International Journal of Hydrogen Energy 93 (2024) 910–924

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Critical perspective on green hydrogen-based seasonal operation of energy-intensive industry sectors with solid products

Jure Voglar [a,**], Blaž Likozar [a,b,c,d,*]

[a] Department of Catalysis and Chemical Reaction Engineering, National Institute of Chemistry, Hajdrihova 19, 1001 Ljubljana, Slovenia
[b] Faculty of Chemistry and Chemical Technology, University of Ljubljana, Večna pot 113, 1001 Ljubljana, Slovenia
[c] Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia
[d] Faculty of Polymer Technology, Ozare 19, 2380 Slovenj Gradec, Slovenia

ARTICLE INFO

Handling Editor: Ramazan Solmaz

Keywords:
Hydrogen economy
Decarbonization
Industrial production
Commodities
Energy policy
Sustainability

ABSTRACT

In the light of a future decarbonized power grid based primarily on non-dispatchable renewable energy sources, the operation of industrial plants should be decarbonized and flexible. An innovative, novel concept combining industrial plants with (i) a water electrolysis unit, (ii) a hydrogen storage unit and (iii) a fuel cell unit would enable seasonal supply-demand balancing in the local power grid and storage of surplus energy in the form of stable solid products. The feasibility of this concept was demonstrated in a case study, taking into account the overall energy balance and economics. The characteristics of the local power grid and the hydrogen round-trip efficiency must be carefully considered when dimensioning the hydrogen units. It was found that industries producing iron and steel, cement, ceramics, glass, aluminum, paper and other metals have the potential for seasonal operation. Future research efforts in the fields of technology, economics and social sciences should support the sustainable flexibility transition of energy-intensive industries with solid products.

1. Introduction

In the future, with a fully decarbonized energy sector based on renewables, maintaining the supply-demand balance will be one of the biggest challenges [1]. This issue will be caused by a large share of intermittent energy production resources (e.g. wind and solar power plants) in the system, which will introduce many more dynamic and unpredictable or hard-to-predict elements into the energy sector. Therefore, flexibility on the demand or supply side will gain significant market value [2].

Flexibility on the energy supply side is limited in the decarbonized society, as the dispatchable generation units are mostly limited to (i) biomass power plants, which require a large amount of fuel that is not always and everywhere available [3], (ii) hybrid solar-biomass power plants [4], (iii) biogas turbines, which are currently mainly in the micro-scale [5], (iv) hydrogen turbines, which are in the testing and development phase [6], (v) hydrogen fuel cells require critical minerals such as Pt to function [7], (vi) pumped-hydro energy systems which require specific terrain topography [8] and (vii) battery energy supply/storage with limited capacity (short-term operation) also require critical minerals [9]. On the other hand, there are many potential candidates on the energy demand side: (i) electric vehicle charging [2], (ii) compressed air energy storage (CAES) systems [10], (iii) heat pumps with heat buffers [2], (iv) pumped-hydro energy systems, (v) water electrolysis [11], (vi) power2X conversion technologies [12], (vii) battery energy supply/storage, and (vii) numerous potential industrial energy users. Moreover, demand-side policies generally have more and greater positive impacts on improving energy security compared to supply-side measures [13]. Industrial energy demand could be (semi-) synchronized with energy supply from some renewable sources through appropriate financial incentives (e.g. government subsidies or time-dependent energy prices), which would enable sector coupling between industry and energy suppliers. This applies to energy in both forms: (i) electrical energy and (ii) hydrogen. While the industrial sector with power demand, e.g. aluminum production [14], could be synchronized with peaks in electricity supply on short time scales (within a day), the larger time scales of seasonal fluctuations should also become supply-demand balanced.

The seasonal energy fluctuations resulting from solar power production at middle and high Earth latitudes [15] and wind power production [16] should be synchronized with the energy demands of the

* Corresponding author. Department of Catalysis and Chemical Reaction Engineering, National Institute of Chemistry, Hajdrihova 19, 1001, Ljubljana, Slovenia.
** Corresponding author.
E-mail addresses: jure.voglar@ki.si (J. Voglar), blaz.likozar@ki.si (B. Likozar).

https://doi.org/10.1016/j.ijhydene.2024.11.018
Received 20 June 2024; Received in revised form 30 October 2024; Accepted 2 November 2024
Available online 6 November 2024
0360-3199/

Abbreviations

CHP	combined heat and power system
SET	sustainable energy technologies
CAES	compressed air energy storage
CCfDs	carbon contracts for difference
CO_2	carbon dioxide
Gt	gigaton
Mt	megaton
TJ	terajoule
EU	European union
DNV GL	Det Norske Veritas
IRENA	International Renewable Energy Agency
PV	photovoltaic
CSP	concentrated solar power
MJ/m^2	megajoule per square meter
N	north of the Equator
Li	lithium
PEM	proton-exchange membrane
kWh	kilowatt-hour
Nm^3	normal cubic meter
BF	blast furnace
DRI	direct reduction iron
H_2	hydrogen (molecular)
CFD	computational fluid dynamics
BOF	basic oxygen furnace
EAF	electric arc furnace
GJ	gigajoule
$CaCO_3$	calcium carbonate
CCS	carbon capture and storage
ESP	electrostatic precipitator
R&D	research and development
GHG	greenhouse gas
LCOH	levelized cost of hydrogen
SO_X	sulfur oxides
NO_X	nitrogen oxides

energy-intensive industrial sector. This could be achieved by producing hydrogen via water electrolysis from the surplus electricity and using the produced hydrogen within the same season (which would allow avoiding the construction and maintenance of huge hydrogen storage facilities) by the industrial sector. Hydrogen is widely used in the oil, gas, petrochemical, aerospace, and automotive industries [17]. Some of the current electrolysis stacks already have very good operational flexibility [18]. The hydrogen produced would be stored in storage tanks close to the industrial plants, which would contain a few days' worth of energy for the selected industrial plant. The industries that would be able to adapt to this seasonal hydrogen operation would benefit from the advantages of a cheaper energy supply. However, the disadvantages of this mode of operation would be associated with seasonal production, such as labor management and an increased need for storage space for their products, unless the season of increased hydrogen supply coincides with their product demand in the market (e.g., increased solar power production used for seasonal cement production would be synchronized with the construction season). The energy would therefore be stored in the form of solid materials, as these are generally more stable (some surface corrosion can occur with metals), easier to handle (warehouse storage) and maintain (no potential leaks compared to fluids).

The decarbonization of industry should go hand in hand with the flexibility transition, as flexible operation of industrial sectors should be environmentally friendly in order to be sustainable. The decarbonization strategies viable for the building materials industry were reviewed by Sbahieh et al. [19]. They identified technological developments as a key factor for the realization of decarbonized building materials. Yao et al. [20] proposed technologies and strategies to decarbonize the chemical industry and analyzed various models such as process simulation, material flow analysis, life cycle assessment, techno-economic analysis and machine learning. An interdisciplinary collaboration between chemical engineering, industrial ecology and economics was proposed to improve the existing integrated models for decarbonization. Environmental and economic assessment of decarbonization strategies for Indian steel industry was carried out considering fuel switching, technology replacement and carbon capture and storage [21]. Hydrogen direct reduction iron pathway results in 84% emission reduction and costs \$112 per ton of carbon dioxide equivalent avoided compared to conventional blast furnace production. The technological aspects of industrial decarbonization are crucial for its implementation. On the other hand, other contextual factors that play an important role must also be considered.

Contextual factors related to industrial decarbonization and the transition to flexibility include economic, financial, political, institutional and social aspects. The impact of green finance on decarbonization has been studied and green bonds have been found to significantly reduce carbon dioxide emissions in both the short and long term [22]. Different types of policy instruments for decarbonization, such as government procurement, taxes and tax exemptions, and green certificates, have been analyzed in terms of technical and socio-economic aspects [23]. With its RePowerEU initiative, the European Commission is planning to subsidize green hydrogen for industry using carbon contracts for difference (CCfDs) to cover the fuel switching costs. CCfDs would cover part of the cost difference between a conventional and a low-carbon product [24]. A case study has shown that CCfDs reduce the cost of carbon abatement in steel production by up to 27% compared to no policy [25]. Since decarbonization policies require public support to be implemented and remain in legislation, a careful analysis of public opinion gives us important insights and can guide us towards targeted actions [26]. Social tipping points describe how social, political, economic or technological systems can quickly transition to a new system state or mode of operation [27]. To support rapid decarbonization, a three-pillared dynamic systems approach to social tipping has been developed. Numerous other contextual factors such as labor management and adaptation [28], a just transition framework [29] and environmental regulations [30] influence the decarbonized flexibility transition of industry, but these are not the main topic of this study as the technical aspects were the main focus.

This review paper examines the new concept of decarbonized, flexible, hydrogen-based solid product production, its feasibility and the current state of technological readiness for its implementation through commodity-based, seasonal energy storage in the energy-intensive solid product industrial sectors. The concept has proven to be feasible in terms of the energy balance and economics. When dimensioning the hydrogen units, the fluctuations of power grid on several time scales should be taken into account. It was found that the payback period is similar to the lifetime of the hydrogen units. Efforts to introduce hydrogen technologies in industry have been most intensive in production of iron and steel, ceramics and glass. A pathway for further development has been identified, leading to the implementation of the concept with a decarbonized, flexible, seasonal hydrogen-based operation of industries with solid products.

1.1. Literature review, knowledge gap and article structure

A large body of research has been conducted on the topic of energy demand flexibility of (residential) buildings [31] and related policy developments [32]. However, demand flexibility or the potential for demand flexibility of various industrial processes has not been frequently considered. Below are some recent relevant examples from the available scientific literature.

Pierri et al. [33] stated that the process industry has the greatest economic potential for demand-side management among industrial consumers. They developed a four-step process industry flexibility assessment methodology and demonstrated its usefulness in a case study of a paper mill in Bayern, Germany. The paper mill's electricity demand was partially replaced by photovoltaic (PV) power supply, resulting in a reduction of specific carbon emissions by 2.5% and 16% in winter and summer, respectively. In this paper mill case study, no change to the existing natural gas-powered combined heat and power (CHP) plant was predicted (except for the electrical connection to the PV panels) and production output was not expected to follow the local energy supply.

The transition to flexibility on the industrial demand side of a county can be monitored using the flexibility index developed by Heffron et al. [34]. Their four-step monitoring approach for flexibility transition consists of: (1) defining policy goals based on a flexibility index, (2) measuring the current state and progress, (3) a stakeholder dialog, and (4) implementing of needed countermeasures. The flexibility index can support the concept of flexibility justice by increasing transparency in the energy system.

Knöttner and Hofmann [35] developed a three-step mixed-integer linear programming optimization model to integrate flexibility into the evaluation of cost-optimal energy supply systems. The total annual costs of a paper mill with full energy carrier flexibility increased by up to 112% compared to the cost-optimal solution, with a significant contribution from increased investment costs. Their approach is suitable for operational optimization alone as well as for combined design and operational optimization.

The social aspects of a just transition to industrial decarbonization were investigated by Gong et al. [36] using the example of container glass production. Public acceptance of sustainable energy technologies (SET) was assessed using a three-dimensional framework consisting of (1) socio-psychological characteristics, (2) perceived internal characteristics, and (3) perceived external contextual factors. The survey was conducted online with 270 valid participants. The results were analyzed and several recommendations for corporate policies and management practices were proposed, such as environmental education and SET promotion via workshops and seminars. Societal contextual factors, alongside technological developments will most likely make a significant contribution to the just transition to a decarbonized society.

