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Context Analysis for Transformative Change in the Ceramic Industry

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Abstract: Foundation industries are under increasing pressure to transform for sustainable development. Ceramics play a key role within foundation industries as a necessary material for building manufacturing facilities. Therefore, transforming the ceramic industry could support changes across other foundation industries as well, making it one of the most important industries to transform. Given the limited finances, staff time, and other resources to support transformative change, this study aims to identify a set of key intervention points to enable transformative change in the ceramic industry in the United Kingdom. A desk-based study, reviewing written industry, government, and scientific materials available in the public domain, was carried out to identify initial key intervention points for transformative change. The PESTLE approach was used to analyse macro factors in political, environmental, social, technological, legal, and economic domains in order to understand how the context enables or constrains change in the ceramic industry. A SWOT analysis was conducted to further consolidate the findings. Our analysis detected over 50 transformative change drivers and barriers and showed that decarbonisation and energy-saving strategies were the main drivers for transforming the UK ceramic industry. On the other hand, foreign government policy and legislation, trade barriers, skills shortages, and costly alternative energy sources were among the major barriers.

Keywords: foundation industries; circular economy; sustainability; decarbonisation; transition management; ceramic industry; transformative change; resource efficiency; dematerialisation; context analysis



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1. Introduction

Foundation industries are essential for the construction and manufacturing sectors, which in turn are vital for sustaining the quality of living in society. Foundation industries supply chemicals, cement, ceramics, glass, metals, and paper. The development of the foundation industries as we know them now is a result of significant technological advancements, enabling them to manufacture materials at a greater scale and at much lower prices. Over the decades, they have continuously evolved to meet expanding demands. Nearly 75% of the materials used in the United Kingdom's (UK) economy are produced by foundation industries [1].

In the UK, the annual production of 28 Mt (metric tonnes) of products (valued at GBP 52 billion) by the foundation industries comes with a harsh price and has a significant impact on our society and environment, as these industries produce 10% of the country's CO₂ emissions [2]. In recent years, the effect of these emissions on climate change has been clearly noticed. On 19 July 2022, temperatures in the United Kingdom topped 40 °C for the first time on record, as a village in Lincolnshire reached 40.3 °C, surpassing the 2019 mark of 38.7 °C recorded at Cambridge Botanic Garden [3]. The UK Met Office issued its first-ever red weather warning for heat, while the UK Health Security Agency issued its first-ever level 4 heat-health alert. Increasing temperatures have, in general,

already shown an effect on the UK for decades. The last decade (2008–2017) has been, on average, 0.8 °C warmer than the average of 1961–1990 [4]. Additionally, since preindustrial times, the average surface temperature of the UK has increased by 1.2 °C, and further warming is expected under all decarbonisation routes outlined by the Intergovernmental Panel on Climate Change [5]. While the UK government's goal is to restrict warming to 1.5 °C, research suggests that we must be prepared for temperatures as high as 4 °C [6]. To prevent this crisis and achieve the Paris Climate Change Agreement target (80% reduction in CO₂ emissions by 2050) [7], these energy-intensive industries must urgently undergo a transformative change.

The UK's ceramic industry was a driving force behind the Industrial Revolution. In its heyday, Stoke-on-Trent was the centre of pottery manufacturing across the globe and was home to more than 2000 kilns, each of which was responsible for firing millions of products each year [8]. The ceramic industry provides its materials and services to other foundation industries. For instance, refractories (high-temperature-resistant ceramics) are extensively used by glass-melting, cement, and ceramic subindustries, each consuming around 8% of refractory production, while the iron and steel industry uses above 65% of the total production [9]. In general, ceramics offer a variety of products, which are the backbone of foundation industries and society, such as bricks, clay roof tiles, clay drainage pipes, gift- and tableware, floor and wall tiles, sanitaryware, refractories, industrial advanced ceramics, and others [10].

In broad terms, the ceramic products manufactured within the ceramic industry are composed of inorganic compounds, primarily oxides, nitrides, carbides, or borides of metals. These nonmetallic solid materials exhibit a distinct set of shared characteristics, including hardness, brittleness, elevated melting temperatures, compressive strength, and resistance to chemical corrosion, electrical conductivity, and thermal effects [11]. They are typically processed at high temperatures, and their production usually involves high-temperature processing techniques, such as sintering, firing, or annealing, which result in achieving the desired properties. The majority of ceramics exhibit a crystalline atomic structure, although a subset may possess a partly amorphous or glassy structure, which led to certain noncrystalline, glassy products being categorised under different classifications/industries, like glass [12,13].

Despite its essential role within the economy, the UK ceramic industry is facing numerous challenges and issues that drive a demand for transformative change. Faced with global competition and growing pressures, the UK ceramic industry has been consolidating, with 54% of operational heavy clay sites closing down in the period of 2000–2021. The heavy clay subindustry manufactures heavy clay construction products (clay bricks, roof tiles, and drainage pipes) and is associated with the bulk of the sector's emissions. A reduction in these emissions is inevitable as climate change calls for the decarbonisation of production. Resource productivity—the value generated from each unit of material that is used—has a high potential to reduce carbon emissions yet is often overlooked [14]. It has been analysed that 50–70% of carbon emissions are directly linked to the production and consumption of materials, with percentages varying depending on where system boundaries are drawn [15]. Evidence suggests that simply recycling materials is unlikely to suffice for a more sustainable pathway forward because the energy required for technical recycling processes and the water required for regenerating materials through primary biomass production would push demand well outside the planet's carrying capacity [16–18]. Hence, calls are growing to go beyond recycling and to dematerialise society in what has been coined a “transformative” circular economy to reduce the overall scale of resource use at a whole-system level [19–21]. In the UK, for example, the average resource use per person would need to be roughly halved [20]. Such transformative changes in resource use will require changes to the political–economic system that are amenable to more sustainable circular business models for companies focused on improving environmental quality and social well-being alongside maintaining economic prosperity [22]. Sustainable circular business models are generally organised into four types, including models to enable

resource flows to narrow (such as product sharing and leasing), slow (such as product reuse, repurpose, and remanufacture), close (such as recycling and industrial symbiosis), and reintegrate (such as landfill with resource recovery) [23,24]. A more sustainable industry is also a prerequisite to attracting new talent to keep manufacturing facilities operational [11].

The UKRI-funded programme “TransFIRE”—Transforming Foundation Industries Research and Innovation Hub, running from 2021 to 2024—takes a unique holistic system approach towards transformative change in UK foundation industries with the strategic objectives of minimising resource use in production processes, reducing carbon emissions, and supporting equal opportunities—thereby addressing the urgent sustainability challenges introduced above [25]. This study aims to answer the following question: How can foundation industries in the UK be transformed? Each foundation industry is being investigated separately, followed by a cross-cutting analysis. This article focuses on the ceramic industry. As a first step, a context analysis was carried out to identify a set of critical intervention points that could be impacted by stakeholders in ceramic and other foundation industries so that a chain of systemwide improvements could be commenced with the available limited capacity to initiate change processes. The context analysis was a desk-based investigation based on publicly accessible industry, government, and scientific documents [10,11,26–28].

This analysis work is the first reported context analysis for the UK ceramic industry, which seeks to determine the essential drivers for, and barriers to, its transformative change. For this purpose, a PESTLE study was conducted to understand the macro (external) forces surrounding organisations in the UK ceramic industry [29], including Political, Economic, Social, Technological, Legal, and Environmental aspects. Each aspect was reviewed to explain its influence on the capacity of this foundation industry’s firms to transform [29]. Building on that, a SWOT analysis was carried out to determine the most significant internal strengths and weaknesses and external opportunities and threats for the ceramic industry. The ultimate aim of this analysis was to identify critical intervention points through which a desired transformational change could be achieved, as well as any factor that might impede the desired change so that such obstacles could be removed.

2. Materials and Methods

The PESTLE approach was applied to analyse the macro context of the ceramic industry in the UK. PESTLE is a framework commonly used in the development of business strategies to analyse how political, economic, social, technological, legal, and environmental factors affect one or a group of organisations [29]. Factors were identified based on each category. Political aspects explore the influence of government and government policies. Economic factors investigate the economy’s structure and performance, including industrial diversity, supply chain relations, and market developments. Interest rates, employment or unemployment rates, the cost of raw materials, and foreign currency rates are also included. Social factors are focused on aspects such as collaborative culture, innovation capacity, citizen perceptions, changing demand, demographics, cultural developments, attitudes, education levels, and lifestyles. Technological aspects consider the pace of technological solutions and innovations available, which may influence the development of, in this case, the ceramic industry. Legal factors focus on the regulatory environment to understand what is lawful and permitted. Environmental aspects pertain to the ability of an organisation to function in a certain location (e.g., access to materials, water) and its impact on the surrounding environment (e.g., carbon emissions, nature conservation).

