Article:

Reaney, I.M. orcid.org/0000-0003-3893-6544, Walsh, B. and Vilarinho, P.M. orcid.org/0000-0001-5161-1360 (2023) Resource efficiency and energy efficiency (REEE) in the Portuguese ceramic industry: towards net zero carbon production. Open Ceramics, 15. 100390. ISSN 2666-5395

https://doi.org/10.1016/j.oceram.2023.100390

Open Ceramics 15 (2023) 100390

Contents lists available at ScienceDirect

Open Ceramics

journal homepage: www.sciencedirect.com/journal/open-ceramics

Resource efficiency and energy efficiency (REEE) in the Portuguese ceramic industry: Towards net zero carbon production

Ian M. Reaney [a,*], Ben Walsh [b], Paula M. Vilarinho [c]

[a] Department of Materials Science and Engineering, University of Sheffield, Sheffield, UK
[b] Transforming Foundation Industries, Innovate UK, UK
[c] Department of Materials and Ceramic Engineering, University of Aveiro, Aveiro, Portugal

ARTICLE INFO

Handling Editor: Dr P Colombo

ABSTRACT

The Portuguese ceramic industry constitutes 0.5% of Gross Domestic Product in Portugal, far higher than most other European nations, and thus it is essential this sector is decarbonised, cost-effectively to preserve jobs and national revenue. Moreover, the small size of the country and the co-location of ceramic factories dominantly in northern Portugal lowers the logistical barriers to act collectively to form networks and engage in collective strategies to push towards net zero carbon production. This article considers Portugal as an ideal case study for strategic and collective action to develop and facilitate carbon mitigation strategies. The article focusses mainly on current and future resource efficiency and energy efficiency strategies but additionally assesses the role of fuel switching (H_2 vs electrification) and low energy densification technologies.

1. Introduction

Ceramics is one of the foundation material industries within Europe and has been an important sector within manufacturing for over 300 years [1]. Portugal is a nation of ~ 10.5 m people with a Gross Domestic Product (GDP) of ~$250 billion per annum [2]. The Portuguese ceramic industry is composed of ~1000 companies, principally concerned with construction and traditional ceramics and employs around 16,000 people. It constitutes 0.5% of GDP, generates a turnover of ~1.2% of GDP and in 2017 was responsible for ~ 4% of the total and almost 17% of industrial consumption of natural gas [3]. Despite its comparatively small population, Portugal is the number one European manufacturer of tableware and in the top 5 for ceramic sanitary and construction products [3]. The importance of the ceramics sector per capita to the Portuguese economy is greater than most European countries and may be viewed as an ideal test case to develop a strategy for net zero carbon production by 2050.

Although advanced, technical and electroceramics such as Al_2O_3, ZrO_2 and $BaTiO_3$ receive the most academic funding and research interest, it is traditional ceramics such as whitewares, sanitary ware and construction materials that constitute the vast majority of production worldwide, with a global market worth ~200–250 billion per annum [4]. However, it is an energy intensive industry with comminution, drying and most importantly sintering or densification (1000–1300 °C) consuming large amounts of fossil fuels through the widespread and almost exclusive use of gas (CH_4) fired continuous and batch furnaces [5]. Further processes involved in ceramic production include the use of water heaters, calcination of raw materials including clays and fluxes and in some instances the treatment of raw materials to remove acid content. It is an industry that thrives on product innovation with new designs for table and sanitary ware emerging on a daily basis but the essentials of manufacturing remain broadly the same as they were over 50 years ago. Consequently, technological innovation is required to decarbonise the ceramics industry and improve its resource efficiency and energy efficiency (REEE).

