainties are divided into the external and internal environments. Within the external environment, technological uncertainties refer to the speed of innovation as an uncertainty. Innovation speed refers to the time required to move from the initial concept to the commercialization of the product. The ability to survive as a start-up hinges on the ability to develop an innovative first product and to maintain the power of innovation. The speed of innovation must be faster than that of the competition. Furthermore, knowledge development within R&D is also essential for a robust innovation system (Alkemade et al., 2006). The application of process innovation methods follows a protocol for the development of new products,

Vol.22, Iss.2, June 2025
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DOI: 10.17879/43998520885

delivery of quality, responsiveness to customer needs, project management and innovation.

Within the internal environment, the innovation process as such is defined as a resource of uncertainty. New technologies alone are not innovations. The necessary knowledge must be applied to combine this technology with market needs to create a profitable opportunity (Tomy & Pardede, 2018).

In contrast, Sevilla-Bernando et al. (2022) make an industry-independent statement about the importance of innovation as a success factor for start-ups. A culture of learning and development is the basis for sustainable growth and continuous innovation of the company (Sevilla-Bernardo et al., 2022).

2.2 Artificial Intelligence

To support the innovation process with AI, it is essential to understand how it works. AI is capable of understanding human communication and generate content that can be interpreted by humans. The following builds the necessary understanding of AI for this paper based on Bahoo et al., 2023.

The application of **machine learning** is essential for the comprehension of the structural and functional characteristics of algorithms, which can be employed to facilitate the acquisition of knowledge from data and the formulation of predictions.

Another area of machine learning is **deep learning** which enables computers to recognize complex patterns and correlations within large amounts of data.

Natural language processing (NLP) endows the machine with the capacity to read and comprehend the language spoken by humans.

The concept of the **artificial neural network (ANN)** is based on the idea of simulating the way the human brain analyzes and processes information. It has the capacity for self-learning, which enables it to achieve better results over time.

Text mining is the process of converting unstructured text into a structured form with the aim of identifying meaningful patterns and new insights.

Data mining, also known as big data, is a technique that allows machines to search through large amounts of information and recognize correlations. It forms an interface between AI, machine learning, statistics and database systems.

This brief summary does not include all the elements that an AI needs to function properly. However, this overview is sufficient to recognize the complexity of the composition of different core functions which enables AI to work sensibly and logically. The core of these functions is that the AI was developed to understand and support humans, for example by supporting an innovation process.

2.3 Innovation

Innovation extends to all levels of a company and can take place both in management and among employees. Furthermore, it can be applied to products and services.

2.3.1 The Versatility of the Innovation Process

The traditional view of the innovation process allows it to be divided into the following steps: Generating or finding ideas, selecting ideas, development and market launch. However, these processes are much more individual if the

Table 1: The eight innovation processes.

#	Type of innovation processes
1.	Traditional process: from idea to launch
2.	Anticipating sales: the tailor-made approach (open order)
3.	Anticipating sales from a given client specification (closed order)
4.	Process started by a call
5.	Process with a stoppage: waiting for the market
6.	Process with a stoppage: waiting for advance of technology
7.	Process with a stoppage: waiting for the market and for the advance of technology
8.	Process with parallel activites

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contingency theory is taken into account. According to the theory there is no best way to organize a corporation, lead a company or make decisions. It considers environmental conditions, organizational structure, management style and technological or market-oriented factors. Salerno et al. (2015) summarized these in their work into eight different innovation processes (Table 1; Figure 4-10). Each of these processes has its own motivations and project contingencies (Salerno et al., 2015).

2.3.2 Emphasizing the Similarities

By analyzing the eight different innovation processes (listed in the appendix), the authors showed that the traditional linear „one-size-fits-all" process ignores many important external conditions as mentioned in the contingency theory. The resulting novel innovation processes itself are not relevant for this paper, but the similarities among them. These manifest themselves in three phases which can be described as idea, selection and development, but they vary in their sequence. These three phases build the early stage of an innovation process and will be very important for the integration of AI into the innovation process which will be discussed in the next chapters.