When constructing the PESTLE analysis, there were four phases involved. The first phase comprised a desk-based study that involved researching and gathering information on which the most updated and widely recognised published visions and roadmaps were reviewed. These were “Paving the way to 2050—The Ceramic Industry Roadmap” [26] and its updated version “Ceramic Roadmap to 2050: Continuing our Path towards Climate Neutrality” [11], “Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050—Ceramic Sector” [27] and its action plan [28], and further written submissions from the

British Ceramic Confederation [10]. The second phase involved drawing out key themes and finding similarities and differences between the documents. The third phase consisted of refining the ideas and repeating the proofs until a tolerable number of points was obtained in each of the six categories of PESTLE. This phase was completed after these selected factors were found to be satisfactory, reasonable, and relatable to each category they were listed in. Finally, the last phase involved comparing the transformative change sought by TransFIRE (Figure 1) to the most widely recognised and publicised sectoral change visions and roadmaps (shown in Section 4). The roadmaps investigated in our analysis were “Paving the way to 2050-The Ceramic Industry Roadmap” [26], “Ceramic Roadmap to 2050: Continuing our Path towards Climate Neutrality” [11], and “Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050—Ceramic Sector” [27], along with some other published reports [10,30]. The outputs included an overview of industry changes suggested in published visions and roadmaps as well as a comparative analysis of the additional industry changes that TransFIRE aims to implement.

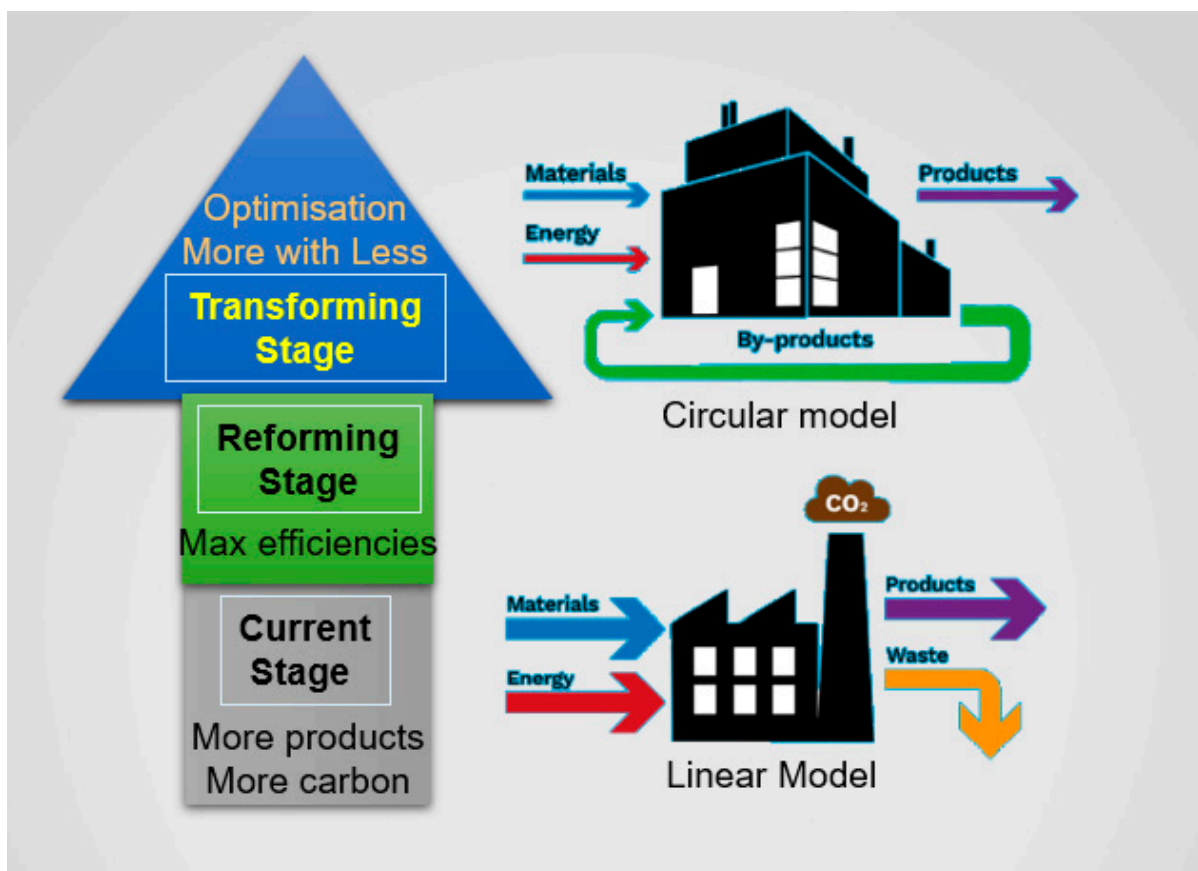


Figure 1. Transformative change from linear model to circular model envisaged by TransFIRE's vision.

Building on the PESTLE analysis, a SWOT analysis was applied. This analysis is a common framework that identifies core Strengths, Weaknesses, Opportunities, and Threats, pulling information from internal sources of the industry (strengths and weaknesses) as well as external forces that may impact the industry's decisions and performance (opportunities and threats) [31].

3. Results

3.1. Roadmaps and Visions

The ceramic industry is of strategic relevance, requiring a high-level plan that sets a broad primary aim and enumerates the essential steps or milestones necessary to accomplish a set of objectives leading to this aim. In the UK and Europe, several sectoral visions

and roadmaps for the ceramic industry have been developed over the last decades, and the most updated and widely recognised published visions and roadmaps are “Paving the way to 2050—The Ceramic Industry Roadmap” [26], its updated version “Ceramic Roadmap to 2050: Continuing our Path towards Climate Neutrality” [11], and “Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050—Ceramic Sector” [27]. Although the first one was issued by the Cerame-Unie European Ceramic Industry Association in 2012, it is still adopted by the British Ceramic Confederation (BCC) as they were one of the contributors [11,26,27]. The last one is a report prepared for the Department of Energy and Climate Change (DECC) and the Department for Business, Innovation, and Skills (BIS) in March 2015. It was the outcome of close collaboration between industry, academics, and government (DECC and BIS), organised and delivered by the report’s authors, Parsons Brinckerhoff and DNV GL.

Several European Commission roadmaps identified 2050 as the target year for their long-term strategies. The Cerame-Unie vision and key EU policy area represented in “Paving the way to 2050—The Ceramic Industry Roadmap” [26] and “Ceramic Roadmap to 2050: Continuing our Path towards Climate Neutrality” [11] was to establish a long-term plan for a competitive low-carbon economy, resource efficiency, energy, and transport. The main focus of the ceramic companies across Europe and the UK was to implement energy-saving best practices, enhance resource efficiency, and transition away from conventional energy sources. It was imperative to consider the life cycle of their ceramic products, including their durability and impact over the use phase. This would show the effect on resources, water and energy savings, and overall reduction in carbon dioxide (CO₂) emissions. This holistic-life-cycle approach should consider environmental indicators, such as biodiversity, ecological and human toxicity, and water use. Building on the current know-how, expertise, and breakthrough technologies would be required to guarantee a smooth transition to a competitive, low-carbon, and resource-efficient economy by 2050. In this regard, some emerging aspects were discussed in the recently updated roadmap entitled “Ceramic Roadmap to 2050: Continuing our Path towards Climate Neutrality” [11]. There was more focus on the circular economy; dematerialisation (to a lesser extent); ceramic products’ durability, reuse, and closed and open-loop recycling; and the analysis of the ceramic product in terms of its reusability and environmental impact. The roadmap recommended some policies to move away from a linear and towards a circular model, in which resources and materials are reused, recycled, or recovered.