2. The importance of resource efficiency and energy efficiency (REEE)

In 2021, the UK Committee for Climate Change (CCC) published its predictions of carbon abatement leading up to 2050 [6] based on existing and potential mitigation strategies within the industrial and construction sectors, both of which are pertinent to the ceramics industry. Fig. 1 shows the cumulative carbon abatement per year until 2050 whilst Fig. 1b is a pie-chart showing the effect of all major technologies/innovations/strategies on carbon abatement by 2050 if we are

* Corresponding author. Department of Materials Science and Engineering, University of Sheffield, Sheffield, S1 3JD, UK.
E-mail address: i.m.reaney@sheffield.ac.uk (I.M. Reaney).

https://doi.org/10.1016/j.oceram.2023.100390
Received 3 February 2023; Received in revised form 8 June 2023; Accepted 14 June 2023
Available online 17 June 2023

to achieve the target of net-zero. It is evident from Fig. 1 that carbon capture and storage (CCS), hydrogen (H_2) and electrification are essential but surprisingly almost 1/3 of mitigation can broadly be badged as REEE, e.g. materials substitution, reduction in use of resources, energy efficient technologies and recycling reuse of waste. Moreover, Fig. 1 illustrates that REEE is in fact the dominant carbon mitigation strategy at least until ~2035. Presenting carbon abatement in this manner leads to the conclusion that whilst 'mega' projects such as electrification of industry, production and distribution of green H_2 and CCS are vital in the fight against climate change, small gains accumulated over longer time periods potentially have a more significant impact than any single abatement technology. This manner of presenting the CCC data, illustrates that decarbonisation through REEE must be accelerated and it is imperative that companies do not simply stick with current production methods before replacing their legacy furnaces with low and zero carbon alternatives as they become obsolete or when carbon taxes become unsustainable.

There are a number of potential carbon mitigation strategies that can be utilised within, and retrofitted to, existing ceramic production such as: low temperature processes (cold/flash sintering) [7,8], heat recovery systems [9], alternative heating technologies (microwave) [10], greater recycling of waste [11,12], minimisation of production and furnace downtime waste (digitisation, AI), lightweighting of products and decarbonisation of raw materials (minimise carbonates). These mitigation strategies must also be accompanied by life cycle [13] and technoeconomic [14] assessment (LCA/TEA) which permit the role of new technologies to be 'stress tested' before going anywhere near a production line. Difficulties may arise in applying LCA/TEA to new process due to the limited availability of primary data. AI driven search engines would help accrue information and databases such as Ecoinvent can serve to provide secondary data to model new processes and substituent materials. Ref 13 succinctly illustrates how LCA may be used to determine that a proposed substituent material (potassium sodium niobate) is more environmentally un-friendly than the incumbent commercial product (lead zirconnate titanate) without the availability of primary data.

Additionally, supply chain modelling can alleviate concerns over the use of recycled feedstock, de-risking the implementation of new technologies and concepts [15]. It is also essential, that the ceramic industry diversifies its workforce in gender and age so that the requisite talent base for new carbon mitigation strategies can be accessed more easily and consistently. Additionally, it is absolutely critical, that the ceramic industry acts collectively to address the challenges ahead, throughout Europe ideally, but because of its peculiar industrial demographics, the country with the most to gain in terms of GDP per capita is arguably Portugal. This collective approach must be aided by government-led initiatives to de-risk carbon mitigation strategies and help identify the ideal technologies to move forward. A 'silo' mentality will guarantee the failure of numerous businesses and the national decline of a vibrant manufacturing sector.

In the following section, current mitigation and future strategies are reviewed. The latter include, digitisation and artificial intelligence, expanded industrial symbiosis and the extended use of heat and energy recovery systems. In the longer term, it is also critical that ceramic companies replace their existing legacy, methane-burning equipment with decarbonised alternatives that are also optimised for REEE. The merits of electrification versus hydrogen are briefly discussed.