2.4 Integrating AI into the Innovation Process

2.4.1 Technology Acceptance Model

The Technology Acceptance Model (TAM) (Figure 1) was introduced in 1986 by Davis et al. as an evolution of the Theory of Reasoned Action (Fishbein & Ajzen, 1975). TAM is a framework in which the **perceived of usefulness** and **perceived ease of use** of a new technology is influenced by various external factors. Perceived usefulness indicates the extent to which the user believes that the new technology will improve his or her own performance. Perceived ease of use, on the other hand, refers to whether the user feels that a great deal of effort is required to use the new technology. An initial high level of effort followed by a steep learning curve can still be perceived as user-friendly.

This model puts these two criteria into relation to explain the usage behavior of new technologies. These external factors influence whether users accept a new technology and their attitude toward it. Figure 1 shows the complete framework. However, the former description is sufficient for this paper.

Empirical studies have demonstrated that for a new AI-based technology to be effectively introduced, the technology must provide sufficient benefits for the user and improve performance in terms of perceived usefulness and perceived ease of use (Agrawal et al., 2019).

The external components that influence these two factors can be explained with the help of the Technology-Organizational-Environmental (TOE) framework, which will be discussed in the following section.

2.4.2 Technological-Organizational-Environmental Framework

The TOE framework was developed by Tornatzky and Fleischer (1990) to examine the introduction of various IT products and services at company level. By incorporating technological, organizational and environmental variables, the TOE framework has become widely accepted. It analyzes technology adoption, technology benefits and value creation from technological innovations. The model is also free of restrictions within sectors or company size. It provides a holistic picture of the acceptance of the technology by users, its implementation, the prediction of potential challenges, its impact on value chain activities and much more (Gangwar et al., 2015),(Baker, 2011).

The **technological factors** pertain to the way technologies are supported within and outside the company. The capacity to integrate new technologies and the suitability of current technologies for the company are also considered.

The **organizational factors** consider the existing

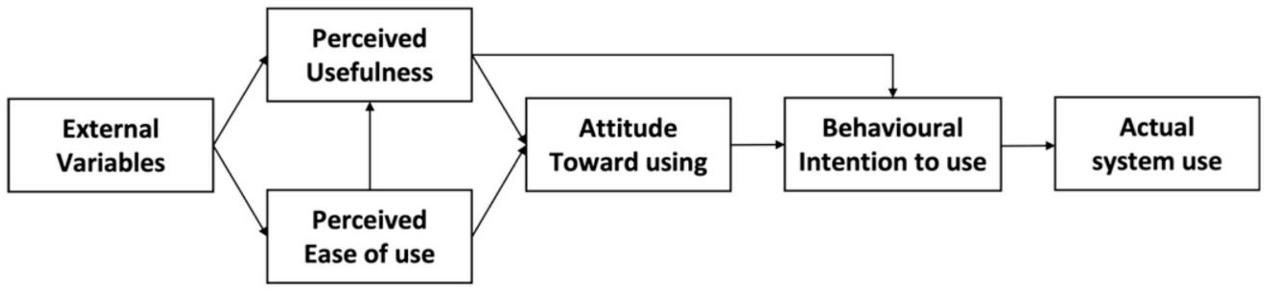

Figure 1: Technology Acceptance Model (TAM). (Davis et al., 1989)

JOURNAL OF
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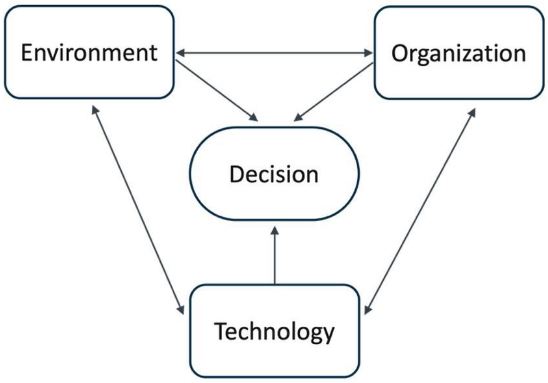

Figure 2: Technological-Organizational-Environmental (TOE) framework (Tornatzky and Fleischer, 1990).

characteristics and resources of the company. Leadership and management communication are also considered. During the decision process, the size of the company and the available resources are also taken into account.