The “Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050—Ceramic Sector” is—as its title implies—more focused on establishing ceramics sectoral pathways to decarbonisation by 2050 [27]. It examined ways to decarbonise and improve the industry’s energy efficiency while maintaining its competitiveness. The UK government declared its commitment to transitioning to a low-carbon economy that includes most energy-intensive industries. These were the objectives of the roadmap, which included (1) improving awareness of the emissions abatement potential of individual industrial sectors, the relative costs of alternative abatement options, and the related business environment; and (2) developing a common evidence base to guide future policy, as well as establishing strategic conclusions and following viable measures to assist in delivering cost-effective decarbonisation in the medium to long term (over the period of 2020–2050). It was mentioned that carbon dioxide emissions from the ceramic industry in the UK were the lowest (1.2 Mt in 2012) among the eight energy-intensive industries (the iron and steel industry emitted 22.8 Mt, chemicals 18.4 Mt, oil refining 16.3 Mt, food and drink 9.5 Mt, pulp and paper 3.3 Mt, cement 7.5 Mt, and glass 2.2 Mt) [27]. It is worth mentioning that the production of each industry in 2012 was 7.180 Mt iron [32], 9.58 Mt crude steel [33], 1.8 Mt plastics [34], 67.07 Mt processed crude oil [35], roughly 1394.5 Mt food [36], slightly lower than 4.25 Mt paper and board [37] (over 4.5 Mt various paper products in total [38]), 7.95 Mt cement [39], above 3 Mt glass products [40], and over 4 Mt various ceramic products [27]. Nevertheless, further work needs to be carried out to reduce emissions by 60% by 2050 for an important industry that contributed a direct value of GBP 1 billion to the UK economy in 2012. Moreover, with the

supply of refractories for high-temperature processes, the ceramic industry holds a central position to support the decarbonisation of other foundation industries.

3.2. PESTLE Analysis

3.2.1. Political

The analysis showed that the EU and UK governments have implemented a set of austerity measures. Industry called for policy support and the development of a policy framework to include increased employment, a resilient supply chain, and expanded capabilities to satisfy current and upcoming market demands [11,26,27]. In addition, the ceramic industry would like policymakers to provide a supportive regulatory framework, which includes a collection of rules and regulations (e.g., health and safety regulations, quality standards, trade legislation, etc.) aimed at promoting the development and growth of the UK's ceramic industry, including measures to keep ceramic manufacturing globally competitive and to consider the increasing threat from imports that would lead to carbon and job leakage to countries outside the UK and EU.

Similar to industry, government actors in the UK have been strongly focused on decarbonisation, but resource efficiency has long remained in the background. Given that more than half of carbon emissions are directly driven by resource use, a greater focus on resource efficiency would be in line with the net-zero agenda [15,41]. Appropriate indicators are required for assessing resource efficiency. Indicators of resource efficiency should incentivise the optimal use of available resources. The European Resource Efficiency Platform (EREP) recommendation proposed a lead indicator to measure resource productivity based on raw materials consumption [42]. Focusing on only resource consumption has some major drawbacks, as the net weight of the material is unrelated to resource efficiency. The raw material consumption indicator only evaluates the density of the materials rather than their functionality or performance. In addition, it lacks a life-cycle value-chain perspective and disregards the direct and indirect environmental impacts of products on downstream producers and consumers [42]. True resource efficiency requires a holistic-life-cycle assessment approach [43]. It takes into consideration all stages of the product, including its durability, its lifespan, and the decrease in resource usage that occurs throughout its use phase [11]. The benefit of taking a whole-system approach to resource efficiency measures is that it can help create a global level playing field and hence improve the competitiveness of UK ceramic companies. Since the ceramic industry is intertwined with the performance and energy efficiency of many other industries, it called on policymakers to adopt a life-cycle view of emissions and consider more than just the carbon released during the manufacturing phase [11].

As resources grow scarcer, consumers will likely require guidance to make more environmentally responsible choices. Industry argues that regulators should assist individuals in avoiding "throwaway" products and choosing materials with a sound life-cycle profile. To support sustainable consumption, green public procurement is a well-known measure to increase demand for more energy- and resource-efficient items (further discussed in Section 3.2.2 on economic factors) [44]. However, given that ceramic companies primarily supply their products to other industries, whether such information and public procurement measures would indeed contribute significantly to the sustainability of production processes remains to be seen. Measures that can influence business-to-business transactions will likely have a greater impact. For example, the government could set higher recycling targets and/or targets for using recyclates for ceramic products used in the UK market, combined with higher tax rates on (products containing higher volumes of) primary resources to make recycled resources relatively cheaper [45]. Additionally, products of higher quality can exhibit longer lifespans and save the original raw resources [11].

In terms of energy policies, while some policymakers have recommended switching the industry from gas to electric kilns once energy sources are decarbonised, this is not an economically viable option right now. There are concerns about the limited economic feasibility of innovative technologies, which diminishes the business case for research,

development, and innovation investments from the industry perspective, thereby putting a greater ask on public-funded research. A supportive research and innovation policy framework is strongly required to develop the necessary breakthrough technologies (covered in Section 3.2.4, highlighting the technological factors) that could cause the appropriate change in a timely manner to attain net-zero 2050 targets [11,26,27]. However, at a system level, changes in the energy market will still be required to make electrification a more economically viable option and to utilise other alternative fuel sources such as hydrogen.

The UK and EU must maintain a clear strategy towards an international legally binding climate agreement (rather than the essentially voluntary agreements currently in place) that imposes a comparable burden on industry in major trading partners that compete with the UK and EU ceramic industry, such as BRICS, Egypt, Mexico, Southeast Asian countries, and the United Arab Emirates [26]. The UK ceramic industry faces investment issues in the absence of maintaining a level-playing-field environment among competitors around the globe. In addition, it is paramount to gain investors' confidence by establishing long-term policy on industrial strategy, energy, and climate.

3.2.2. Economic

Ceramics play a pivotal role in the world's economy. Their global market was valued at roughly USD 229.13 billion in 2018, with predictions indicating an 8.6% compound annual growth rate (CAGR) from 2019 to 2025 [30,46]. The ongoing rise in the construction industry, technical breakthroughs in nanotechnology, 3D printing, and ceramics in the health sector (e.g., oral healthcare via the creation of dental crowns, implants, and bridges) all contribute to the increasing demand for ceramic products [30].

The UK ceramic industry employs over 20,000 people, and its annual sales reached around GBP 2 billion in 2020 [10]. According to the BCC, approximately 100 ceramic manufacturer companies operated 150 sites in the UK in 2012, accounting for 90 percent of the industry's turnover [27]. Nowadays, the BCC has over 90 member companies that operate at 160 sites around the UK; their membership covers over 90% of the ceramic companies active in the UK [10]. The majority (around 75%) of companies in the UK are SMEs, each of which operates at just a single production site, alongside larger UK-based and multinational corporations with several manufacturing sites. Small and medium enterprises (SMEs) are considered the majority of these ceramic companies to the extent that over 200,000 people in the EU-27 were employed by SMEs (in the EU and UK), which was around 80% of the total working labour in the European ceramic industry [26]. SMEs have either a turnover of <GBP 45 million or their balance sheet total is <GBP 38 million, and they have fewer than 250 employees [11,26].

There was a significant decline in the total revenues of this industry (comprising heavy clay, whitewares, refractories, and technical ceramics) due to the recession in demand from GBP 1953 million in 2000 to GBP 953 million in 2010, and the industry started its slow recovery beginning in 2013 (over GBP 1000 million as the total revenue) [27]. The impact of the COVID-19 situation on the total revenue was also noticeable. About 60% of BCC member factories temporarily shut down in March 2020, and some parts of the industry suffered very low demand during lockdowns (tableware and giftware suppliers) [10]. Nonetheless, other parts of the ceramic industry, particularly the manufacturing of refractories, clay, porcelain, and ceramic stone and glass, grew by 12.9% in January 2021 compared with February 2020 [47].

It is vital to ensure that future decarbonisation and energy-efficiency efforts preserve the UK industry's overall cost-competitiveness relative to enterprises operating in other parts of Europe, Asia, and the US [26,27]. This strategic conclusion connects to external issues influencing the industry's business environment. These include energy security and energy and carbon cost comparisons (both actual and perceived), which are crucial investment criteria. By 2050, demonstrations should show a sustainable, uninterrupted, and economical supply of alternative fuels, such as biogas and syngas, and proven (break-

through) technologies (see Section 3.2.4). This is critical since efficient kilns must operate continuously and cannot be abruptly shut down due to power supply issues [26].

Investors need stable and globally competitive energy and carbon pricing and a signal from the government about the direction in which it seeks to take the energy market [27]. The reduction in energy consumption is essential in order to maintain competitiveness and profitability. At the same time, additional costs are incurred to improve efficiencies and meet the energy reduction targets according to regulations. In addition, higher energy prices and the unavailability of capital (scarcity of funding) remain significant obstacles that contribute to the issue of the attractiveness of investments in the UK. Small-scale investments are often funded internally and at the site level, with the expectation of rapid returns. In the case of large multinationals, the limited availability of capital for improvement projects due to the high level of competition for internal funds and other initiatives more directly tied to the core business are significant barriers. Even with the availability of internal financing, the potential returns are not encouraging decision-making processes to invest in UK sites and operations. Higher UK costs and the perceived uncertainty of business conditions make longer-term UK manufacturing investments harder or impossible to justify. These factors strongly influence potential returns on which international management boards rely to allocate capital. Regrettably, other markets (particularly Asia) could provide higher potential returns, and the UK's position to present a solid business case and reach the point of financing is concerning. SMEs often have difficulties in securing funding for medium- and large-scale projects and in resorting to other outside capital sources. As a result, a serious issue is facing the ceramic works in the UK, which is represented in the negative balance of trade in ceramics with roughly GBP 1 billion more imports than exports (in 2019) [10].