3. Current carbon mitigation strategies

The ceramics industry already adopts a number of energy and carbon mitigation protocols, including optimization of motors, turbines, pumping and ventilation systems and compressed air systems; refurbishment of kilns to improve burner efficiency; improvements in dryer and spray dryer technology. Heat recovery systems are employed which often involve the redirection and recirculating of hot air and gases. Industrial symbiosis is increasing driven by the high cost of land-fill and disposal of waste product and there is a recognition of the need for a reduction of water usage by replacing wet with dry processes. Energy management systems through monitoring and control systems are often utilised although real time adjustments in the process is limited. The application of these measures varies widely with many companies demonstrating great awareness of the need for carbon mitigation within the context of an industry that fundamentally relies on methane as its key fuel source.

4. Future carbon mitigation strategies

4.1. Digitisation and artificial intelligence

There are a wide range of sensors (heat, moisture, pressure, PO_2 and motion) now available that are able to help digitise ceramic production, Fig. 2 [16]. Take up of this technology is limited however, with only modest penetration within the ceramics community. Yet it is an industry that has multiple different aspects to production. Pressing, transport of products, printing, glazing and final densification are common throughout much of the industry and each step may be monitored electronically using the correct sensing systems [17]. Even when such

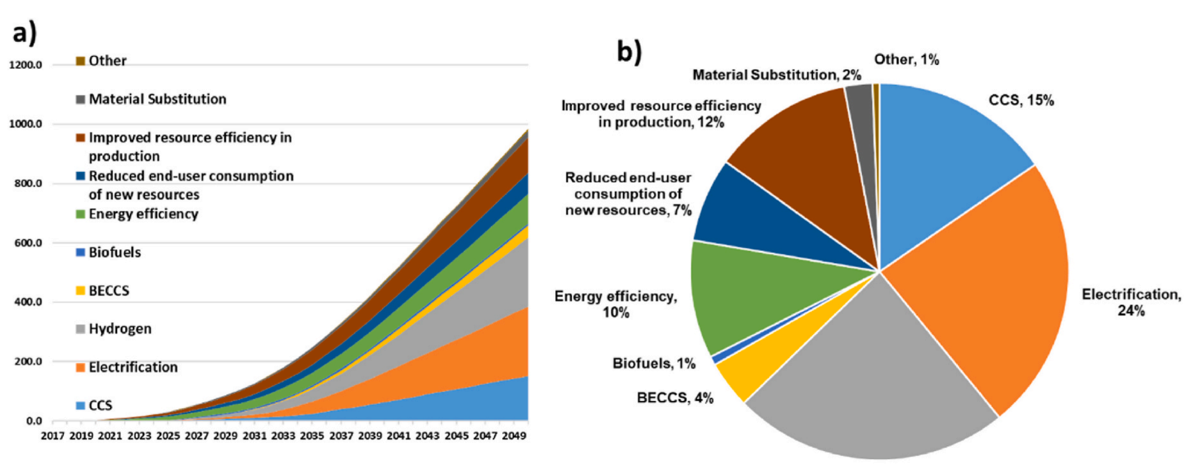

Fig. 1. a) Cumulative carbon abatement from 2017 to 2050 based for industry and construction based on date from the United Kingdom Committee for Climate Change and b) Snapshot of cumulative contributions to carbon abatement at 2050. CCS = carbon capture and storage and BECCS = bioenergy with carbon capture and storage [6].

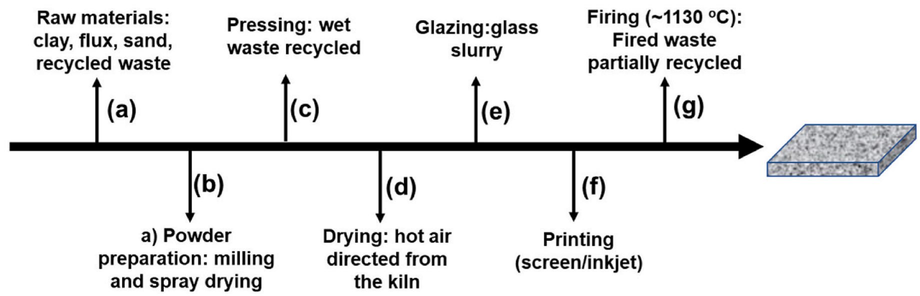

Fig. 2. Schematic flow diagram of ceramic tlle (a to g) production illustrating the type and location of potential sensor and control systems that could be utilised: a) and b) particle size control; c) pressure sensing; d) temperature control systems; e) and f) slurry viscosity control and g) temperature/PO_2 (if reducing conditions are required)..