The **environmental factors** pertain to the question of whether the introduction of new technology will enhance the company's competitiveness or operational efficiency. Government regulations and industry trends also exert a significant influence on the acceptance and speed of adoption of new technologies (Na et al., 2022).

2.4.3 AI-Augmented Innovation Process

The integration of AI within innovation management introduced a new era of AI-augmented innovation processes. This has led to a significant transformation in the way companies work, with a greater focus on creativity and problem-solving. In particular, the early stages of innovation have been revolutionized by the integration of AI with the introduction of new tools that facilitate exploration, brainstorming, prototyping and development. The user-friendly nature of modern AI tools enables a broader user base to participate in specific innovation processes without any special prior knowledge. For instance, these tools can be utilized to generate preliminary prototypes of a digital product without the necessity for the user to possess extensive programming expertise. This eliminates the significant discrepancy between the concept and a tangible initial prototype. Bilgram & Laarmann's (2023) research provides an overview of the phases of the innovation process in which AI enhances efficiency. The generation of ideas and the prototyping phase are of particular significance. The integration of AI tools not only accelerates the whole innovation process, but also has a positive impact on costs, the innovation speed and the efficiency of workflows within a company (Bilgram & Laarmann, 2023).

A practical example of AI-augmented innovation can be found in the chemical industry. Evonik anticipates that AI will significantly accelerate innovation over the next 5–10 years, particularly through applications such as molecular property prediction, which reduces experimental costs and speeds up product development. Additional use cases include supply chain automation, process optimization, and predictive maintenance, supported by large, high-quality industrial datasets. These developments demonstrate how AI facilitates more efficient, data-driven innovation processes in complex industrial environments (Kanzler, 2024).

The work of Kakatkar et al. (2020) examines the significance of analytics performed by AI tools in the context of decision-making and strategy which are crucial elements of the early exploration phase of the innovation process. The performance-enhancing effects of AI on innovation processes can be substantiated by empirical case studies. Kakatkar et al. (2020) describe several real-world applications in which AI contributed to measurable improvements in both speed and quality of innovation-related tasks. In one case, an innovation team working on identifying lead users and relevant problems in the semiconductor industry completed their analysis in four weeks. According to the authors, a purely manual approach would have required between 16 and 20 weeks for the same results, indicating a substantial time saving. In another case, AI algorithms achieved an accuracy rate of 75 % when classifying consumer needs based on large volumes of user-generated content. This allowed for a broader and more systematic exploration of the problem space than would have been feasible using traditional qualitative methods. Moreover, in the evaluation of product ideas, a random forest model developed by the team was up to 23 % more accurate in predicting expert ratings than the average crowd-based assessment. These findings illustrate how AI can accelerate the front-end of innovation, reduce analytical effort, and enhance the

Vol.22, Iss.2, June 2025
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reliability of decision-making processes.
The authors identify the potential of AI to provide more profound insights into market trends, user behavior and technological advances. This potential can assist in the identification of opportunities and threats within the market. Thus, AI analyses assist companies in generating innovative ideas and evaluating them, supporting the entire innovation process. AI-supported processes yield secure innovation strategies based on extensive data and market orientation (Kakatkar et al., 2020).