3.2.3. Social

Social factors are focused on socio-cultural aspects. The ceramic industry could better comprehend customer demands and desires in a social context. Changes in family demographics, cultural trends, attitudes, education levels, and lifestyles are all included in these social factors. Social/socio-cultural factors represented in the public narrative, community perceptions, and others are not significantly considered in the available visions and roadmaps. However, some aspects related to social features and personal development could be found [11,26,27].

Throughout history, ceramics have left a remarkable legacy, offering civilisations and cultures many variations to choose from. They shaped the cultures and were valuable tools that built many civilisations [26]. Ceramic artefacts enabled early societies to create watertight containers. This implies they might have prepared items such as vegetables and meats. Larger populations survived as food production technologies improved; for example, through pottery, which is an art form that evolved from the demands of everyday living. Historians and archaeologists value ceramics, which, if discovered at archaeological sites, assist in conveying the story of past societies. These items have the potential to endure for tens of thousands of years. They assist in answering questions about civilisations about which we know very little. This emphasises the significance of the ceramic industry and the materials it produces in the construction of civilisations and the fulfilment of human needs.

Recognising the significance of strategy and personal leadership skills in the context of decarbonisation and energy efficiency, as well as increasing the industry's immediate and long-term competitiveness, is vital for the ceramic industry, the government, and other stakeholders. The Ceramics Decarbonisation Leadership Group created a Ceramic Skills Group that coordinated decarbonisation and energy-efficiency skill efforts with key stakeholders (businesses, academia, education/skills agencies, and government) and collaborated with related industry groups (where appropriate) [28]. Also, the Ceramic Skills Group should conduct a skills audit to identify the ceramic industry's decarbonisation and energy-efficiency learning requirements and determine how they could be met. The training opportunities for persons working in the ceramic industry should be improved

by collaborating with colleges, universities, and training organisations to provide more continuing professional development (CPD) courses, short courses, and part-time degrees for continuous training and development. Eventually, the group developed a strategy for recruiting and retaining STEM (science, technology, engineering, and mathematics) individuals in the ceramic and other foundation industries. The strategy helps to conduct a gap analysis, first within the ceramic industry but potentially including other industries, to better understand current activities and identify areas where more development is required.

The ceramic industry requires the skills and efforts of scientists, engineers, technicians, and production managers. It also requires various skills, such as research, design, customer service, sales, marketing, IT, and support services such as human resources and finance, all of which are critical in this industry [48]. In addition, applying new advanced technologies needs more labour power, and breakthrough technologies may appeal to the younger generation. As a result, there could be an opportunity to recruit more young people to work in the ceramic field.

There can be some associated social and health concerns related to the ceramic industry, particularly if health regulations are not followed and labourers' health, safety, and well-being are compromised. Health risks of brickmaking are mostly caused by inhaling smoke and doing physically hard labour outdoors for extended periods of time, in tandem with harsh weather conditions that can cause heatstroke and other diseases such as respiratory infections and pneumonia [49]. Other health hazards are connected with the protracted posture used by kiln workers, which often results in severe musculoskeletal difficulties [50]. In some cases, the industry could lead to high death rates, such as in Dhaka, Bangladesh, where brick manufacturing has caused about 2200 to 4000 premature deaths and 0.2 to 0.5 million annual asthma attacks [51]. Social issues are strongly present in some environments where labourers from the most vulnerable communities regularly work in abhorrent and exploitative conditions, which are regarded by some as modern-day slavery, with frequent documentation of child labour [30]. All of the aforementioned points are strong arguments for limiting imports and advocating for better controlled health and safety conditions at ceramic production sites.

3.2.4. Technological

The ceramic industry is deemed energy-intensive since the energy used in its manufacturing accounts for around 30% of the entire production cost. In Europe, the ceramic industry relies heavily on natural gas, with an energy mix that includes 85–92% gas and 8–15% electricity [26,52]. In the UK, the ceramic industry requires around 4.7 TWh energy per year, with gas accounting for 80–82% of the energy mix [28,30].

It is of critical importance to decarbonise the ceramic industry in the UK due to its considerable level of GHG emissions. For instance, brick manufacturing in the UK emits an average of 234 kg CO₂/tonne, with a typical energy use of 706 kWh/tonne [53]. Globally, on average, the manufacture of one brick uses 2.0 kWh of energy and emits 0.4 kg of carbon dioxide [54,55]. The kiln type is a significant factor that can reduce emissions and save energy. Owing to their heat-recovery qualities, continuous kilns are more energy-efficient than their intermittent counterparts [56]. Other necessary measures to take to improve efficiency during the brickmaking process include improving fuel feeding best practices, providing periodic maintenance of kiln walls, reducing leakages, providing proper fuel preparation, improving supervision of the firing operation, ensuring adequate drying of the bricks, and reducing the mass of each unit by increasing its perforations [57].

Energy consumption reductions could be accomplished by installing improved kilns, dryers, thermostats, and seals, as well as automated control and thermal insulation [27]. Smart manufacturing facility design can recover excess heat from the kiln to the dryer in an intelligent layout. Initiatives to recover waste heat led to the installation of 250 combined heat and power generation plants in Europe until 2012 [26].

For the ceramic industry overall, most of the available technologies are focused on decarbonisation and supporting the UK net-zero 2050 targets for GHG emissions [11,26,27]. Several current technologies are used for reducing carbon emissions:

- On-site combined heat and power generation;
- Process optimisation;
- New kiln design including electrified models;
- Energy management;
- Raw materials formulation changes for more efficient firing energy;
- Clay/raw material preconditioning;
- Heat exchanger in kiln stack.

Alongside the available technologies, research and innovation continue for breakthrough technologies such as low-temperature heat recovery from kiln exhaust, on-site syngas and biogas, and carbon capture and storage (CCS).

Decarbonisation technologies have significantly contributed to reducing the carbon footprint in the UK [2]. The emissions reduction model (1990–2050) was developed based on actual emissions data from the bricks, roof tiles, wall and floor tiles, and refractories industries (comprising 90% of the ceramic industry). It was found that a 65% reduction in CO₂ emissions may be possible when the aforesaid available and breakthrough technologies are implemented [27].

Decarbonisation of electricity in the UK and EU has been taking place for the last decades (since the 1990s), while emissions from ceramic production arise from using fuel (mainly natural gas). If half of all kilns were converted to electric kilns during the period of 2030–2050 and the remainder to syngas or biogas cofired with natural gas, emissions could only be reduced by 78% compared with 1990 levels [26]. Nevertheless, an enormous barrier prevents the complete implementation of this option. Firstly, the capital cost of this option would be approximately EUR 90 billion plus significant further costs (e.g., the development of breakthrough technologies in electric kiln efficiency and running costs) [26]. Furthermore, the energy bill for the manufacturing industry (including typical tile factories) in Great Britain has climbed dramatically from autumn 1990 to autumn 2022, from 0.0350 to 0.2101 GBP per kWh for electricity, and the prices of natural gas (90% decile) have skyrocketed from 0.0155 to 0.1765 GBP per kWh over the same period [58].

Cerame-Unie is engaged in the future Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) public–private partnership (PPP) and is committed to processing industry innovation. SPIRE helps the process industries transition to become more resource- and energy-efficient in line with their roadmaps [26]. The SPIRE roadmap called for a 20% decrease in nonrenewable, primary raw material intensity and a 30% reduction in fossil fuel intensity by 2030 compared to levels in 2012.

Other technological strategies were investigated, which were not carbon-emission-reduction focused. For instance, light-activated antibacterial surface coatings on antibacterial tiles can fight hospital microorganisms and viruses such as MRSA and other disease-causing pathogens. Vitrified clay pipes transport wastewater safely and efficiently from buildings and roadways to treatment facilities. Vitrified clay remains inert even when exposed to severe temperatures or chemical assault. Up to 27% of the raw material utilised in vitrified clay pipe manufacturing is recycled clay [26]. Also, “intelligent ceramics” such as sensors embedded in ceramic floors can detect human presence and activate traffic signals. At the same time, wall tiling combined with heating systems prevents snow and ice accumulation at transportation hubs.