The decarbonization of various industrial sectors has been a focus of many recent research studies. The energy-intensive industrial sectors considered were: (i) iron and steel [37], (ii) cement [38], (iii) ceramics [39], (iv) glass [40], and even several industrial sectors were considered [41]. However, a perspective for the provision and implementation of both decarbonized and flexible supply-demand balanced industrial sectors in a future decarbonized power grid is missing.

From the review of available literature, there is a knowledge gap regarding the design, organization and product storage of flexible decarbonized seasonal operation of energy-intensive industrial sectors with solid products. The main novelty of this work is the introduction of a green hydrogen-based method for flexible seasonal production of solid commodities such as cement. The future role of green hydrogen in the production of various solid materials is also investigated.

This article consists of seven main sections. First, Section 1 familiarizes the reader with the need for providing supply-demand power flexibility and current methods to provide it. The second section is dedicated to state-of-the-art research approaches to power flexibility and industry decarbonization and identifies the main knowledge gap. The research methods are described in Section 3, followed by a context description of global carbon dioxide emissions, the energy landscape and its evolution (Section 4). In Section 5, a case study of industrial plants connected to an intermittent renewable power grid was conducted both in short and long term. The future role of green hydrogen in various energy-intensive industrial sectors with solid products is discussed and reviewed in Section 6. Section 7 presents the conclusions and discusses future prospects.

2. Methods

After identifying and describing the main problem with supply-demand power grid balancing with intermittent energy sources, the current state of knowledge was examined and knowledge gap identified. The seasonal production of solids and their use as an alternative energy storage medium has not yet been investigated in the current research literature. Global trends in carbon dioxide emissions associated with energy use were examined to assess potential emission reductions and future power grid developments. A feasibility study was carried out on hypothetical cases of energy-intensive industrial plants to assess the potential issues in the dimensioning, operation and financing of such seasonally flexible production facilities. Unfortunately, due to universality of the main concept of energy storage with solid products and the dependence on specific conditions, such as the type of industry, the characteristics of the local power grid and the optimization objectives (e.g. constant power in the local grid), the main data in this work are not quantitative but rather descriptive. However, this fact does not mean that the proposed innovative method for balancing energy supply and demand is not a viable field for further scientific exploration. A literature review was conducted on the current possibilities of using green hydrogen in various industries, as a certain amount of energy in the form of green hydrogen must be supplied to industrial plants to enable their seasonally flexible operation. In the end, conclusions with perspective for future development were drawn from the results presented.

Fig. 1 illustrates the workflow connected to the research activities and the key aspects related to the decarbonized flexibility transition of the industrial sectors. The limitations of the study lie mainly in the lack of specificity for individual cases of industrial plants and power grids. Since the main concept is universal, it has been described in its general form. Further research studies are encouraged to focus on specific cases and strategies for flexible, decarbonized industrial operation. These studies would provide numerical results, their analysis and interpretation.

3. Context description - CO_2 emissions, energy sources - current state and future perspective

The energy-intensive industrial sectors that are difficult to electrify and are already at least partially adapted to hydrogen energy supply are (i) the iron and steel industry [42], (ii) cement production [43] and (iii) the chemical industry [44]. Global CO_2 emissions from the production of iron and steel, cement and chemicals in 2022 amounted to 2.6 Gt, 2.4 Gt and 935 Mt, respectively [45]. As the chemical industry in most cases produces fluids such as ammonia and methanol, its green hydrogen-based seasonal operation was not examined in this paper, while its decarbonization potential was reviewed by Gailani et al. [41]. The industries also considered were production of ceramics and glass, which emit about 400 Mt [46] and 86 Mt [47] of CO_2 per year globally, respectively. Fig. 2 shows the structure of global CO_2 emissions in 2022 b y sector with a focus on industrial CO_2 sources. Industrial heat accounts for 2/3 of industrial energy demand and almost 1/5 of global energy consumption, while it also accounts for the largest share of direct industrial CO_2 emissions [48].

Within the global energy supply in 2021 only 5.2% of it is renewable (excluding biofuels and nuclear power). On the other hand, the share of renewable energy in the electrical energy generated worldwide is 26.0% [50]. Renewable energy sources are therefore a non-negligible part of the current global electricity mix. Among the renewable sources of electricity wind and solar account for 25.2% and 13.8%, respectively (Fig. 3).

The European union (EU) with its 27 member countries has made

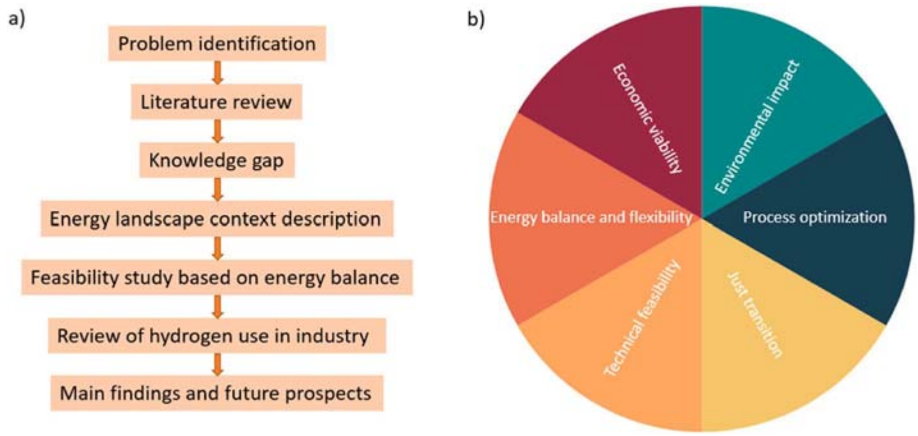

Fig. 1. Flowchart diagram representing the research workflow (a) and important features related to the decarbonized flexibility transition of energy-intensive industries (b).

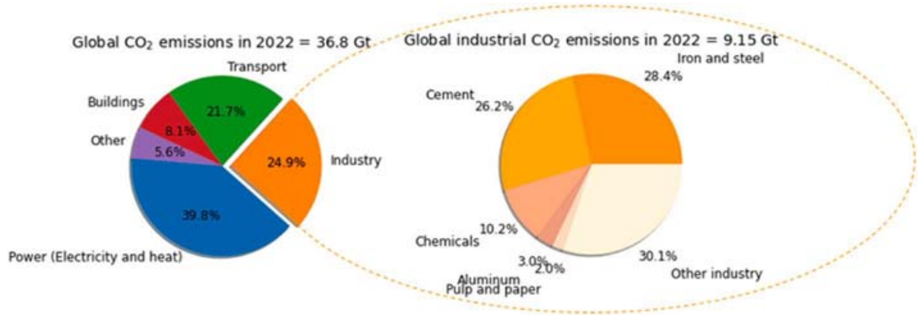

Fig. 2. Global CO_2 emissions in 2022, data source [49].

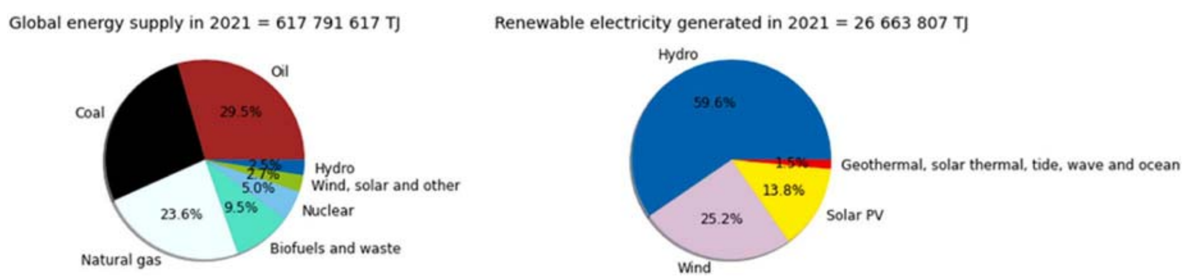

Fig. 3. Global energy supply by source in 2021 (left) and renewable electricity by source (right), data source [50].

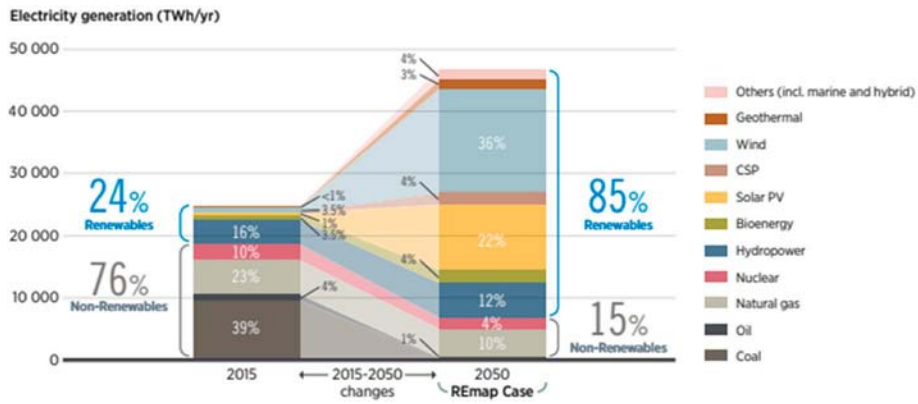

Fig. 4. Perspective for the future electrical energy mix (CSP - concentrated solar power) [54]. Copyright ©IRENA 2018.

great progress in decarbonizing its electricity in 2023, as emission from the EU power sector have decreased by 19% (−157 Mt of CO_2 equivalent), annually. This is the result of a sharp annual reduction of electricity produced from fossil sources (coal power by 26% and gas power by 15%) and a large share (44%) of renewable sources in the electricity mix, with 27% coming from wind and solar energy [51].

As the share of the renewables in the future power grid is expected to increase to 85% (estimated by DNV GL, [52]) or 90% (International Renewable Energy Agency (IRENA) estimate, [53]) by 2050, with the majority of electricity being generated by onshore wind energy and solar photovoltaics (PV) ([54], Fig. 4), the gird stability will have to be balanced and maintained by the demand side.

Looking at the solar PV power source, for example, its potential contribution to the significant seasonal fluctuations in the power fed into the grid can be clearly seen in Fig. 5. The monthly-average solar radiation (calculated over a year) at latitudes 43° 4′ N and 47° 36′ N is 16.2 MJ/m^2 and 13.3 MJ/m^2, respectively. The ratio of maximal to minimal monthly-average value at latitudes 43° 4′ N and 47° 36′ N is 1.83 and 5.64, respectively. Therefore, the seasonal variability of PV output increases rapidly with increasing of the Earth's latitude.

Most solid products (e.g. steel, cement) could be stored relatively easily and used when needed. Therefore, these commodities would allow stable long-term storage of seasonal energy surpluses in the system. The current economic model should be adapted to the new decarbonized energy system to allow the seasonal operation of energy-intensive industries and a higher capacity and duration of storage of their products. Companies need to find a balance between the lower energy cost (their higher power flexibility) and the higher costs of storing their products. It is also worth noting that the transition to using hydrogen will in itself require investments related to adaptations. Financial development experts already envision the green finance transition to sustainable finance in the post-Covid-19 era with various policy options and instruments, such as sovereign green bonds and green securities [56]. Some of these financial development strategies would enable the transition of the energy-intensive solid commodity industry to seasonal flexibility and decarbonization.

4. Case study of industrial plants connected to an intermittent renewable power grid

The energy-intensive industrial plants of the future shall be planned and constructed with the local power grid in mind, so that they can flexibly manage their power demand and, on a smaller scale, their supply. In addition to the necessary production infrastructure, these factories would also have a water electrolysis unit, a hydrogen storage unit and a fuel cell unit. These three units together form an energy buffer that is primarily used to compensate for short-term power fluctuations within a day and up to a few days. For example, when the maximum solar power will be supplied to the grid during the day, the water electrolysis unit would produce hydrogen from the excess electricity and store it to convert it back into electricity during the power shortage the next evening and morning, as shown schematically in Fig. 6(a and b).

