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The Contribution of Renewable Energy Technologies in Industrial Decarbonization

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ABSTRACT: The necessity to mitigate climate change requires the substitution of fossil fuels with carbon-free energy sources and fuels. The industrial sector has significant contribution in global GHG emissions and its decarbonization is necessary for the achievement of the global climate targets. The possibility of using various sustainable energy technologies in industries reducing their carbon footprint has been explored and the challenges hindering their adoption have been highlighted. The sustainable energy technologies and fuels studied include solar photovoltaic systems, wind turbines, solar thermal heating and cooling systems, solid biomass and biogas, energy storage and green hydrogen. Although most of the abovementioned benign energy systems are mature, reliable and cost-efficient several challenges prevent their broad use in industries. Our work indicates that several existing sustainable energy technologies can be used in industries providing heat, cooling and electricity reducing or completely eliminating their carbon emissions. Industries can overcome the challenges and use one or more of these benign energy technologies reducing their carbon emissions. The current study could be useful to policy makers for developing appropriate policies promoting industrial decarbonization and to industries which can reduce their carbon footprint using the abovementioned sustainable energy technologies.

KEYWORDS: electricity, energy storage, heat, industrial decarbonization, renewable energies, solar energy

1. INTRODUCTION

Decarbonization of industrial processes is necessary for the achievement of the global target for net-zero carbon emissions in the coming decades. Industry is responsible for around one third of global carbon emissions while decarbonization of various industrial sectors is rather difficult with the existing energy technologies (1), (2), (3). Several zero-carbon fuels and energy sources can replace the use of fossil fuels for heat, cooling and power generation in industrial processes reducing the energy-related carbon footprint (4), (5), (6), (7). These include solar energy, wind energy, biomass and biogas, solar thermal heating and cooling, energy storage and green hydrogen (8), (9), (10). The deployment of these energy sources and fuels can generate carbon-free heat and electricity in industries. Several studies worldwide have been focused in industrial decarbonization indicating various pathways for its achievement (11), (12), (13).

The aim of the current work is to study various aspects of using several sustainable energy sources and technologies in industries, replacing carbon-related energy and fuels, reducing or eliminating their carbon emissions.

The present study analyzes the existing challenges in the promotion of several clean energy technologies in the industrial sector that could facilitate the reduction of scope 1 and scope 2 carbon emissions. It could be useful to policy makers, to industries and to companies related with sustainable energy technologies.

2. LITERATURE SURVEY

The energy transition in tissue paper industry through solid biomass combustion and gasification has been studied (1). The authors stated that the tissue paper industry is an energy-intensive hard-to-abate sector. They mentioned that use of woody biomass in cogeneration plants can reduce the CO_2 emissions in paper industry by up to 80%. The decarbonization of thermal processes in industry has been examined (2). The author stated that industrial heat makes up two-thirds of industrial energy demand worldwide. He also mentioned that six industrial sectors including steel, chemicals, cement, pulp and paper, aluminum and oil refining produce more than 77% of global industrial emissions. The use of hydrogen in industrial decarbonization has been analyzed (3). The authors stated that there is a lack of low-carbon options available for "hard to decarbonize industries". They mentioned that green hydrogen is a potential solution for energy production in industries which can be also used for energy storage. However, the current production cost of green hydrogen is not competitive with the cost of other fuels like natural gas.