In general, the ceramic industry needs to investigate and deploy innovative technologies to reduce energy usage and carbon emissions. Substantial changes to kilns will be necessary, requiring significant capital investment with a slow return on investment given that the lifespan of a kiln is greater than 40 years, making replacement generally financially unfeasible. Moreover, the expenses and risks associated with developing new techniques make funding difficult. For example, although CCS could be an effective breakthrough technology for CO₂ emission reduction, the diluted CO₂ concentration and mixing of many

gases in the kiln exhaust make its usage costly. The cost of commercial-scale demonstration projects required before adopting new technologies is sometimes too high for one business to bear. Collaboration and cofunding are viable options; nevertheless, corporations may face restrictions when partnering with direct competitors. There may be some opportunities for the ceramic industry to solve common challenges with other industries that also rely on high-temperature processes, such as the cement, glass, iron, and steel industries.

3.2.5. Legal

Political and legal elements overlap, but the main distinction is that political factors are governed by government policy, while legal aspects include laws and regulations, which were occasionally stated in the available ceramic industry roadmaps [11,26]. Without a shift in policy to measure emissions over their entire life cycle rather than just during production, there is a risk that consumers are either driven to ceramic materials manufactured in less environmentally stringent countries or to less durable products with higher annualised emissions [26]. This strategy is destructive to the UK and EU economies, which face unfair global competition, and to global emissions—given that adopting low-carbon technologies is likely to increase product prices while companies are not compared on equal footings in a global context—resulting in the increased offshoring of ceramic manufacturing and growing imports, thereby driving carbon leakage as observable in the ceramic industry. With carbon emissions tightly linked to energy demand, research has shown that industrial energy demand used for meeting UK materials consumption has been relatively stable for the past 40 years (Norman et al., 2021) [59]. Some in the ceramic industry argue for eliminating World Trade Organisation “infringements” with regard to procurement and “red tape” [11], expressing a belief that no government will be competent enough to deal with the challenges and thus the better alternative would be to allow for unregulated global markets to self-govern [60]. However, the deregulating of markets from social and environmental regulations within neoliberal political economies can also be seen as being at the heart of the multiple environmental and economic crises facing humanity to date [61]. Ambitious regulations are necessary for sustainable production, but companies need to be protected from unfair trade practices (such as imports of products with high environmental and social costs, counterfeiting, intellectual property rights violations, and dumping) with measures that enable sustainable resource use. For example, standardised approaches to whole-system life-cycle carbon assessments could be used to create a global level playing field.

A significant portion of the ceramic industry is a participant in the EU Emissions Trading Scheme (EU ETS) and is bound to the Industrial Emissions Directive (IED) and Environmental Permitting Regulations (EPR) [28]. Apart from this, the primary climate-related laws and regulations affecting the ceramic industry directly are as follows:

- Climate Change Levy (CCL);
- Climate change agreements (CCA);
- Energy Savings Opportunity Scheme (ESOS).

For enterprises with broader corporate undertakings:

- Carbon Reduction Commitment Energy Efficiency Scheme (CRC);
- Mandatory greenhouse gas (GHG) reporting.

Additionally, ceramic companies are influenced by electricity-related policies such as the following:

- Indirect EU ETS costs;
- Carbon price floor (CPF)/carbon price support (CPS);
- Levy Control Framework (LCF);
- Renewables Obligation (RO);
- Feed-in tariffs (FiTs);
- EMR (electricity market reform) FiTs with contracts for difference (CfD);
- EMR capacity market (CM).

Last but not least, other areas of regulations affect the ceramic industry and its sectors, such as health and safety, resources and waste management, and planning regulations. The implementation of existing, and introduction of new, regulations can help to enhance environment and climate neutrality. Changes to the building regulations may improve the energy efficiency of buildings and/or decrease carbon emissions, all while driving demand for clay construction goods [28]. Compliance with regulations could help to ensure reaching net-zero 2050 GHG emission targets.

3.2.6. Environmental

With the increasing significance of sustainability, this factor is becoming increasingly fundamental to how the ceramic industry must operate. Climate change, carbon footprint, recycling techniques, and waste disposal are essential factors that control the policies, legislations, technological-related strategies, and more to a great extent.

Climate change is an important topic that holds the attention of world leaders, policymakers, foundation industries officials, and others. Most of the foundation industries visions and roadmaps were established to combat this issue, having some strategies in place [10,11,26,27]. The analysis of different technological pathways was carried out to show that the maximum technology pathway could enable an emissions reduction of 60% by the year 2050 relative to the 2012 base year. This pathway simulated the deployment of a vast range of technical options (stated in Section 3.2.4). Conversely, the business-as-usual pathway (no large changes) could result in a 27% decrease in emissions compared to the reference year (2012), thanks to incremental improvements to existing technology and the widespread use of the best available technology. Potential actions to reduce carbon emissions are dominated by energy measures, while opportunities to reduce carbon emissions through greater resource efficiency and demand reduction tend to be underrepresented in industry and government roadmaps/visions.

The ceramic industry consumes raw materials from other parts of the economy and distributes its products to them. There needs to be a standardised method to calculate the total carbon footprint of a product across its entire life cycle. A ceramic construction product or refractory material for a glass furnace, for example, may provide considerable energy savings during its lifetime of usage [26]. Broader methods to monitor and allocate these products may allow investments to be made while considering life-cycle benefits (as discussed in Section 3.2.1).

Over the last two decades, measures have been taken for more efficient kiln designs, kiln firing, and natural gas substitution for solid fuels. In addition, upgrading from intermittent (batch) to continuous technology (tunnel or rapid-fire roller kiln) helped decrease carbon emissions. A reduction in energy costs occurred; for example, there was a 39% decrease in energy used for the production of 1 m² brick over the period 1990–2007 and a 47% decrease for the production of one tonne of wall and floor tiles over the period 1980–2003 [11,26]. This reduction in energy usage was accompanied by a significant reduction in emissions. For instance, one UK hotel tableware manufacturer achieved a 79% emission reduction by shifting from a twice-fired process to a single-firing process [2].

Strategic plans by the ceramic industry target a further shift towards alternative fuels and renewable energy in their energy mix. The most promising strategy was to switch from natural gas to biogas, or syngas from biomass or waste, and retrofit the existing kilns. Despite efforts to employ these renewable or waste-recovery-based technologies, the major shortcoming was the biogas price (two to three times that of natural gas), given that a clay kiln consumes 80% of natural gas inlet to the industry. Substitution with syngas (technically possible up to 80%) in some plants could result in CO₂ emissions reduction by 30% [26]. At the EU level, SPIRE supports the development of alternative fuels as a substitution for natural gas but has yet to attain full industrial reliability via securing affordable and sustainably produced biomass or long-term-waste supplies [26]. For both biomass and long-term-waste generation, strong sustainability concerns have been raised,

and whole-system assessments are necessary to assure the sustainability of such approaches to fuel switching.

Different techniques to reduce carbon emissions are shown in the current roadmaps [2–4]. Renewable energy sources can take part in carbon emission reduction efforts. For instance, solar panels were installed in some ceramic factories in Spain, and research works on solar ovens for drying ceramics (200–300 °C) were conducted in Almeria Solar Platform, Andalusia, Spain. Other techniques can be related to spatial factors. For example, relocating industries and employees to decrease overall industry emissions is environmentally beneficial since it reduces long-distance transportation, and as a result, the total CO₂ emission is reduced.

Carbon emissions from the ceramic industry vary depending on the type of product manufactured, the manufacturing stage, and the fuel used. In 2010, CO₂ emissions from the brick and roof tile, refractory, and wall and floor tile industries accounted for 90% of total ceramic industry emissions (19 Mt, 66% from fuel consumption, 18% from electricity, and 16% from process emissions). On a global scale, CO₂ emissions emerging from the ceramic industry surpass 400 Mt a year, and brick manufacturing accounts for 20% of the world's black carbon emissions and 2.7% of annual worldwide CO₂ emissions [30]. The carbon footprint of an earthenware ceramic piece (e.g., fired clay bricks) weighing 0.417 kg was estimated to be 1.22 kg CO₂e (equivalent) [62]. Throughout the production process, drying, firing, and cooling account for the majority of energy use. Approximately 75% of the entire energy cost and more than 50% of the necessary energy are incurred during the firing phase [63,64]. Therefore, above 80% of GHG emissions occur in the firing and drying stages [65]. The yearly energy end-use for firing ceramics using natural gas is estimated at 182 TWh, with the firing process emitting around 265 kg CO₂/t of fired tile [66]. Retrofitting existing facilities by switching to alternative fuels can reduce emissions from fuel consumption. Moreover, the ceramic industry's electro-intensity is predicted to grow by 2050 as specific processes transition from gas to electric firing (e.g., electric arc furnaces and electric induction furnaces operating above 2000 °C). Nevertheless, some process emissions cannot be eliminated, due to the breakdown of carbonates in raw materials such as limestone, dolomite, or magnesite [27].