The above graphical representation (Fig. 6a and b) is a simplified case, as it does not take into account the power demand of the industrial plant, while the power of the water electrolysis unit must be at least 0.69 of the relative local grid power supply and the power output of the fuel cell unit must be at least 0.31 of the relative local grid power supply. Of course, this case could also be realized without the industrial plant with solid products, but only with a stand-alone unit for balancing the local power grid, which only consists of the three main elements water electrolysis unit, hydrogen storage unit and fuel cell unit. On the other hand, Fig. 6 (c, d) represents the all-day operation of the plant, where the plant has a maximal power consumption of 0.5 of the relative local grid power supply and a maximal water electrolysis unit power of also 0.5 of the relative local grid power supply. A similar approach was taken in Fig. 6 (e and f), with the only difference being that operation of the plant is restricted to an 8-h working schedule (with the exception of the water electrolysis and hydrogen storage units) from 8:00 to 16:00. In both operating modes, additional energy can be supplied to the plant (if required) from the hydrogen storage via the fuel cell unit. At the same time, the entire local grid power supply is used by the plant, which would be desirable if the PV panels were mounted on the factory building. Alternatively, part of the local grid electricity could be used by the factory, while the rest of the grid electricity would be available for other power consumers.

The day-to-day fluctuations of the local grid would be balanced in the same manner as the intra-day fluctuations. It is therefore proposed to dimension the capacity of the hydrogen storage system so that it covers the energy requirements of an industrial plant for a few days of operation. In this way, the daily power fluctuations due to weather conditions (solar radiation and/or wind speed) could be effectively managed while maintaining factory operation.

If the long-term or seasonal power fluctuations and the seasonal flexibility of the plant are considered, the monthly average values of power supply and demand become relevant. The hypothetical local power supply was created using two linear functions for the simulation of the relative local grid power supply, with a maximum value of 1 in August and a minimum value of 0.5 in December, as shown in Fig. 5(a and b).

Four different scenarios were identified for seasonal operation: (1) seasonal operation, (2) constant grid power service, (3) year-round flexible operation and (4) full utilization of local power supply. The maximum power demand of the factory was dependent on the scenario, expressed in relative local grid power, the values are: 0.25 (below 0.5), 0.5, 0.75 (between 0.5 and 1) and 1, for scenarios 1, 2, 3 and 4, respectively. Fig. 7 graphically depicts all four scenarios, where 50% of the factory power is used for hydrogen production and the other 50% as electrical energy. The factory's electrical energy, which is used for water electrolysis and direct electricity use, could of course also be in a different ratio.

Seasonal operation (scenario 1) would in this case (Fig. 7 a) operate for only 5 months of the year. Scenario 2, shown in Fig. 7 (b), provides a

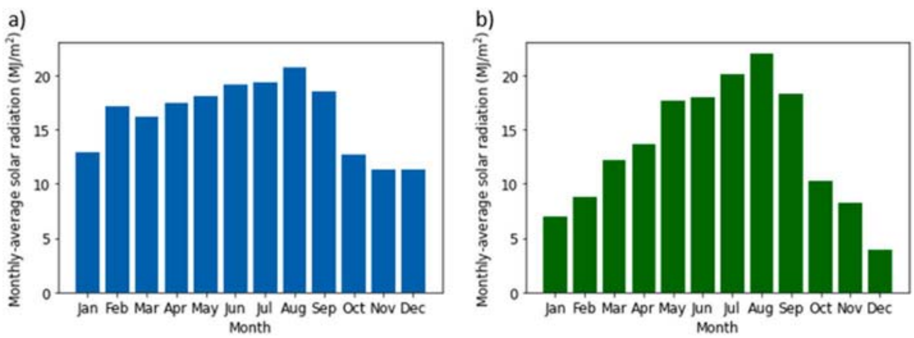

Fig. 5. Calculated monthly-average solar radiation on a tilted surface at latitude angle 43° 4′ N (a) and 47° 36′ N (b), data source [55].

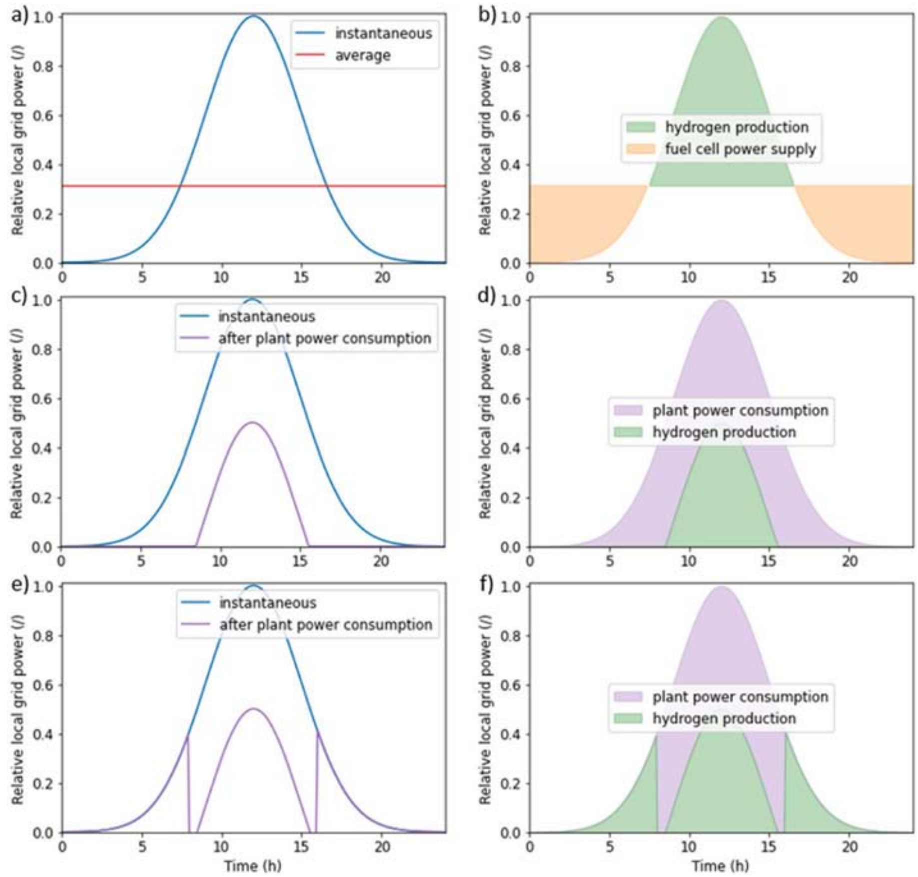

Fig. 6. Graphical representation of the hypothetical daily fluctuation of the local power grid represented with a Gaussian function (a) and its balancing (b) during the period without industrial plant operation (e.g. at weekends) and within the period with continuous (c, d) and 8-h working schedule (e, f) plant operation.

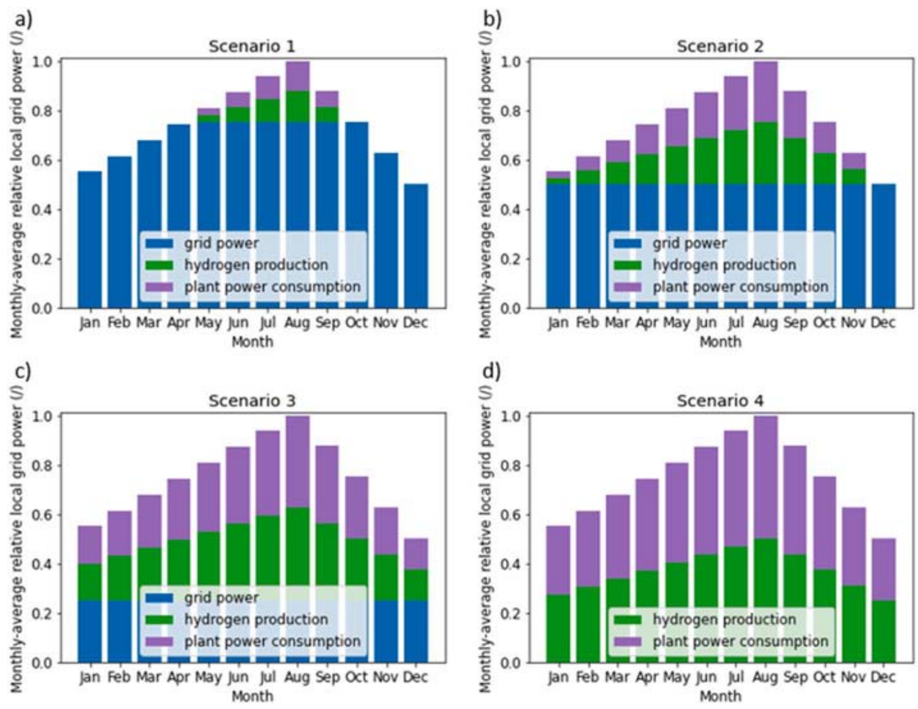

Fig. 7. Four proposed seasonal operation scenarios for energy-intensive industrial plants.

constant local grid power service, while the factory stops operating for one month of the year (December). Scenario 3 (Fig. 7 c) also provides a constant local grid power, but at a lower level than in scenario 2. Therefore, scenario 3 allows flexible operation throughout the year. The last case (scenario 4, Fig. 7 d) consumes the entire available local power supply.

It is worth noting that the planning, design and dimensioning of this type of plants should consider short-term fluctuations in the local grid power supply, as the maximum monthly average values are very likely to be lower than the actual power maxima. If the aim is to completely eliminate local grid power fluctuations, the water electrolysis unit should therefore have a higher maximum power than can be inferred from the monthly average power values alone. Round-trip hydrogen storage (electricity-to-hydrogen-to-electricity) efficiency, which is around 40% at the current state of technology [57], should also be taken into account when dimensioning the hydrogen units.

The work with the case study of industrial plants connected to an intermittent renewable power grid assesses the feasibility of effective and reliable local grid supply-demand balancing. It has been shown that the relative power of plant's direct electrical demand and water electrolysis unit are the key factors influencing the degree of supply-demand balancing done by the industrial facility. Also, the hydrogen storage unit's capacity and power of the fuel cell unit play an important part in the overall management and operation of the industrial facility.