sensors are fitted to production lines, modification to production is not done in real time, often occurring after a failed production run. Fully digitised systems should include AI which permits, via the use of appropriate algorithms, the real manipulation of a process (within seconds) to optimise production and maintain, for example, the health of a furnace [18]. Such AI driven sensing and control systems are increasingly common in other areas of manufacturing such as aerospace but penetration into more traditional industries is sparse. Wastage in production through breakage, inappropriate firing, pinholes in the glaze and flaws in the decorative printing is notoriously high, depending on complexity of the design and thickness of the product [19]. Even a modest reduction in wastage, through better automated sensor and control could lead to significant raw material and energy savings. Although difficult to calculate the precise savings, it is reasonable to assume that a decrease in wastage by 10% would decrease the energy in production and raw material costs by approximately the same amount, subject to a full LCA and TEA of the process. The major road-blocks to retro-fitting this technology to existing ceramic production is not only cost but also the skillsets required to operate these systems which are far outside the core expertise of the average ceramic workforce. Nonetheless, investing in such systems has been shown to increase the efficiency of production in advanced manufacturing and an 'Industry 4.0' approach is vital for the future of the European ceramics industry.

4.2. Waste heat recovery systems

Heat recovery or re-use in ceramic production commonly takes the form of channelling hot gases to aid the drying of products or its recirculation to pre-heat where appropriate. Typically these processes use recovered heat >500 °C but heat recovery at low temperature through, e.g heat-pipe technology, is rarely addressed [20] Heat pipe technology for heat recovery at low temperature is composed of a sealed tube with a working fluid at saturation pressure and temperature [20]. It utilises a two-phase heat-transfer phenomenon to transport the heat from the evaporator to the condenser (Fig. 3) and offers an isothermal surface. i.e., a uniform wall temperature along each section of the heat pipe. Heat Pipe Heat Exchangers (HPHE) consist of a series of heat pipes staggered in a defined arrangement to recover heat from an exhaust stream which is then transferred to a heat sink such as water, air or thermal oil [20]. HPHEs present many benefits such as: i) multiple redundancy as each heat pipe is a heat exchanger; ii) better fouling management due to the use of smooth shell material surface, iii) ease of cleaning and maintenance. The heat pipe heat exchanger has large door panels on each side that can be removed to access the heat pipes for cleaning, iv) isothermal operation due to the two phase phenomena of each individual heat pipe with the variety of working fluids allowing a large range of exhaust temperatures applications and v) ease of scaling and customising (heat pipe heat exchangers are bespoke designs for specific applications) [20]. HPHEs (Fig. 4) are composed of robust engineering materials in which the thermal resistance of the pipe is low, with a fast thermal response