During the use phase, ceramics can contribute significantly to residential energy savings and reduce carbon emissions accordingly. For example, ventilated facades may boost a building's energy efficiency by 40% [26]. As a result, 100 million tonnes of CO₂ could be eliminated by 2050 using suitable ceramic products such as thermal insulating clay blocks or ventilated cavity walls with clay facades in residential homes. Also, applying refractories in the steel industry saved 3.15 million tonnes of CO₂ in the annual production of cars in Europe [26].

Emissions are not limited to CO₂ only. This can be extended further to entail contaminants such as nitrogen dioxide, nitrogen oxide, total organic compounds (including ethane, methane, and volatile organic compounds [VOCs]), fluorides, particulate matter (PM), carbon monoxide (CO), sulphur dioxide, tropospheric ozone (O₃), heavy metals, and hazardous air pollutants (HAPs) [67,68]. These toxins have been linked to a slew of serious health issues in people and animals, as well as harm to agriculture, land cover, vegetation, and biodiversity [69,70].

Manufacturing ceramics has other environmental impacts. For instance, brick manufacturing uses earth clay and thus affects organic soils used for agricultural purposes, and the sector demands large volumes of water [71–73]. In the UK context, a huge sum of raw materials is imported, particularly for the technical ceramics and refractories sectors, which seek a wide variety of nonindigenous minerals of appropriate quality [10]. It is essential to find the adequate best practice recycling technique to limit the use of some imported raw materials used for manufacturing purposes and instead encourage their substitution with industrial waste products, such as fly ash for bricks production and spent refractories integrated into virgin raw materials mix.

Recycling is an important aspect that affects the environment. Crushed brick chips may be used in other industries as landscaping or raw materials. Alternative, recycled, and secondary-source materials accounted for up to 20% of total material utilisation in certain British ceramic firms (in 2010), with 200,000 tonnes of clay being substituted in one year by resources that would otherwise be destroyed. In the construction industry, unfired clay may be reused, while imperfectly fired bricks were broken and utilised as aggregates. In the refractory industry throughout Europe, 20% of used refractories were recycled into refractory applications, 27% were recycled in nonrefractory applications, 35% were dissolved during use, and just 18% were discarded as unusable waste [27].

The preservation of the environment is not just concerned with climate change; water conservation is also a critical component [11]. Ceramics contribute to the recycling of water via the usage of porous ceramic filters and the use of rainwater. Additionally, many ceramic producers have their own wastewater treatment works. Furthermore, developments in the sanitaryware industry led to a dramatic decrease in water consumption in the last two decades.

3.3. Drivers and Barriers

A PESTLE analysis improves our understanding of the potential strategic orientation of an industry by evaluating the impact of the external environment. It can help to identify enablers/drivers that can drive transformative change, and obstacles/barriers that could hinder this change. Results from a desk-based literature review are summarised in Table 1.

As listed in Table 1, our analysis detected over 25 drivers and 25 barriers to transformative change. Most of these drivers and barriers are interconnected with, and affected by, one another. For instance, the government shapes and implements international agreements on decarbonisation to meet UK net-zero 2050 targets, put into action through environmental policies and regulations. Ceramic companies, in turn, have to employ decarbonisation options, such as the use of alternative fuels. Many of these options incur higher costs due to high energy prices. Higher costs in the UK lower the return on investment compared to similar measures in other countries, adversely impacting the potential for SMEs/sites in the UK to attract investment in research, development, and innovation. Implementation of innovations is further held back due to a shortfall of skilled workers throughout the chain, including in research, process design, building new production facilities, and, ultimately, operating upgraded facilities. These interactions are resulting in carbon and job leakage.

To create a level playing field, political and legal factors were identified as particularly significant, with measures such as policy engagement, government support for FIs (e.g., through green procurement rules, subsidies, etc.), supportive R&I policy frameworks, long-term policies (e.g., energy, climate, resources), and support for new regulations. This support can help drive transformation and achieve climate targets. Specific COP27 targets of the United Nations Climate Change Conference include encouraging nations to increase their nationally determined contributions (NDCs) under the Paris Agreement, which describe each country's goal to cut greenhouse gas emissions, promote energy efficiency and clean energy, and enhance climate finance cooperation [74]. As a consequence of COP27 decisions, countries confirmed their commitment to restrain the global temperature rise to 1.5 °C above preindustrial levels [75], a target that is increasingly under pressure [76].

The most influencing barriers in this category, according to the studied PESTLE factors, are the uneven global playing field, which leads to carbon and job leakage by imports, incompliance with common international policies (industry, climate), unavailability of carbon emission calculation legislation, lack of green procurement, and foreign governments' policy changes. Additionally, in the UK, the definition of waste continues to cause challenges for recycling due to ineffective and inefficient regulatory processes, preventing waste materials from being legally recognised and therefore economically valued as an input material for production processes, putting limits on investment in recycling solutions and making it more challenging to sell a ceramic product made from waste at a fair price.

Table 1. The PESTLE analysis including drivers and barriers for transformative change in the UK ceramic industry.

PESTLE	Driver	Barrier
Political/Legal	<ul style="list-style-type: none"> • Policy engagement • Job potential of transformed industries • Resilient supply chains • Research and innovation policy framework • Long-term policies (e.g., energy, climate, resources) • Creation of a global level playing field in carbon assessments • Support for new/modified regulations (energy-saving, carbon reduction) • Government support (e.g., green procurement rules, subsidies, etc.) • Carbon/landfill taxes • COP27 targets 	<ul style="list-style-type: none"> • Uneven global level playing field (industry, climate) leading to carbon and job leakage from imports • No standard approach to carbon emission assessment • Definition of waste (and eliminating barriers to waste use) • Trade barriers (e.g., quotas, nontariff, restricted trade agreements, etc.) • Foreign governments policy changes (e.g., changes to trade agreements, regulations or standards, tariffs or quotas on ceramics exported from the UK, etc.)
Economic	<ul style="list-style-type: none"> • Reduction of manufacturing costs, improvement of resource efficiency, and recycling of crushed ceramics • Large number of SMEs • Investment in R&D and breakthrough technologies • A comprehensive definition of “cost” according to Fls (e.g., including nonmonetary aspects such as carbon) 	<ul style="list-style-type: none"> • Decreasing demand for UK products but increasing number of imports • Costs incurred to abide by regulations • High energy price • Decrease in returns on investment due to high costs • Limited capital availability • Resource access challenges for manufacturing sites
Social	<ul style="list-style-type: none"> • Insufficient number of people with STEM background in the industry • Growing social pressure to reduce emissions and waste • Green jobs at diverse skills levels for new technology • Ceramic skills groups • Training opportunities • More labour for new tech • UK investment in apprenticeships 	<ul style="list-style-type: none"> • Insufficient access to skilled staff • Lack of awareness about climate and environmental crises among staff in ceramic industry • Insufficient access to new people with STEM background • Underdeveloped equality, diversity, and inclusion strategies • Inability to clearly communicate carbon and other impacts and benefits to customers
Technological	<ul style="list-style-type: none"> • UK net-zero 2050 targets • Availability of variety of low-carbon technologies • Reduction in overall energy consumption (led to continuous upgrading of equipment and revising tech strategies) • Intersector cooperation • Innovation in energy-efficient products 	<ul style="list-style-type: none"> • Narrow focus on energy for decarbonisation, missing resource efficiency/dematerialisation opportunities • High cost of alternative energy • Limited funding/investment • Skills shortage to commission/operate innovative technologies
Environmental	<ul style="list-style-type: none"> • Climate change • Energy-saving strategies • Alternative fuels/renewables • Treatment facilities inside ceramic factories (e.g., wastewater treatment plants) • A clear understanding of product life cycle and CO₂ emissions • Waste reduction targets 	<ul style="list-style-type: none"> • Heavily carbon-focused roadmaps • Unavoidable process (CO₂) emissions • Unequal global playing field, leading to exporting UK’s CO₂ emissions to locations with lesser controls • Proximity of raw materials to manufacturing sites (e.g., transportation emissions)

The ceramic industry considers the large number of SMEs in its sectors as an economic incentive and driver [11]. Nevertheless, SMEs may have a lower capability to innovate due to reduced access to capital and skilled innovation personnel, while being constrained by general costs incurred to abide by regulations, a negative balance of trade due to importing, and elevated energy prices. In contrast, independent companies and SMEs are adaptable and can readily change tack and alter their financial strategies. Moreover, they can create local jobs and hence contribute to regional economic gross value added.