2.5 Framework - Implementing an AI-Augmented Innovation Process

The factors obtained from the literature can be used to propose a framework that focuses on an AI-augmented innovation process (Figure 3). The left side of figure 3 is based on the fact that start-ups have to recognize innovation as a success factor and prioritize it accordingly. To create awareness of potential barriers to implementation in companies, this framework is based on the two previously introduced TAM and TOE frameworks.
As mentioned before, TAM covers two factors: perceived usefulness and perceived ease of use. Because these are influenced by external factors, the TOE framework is also applied. It considers technological, organizational and environmental factors that can influence the adoption and thus the implementation of the new technology. This builds the TOE-TAM branch in the top center of the figure.
If innovation is recognized as a success factor and the TOE-TAM branch of the framework is considered, an AI-augmented innovation process may occur. As previously discussed, the innovation process takes different paths depending on its circumstances.
Despite the variability within the process steps and their sequence, commonalities are identified. These similarities are reflected in the three phases: Ideas, Selection and Development and form the early phases of the innovation process. This is displayed in the bottom center of the figure. The result is an AI-augmented innovation process in the center of the figure. The newly created process can assist in making the early phases of an innovation process more efficient and effective as shown by the different results on the right side. The newly created framework (Figure 3) can assist in making the early phases of an innovation process more efficient and effective as shown by the different results on the right side. This is particularly evident when analyzing how AI contributes to the core phases of innovation.
In the **idea generation phase**, AI facilitates the detection of

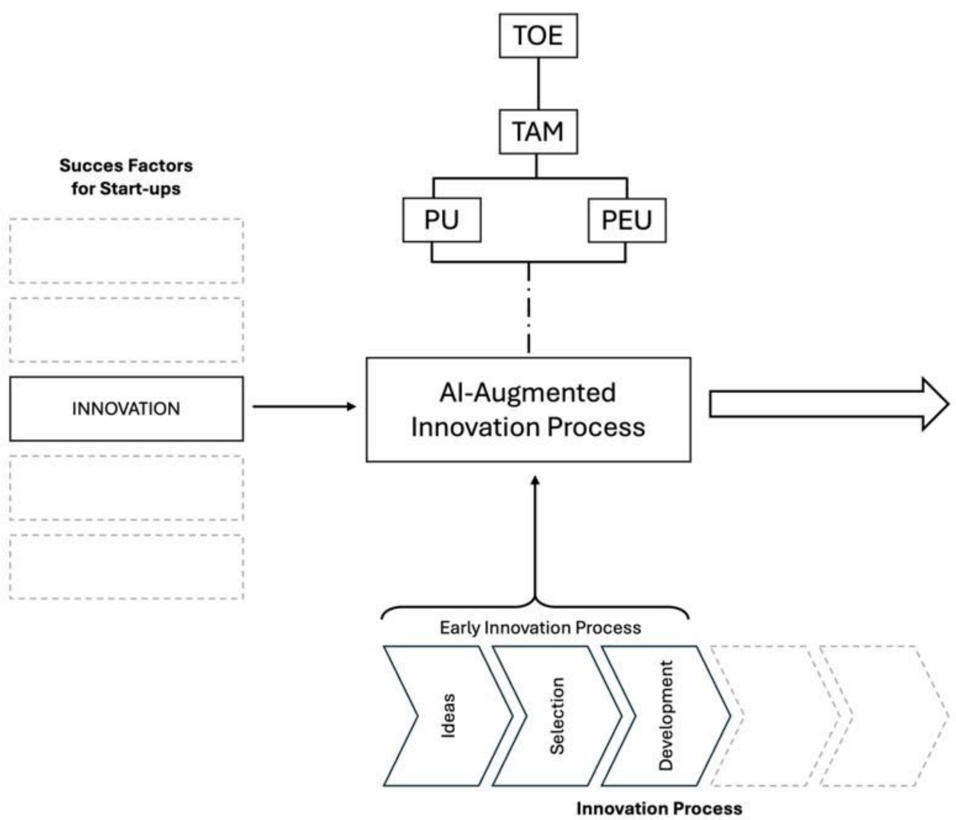

Figure 3: Proposed Framework for implementing an AI-augmented Innovation Process in Start-Ups.

Vol.22, Iss.2, June 2025
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DOI: 10.17879/43998520885

emerging customer needs and market gaps through large-scale analysis of digital data sources. For instance, Kakatkar et al. (2020) found that AI tools identified consumer needs from 1.75 million online posts with 75 percent classification accuracy.

In the **idea selection phase**, AI-based models can improve decision quality by predicting concept performance. The same study showed that a random forest algorithm predicted expert evaluations up to 23 percent more accurately than community-based assessments.