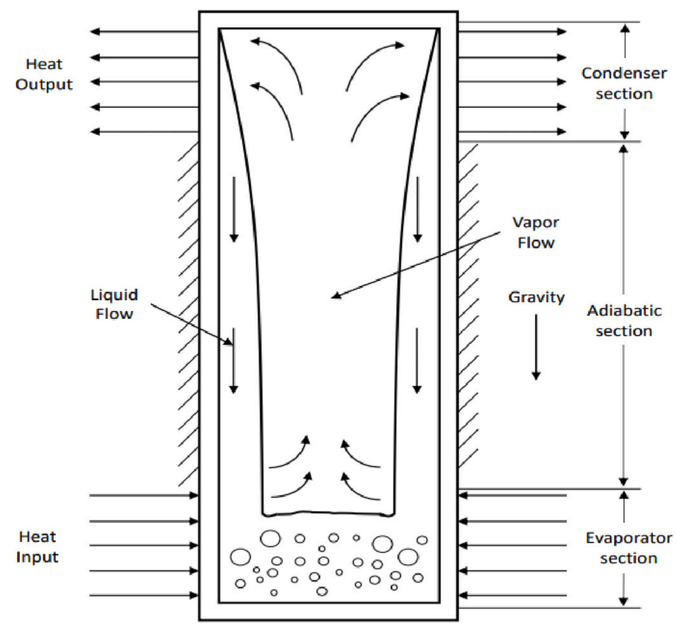

Fig. 3. Heat pipe schematic (courtesy of Hussam Jouhara, Brunel University.

due to their two-phase (gas/liquid) heat transfer technology. They are also passive since the condensed liquid is retuned from the condenser to the evaporator by gravity without the need for any mechanical power [20].

4.3. Resource efficiency: recycled waste streams and industrial symbiosis

Generally speaking most traditional ceramic production re-uses all 'wet-waste' up until the point of the pre-fire or firing process. However, after pre-fire or firing, waste is more difficult to incorporate directly into the product and most processes generate more than they can use within the factory. The most obvious solution is to minimise waste in production with greater control over process conditions such as pressing, transport of product, glazing and firing. A thorough understanding of the process steps in terms of the particle size, phase evolution and microstructure is recommended which may be achieved through in-house monitoring and interaction with academic partners and Research Technology Organisations to obtain access to the appropriate characterisation equipment. If waste cannot be eradicated and is in greater quantities than can be recycled in the company (the most likely scenario), a supply chain network is required which identifies potential 'users' of that waste [21]. To successfully achieve such as network, the nature of the waste must be characterised fully and its properties known. In addition, it must be available in sufficient quantity and regularity to satisfy the supply chain requirements of the recipients. Amalgamating

Fig. 4. Heat pipe heat exchanger retro-fitted to legacy ceramic furnace (courtesy of Hussam Jouhara, University of Brunel).

and homogenising the waste is recommended, so that large enough quantities with known physical characteristics are available for re-use. Nonetheless, there is great potential here particularly if one large volume industry can use the waste of another such as ceramic waste to cements and metal foundry sand to cement and ceramics.

The use of non-factory waste is a more complex issue. Supply chains must be guaranteed, transport costs, if a distributed source, must not be exorbitantly costly and energy intensive and the carbon abatement through use of that waste must be positive. This requires use of LCA and TEA [12,13] to identify environmental and carbon hotspots in the process and to establish the base costs to the companies who wish to re-use non-ceramic factory waste streams. One of most documented examples of non-factory waste re-use in construction materials is bricks fabricated from 20% recycled plastic and foundry sand proposed by Rhino Machines [22].

The use of lower embodied carbon constituents in production is an on-going trend in ceramic manufacturing with $CaCO_3$ being replaced as a flux with raw materials that do not decompose to produce CO_2. Clay sources that are more environmentally friendly are also being targeted to create 'sustainable product portfolios' demanded by some customers. However, few companies have the ability to modify their compositions directly on site as the mixed/milled and granulated raw materials are often bought in bulk from a centralised supplier. A strong consumer pull is required along with collective action between ceramic manufacturers and powder suppliers to encourage alternative 'Eco' products to be mass produced.

4.4. Next generation furnaces

To decarbonise in the medium term, CH_4-burning legacy furnaces must be replaced or modified to use green H_2 or be electrified. The debate as to which is most suitable is difficult but factors to take into account are the availability of 'green' or at least 'blue' hydrogen, its distribution network (if your factory is located near a hydrogen cluster then this technology is more feasible) and cost of production (to generate hydrogen through electrolysis is 60–80% energy efficient depending on the exact process [23]). Other factors include, the effect of hydrogen on the product itself (e.g. colour and mechanical integrity) which urgently need investigating. Moreover, the long-term effect of using H_2 on furnace linings and furniture is unknown. Up to 20% H_2/CH_4 mixtures are envisaged in the short term [24] but this is only a stop-gap measure until full decarbonisation can be achieved.