A similar study [33] was carried out, with the difference that it did not consider any changes to the existing factory, but assumed its connection to the PV power supply, which led to partial decarbonization. In addition, power supply fluctuations were not considered in detail, but only at a monthly averaged level. The partial replacement of natural gas with green hydrogen in the production of ceramics was investigated by Sousa et al. [58]. With this mode of operation, the ceramics factory would reduce its CO_2 emissions by 3000 tons per year. A waste heat recovery system (with a steam Rankine cycle connected to an organic Rankine cycle, an alkaline electrolysis unit, oxygen and hydrogen tanks for high-pressure storage, a blending unit and a reactor for the combustion of the blended gas) for a cement plant was developed and analyzed [59]. When the cement furnace was fired with a 20% hydrogen-80% natural gas blend, the CO_2 content in the flue gasses decreased from 34 to 28%. Mati et al. [60] virtually simulated the operation of a paper mill that was retrofitted with PV panels, an electrolyzer, a hydrogen storage system and a hydrogen gas turbine-based cogeneration system. This configuration unfortunately did not provide supply-demand flexibility to the power grid. Ademollo et al. [61] proposed and analyzed a novel hydrogen-based cogeneration system in the pulp and paper industry. Their system was powered by multiple energy sources (e.g. power grid, natural gas and locally produced hydrogen) and was able to reduce CO_2 emissions by 25% compared to a conventional gas turbine-based configuration. The decarbonization and hydrogen integration of the steel industry was studied by Shahabuddin et al. [62]. They concluded that direct reduction of iron with an integrated electric arc furnace is the most mature (full maturity is expected to be reached by 2035) technology to integrate hydrogen, while the process can reduce CO_2 emissions by up to 95%. Different scenarios of off-grid transformation for a food factory were evaluated based on renewable resources considering elements: PV panels, wind turbine, battery, hydrogen storage tank, fuel cell, water electrolyzer and steam methane reformer [63]. Hydrogen production through methane reforming was found to be cheaper than water electrolysis, while water electrolysis provides a decarbonized solution. A grid-connected carpentry workshop with a photovoltaic (PV) plant, a stationary battery and a fleet of electric vehicles was considered to increase the flexibility of the manufacturing system [64]. No study was found in the available literature that includes full decarbonization, flexibility and the use of hydrogen in industrial production. Therefore, the work in Section 5 provides a novel pathway to fully decarbonize and flexibilize several industrial sectors, which could be supported by numerical optimization algorithms such as [35] and multicriteria decision-making approaches [65].

An alternative concept of decarbonized, flexible factories with solid products comes to mind. This concept would require the factory to be fully electrified and have battery energy storage unit that offers a round-trip storage efficiency of around 80% [66], which is significantly higher than in case of hydrogen energy storage (~40%). However, the industry is not yet completely electrified [67] and Li-ion battery storage systems have a duration at rated power of up to ~4 h [68]. Therefore, with the current state of battery technology, only the daily fluctuations in the power grid can be covered to a certain extent. In the future, as the electrification of industry and battery technologies evolve, this concept could provide a more energy-efficient option for decarbonized, flexible factories.

The feasibility of the main concept of green hydrogen-based seasonal operation of energy-intensive industry sectors with solid products has been demonstrated in principle. However, the implementation of this concept either with planning and construction of new plants or with the modification/retrofitting of existing factories would require careful and complex decision making with consideration of numerous influencing factors, such as.

- Local power grid characteristics in short- and long-term with consideration of maximum power, power fluctuations and other local power consumer's needs.
- Collaboration and partnership with local power grid operators to ensure effective supply-demand flexibility.
- Technical characteristics of the industrial sector that determine the proportions and magnitudes of the electricity demand for direct use and the need for green hydrogen.
- Main priorities and their order of importance for the management of the factory, such as: local grid power supply-demand balancing, economic viability (low investment costs, low operating costs, external financial incentives and support), company reputation, social impact on the community, environmental impact, production capacity.
- Labor availability and management, considering work-life balance, stable income, safety and workers' rights.
- Government regulation and support through policy and legal framework.

An estimate of the payback period was made for the three hydrogen units, the results of which are shown in Table 1. The investment and operating costs of the PEM (proton-exchange membrane) electrolysis unit were taken from Ref. [69] and the energy consumption of the

Table 1
Values for payback period estimation of hydrogen units with results.

	PEM electrolyzer	Compressed hydrogen storage tank	Fuel cell
Nominal power (kW)	10	/	5
Storage capacity (Nm^3)	/	60	/
Investment cost (€)	17,500	2700	11,000
Operational cost (€/year)	875	81	219
Time of annual operation (h/year)	1752	/	876
Electrical energy consumed/produced annually (kWh/year)	17,520	/	4380
Price of electrical energy (€/kWh)	−0.05	/	0.50
Total investment costs (€)	31,200		
Total annual income (€/year)	3066		
Total annual operation costs (€/year)	1175		
Annual cash flow (€/year)	1891		
Payback period (year)	16.5		

electrolyzer was assumed to be 5.1 kWh/Nm^3 of hydrogen [70]. The investment cost of the hydrogen storage tank was calculated with the help of [71], while the annual operating costs were assumed to be 3% of the investment cost. The investment and operating costs for the fuel cell were estimated using [72]. The income of the hydrogen units was assumed to come only from the purchase and sale of the electricity, while the hydrogen consumed by the plant was not considered as it is used for the production process. The PEM electrolyzer and the fuel cell would operate at their nominal power equivalents for 20 and 10% of the time, respectively. Dynamic electricity pricing [73] was considered. The electricity consumed by the PEM electrolyzer would have a negative price of −0.05 €/kWh, as negative prices have already occurred on the electricity market [74]. It was assumed that the electricity generated by the fuel cell would be sold to the local power grid at a price of 0.50 €/kWh. The payback period was calculated by dividing the total investment costs by the annual cash flow, resulting in 16.5 years. This period is shorter than the typical lifetime of the hydrogen units (of around 20 years or more) and would therefore allow for the replacement of the hydrogen units at the end of their operation. However, the initial investment would most likely not be fully covered by the operation of the hydrogen units alone, unless external financial support was available.

It is important to note that the calculation of the payback period is based on several assumptions that may not apply in some specific cases. However, the order of magnitude of the results is relevant in several scenarios and it is encouraging to see that the payback period and the lifetime of the hydrogen units have similar values. Financing the construction of hydrogen units and building or retrofitting the factory, as well as building a storage facility, would require substantial initial investment. The greatest potential for shortening the payback period of the hydrogen units is in changing of the electrical energy prices. Forecasts of energy prices should be considered to optimize the operation of hydrogen units as described in Ref. [75].

5. Potential future roles of hydrogen in energy-intensive industrial sectors

The two most important future roles of hydrogen in energy-intensive industrial sectors are (i) as a reducing agent and (ii) as an alternative fuel for process heating through combustion. A summary of the technological readiness for the use of green hydrogen in different sectors is presented in Table 2. Further detailed explanations can be found in the following subchapters.

Table 2
Overview of the different degrees of adoption to hydrogen technologies in energy-intensive industrial sectors with solid products.

	Laboratory experiments	Pilot plants	Industrial facilities	Conceptual design and operation
Iron and steel industry	✔	✔	✔[a]	✔
Cement production	�	�	✔[a]	�
Ceramics industry	�	�	✔[a]	✔
Glass production	�	✔[a]	✔[a]	✔
Aluminum production	�	✔	�	�
Pulp and paper industry	�	�	�	✔
Reduction of non-ferrous metals	✔	✔[a]	✔[b]	�

[a] In construction/progress.
[b] For some metals, especially dedicated laboratory experiments are not necessary in some cases to use hydrogen in the production of solid commodities.

5.1. Hydrogen use in the iron and steel industry

In the production of iron and steel, hydrogen can play two key roles: (i) as a reducing agent to reduce iron oxide and (ii) as a fuel for steel plants [42]. Primary hydrogen metallurgy (conversion of iron ore into iron) can take place in the blast furnace (BF) or in the gas-based direct reduction iron (DRI) process. In secondary hydrogen metallurgy (conversion of pig iron, sponge iron or scrap metal into steels), hydrogen is used as a fuel to preheat the ladle furnace. It is important to know that hydrogen can also be used as a fuel in furnaces for the heat treatment processing of steel.

5.1.1. Ironmaking

Unfortunately, even when injecting pure green hydrogen (the injected gasses usually contain a certain amount of hydrogen - H_2), the BF process still relies on carbon (coke) as the dominant reducing agent and therefore hydrogen cannot completely replace coke in the production of BF pig iron (hot metal in Fig. 8) [42]. Several studies have been conducted on hydrogen injection and its effects on the BF process. Lyu et al. [76] found that the optimum H_2 content of gas-injected BF should be between 5 and 10%. A computational fluid dynamics (CFD) study [77] found that the maximum hydrogen injection that allows stable BF operation is 30 and 15 kg per ton of hot metal for hydrogen alone and in combination with natural gas, respectively. Another CFD modelling approach [78] investigated the co-injection of hydrogen and coal with a turbulent gas-particle flow and different injection schemes. The hydrogen shaft injection was numerically modelled and found to significantly affect the BF performance [79]. The BF process with hydrogen can reduce CO_2 emissions from steelmaking by up to 21.4% [80], but it cannot be fully decarbonized unless the CO_2 would be captured [81]. BF with hydrogen injection is therefore only an intermediate step on the way to a fully decarbonized ironmaking process that requires less adaptation and investment than the direct hydrogen reduction methods.

Hydrogen gas-based direct reduction iron in the shaft furnace (Fig. 8 on the right-hand side) is a fully decarbonized way of iron production (sponge iron is produced). Boretti [82] investigated the market perspective of hydrogen direct reduction of iron and found it to be positive, with important factors such as decarbonization and climate targets, policy support and incentives, investor interest, industry collaboration, technological progress, sustainability and brand value. An experimental study on the H_2 reduction reaction of fine Fe_2O_3 particles was conducted by Li et al. [83] in a vibrating fluidized bed reactor. The maximum yield was 98% at a temperature of 500 °C. A comprehensive study investigated the solar/wind power and electrolysis capacity requirements for grid-assisted renewable hydrogen DRI steel production in an electric arc furnace, where a 70% reduction in emissions (compared to conventional DRI-electric arc furnace steel production) was associated with a 10% increase of costs [84]. Several projects based on the hydrogen DRI process in shaft furnaces are underway around the world, including HYBRIT (Sweden), SALCOS (Germany), and H_2 Green Steel (Sweden) [85]. Research efforts [86] were also directed towards the production of iron by hydrogen plasma reduction of iron ore, which requires lower temperatures than traditional iron ore processing in blast furnaces with coke. Hydrogen plasma iron ore processing requires less energy than carbothermic reduction, mainly because pelletization, sintering and cokemaking are not required.

5.1.2. Steelmaking

In traditional steelmaking, where pig iron is produced with BF, impurities (e.g. carbon) must be removed/oxidized in a basic oxygen furnace (BOF), in which a lance blows high-purity oxygen at supersonic speed over the molten iron [87]. This process inevitably produces CO_2 through the oxidation of carbon and slag through the oxidation of other elements. Therefore, decarbonization of the traditional BOF process would require carbon capture technology. The slag produced in the BOF

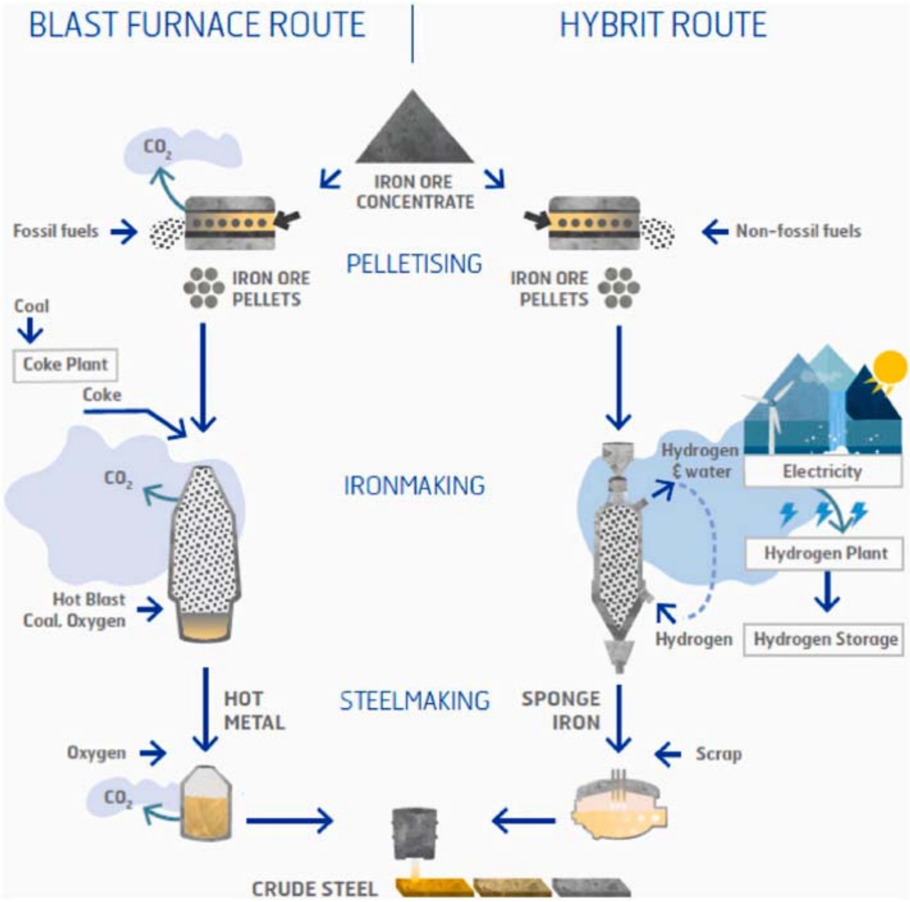

Fig. 8. Comparison between traditional blast furnace (BF) and hydrogen direct reduction iron (DRI) crude steel production [85]. Copyright © 2021 Elsevier Ltd.

process is recovered and recycled. After BOF processing, the alloying elements are added to produce crude steel of the desired grade.