The hybrid solar-wind potential for industrial decarbonization strategies has been assessed (4). The authors examined the impacts of an increasing share of wind and solar electricity production on reducing carbon intensity in various sectors. They stated thar using renewable fuels in energy production is a cost-effective pathway for industrial decarbonization. The optimal integration of solar heat and solar photovoltaics in industrial decarbonization has been studied (5). The authors stated that production of heat and electricity from solar energy sources, in temperatures higher than 500ºC, is a potential solution for reducing CO_2 emissions in the industrial heating sector. They mentioned that in hot climate both the parabolic trough system and the solar-PV system can achieve decarbonization in industrial heat production. The technology and policy options for deep decarbonization have been reviewed (6). The authors stated that the production of heavy industry commodities is responsible for 1/3 of the annual global GHG emissions. They mentioned that there are technology options which can decarbonize industrial processes such as biomass use, renewable electricity and geological storage of CO_2. The energy solutions for decarbonizing industrial heat processes in various areas in the world have been explored (7). The authors stated that heat pumps are the optimal solution for low temperature heat while biomass is the second prevalent solution in many areas. For medium and high temperatures electrification is an attractive solution while biomethane is also a promising fuel if there are incentives supporting its production and use. The optimal uses of biomass in decarbonizing energy systems have been analyzed (8). The authors have conducted a comparative assessment regarding several CO_2 removal pathways using biomass resources taking into account various technologies and costs. The decarbonization of industrial processes focusing on low-temperature solar heat (80-150ºC) has been explored (9). The authors stated that low temperature solar-collectors have high efficiencies while solar thermal technologies are cheap and reliable solutions. They mentioned that for several reasons solar heat is not used extensively in industrial processes. The role of hydrogen in decarbonizing the U.S. industry has been reviewed (10). The authors stated that there is a growing interest in hydrogen for industrial decarbonization while hydrogen technologies have high readiness level. They mentioned that the primary challenge lies in reducing the clean hydrogen production cost to \$0.4-0.7/kgH_2 to compete natural gas. The use of renewable heat and electricity for decarbonization of energy-intensive industries has been investigated (11). The authors have provided a catalogue of zero-carbon energy technologies available for decarbonization of energy intensive industries. They stated that carbon-free heat can be provided with heat pumps, concentrated solar power and geothermal energy. Additionally, biomass, biomethane and green hydrogen can be used for carbon-free heat generation in industries. The decarbonization of the heat sector using solar and wind power in Australia has been examined (12). The authors stated that electrification of industrial processes, currently based on fossil fuels, is a necessary step to achieve the emissions' reduction goals. They stated that electrification of industrial steam generation can be achieved with a technology mix using wind turbines, solar-PVs and concentrated solar thermal systems combined with heat storage. The carbon neutral heat supply strategies for industrial decarbonization have been explored (13). The authors studied solar-PV heating and waste incineration heating. They mentioned that industrial heating through solar-PV systems is based on electrothermal equipment such as electric boilers and heat pumps. The contribution of solar photovoltaics in the decarbonization of the power sector has been studied (14). The authors have developed an analytical method for the calculation of the future reduction of CO_2 emissions due to deployment of solar-PVs for power generation as well as the additional financial cost incurred by solar-PV deployment. The energy storage in industrial decarbonization has been explored (15). The authors focused on three energy storage technologies including electrochemical storage, heat storage and chemical storage. They also analyzed the opportunities and barriers for using the abovementioned energy storage technologies in industry. The energy storage in industries has been reviewed (16). The authors stated that flexible integrated and responsive industrial energy storage is essential to transitioning from fossil fuels to renewable energies. They mentioned that the most common systems of energy storage include thermal, chemical, electrochemical and mechanical storage. A report related with solar thermal heating and cooling in industries has been published (17). The report stated that solar water heating is a mature technology facing increasing competition from other renewable energy technologies such as solar-PV powered heat pumps. It is also mentioned that solar thermal energy has fewer applications in the industrial sector compared to the residential sector. The potential role of biomethane for the decarbonization of transport focusing in Italy has been studied (18). The authors stated that Italy has several operating biogas plants and considerable potential feedstock for biogas/biomethane production. They mentioned that biomethane can contribute significantly in the decarbonization of the transport sector in Italy. The role of biogas and biomethane in the decarbonization pathway has been analyzed (19). The authors stated that biogas has the potential to play a significant role in the transition to decarbonized energy systems. They mentioned that it can be used in all sectors in modern societies reducing their carbon emissions. The decarbonization of industrial heat has been examined (20). The authors stated that industrial decarbonization is rather difficult due to the vast inhomogeneous array of processes comprising the sector. They examined four zero-carbon industrial heating technologies including: a) zero-carbon fuels, b) zero-carbon heat sources, c) electrification of heat, and d) better heat management. The thermal energy storage in solar-assisted energy systems has been studied (21). The authors stated that integration of sensible thermal energy storage with solar-integrated industrial heat processes can facilitate industrial decarbonization. The energy storage in industries has been investigated (22). The authors studied the integration of chemical and thermal energy storage in industrial applications. They mentioned that energy storage will be a fundamental pillar of the sustainable energy transition in industries. The role of thermal energy storage in the promotion of carbon neutrality has been analyzed (23). The authors stated that during energy generation large amounts of waste heat are produced. The recovery and reuse of the waste heat is difficult due to mismatch between heat supply and demand in several sectors and processes. Therefore, the authors mentioned, thermal energy storage is necessary for efficient utilization of waste heat for achieving carbon neutrality. The technical and economic feasibility of net-zero carbon emission hotels have been studied (24). The author stated that there are several zero-carbon energy technologies which can be used in hotels providing heat, cooling and electricity. He mentioned that these technologies are mature, reliable and cost-effective. The feasibility of developing net-zero emissions residential buildings in the island of Crete, Greece has been examined (25). The author stated that the use of solar energy, solid biomass and low enthalpy environmental heat, instead of fossil fuels, can eliminate all the life-cycle carbon emissions of the residential building generating additionally the electricity required in the electric cars of the building's occupants.