Socially, the lack of personnel with STEM backgrounds in the ceramic industry holds back transformative change. Therefore, there are considerable training opportunities, recruitment strategies for STEM individuals, already established ceramic skills groups, and UK investment in apprenticeships, but training to increase people's carbon and environmental literacy may still be required. Nevertheless, the ceramic industry lacks satisfactory ED&I strategies and plans to guide moral response to driving change and enable a "just transition" [77].

Technology-wise, decarbonisation technologies are extensively researched [13,27,30,40,78]. There is a large set of decarbonisation options and technologies, which is considered a main technological driver supported by intersector cooperation. Nonetheless, this results in a myopic concentration on energy for decarbonisation, neglecting the potential for resource efficiency and dematerialisation. On the barriers side, skills and funding are limited, and energy prices are soaring, hindering transformative technological change.

Reduction of carbon and waste emissions is a worldwide environmental concern. Its effect on climate change and ecosystems has already been clearly noticed. Energy use and carbon emissions are strongly interrelated. Therefore, promoting more resource- and energy-efficient processes and resource- and energy-saving strategies are key drivers in this aspect. Nevertheless, the great focus on decarbonisation and carbon-related issues could lead us to ignore other environmental issues linked to the industry, such as water, excessive resource usage, and so forth.

3.4. SWOT Analysis

A SWOT analysis was carried out to identify potential approaches to respond to the findings of the PESTLE analysis (Table 2). In this case, the ceramic industry was used as the unit of analysis; the analysis identified strengths and weaknesses within the ceramic industry and opportunities and threats impacting the ceramic industry [31].

A number of observations can be made when analysing the interactions between the strengths, weaknesses, opportunities, and threats. Some internal strengths could be used to make the most of opportunities. The ceramic industry could find substitutes from the waste and by-products from other industries and communities to decrease its imports. This offers a unique opportunity for industrial symbiosis and optimising material and energy flow between foundation industries. It can be achieved via resource reuse, recycling of waste and by-products, and conducting of a holistic-life-cycle evaluation of ceramic products. Strengths such as the high durability of products (less for better) add value to a research- and practice-driven hub such as TransFIRE, sharing best practices from the ceramic industry with other foundation industries. Current weaknesses, such as the decreasing (global) competitiveness of the ceramic industry due to higher energy and regulatory costs in the UK, can be managed through supportive trade and public procurement policies by the government. The opportunity of TransFIRE supports the accelerated development of low-temperature energy and resource-saving techniques and innovative production methods by bundling the expertise from all foundation industries.

Table 2. The SWOT analysis for the UK ceramic industry.

Strengths	Opportunities
<ul style="list-style-type: none"> • Ability to minimise resource use with recycling. • Strong focus on the durability of ceramic material. • Focus on the holistic-life-cycle approach of the product. • More employment opportunities. • Ability to develop a cutting-edge ED&I plan. 	<ul style="list-style-type: none"> • Support UK net-zero 2050 targets. • Reduce resource use with industrial symbiosis and optimum material and energy flow between foundation industries. • Support other heat-intensive industries to reduce emissions through lower-carbon refractory supplies and social/economic interactions along the chain. • Knowledge exchange between foundation industries.
Weaknesses	Threats
<ul style="list-style-type: none"> • Access to skilled staff for low-carbon technologies. • No clear statements on ED&I strategies. • No clear plan for recycling of new waste materials and by-products (becoming a self-sufficient industry). • Does not fully support the complete transition of firing gases from natural gas to biomass and/or syngas (alternative fuels) and the electrification of kilns and other thermal treatment equipment. • Low competitiveness arising from limited collaboration on R&D due to competition concerns among the ceramic companies. 	<ul style="list-style-type: none"> • Carbon and job leakages due to increased imports and a lack of level-playing-field international legislation. • Unfair trade practices and agreements. • Unfair competition with major global trading partners without internationally legally binding climate agreement and internationally standardised supervision of its execution. • High energy costs. • Limited availability of capital.

Some internal strengths could be used to face threats. For example, the preference for a globally standardised whole-life-cycle approach to assess carbon emissions of ceramic products could be adopted into (inter)national regulations to create fairer trade conditions in which companies compete based not only on price but also on environmental performance. This would reduce the threat of unfair trade practices that result in carbon and job leakage from the UK. Moreover, a hub such as TransFIRE can support collaboration across various foundation industries on resolving shared concerns and threats.

There are some weaknesses which can be turned into opportunities. These are sought by the transformative change process and different government-supported projects that handle setting out strategies and plans for this change. Skills shortages and unsatisfying ED&I structures are weakening the industry's position. TransFIRE supports the establishment of better working environments within the ceramic industry through targeted actions to improve the ED&I agenda. The current insufficient plans for the recycling of other waste materials and by-products arise from the fact that the industry is self-sufficient and largely recycles its own waste [11]. Nevertheless, there are better options outside the ceramic industrial sphere that could be found through industrial symbiosis. Moreover, the industry does not fully support the complete transition of firing gases from natural gas to biomass and/or syngas (alternative fuels), and the electrification of kilns and other thermal treatment equipment. On the other hand, TransFIRE critically reviews dematerialisation and decarbonisation options and cross-foundation industries best practices on minimising material and energy resource usage, thus providing solutions and opportunities for the ceramic industry.

In terms of the cross-over between weaknesses and threats, reusing wastes and by-products may affect the quality of the final product, and investment in research and innovation would have to help minimise risks that durability and performance could reduce. A sustainable source of supply should be available, i.e., waste and by-product materials should be treated, modified, and supplied continuously.

4. Discussion and Next Steps

The context analysis combined with a SWOT analysis of the ceramic industry could help identify key intervention points to enable transformative change. A number of ceramic industry roadmaps published in the last decade were scrutinised and analysed, and the results were summarised in Tables 1 and 2. The study was limited to a small number of publicly available roadmaps relevant to the context of transforming the ceramic industry. Publications on the subject of context analysis for changing the UK's ceramic industry are scarce and not readily available. Moreover, this study presented in-depth analytical findings and discussions, which are further enriched in this section.

4.1. Dematerialisation

There is frequently a temptation to concentrate on decarbonisation in all the political, economic, social, technological, legal, and environmental macro factors. Almost all roadmaps were tailored specifically to address this issue, while some references to recycling and reuse of ceramic materials and improving resource efficiency were occasionally pointed out. Dematerialisation and all its related aspects were mentioned in only one of the roadmaps [11]. More supply chain cooperation was proposed for technical and business model innovation that may raise the value of goods while utilising fewer materials. This would imply that foundation industries, for example, would produce lighter and/or more leasable items, join refurbishing and remanufacturing sectors, and develop products that work better and last longer.

There is an opportunity to give more attention to using fewer resources and dematerialise our society in the ceramic industry's industrial roadmaps, because this is already an approach that the ceramic industry is familiar with but could accelerate more through interactions along their supply chains. Resource security is increasingly an issue under the conditions of growing global resource use, while resource use directly drives carbon emissions, too. Similar to the current roadmaps [27,28], a "Ceramic Sector Joint Industry-Government Industrial Dematerialisation and Resource Efficiency Roadmap to 2050" may exist in the future and could be formulated to shed light on material usage, recyclability of ceramic products, dematerialisation methods, material recovery techniques, and strategies, while maintaining product durability. For dematerialisation to work, new logistics, production methods, and business models must also be considered.

4.2. Reflecting upon TransFIRE's Ambitions

Compared with the visions and roadmaps mentioned in this study, TransFIRE offers a transformative vision that relies on three main pillars: minimisation of resource use in the production process, optimisation of waste and by-product reuse, and the transformation of practices to contribute to the dematerialisation of society, thereby creating equal opportunities for people and communities.

Establishing a proactive, interdisciplinary, and inclusive research- and practice-driven research and innovation hub will ensure the achievement of the projects' aims, of which some are aligned with the other aforementioned sectoral change visions and roadmaps. For instance, similar to TransFIRE, improving the competitiveness of the foundation industries, working with their communities, and supporting the UK plan to achieve almost net-zero emissions of greenhouse gases by 2050 (AKA UK net-zero 2050 targets for GHG emissions) are listed in the existing published visions and roadmaps for sectoral change, their agendas, and their action plans. Furthermore, some additional changes proposed by TransFIRE were never mentioned in the investigated visions and roadmaps, such as the support for an ED&I strategy for the ceramic foundation industry. Moreover, mapping and optimising the flow of all resources between FIs and their supply chains is another additional important area, where the UK generally has not made strong progress yet. TransFIRE aims to support the development of a policy framework for transformative change in foundation industries. The transformative change in the foundation industries envisaged by TransFIRE is illustrated in Figure 1.