Electrification also requires new infrastructure as the power to operate a large furnace is far too great for a conventional supply. This technology to provide a power supply is however well known and electric arc furnaces have been in operation in the steel industry for many decades [25]. Other challenges for electrification include homogeneity of the temperature. This is more difficult to attain through electric heating elements and further work is required for the design of continuous electric furnaces suitable for the wider ceramic industry. However, the fabrication of multilayer capacitors is dominated by continuous electric furnaces [26] so technology exists in related industries albeit not currently for traditional ceramics whose requirements for capacity are greater. Individual capacitors are of the order of mm and fired in trays consisting many thousands of parts. The size of a typical capacitor kiln tunnel is thus much smaller than for traditional ceramics.

The choice of hydrogen versus electrification is a topic that must be discussed across the ceramic sector and at government level. Companies however, are urged to engage collectively with furnace designers to establish designs and prototypes for the next generation of furnaces. Retrofitting furnaces to burn H_2 may seem cost effective in the short to medium term but may lock the company into a technology that is expensive in the long term. Irrespective of the choice fuel for decarbonisation, the essential tenets of REEE remain valid and new furnaces must have better control systems through digitisation and superior energy efficiency through the use of heat recovery systems. Recycling and repurposing of waste as a raw material must also be at the heart of all products and product designs as we move forward.

4.5. Low energy sintering technologies

The scientific literature is replete with articles that describe methods for the low energy densification of ceramics, including field assisted sintering, cold sintering and 'fast' sintering and the reader is referred to Ref. [14] for a comprehensive overview of many of these technologies along with their carbon abatement potential. Notably, the FLASHPOR (Proj Nº 070302), funded by the Portuguese government in 2019, is one of few projects that focus on traditional ceramics, investigating the use of field assisted sintering in the densification of porcelains. Mostly however, these processes refer to batch rather than continuous production and focus on advanced and technical ceramics [14]. Their potential impact therefore on traditional ceramics at this juncture remains low in the short term. However, there are reports of room temperature pre-sintering (80%) of Al_2O_3–SiO_2 brick refractories using hybrid cold/flash sintering [27] which illustrate that at least in some large volume ceramic industries there is potential for new and disruptive technologies to reduce carbon emissions.

5. Conclusions

The 'fossil fuel' era which has driven globalisation and commercialisation is coming to an end and increasingly, we will no longer be able to use a fuel source for which the embodied energy was generated millions of years in the past, accessible by digging and drilling into the earth. Energy will be more expensive and must be treated as a precious resource to be used appropriately and carefully. These statements equally apply to the raw materials that we use. Whilst the raw materials in traditional ceramics (feldspar, limestone, clay and sand) are not scarce in themselves, there is an energy and environmental cost in their mining, refinement and transportation. Yield in production must be maximised to extend their lifetime and reduce the total carbon footprint of these mineral resources. The most expensive raw material with the highest embodied energy in the fabrication of any modern ceramic article is the recycled waste from its own production.

Portugal is unique in that the ceramic sector constitutes 0.5% of its GDP, far higher than most other European nations and thus has much to gain by developing decarbonised production. In addition, due to the small size of the country and the location of ceramic factories dominantly in the North, Portugal therefore has a low logistical barrier to act collectively and is well-placed to form the kind of networks and collective strategies required to push towards net zero in the coming years.

Declaration of competing interest

The 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.

Acknowledgments

I. M. Reaney acknowledges the Engineering and Physical Sciences and Research Council Grant, EP/V026402/1: Transforming the Foundation Industries: a Network+: Towards Value by Innovation. P.M. Vilarinho's contribution was developed within the scope of the project CICECO-Aveiro Institute of Materials, UIDB/50011/2020, UIDP/50011/2020 & LA/P/0006/2020, FLEXIDEVICE project PTDC/CTMCTM/29671/2017, and FLASHPOR project (FLASHPOR - FLASH as an alternative sintering technology for porcelain - 17/SI/2019; Proj nº 070302).