The refining of sponge iron or the melting of scrap metal and its subsequent refining takes place in ladle furnaces. Currently, most ladle furnaces are heated using the electric arc heating method and are referred to as electric arc furnaces (EAFs). They use three graphite electrodes connected to the electrical power supply to heat the material in the vessel [88]. The main heating of the ladle is therefore already electrified. Hydrogen oxyfuel combustion can be used to preheat the ladles, where natural gas is commonly used [89].

Study on the substitution of natural gas with hydrogen for heating with combustion was performed by Aniello et al. [90]. They discovered that an increased hydrogen content leads to overheating and flashback in the multi-perforated premixed natural gas burners and the combustion of pure hydrogen is only possible under ultra-lean conditions. Therefore, the operating parameters of the burner must be carefully modified or even the burner replaced/redesigned [91] in order to achieve stable operation and a comparable heating performance.

The current demand for green hydrogen-based steel is limited and will only account for 2% of total steel production by 2030. However, a period of accelerated growth is expected around 2040. Global demand is expected to reach 660 Mt by 2050, representing 35% of current total steel production [92]. It is therefore expected that the decarbonization of the steel industry will take place in the near future.

5.1.3. *Heat treatment of steel*

Most heat treatments of steel are carried out in natural gas (oxyfuel) furnaces, which with some adaptations could be converted into green hydrogen furnaces [93]. The other option is to replace these steel heat treatment furnaces with electric furnaces [94]. The local energy system and energy prices for electricity and hydrogen should be carefully considered when purchasing/designing the furnaces.

5.2. *Hydrogen use in cement production*

Cement production (Fig. 9) requires about 3.3 GJ of thermal energy per ton of clinker [95]. Fossil fuels used to heat the cement kilns are responsible for approximately 45% of carbon emissions in cement production [96]. Green hydrogen and/or electrification could potentially provide up to 100% of the heat in the system, but the complexity and cost of developing and deploying hydrogen-powered kilns is high [97]. The CEMEX plant in Spain already uses a mixture of natural gas and hydrogen for combustion in a kiln [87], while CEMEX and the Finnish-Dutch company Coolbrook are looking at ways to fully electrify the cement production process [96]. However, no fuel for the heat supply avoids the process emissions from the calcination of $CaCO_3$. To achieve complete decarbonization of cement production, carbon capture and storage (CCS) or CO_2 utilization technologies must therefore be deployed [98]. A concept for the production of synthetic fuels using CO_2 from the cement industry and green hydrogen was developed and analyzed by León et al. [99].

5.3. *Use of hydrogen in the production of ceramics*

The production of ceramics, including bricks, tiles, clay pipes, refractory materials, expanded clay aggregates and sanitaryware takes place in multiple consecutive steps: (i) preparation of raw materials (milling with/without spray drying or drying), (ii) forming (isostatic pressing, extrusion or pressure casting), (iii) drying (water removal usually with waste heat from the kiln), (iv) heating (in most cases to

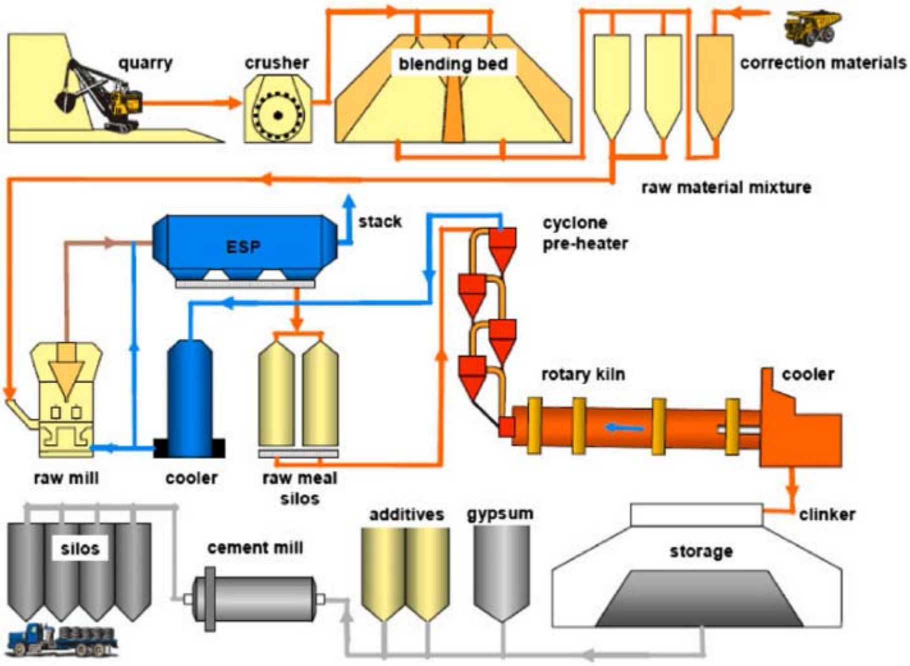

Fig. 9. Schematic representation of cement production (ESP - electrostatic precipitator) [100]. Copyright © 2012 Elsevier Ltd.

800 °C to degas the pieces), (v) firing (between 850 and 1350 °C, reducing porosity), cooling (vi), (vii) sorting and packaging (Fig. 10, [101]).

Project for the use of hydrogen in the ceramics industry is already being developed by Iberdrola and Porcelanosa [102,103]. It is important to note that hydrogen has different properties than natural gas and hence requires specialized burners for heating applications [101]. Ding et al. showed that the use of green hydrogen for firing can reduce emissions by 30.1%. Fuel switching to hydrogen has been highlighted as one of the viable solutions for decarbonizing the heavy clay industry [104].

5.4. Glass produced with green hydrogen

Glass products can be divided into three main categories: (i) container glass, (ii) flat glass, and (iii) glass fibers. Electrical melting and (oxyfuel) hydrogen combustion or a combination of both, so-called hybrid melting, are the most promising options to decarbonize the glass industry, although further research and development (R&D) efforts are needed [106]. Around 80% of the total energy required for glass production is consumed when heating (melting in Fig. 11) the raw materials in a furnace at a temperature of more than 1500 °C [107]. The projects H2GLASS [108], HyGlass [109], HyNet [110], Glass Futures [111] and Kopernikus P2X [112] deal with hydrogen and its feasibility as an alternative energy source for combustion in the glass industry. The waste heat recovery is also an important step towards increasing the sector's energy efficiency.

The decarbonization of glass production is the topic of multiple literature sources. A bottom-up model was developed to accurately predict the future CO_2 emissions of the German container and flat glass industry, taking into account different technical pathways [40]. The fuel switching measures were consistent with the temperature increase of 2 °C above pre-industrial levels. Del Rio et al. [107] reviewed the available literature and found that there is no consensus on the most promising technologies to achieve net-zero emissions in the glass industry, which is associated with numerous barriers such as economic viability and infrastructural capacity. UK technology roadmaps for the decarbonization of the glass sector have been developed based on three scenarios with greenhouse gas (GHG) emission reductions by 2050 (compared to 1990) of 78, 88, and 79% [113].

5.5. Hydrogen in other industries

In addition to the production of iron and steel, cement, ceramics and glass, hydrogen can also be used as a reducing agent or energy source in other industries with solid products.

5.5.1. Aluminum production

Aluminum production emitted 270 Mt of CO_2 worldwide in 2022 (about 3% of the world's direct industrial CO_2 emissions) [45]. Alumina refining of bauxite ore, known as the Bayer process [115], requires large quantities of heat, which could be provided by hydrogen burners. The production of carbon anodes (for aluminum smelting) requires calcined petroleum coke, coal tar, petroleum pitch and/or cleaned recycled anodes, which are baked in furnaces at 1100 °C [116], the energy source for baking could again be hydrogen. The final stage of aluminum production is aluminum smelting (Hall-Héroult process), which is an electrolytic reduction of aluminum oxide dissolved in molten cryolite and requires energy in the form of electricity [117]. The heat for the production of secondary aluminum (remelting and recycling of aluminum) could also be applied by hydrogen combustion. The company Hydro Havrand has produced the world's inaugural batch of recycled aluminum powered by renewable hydrogen in Navarra, Northern Spain [118]. Heat for the casting of aluminum parts [119] and the heat treatment of aluminum alloys [120] could also be decarbonized through the use of hydrogen.

5.5.2. Pulp and paper industry

The pulp and paper industry is responsible for approximately 6% of global industrial energy consumption and 2% of direct industrial CO_2 emissions [121]. Decarbonizing the pulp and paper industry or reducing its emissions can be performed with several (41) different technologies, processes and emerging options, with no single approach standing out. However, financial and economic aspects were identified as the main barriers. A case study of a decarbonized paper mill with PV power plant, water electrolysis unit, hydrogen storage, hydrogen-based cogeneration system and power grid connection (Fig. 12) was conducted by Mati et al. [60]. The system they proposed consumes 4209 tons of green hydrogen