4.3. Reflecting on the Broader Literature on Ceramic Industry Decarbonisation

In this study, drivers and barriers were identified based on PESTLE analysis that highlighted numerous critical factors and measures. The majority of studies do not take a holistic approach that scrutinises the entirety of the factors affecting the ceramic industry. Many studies in the literature instead concentrate on a smaller area of either the tile or brick sectors. Compared to what the literature holds in this regard, most of the reports were limited to one or two aspects of the various aspects covered in this article [13,30,78,79]. Moreover, they were concerned with the world's situation in general and not with addressing the UK's context specifically. A few systematic reports sought to identify options for mitigating the climatic impacts of ceramic products and their emissions [13,30,78].

These reports investigated the identification of determinants of energy and carbon emissions and barriers to tackle. For instance, Del Rio et al. utilised a sociotechnical system approach to determine existing alternatives to abate the climate effects of ceramic production so that its product life cycle would be more sustainable; identify technical innovations to make ceramic manufacturing low-carbon; and find out benefits from applying a more carbon-friendly process in ceramics manufacturing [30]. Fifteen approaches to decarbonise the ceramic industry were reported, most of which were highlighted in this study, such as electrification, use of alternative fuels, waste recycling, and others. They critically reviewed sociotechnical decarbonisation options and compiled 32 emerging innovative technologies for making ceramic manufacturing more sustainable on different levels. At the ceramic manufacturing level, they proposed the usage of microwave-assisted drying and firing, hybrid kiln, heat pipe exchanger, cold sintering, optimisation of the recirculation of drying air, airless drying, fast-firing, inertising, and more. At the level of options for raw materials extraction and alternatives to replace ceramics, they listed optimising raw materials, recycling sludge from other industries, incorporating new materials to improve the ceramics' design, and others as promising options.

4.4. Industry Reflections

More discussions with the industry through numerous meetings, workshops, and other activities (e.g., training, secondments, etc.) can provide further information on the context of the ceramic foundation industry.

The context analysis conducted in this study is the first step towards the envisaged transformative change. TransFIRE held a Ceramics TWG workshop in January 2022; participants included representatives from academia and industry. The preworkshop discussion began with the presentation of drivers and barriers based on analyses of relevant roadmaps and PESTLE. A participatory situational analysis (PSA) was used to articulate an action-oriented agenda for the development of research programmes and/or the uptake of research outcomes [80]. Furthermore, the PSA approach helps identify the key actions and gaps in expertise needed to enable transformative change that specific actors could take to remove barriers or make the most of the drivers required for transformative change [80]. Figure 2 depicts the context-analysis-supported process flow diagram and PSA approach followed by TransFIRE. Further discussions were developed to link the drivers and barriers to the actors in control (of helping to resolve barriers and/or making the most of the drivers to transform the ceramic industry), actions they can take, and gaps in expertise that TransFIRE can contribute to solving. Further interviews, workshops, and discussions are underway to generate a common vision and strategy for the transformation of foundation industries.

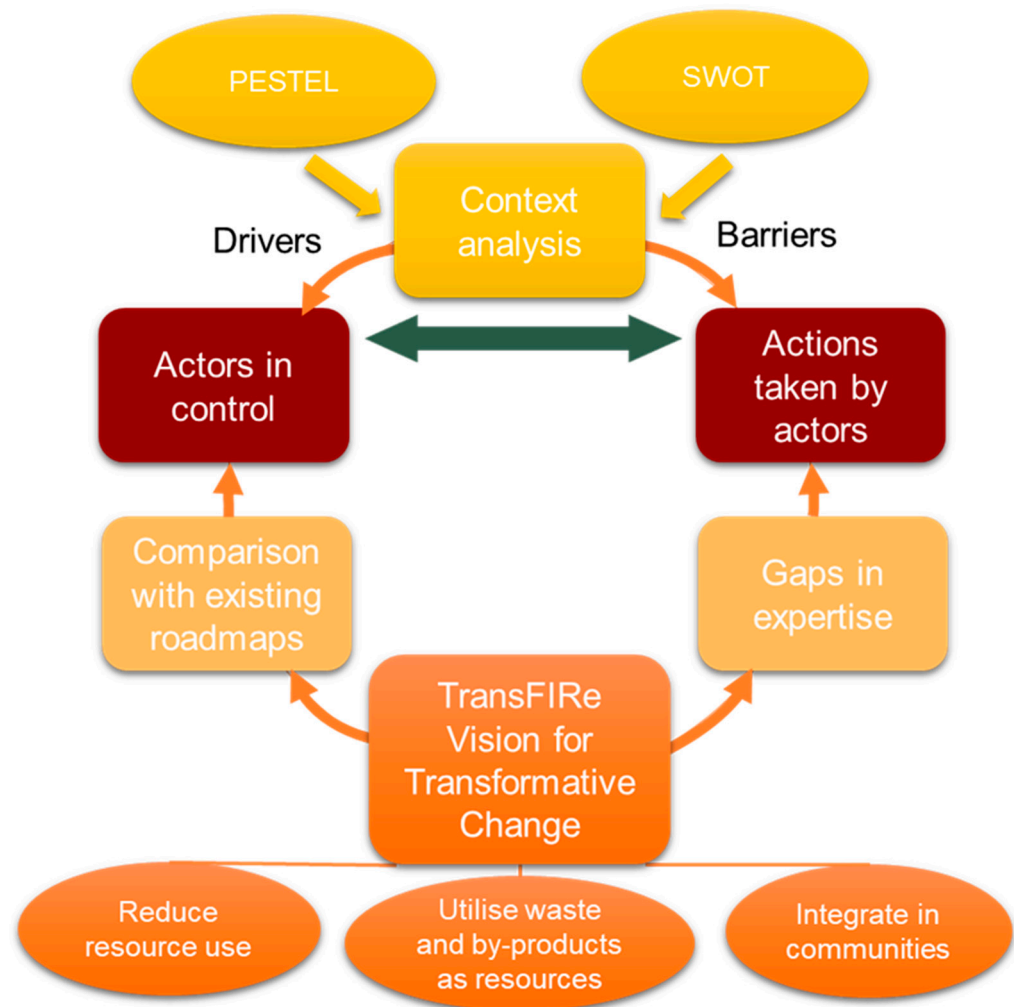


Figure 2. Context-analysis-backed process diagram for determining key intervention points, drivers, barriers, actors, action, and gaps in expertise.

5. Conclusions

This research work depicted the context analysis for transformative change in the ceramic industry and the role of TransFIRE in transforming UK foundation industries. The PESTLE analysis was the first stage in starting conversations to understand where measures could be taken to make the most difference. PESTLE included Political, Economic, Social, Technological, Legal, and Environmental aspects. The findings were further refined in a SWOT analysis to determine the ceramic industry's primary internal Strengths and Weaknesses, as well as external Opportunities and Threats.

Key findings include that transformative change in the ceramic industry is primarily driven by carbon reduction targets, combined with technical innovation to reduce and alter energy use. In the short term, the ceramic industry could make progress by adopting more industrial symbiosis to optimise material and energy flow between foundation industries, thereby substituting imported raw materials with waste and by-products sourced in the UK. Material and energy use could be further reduced through knowledge exchange between foundation industries and the adoption of best practices to make savings in production processes.

Urgent policy challenges to resolve include issues around the definition of waste that constrain resource reuse but, arguably more importantly, resolve global trade threats. The UK ceramic industry is facing decreasing (global) competitiveness due to higher energy and regulatory costs in the UK, which could be managed through supportive trade and green procurement policies by the government. Implementation of regulations for

holistic-life-cycle evaluation of ceramic products sold in the UK can help create a level playing field and support demand for sustainable products, which in turn can enable investment in manufacturing facilities in the UK. This would reduce the threat of unfair trade practices that result in carbon and job leakage from the UK. Domestically, collective action is needed to further cover urgent skills gaps in the ceramic industry, combined with a resilient ED&I strategy to make the industry a more attractive place to work.

Important technical and economic innovation challenges remain in the industry's ability to switch away from fossil fuels (natural gas) to alternative fuels such as biomass and/or syngas, the electrification of kilns, and other thermal treatment equipment. Focuses on resource efficiency and dematerialisation in support of decarbonisation targets were largely missing from existing roadmaps and visions.

Current roadmaps can only partially help the UK ceramic industry reach net-zero targets. Further plans for transformative change in the ceramic industry will be coproduced with industry, government, and community representatives as part of TransFIRE. Working in an international context, the UK ceramic industry can coproduce solutions for transformative change that can be transferred to other countries.

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