In the **development phase**, AI supports faster prototyping and early testing. As described by Bilgram and Laarmann (2023), low-code AI tools enable even non-technical users to convert concepts into tangible prototypes more efficiently. These examples illustrate how AI enhances innovation speed, reduces resource requirements, and increases decision accuracy across all phases.

3. Conclusion

It is of great consequence for young companies to identify innovation as a factor conducive to success. Innovation contributes to increasing competitiveness, overcoming uncertainties and to the sustainable growth of the company. Once innovation has been identified as a critical success factor, the innovation process itself can be adapted. The literature indicates that innovation processes diverge from the traditional „one-size-fits-all" approach. In reality, the processes are individual due to their different structures. Despite the different sequences within the process, however, idea generation, selection and development were identified as commonalities. These phases usually form the beginning of the entire innovation process. The literature indicates that AI can play a supportive role in these phases, exerting a significant impact on the quality, quantity and speed of the process.

To successfully integrate AI into business activities, the technology faces a number of challenges. These challenges are described by the TOE and TAM frameworks. The TAM refers to the personal benefit and perceived ease of use and puts these in relation to each other in order to predict the behavioral intention to use. These two factors are influenced by external variables which can be identified using the TOE model. The TOE framework shows that a company requieres the ability to integrate AI tools reasonable and that they must be compatible with existing technologies and company activities. Furthermore, the company needs a communicative innovation management with good leadership skills. Also, the size and available resources must be considered for decision-making. Finally, the potential increase in competitiveness or efficiency of business activities through AI must be considered. Government regulations and trends within the market also influence whether and how quickly a new technology is integrated.

Once AI has been successfully integrated into the innovation process, the result is an AI-augmented innovation process. These AI enhancements can support the early phases of the innovation process, resulting in a significant acceleration of innovation.

The aim of this thesis was to investigate the influence of AI on the speed of innovation. This objective was successfully achieved and can be proposed as proposition (P1).

P1: *Considering the framework provided, using an AI-augmented innovation process may lead to a positive impact on the innovation speed of a start-up.*

Additionally, other factors were identified that positively influence the innovation process. These include reducing the costs of the innovation process and the number of human errors. AI is also able to process large amounts of data, which can improve innovation strategies (Yams et al., 2020).

3.1 Outlook and Discussion

The current state of knowledge for AI-augmented innovation processes is extremely limited due to a lack of literature. Often, only industry-specific studies have been carried out which is why it is difficult to make general statements. In this thesis, a newly created framework was used to form a hypothesis that implies a positive influence on the innovation process. **P1** is to be empirically examined with the help of field studies conducted in start-ups.

When interpreting this work, it is essential to consider the rapidly evolving landscape of AI and AI-related research. The dynamic nature of this field makes it challenging to assess the current state of art and the extent of AI development.

Further research should also determine whether the use of AI raises ethical concerns (Hagendorff, 2020). Additionally, the potential decrease in human creativity through the use of AI tools may be considered in this context (Hughes et al., 2021).

Furthermore, an important point to consider, particularly for start-ups, is the cost dimension associated with the adoption of AI technologies. In contrast to established firms, start-ups typically operate under tight financial and personnel constraints. However, the integration of AI often requires significant investment in IT infrastructure, access to high-quality data, and skilled personnel. These requirements

JOURNAL OF
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present substantial challenges that many young firms are unable to meet (Wamba-Taguimdje et al., 2020). As a result, cost barriers can limit the ability of start-ups to fully exploit the potential of AI within their innovation processes.
Viewed through the lens of the Technology–Organization–Environment (TOE) framework, this challenge highlights the close interconnection between technological and organizational factors in the start-up context. Technological readiness, such as access to appropriate tools, must be aligned with organizational capability, including leadership competence and agile workflows, to ensure successful implementation. While large enterprises benefit from structural and financial advantages, start-ups compensate through flexibility and a strong innovation orientation. These strengths can be leveraged through scalable and cost-effective AI solutions. Modular, cloud-based tools and low-code or no-code environments offer accessible entry points, enabling start-ups to implement AI strategically despite limited resources.

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