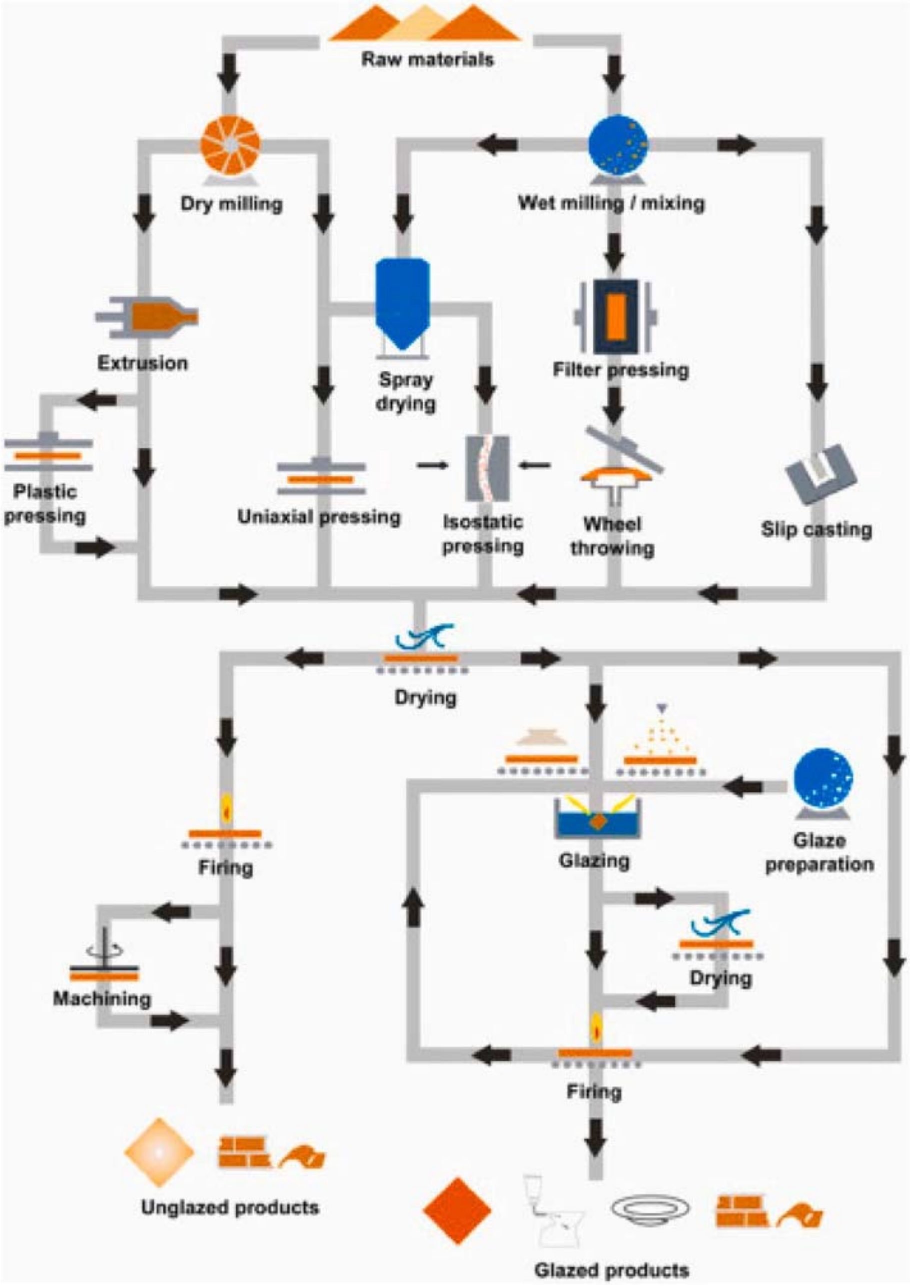

Fig. 10. Traditional manufacturing process for ceramics [105]. Copyright © 2014 Elsevier Ltd.

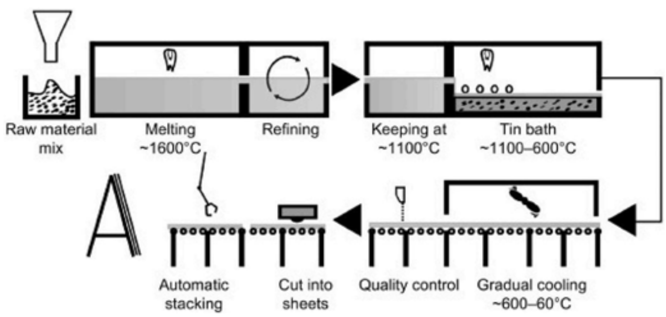

Fig. 11. Flat glass production using the float glass process developed by Pilkington Brothers in 1959 [114]. Copyright © 2016 Elsevier Ltd.

per year, which enables a saving of 29,273 tons of direct annual CO_2 emissions. On the other hand, the investment costs for systems of this size are prohibitive. Obrist et al. [122] investigated different technology pathways of the Swiss pulp and paper industry to achieve climate and energy policy goals. Hydrogen was not identified as a cost-optimal fuel for heating, but as an intermediate source for heating before the transition to high-temperature heat pumps. Net-zero CO_2 emissions by 2050 were proposed to be achieved with electrification of the heat supply with high-temperature heat pumps and biomass CHPs.

5.5.3. Reduction of non-ferrous metals

Hydrogen can be a reducing agent in the processing of non-ferrous metal oxides. This technology is already used commercially for tungsten (W), molybdenum (Mo), nickel (Ni) and cobalt (Co). It could also be used for a variety of other metals, e.g. Cu, Ti, Cr, Mn, and the recovery of valuable metals from secondary resources (e.g. Zn from EAF dust, Pb

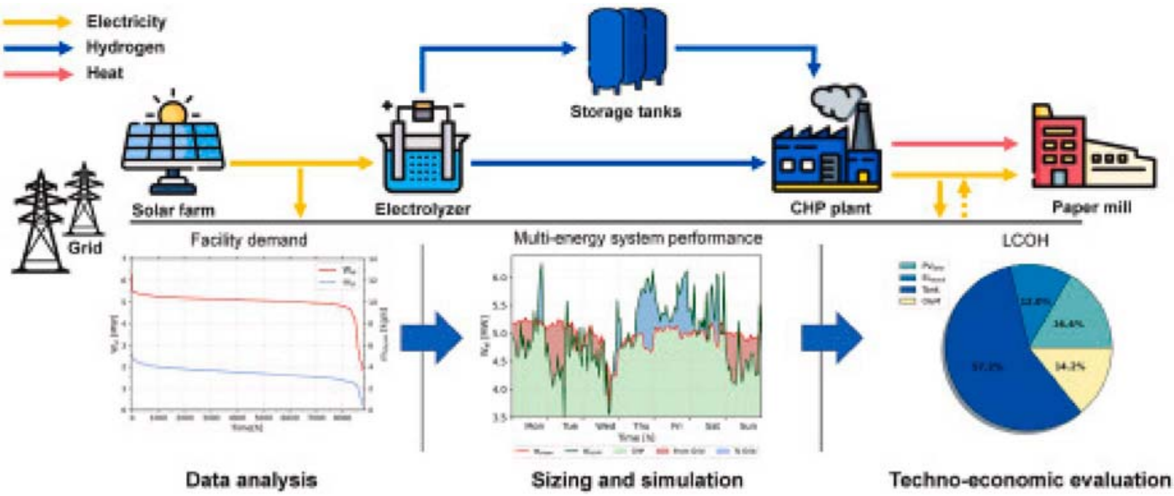

Fig. 12. Schematic representation of a decarbonized paper mill and its analysis (CHP - combined heat and power system, LCOH - levelized cost of hydrogen) [60].

from slag) [123]. The HARARE project [124] aims to use hydrogen as a reducing agent for the recovery of metals from metallurgical waste originating from copper and aluminum production processes. Hydrogen plasma reduction processes for the reduction of oxide minerals offer potential for future developments [125].

6. Conclusions and future prospects

In the present work, an initial literature review has highlighted the research gap in the planning, organization and product storage of flexible, decarbonized seasonal operation of energy-intensive industry sectors with solid products. This was the impetus for an innovative method for a green hydrogen-based sustainable decarbonized flexible operation of industrial facilities with three additional elements: (i) water electrolysis unit, (ii) hydrogen storage unit and (iii) fuel cell unit. The concept was investigated through a feasibility study for industrial plants connected to an intermittent renewable power grid and providing supply-demand energy balancing. The presented case study revealed that appropriate dimensioning of the three additional factory units is crucial for providing the desired level of supply-demand balancing, which was demonstrated by four proposed seasonal operating scenarios. In particular, in cases where the power generation unit is mounted on the factory building (e.g. PV panels) or located nearby (to avoid transmission losses), it is desirable that all the electricity generated is consumed by the industrial subject. The practical implementation of the novel concept would be linked to six identified groups of key influencing factors: (i) characteristics of the local power grid, (ii) cooperation and partnership with the local power grid operators, (iii) technical characteristics of the industrial sector, (iv) main priorities and their sequencing, (v) availability of labor and management, and (vi) government regulation and support. The economic viability of the case was examined calculating the payback period of hydrogen units. It was found that the payback period of 16.5 years is in a similar timeframe to the typical lifetime of hydrogen units, which is encouraging. The main impact on the economics of industrial projects of this type will be future electricity prices. The planning of new industrial plants or the retrofitting of existing plants could be carried out with the help of modern computational tools via optimization algorithms and possibly also artificial intelligence.

The current and future role of hydrogen in industrial facilities with solid products was examined on the basis of a literature review. It was found that the iron and steel industry is the most mature part of the energy-intensive industry in terms of the use of green hydrogen, as several laboratory studies as well as pilot-scale studies have been conducted or are currently underway. The use of hydrogen in cement production, on the other hand, is mainly conceptually studied, with the exception of the natural gas/hydrogen kiln. A similar level of research can be seen in the use of hydrogen in the ceramics industry, where an industrial-scale project is underway. In contrast, there are several projects to decarbonize glass production. Other industrial sectors could also supply heat via the combustion of green hydrogen, e.g. aluminum production and the pulp and paper industry. Hydrogen can also serve as a reducing agent for the production or recovery of certain non-ferrous metals, e.g. Pb, Zn, Cu.

Current limitations and potential problems in implementing the concept of seasonal based industrial operation are: (i) the need for research and development (R&D) of hydrogen technologies and their implementation in industrial sectors, (ii) high investment costs, (iii) an increased need for product storage, (iv) the seasonal need for manpower and the potential socio-economic problems associated with it, unless a high degree of robotization is introduced, and (v) the need for prudent energy management and careful planning (electricity and stored hydrogen). On the other hand, seasonal operation of the industry will bring the following benefits: (i) lower energy prices, (ii) energy independence and sovereignty - independence from foreign energy sources (iii) ensuring stability of the power grid, (iv) decarbonized production, (v) oxygen produced by water electrolysis that could be used for oxyfuel H_2 combustion or as a chemical in industrial processes or sold on the market, and (vi) reduction of other harmful pollutants such as SO_X, NO_X and particulate matter.

Future research efforts should focus on the following: (i) conducting detailed case studies on flexible, decarbonized, seasonal operation of energy-intensive industry sectors with solid products and also industry in general, (ii) creating multifactorial optimization methods/algorithms for the design, dimensioning and management of future flexible, decarbonized factories, (iii) financial development of instruments that enable sustainable, decarbonized production of commodities, (iv) policy development for a decarbonized, flexible industry and their subsequent implementation by governments, (v) further investigation of technological pathways focusing on electrification and hydrogen use towards a decarbonized energy-intensive industry, (vi) further social science research into public opinion on industrial decarbonization and strategies to create positive attitudes towards a just transition to a decarbonized society, and (vi) development of effective approaches to human resource management in relation to seasonal variations in workload.

CRediT authorship contribution statement

Jure Voglar: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Blaž Likozar:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Data availability

Data will be made available on request.

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.

Acknowledgements

B.L. thanks the Slovenian Research and Innovation Agency for support through core funding P2-0152 and project funding J7-4638, N2-0291. B.L. thanks the European Regional Development Fund for funding the H2GreenFUTURE project. B.L. also gratefully acknowledges the support of the HyBReED program, which is co-financed by the Republic of Slovenia, the Ministry of Higher Education, Science and Innovation and the European Union - NextGenerationEU.