References

[1] https://chloristableware.com/blog/ceramic-history-origin/.
[2] https://tradingeconomics.com/portugal/gdp.
[3] H. Monteiro, P.L. Cruz, B. Moura, Integrated environmental and economic life cycle assessment of improvement strategies for a ceramic industry, J. Clean. Prod. 345 (2022), 131173.
[4] https://www.grandviewresearch.com/industry-analysis/ceramics-market.
[5] https://cerameunie.eu/media/ambd23os/ceramic-roadmap-to-2050.pdf.
[6] https://www.theccc.org.uk/.
[7] J. Guo, H. Guo, A.L. Baker, M.T. Lanagan, E.R. Kupp, G.L. Messing, Cold sintering: a paradigm shift for processing and integration of ceramics, C. A. Randall 55 (38) (2016) 11457–11461.
[8] https://patents.google.com/patent/US20130085055A1/en.
[9] https://heatmatrixgroup.com/industries/ceramics/.
[10] https://www.osti.gov/servlets/purl/1406412.
[11] https://www.interregeurope.eu/good-practices/symbiosis-practices-in-ceramic-sector.
[12] https://cerameunie.eu/topics/construction-sustainability/circular-economy/circular-economy-innovation-spinning-the-industrial-symbiosis/.
[13] T. Ibn-Mohammed, S.C.L. Koh, I.M. Reaney, A. Acquaye, D. Wang, S. Taylore, A. Genoves, Integrated hybrid life cycle assessment and supply chain environmental profile evaluations of lead-based (lead zirconate titanate) versus lead-free (potassium sodium niobate) piezoelectric ceramics, Energy Environ. Sci. 9 (2016) 3495–3520.
[14] T. Ibn-Mohammed, C.A. Randall, K.B. Mustapha, J. Guo, J. Walker, S. Berbano, S.C.L. Koh, D. Wang, D.C. Sinclair, I.M. Reaney, Decarbonising ceramic manufacturing: a techno-economic analysis of energy efficient sintering technologies in the functional materials sector, J. Eur. Ceram. Soc. 39 (6) (2019) 5213–5235.
[15] https://www.emerald.com/insight/content/doi/10.1108/JM2-06-2018-0081/full/html.
[16] https://www.zi-online.info/en/artikel/zi_Measuring_and_control_systems_for_the_ceramic_industry_3143434.html.
[17] https://iopscience.iop.org/article/10.1088/1757-899X/912/3/032027/pdf.
[18] https://www.nist.gov/blogs/manufacturing-innovation-blog/artificial-intelligence-manufacturing-real-world-success-stories.
[19] https://www.aidic.it/cet/18/70/071.pdf.
[20] Hussam Jouhara, Waste Heat Recovery in Process Industries, 2021, ISBN 978-3-527-83001-5.
[21] https://www.aspire2050.eu/sites/default/files/users/user85/mt210042.pdf.
[22] https://archello.com/news/india-based-rhino-machines-introduces-brick-made-from-recycled-plastic-and-sand.
[23] S. Shiva Kumar, V. Himabindu, Hydrogen production by PEM water electrolysis – a review, Mater. Sci. Energy Tech. 2 (3) (2019) 442–454.
[24] https://www.keele.ac.uk/sustainable-futures/ourchallengethemes/providingcleanenergyreducingcarbonemissions/hydeploy/.
[25] http://www.rollingmill-machinery.com/news/The-History-of-Electric-Arc-Furnace.html.
[26] https://www.jtektthermos.com/lp/mlcc/.
[27] https://www.lucideon.com/uploads/pdfs/cin-event-presentations/Flash-Sintering-CIN-event-April-2021.pdf.