3. CLASSIFYING CARBON EMISSIONS IN INDUSTRY

The carbon emissions are classified into three categories: Scope 1, Scope 2, and Scope 3 emissions. This categorization helps industries understand the sources of their emissions and develop targeted strategies for reduction.

Scope 1 emissions are direct carbon emissions that originate from sources owned or controlled by an organization. In industrial settings, these include emissions from on-site fuel combustion in boilers, furnaces, and generators, as well as emissions from company-owned vehicles and industrial processes such as cement or steel production. Because Scope 1 emissions are under direct operational control, industries can reduce them through measures such as improving energy efficiency, switching to low-carbon fuels, electrifying equipment, and adopting cleaner production technologies.

Scope 2 emissions are indirect emissions associated with the generation of purchased energy consumed by an organization, primarily electricity, steam, heating, or cooling. Although these emissions occur off-site at power plants, they are attributed to the industrial user because energy consumption drives their production. Industries can mitigate Scope 2 emissions by increasing energy efficiency, sourcing renewable electricity through power purchase agreements, installing on-site renewable energy systems, or purchasing green energy certificates.

Scope 3 emissions include all other indirect emissions that occur throughout an organization's value chain and are often the largest and most complex category for industry. These emissions arise from activities such as the extraction and production of purchased raw materials, transportation and distribution, waste disposal, business travel, employee commuting, and the use and end-of-life treatment of sold products. While Scope 3 emissions are not directly controlled by companies, industries can influence them by engaging suppliers, improving product design, optimizing logistics, and encouraging customers to use products more efficiently.

In the following sections the use of several renewable energy technologies which can reduce the scope 1 emissions in industries are examined.