References

[1] Laimon M, Mai T, Goh S, Yusaf T. Energy sector development: system dynamics analysis. Appl Sci 2019;10:134.
[2] Schaeffer GJ. Energy sector in transformation, trends and prospects. Procedia Comput Sci 2015;52:866–75.
[3] Teixeira TR, Ribeiro CAAS, dos Santos AR, Marcatti GE, Lorenzon AS, de Castro NLM, et al. Forest biomass power plant installation scenarios. Biomass Bioenergy 2018;108:35–47.
[4] Osat M, Shojaati F, Osat M. A solar-biomass system associated with CO2 capture, power generation and waste heat recovery for syngas production from rice straw and microalgae: technological, energy, exergy, exergoeconomic and environmental assessments. Appl Energy 2023;340:120999.
[5] Zhu G, Chow T-T, Lee C-K. Performance analysis of biogas-fueled Maisotsenko combustion turbine cycle. Appl Therm Eng 2021;195:117247.
[6] Cappelletti A, Martelli F. Investigation of a pure hydrogen fueled gas turbine burner. Int J Hydrogen Energy 2017;42:10513–23.
[7] Felseghi R-A, Carcadea E, Raboaca MS, Trufin CN, Filote C. Hydrogen fuel cell technology for the sustainable future of stationary applications. Energies 2019; 12:4593.
[8] Blakers A, Stocks M, Lu B, Cheng C. A review of pumped hydro energy storage. Progress in Energy 2021;3:022003.
[9] Hesse HC, Schimpe M, Kucevic D, Jossen A. Lithium-ion battery storage for the grid—a review of stationary battery storage system design tailored for applications in modern power grids. Energies 2017;10:2107.
[10] Kosowski K, Piwowarski M, Włodarski W, Ziemiański P, Pawlak G. Technical and economic analysis of energy storage in the compressed air technology with low capacity for the production plant. Energy Convers Manag 2023;282:116872.
[11] Almutairi K, Dehshiri SSH, Dehshiri SJH, Mostafaeipour A, Techato K. An economic investigation of the wind-hydrogen projects: a case study. Int J Hydrogen Energy 2022;47:25880–98.
[12] Mirzaei MA, Mehrjerdi H, Saatloo AM. Look-ahead scheduling of energy-water nexus integrated with Power2X conversion technologies under multiple uncertainties. Sustain Cities Soc 2023;99:104902.
[13] Bento N, Grubler A, Boza-Kiss B, De Stercke S, Krey V, McCollum DL, et al. Leverage demand-side policies for energy security. Science 1979;383:946–9. 2024.
[14] Kvande H. The aluminum smelting process. J Occup Environ Med 2014;56:S2.
[15] Vasisht MS, Srinivasan J, Ramasesha SK. Performance of solar photovoltaic installations: effect of seasonal variations. Sol Energy 2016;131:39–46.
[16] Ouammi A, Dagdougui H, Sacile R, Mimet A. Monthly and seasonal assessment of wind energy characteristics at four monitored locations in Liguria region (Italy). Renew Sustain Energy Rev 2010;14:1959–68.
[17] Hosseini Dehshiri SJ, Amiri M. An integrated multi-criteria decision-making framework under uncertainty for evaluating sustainable hydrogen production strategies based on renewable energies in Iran. Environ Sci Pollut Control Ser 2023;30:46058–73.
[18] Lange H, Klose A, Lippmann W, Urbas L. Technical evaluation of the flexibility of water electrolysis systems to increase energy flexibility: a review. Int J Hydrogen Energy 2023;48:15771–83.
[19] Sbahieh S, Serdar MZ, Al-Ghamdi SG. Decarbonization strategies of building materials used in the construction industry. Mater Today Proc 2023.
[20] Yao Y, Lan K, Graedel TE, Rao ND. Models for decarbonization in the chemical industry. Annu Rev Chem Biomol Eng 2024;15.
[21] Johnson S, Deng L, Gençer E. Environmental and economic evaluation of decarbonization strategies for the Indian steel industry. Energy Convers Manag 2023;293:117511.
[22] Al Mamun M, Boubaker S, Nguyen DK. Green finance and decarbonization: evidence from around the world. Financ Res Lett 2022;46:102807.
[23] Peñasco C, Anadón LD, Verdolini E. Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. Nat Clim Change 2021;11: 257–65.
[24] International Renewable Energy Agency (IRENA). Carbon contracts for difference. n.d. https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-hydrogen/16-Carbon-contracts-for-difference. [Accessed 23 October 2024].
[25] Richstein JC, Neuhoff K. Carbon contracts-for-difference: how to de-risk innovative investments for a low-carbon industry? iScience 2022;25.
[26] Bretter C, Schulz F. Public support for decarbonization policies in the UK: exploring regional variations and policy instruments. Clim Pol 2024;24:117–37.
[27] Eker S, Wilson C, Höhne N, McCaffrey MS, Monasterolo I, Niamir L, et al. Harnessing social tipping dynamics: a systems approach for accelerating decarbonization. One Earth 2024;7:976–88.
[28] Mayfield E, Jenkins J, Larson E, Greig C. Labor pathways to achieve net-zero emissions in the United States by mid-century. Energy Pol 2023;177:113516.
[29] Upham P, Sovacool B, Ghosh B. Just transitions for industrial decarbonisation: a framework for innovation, participation, and justice. Renew Sustain Energy Rev 2022;167:112699.
[30] Yang L, Ma Z, Ma M, Xu Y. Decarbonization, environmental regulation, and economic boom: an indicator assessment based on the industrial waste. Front Energy Res 2022;9:838852.
[31] Li H, Wang Z, Hong T, Piette MA. Energy flexibility of residential buildings: a systematic review of characterization and quantification methods and applications. Advances in Applied Energy 2021;3:100054.
[32] Mlecnik E, Parker J, Ma Z, Corchero C, Knotzer A, Pernetti R. Policy challenges for the development of energy flexibility services. Energy Pol 2020;137:111147.
[33] Pierri E, Hellkamp D, Thiede S, Herrmann C. Enhancing energy flexibility through the integration of variable renewable energy in the process industry. Procedia CIRP 2021;98:7–12.
[34] Heffron R, Körner M-F, Wagner J, Weibelzahl M, Fridgen G. Industrial demand-side flexibility: a key element of a just energy transition and industrial development. Appl Energy 2020;269:115026.
[35] Knöttner S, Hofmann R. Assessment and conceptualization of industrial energy flexibility supply in mathematical optimization in a competitive and changing environment. Energy Convers Manag 2024;304:118205.
[36] Gong Y, Zhang S, Lun X, Sun Y. Just transition as practitioners' acceptance of technical solutions to decarbonize: insights from the glass manufacturing industry. Energy Pol 2024;192:114268.
[37] Kazmi B, Taqvi SAA, Juchelková D. State-of-the-art review on the steel decarbonization technologies based on process system engineering perspective. Fuel 2023;347:128459.
[38] Griffiths S, Sovacool BK, Del Rio DDF, Foley AM, Bazilian MD, Kim J, et al. Decarbonizing the cement and concrete industry: a systematic review of socio-technical systems, technological innovations, and policy options. Renew Sustain Energy Rev 2023;180:113291.
[39] Ding K, Li A, Lv J, Gu F. Decarbonizing ceramic industry: technological routes and cost assessment. J Clean Prod 2023;419:138278.
[40] Zier M, Pflugradt N, Stenzel P, Kotzur L, Stolten D. Industrial decarbonization pathways: the example of the German glass industry. Energy Convers Manag X 2023;17:100336.
[41] Gailani A, Cooper S, Allen S, Pimm A, Taylor P, Gross R. Assessing the potential of decarbonization options for industrial sectors. Joule 2024.
[42] Liu W, Zuo H, Wang J, Xue Q, Ren B, Yang F. The production and application of hydrogen in steel industry. Int J Hydrogen Energy 2021;46:10548–69.
[43] Juangsa FB, Cezeliano AS, Darmanto PS, Aziz M. Thermodynamic analysis of hydrogen utilization as alternative fuel in cement production. S Afr J Chem Eng 2022;42:23–31.
[44] Rambhujun N, Salman MS, Wang T, Pratthana C, Sapkota P, Costalin M, et al. Renewable hydrogen for the chemical industry. MRS Energy & Sustainability 2020;7:E33.
[45] International Energy Agency: IEA. Net Zero Roadmap. A global pathway to keep the 1.5 °C goal in reach. n.d. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach. [Accessed 28 February 2024].
[46] Del Rio DDF, Sovacool BK, Foley AM, Griffiths S, Bazilian M, Kim J, et al. Decarbonizing the ceramics industry: a systematic and critical review of policy options, developments and sociotechnical systems. Renew Sustain Energy Rev 2022;157:112081.
[47] Westbroek CD, Bitting J, Craglia M, Azevedo JMC, Cullen JM. Global material flow analysis of glass: from raw materials to end of life. J Ind Ecol 2021;25: 333–43.
[48] International Energy Agency: IEA. Clean and efficient heat for industry n.d. https://www.iea.org/commentaries/clean-and-efficient-heat-for-industry. [Accessed 29 February 2024].

[49] International Energy Agency: IEA. CO2 Emissions in 2022 n.d. https://www.iea.org/reports/co2-emissions-in-2022. [Accessed 29 February 2024].
[50] International Energy Agency: IEA. Energy statistics data browser n.d. https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Energy/20supply&indicator=TESbySource. [Accessed 29 February 2024].
[51] Brown Sarah, Jones Dave. European Electricity Review 2024 n.d. https://ember-climate.org/insights/research/european-electricity-review-2024/. [Accessed 24 April 2024].
[52] European Commission. Renewable energy sources to account for 85% of global electricity production by 2050. n.d. https://smart-networks-energy-transition.ec.europa.eu/news/renewable-energy-sources-account-85-global-electricity-production-2050. [Accessed 29 February 2024].
[53] United Nations. Renewable energy – powering a safer future n.d. https://www.un.org/en/climatechange/raising-ambition/renewable-energy. [Accessed 29 February 2024].
[54] International Renewable Energy Agency (IRENA). Global Energy Transformation: A Roadmap to 2050 n.d. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf (accessed March 1, 2024).
[55] Vijayakumar G, Kummert M, Klein SA, Beckman WA. Analysis of short-term solar radiation data. Sol Energy 2005;79:495–504.
[56] Falcone PM, Sica E. Sustainable finance and the global health crisis. Taylor & Francis; 2023.
[57] Adams MJ, Wadge MD, Sheppard D, Stuart A, Grant DM. Review on onshore and offshore large-scale seasonal hydrogen storage for electricity generation: focusing on improving compression, storage, and roundtrip efficiency. Int J Hydrogen Energy 2024;73:95–111.
[58] Sousa J, Azevedo I, Camus C, Mendes L, Viveiros C, Barata F. Decarbonizing hard-to-abate sectors with renewable hydrogen: a real case application to the ceramics industry. Energies 2024;17:3661.
[59] Ozturk M, Dincer I. Utilization of waste heat from cement plant to generate hydrogen and blend it with natural gas. Int J Hydrogen Energy 2022;47:20695–704.
[60] Mati A, Ademollo A, Carcasci C. Assessment of paper industry decarbonization potential via hydrogen in a multi-energy system scenario: a case study. Smart Energy 2023;11:100114.
[61] Ademollo A, Mati A, Pagliai M, Carcasci C. Exploring the role of hydrogen in decarbonizing energy-intensive industries: a techno-economic analysis of a solid oxide fuel cell cogeneration system. J Clean Prod 2024;469:143254.
[62] Shahabuddin M, Brooks G, Rhamdhani MA. Decarbonisation and hydrogen integration of steel industries: recent development, challenges and technoeconomic analysis. J Clean Prod 2023;395:136391.
[63] Li X, Gao J, You S, Zheng Y, Zhang Y, Du Q, et al. Optimal design and techno-economic analysis of renewable-based multi-carrier energy systems for industries: a case study of a food factory in China. Energy 2022;244:123174.
[64] Bartolucci L, Cordiner S, Mulone V, Santarelli M, Lombardi P, Arendarski B. Towards Net Zero Energy Factory: a multi-objective approach to optimally size and operate industrial flexibility solutions. Int J Electr Power Energy Syst 2022;137:107796.
[65] Hosseini Dehshiri SJ, Zanjirchi SM. Comparative analysis of multicriteria decision-making approaches for evaluation hydrogen projects development from wind energy. Int J Energy Res 2022;46:13356–76.
[66] Dufo-López R, Bernal-Agustín JL. Techno-economic analysis of grid-connected battery storage. Energy Convers Manag 2015;91:394–404.
[67] Wei M, McMillan CA, de la Rue du Can S. Electrification of industry: potential, challenges and outlook. Current Sustainable/Renewable Energy Reports 2019;6:140–8.
[68] Albertus P, Manser JS, Litzelman S. Long-duration electricity storage applications, economics, and technologies. Joule 2020;4:21–32.
[69] United States Department of Energy. DOE hydrogen program record 24005: clean hydrogen production cost scenarios with PEM electrolyzer technology. n.d. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf?sfvrsn=8cb10889_1. [Accessed 24 September 2024].
[70] Astriani Y, Tushar W, Nadarajah M. Optimal planning of renewable energy park for green hydrogen production using detailed cost and efficiency curves of PEM electrolyzer. Int J Hydrogen Energy 2024;79:1331–46.
[71] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M. Large-scale compressed hydrogen storage as part of renewable electricity storage systems. Int J Hydrogen Energy 2021;46:15671–90.
[72] Cigolotti Mg V. Stationary fuel cell applications n.d. https://www.ieafuelcell.com/fileadmin/publications/2021/2021_AFCTCP_Stationary_Application_Performance.pdf. [Accessed 24 September 2024].
[73] Mayyas A, Wei M, Levis G. Hydrogen as a long-term, large-scale energy storage solution when coupled with renewable energy sources or grids with dynamic electricity pricing schemes. Int J Hydrogen Energy 2020;45:16311–25.
[74]] Seel J, Millstein D, Mills A, Bolinger M, Wiser R. Plentiful electricity turns wholesale prices negative. Advances in Applied Energy 2021;4:100073.
[75] Grueger F, Hoch O, Hartmann J, Robinius M, Stolten D. Optimized electrolyzer operation: employing forecasts of wind energy availability, hydrogen demand, and electricity prices. Int J Hydrogen Energy 2019;44:4387–97.
[76] Lyu Q, Qie Y, Liu X, Lan C, Li J, Liu S. Effect of hydrogen addition on reduction behavior of iron oxides in gas-injection blast furnace. Thermochim Acta 2017;648:79–90.
[77] Okosun T, Nielson S, Zhou C. Blast furnace hydrogen injection: investigating impacts and feasibility with computational fluid dynamics. JOM 2022;74:1521–32.
[78] Liu Y, Hu Z, Shen Y. CFD study of hydrogen injection in blast furnaces: tuyere co-injection of hydrogen and coal. Metall Mater Trans B 2021;52:2971–91.
[79] Yu X, Hu Z, Shen Y. Modeling of hydrogen shaft injection in ironmaking blast furnaces. Fuel 2021;302:121092.
[80] Yilmaz C, Wendelstorf J, Turek T. Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. J Clean Prod 2017;154:488–501.
[81] Oda J, Akimoto K, Sano F, Homma T. Diffusion of CCS and energy efficient technologies in power and iron & steel sectors. Energy Proc 2009;1:155–61.
[82] Boretti A. The perspective of hydrogen direct reduction of iron. J Clean Prod 2023;429:139585.
[83] Li S, Zhang H, Nie J, Dewil R, Baeyens J, Deng Y. The direct reduction of iron ore with hydrogen. Sustainability 2021;13:8866.
[84] Elsheikh H, Eveloy V. Renewable hydrogen based direct iron ore reduction and steel making with grid assistance. Energy Convers Manag 2023;297:117544.
[85] Wang RR, Zhao YQ, Babich A, Senk D, Fan XY. Hydrogen direct reduction (H-DR) in steel industry—an overview of challenges and opportunities. J Clean Prod 2021;329:129797.
[86] Sabat KC, Murphy AB. Hydrogen plasma processing of iron ore. Metall Mater Trans B 2017;48:1561–94.
[87] Pisciotta M, Pilorge H, Feldmann J, Jacobson R, Davids J, Swett S, et al. Current state of industrial heating and opportunities for decarbonization. Prog Energy Combust Sci 2022;91:100982.
[88] Daneshmand S, Vini MH. Investigation of TiO2/SiC coating on graphite electrodes for electrical arc furnaces. J Mater Eng Perform 2024;33:3188–206.
[89] Iplik E, Adendorff M, Muren D. Hydrogen oxyfuel combustion for energy-intensive industries. Clean energy technologies-hydrogen and gasification processes. IntechOpen; 2022.
[90] Aniello A, Poinsot T, Selle L, Schuller T. Hydrogen substitution of natural-gas in premixed burners and implications for blow-off and flashback limits. Int J Hydrogen Energy 2022;47:33067–81.
[91] Palacios A, Bradley D. Conversion of natural gas jet flame burners to hydrogen. Int J Hydrogen Energy 2021;46:17051–9.
[92] Watari T, McLellan B. Global demand for green hydrogen-based steel: insights from 28 scenarios. Int J Hydrogen Energy 2024;79:630–5.
[93] Schmitz N, Sankowski L, Kaiser F, Schwotzer C, Echterhof T, Pfeifer H. Towards CO2-neutral process heat generation for continuous reheating furnaces in steel hot rolling mills–a case study. Energy 2021;224:120155.
[94] Cucos I, Munteanu C, Mirea C. The electric furnaces for heat treatment with PID predictiv system. Appl Mech Mater 2015;809:778–83.
[95] Schorcht F, Kourti I, Scalet BM, Roudier S, Delgado SL. Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide: industrial emissions directive 2010/75/EU:(Integrated pollution prevention and control). 2013.
[96] CEMEX. CEMEX and Coolbrook electrify cement production process. n.d. https://www.cemex.com/w/cemex-and-coolbrook-electrify-cement-production-process. [Accessed 1 March 2024].
[97] Fennell PS, Davis SJ, Mohammed A. Decarbonizing cement production. Joule 2021;5:1305–11.
[98] Schneider M, Hoenig V, Ruppert J, Rickert J. The cement plant of tomorrow. Cement Concr Res 2023;173:107290.
[99] León D, Amez I, Castells B, Ortega MF, Bolonio D. Techno-economic analysis of the production of synthetic fuels using CO2 generated by the cement industry and green hydrogen. Int J Hydrogen Energy 2024;80:406–17.
[100] de Queiroz Lamas W, Palau JCF, De Camargo JR. Waste materials co-processing in cement industry: ecological efficiency of waste reuse. Renew Sustain Energy Rev 2013;19:200–7.
[101] Del Rio DDF, Sovacool BK, Foley AM, Griffiths S, Bazilian M, Kim J, et al. Decarbonizing the ceramics industry: a systematic and critical review of policy options, developments and sociotechnical systems. Renew Sustain Energy Rev 2022;157:112081.
[102] Iberdrola. Iberdrola and Porcelanosa launch their first project to electrify ceramic production by combining renewables, green hydrogen and heat pump technology n.d. https://www.iberdrola.com/press-room/news/detail/iberdrola-porcelanosa-launch-their-first-project-electrify-ceramic-production-combining-renewables-green-hydrogen-heat-pump-technology. [Accessed 28 February 2024].
[103] Porcelanosa. PORCELANOSA and Iberdrola promote a decarbonisation plan for the ceramics industry n.d. https://www.porcelanosa.com/trendbook/en/porcelanosa-iberdrola-ceramic-industry-decarbonization-plan/. [Accessed 28 February 2024].
[104] Mödinger F. Decarbonization of the heavy clay industry. Interceram-International Ceramic Review 2020;69:20–7.
[105] Monfort E, Mezquita A, Vaquer E, Celades I, Sanfelix V, Escrig A. Ceramic manufacturing processes: energy, environmental, and occupational health issues. 2014.
[106] Zier M, Stenzel P, Kotzur L, Stolten D. A review of decarbonization options for the glass industry. Energy Convers Manag X 2021;10:100083.
[107] Del Rio DDF, Sovacool BK, Foley AM, Griffiths S, Bazilian M, Kim J, et al. Decarbonizing the glass industry: a critical and systematic review of developments, sociotechnical systems and policy options. Renew Sustain Energy Rev 2022;155:111885.
[108] H2GLASS n.d. https://h2-glass.eu/?cn-reloaded=1. [Accessed 28 February 2024].

[109] NRW.Energy4Climate. HyGlass n.d. https://www.energy4climate.nrw/en/topics/best-practice/hyglass. [Accessed 28 February 2024].
[110] HyNet n.d. https://hynet.co.uk/. [Accessed 28 February 2024].
[111] Glass futures. n.d. https://www.glass-futures.org/. [Accessed 28 February 2024].
[112] Federal Ministry of Education and Research. Kopernikus P2X n.d. https://www.kopernikus-projekte.de/en/projects/p2x. [Accessed 28 February 2024].
[113] Griffin PW, Hammond GP, McKenna RC. Industrial energy use and decarbonisation in the glass sector: a UK perspective. Advances in Applied Energy 2021;3:100037.
[114] Achintha M. Sustainability of glass in construction. Sustainability of construction materials. Elsevier; 2016. p. 79–104.
[115] Alamdari H. Aluminium production process: challenges and opportunities. Metals 2017;7:133.
[116] Kermeli K, ter Weer P-H, Crijns-Graus W, Worrell E. Energy efficiency improvement and GHG abatement in the global production of primary aluminium. Energy Effic 2015;8:629–66.
[117] Deng L, Johnson S, Gencer E. Environmental-Techno-Economic analysis of decarbonization strategies for the Indian aluminum industry. Energy Convers Manag 2022;274:116455.
[118] Renewable Hydrogen Coalition. World-first aluminium produced with renewable hydrogen. n.d. https://renewableh2.eu/stories/world-first-aluminium-produced-with-renewable-hydrogen/. [Accessed 28 February 2024].
[119] Lovatt AM, Bassetti D, Shercliff HR, Brechet Y. Process and alloy selection for aluminium casting. Int J Cast Metals Res 2000;12:211–25.
[120] Kumar NMS, Pramod GK, Samrat P, Sadashiva M. A critical review on heat treatment of aluminium alloys. Mater Today Proc 2022;58:71–9.
[121] Del Rio DDF, Sovacool BK, Griffiths S, Bazilian M, Kim J, Foley AM, et al. Decarbonizing the pulp and paper industry: a critical and systematic review of sociotechnical developments and policy options. Renew Sustain Energy Rev 2022;167:112706.
[122] Obrist MD, Kannan R, Schmidt TJ, Kober T. Long-term energy efficiency and decarbonization trajectories for the Swiss pulp and paper industry. Sustain Energy Technol Assessments 2022;52:101937.
[123] Rukini A, Rhamdhani MA, Brooks GA, Van den Bulck A. Metals production and metal oxides reduction using hydrogen: a review. Journal of Sustainable Metallurgy 2022;8:1–24.
[124] CORDIS - EU Research & Development projects. Hydrogen as the Reducing Agent in the REcovery of metals and minerals from metallurgical waste n.d. https://cordis.europa.eu/project/id/958307. [Accessed 28 February 2024].
[125] Sabat KC, Rajput P, Paramguru RK, Bhoi B, Mishra BK. Reduction of oxide minerals by hydrogen plasma: an overview. Plasma Chem Plasma Process 2014;34:1–23.