4. ON-SITE GENERATION AND USE OF SOLAR PHOTOVOLTAIC ELECTRICITY IN INDUSTRIES

Among the various renewable energy technologies available, solar photovoltaic (solar-PV) energy has emerged as a key solution for reducing carbon emissions in industrial operations. Its scalability, declining costs, and environmental benefits make it an attractive option for supporting the transition to low-carbon industry. Solar-PV technology converts sunlight directly into electricity without combustion, thereby producing zero operational emissions. This characteristic makes it particularly valuable for decarbonizing industrial electricity consumption, which is often associated with carbon-intensive power generation. By installing rooftop or ground-mounted solar-PV systems, industries can generate clean electricity on-site, reducing dependence on fossil-fuel-based grids and lowering overall emissions. In energy-intensive industries such as cement, steel, chemicals, and manufacturing, even partial substitution of conventional electricity with solar power can lead to substantial emission reductions. Another important advantage of solar-PV in industrial decarbonization is its economic viability. Over the past decade, the cost of solar-PV modules has decreased dramatically, making solar energy one of the most cost-competitive power sources worldwide. For industries, this translates into long-term energy cost savings and protection against volatile fossil fuel prices. Additionally, government incentives, carbon pricing mechanisms, and corporate sustainability commitments further enhance the financial attractiveness of solar-PV investments. Solar-PV also supports industrial electrification, which is a cornerstone of deep decarbonization strategies. As industrial processes shift from fossil-fuel-based heating and power to electric alternatives—such as electric boilers, heat pumps, and electrolysis—clean electricity becomes essential. Solar-PV can supply a portion of this electricity demand, particularly when combined with energy storage systems that address intermittency and ensure reliable power supply. Despite its benefits, challenges remain. Solar-PV generation is intermittent and dependent on weather conditions, which can limit its ability to meet continuous industrial energy demands. However, integrating solar-PVs with battery storage, hybrid renewable systems, and smart energy management can significantly mitigate these limitations. Therefore, solar-PV energy plays a vital role in industrial decarbonization by providing clean, cost-effective, and scalable electricity. While it may not fully replace all fossil fuel uses in industry, its integration into industrial energy systems is essential for achieving long-term emission reduction targets and supporting a sustainable industrial future. The challenges related with the on-site generation and use of solar photovoltaic electricity in industries are presented in table 1.

Table 1. Challenges regarding the on-site generation and use of solar photovoltaic electricity in industries

1	High initial capital cost for solar-PV panels, inverters, and installation
2	Intermittency and variability due to weather, day-night cycles, and seasonal changes
3	Large space requirements for rooftop or ground-mounted solar-PV systems
4	Integration challenges with existing industrial electrical systems and load management
5	Maintenance and performance issues, such as dust accumulation, panel degradation, and inverter faults
6	Economic feasibility and long payback period, particularly in regions with low solar irradiance

Source: own estimations

5. ON-SITE GENERATION AND USE OF WIND ELECTRICITY IN INDUSTRIES

Transitioning to renewable energy sources is a key strategy to reduce these emissions, and wind energy has emerged as one of the most effective and scalable solutions for decarbonizing industrial power consumption. Wind energy generates electricity by harnessing the kinetic energy of moving air through wind turbines, producing power without direct carbon emissions. For industrial facilities, wind energy can significantly reduce reliance on fossil-fuel-based electricity, particularly in regions with strong and consistent wind resources. Large manufacturing plants, mining operations, and processing industries often require substantial amounts of electricity, making them well suited to benefit from utility-scale or on-site wind power installations. One of the major advantages of wind energy in industrial decarbonization is its cost competitiveness. Technological advancements, improved turbine efficiency, and economies of scale have led to a substantial decline in the cost of wind power over the past decade. In many regions, onshore wind is now among the cheapest sources of new electricity generation. Industries can access wind energy through direct ownership of wind farms, power purchase agreements (PPAs), or partnerships with renewable energy developers, enabling long-term price stability and reduced exposure to fossil fuel price volatility. Wind energy also plays a crucial role in supporting the electrification of industrial processes. As industries adopt electric alternatives such as electric furnaces, motors, and electrolyzers for hydrogen production, the demand for clean electricity increases. Wind power can supply large volumes of low-carbon electricity, particularly when combined with grid interconnections and energy storage solutions. Furthermore, wind-generated electricity can be used to produce green hydrogen via electrolysis, offering a pathway to decarbonize hard-to-abate sectors such as steel, chemicals, and refining. However, wind energy integration presents certain challenges. Its variable and location-dependent nature can create mismatches between electricity generation and industrial demand. Addressing these challenges requires grid flexibility, energy storage systems, demand-side management, and hybrid renewable energy systems that combine wind with solar or other clean energy sources. Therefore, wind energy is a powerful enabler of industrial decarbonization, offering a clean, cost-effective, and scalable source of electricity. While it cannot address all industrial emissions on its own, its integration into industrial energy systems is essential for reducing carbon footprints, supporting electrification, and advancing the transition toward a sustainable and low-carbon industrial sector. The challenges related with the on-site generation and use of wind electricity in industries are presented in table 2.

Table 2. Challenges regarding the on-site generation and use of wind electricity in industries

1	Intermittency and variability of wind, causing unreliable power supply
2	Wind turbines can be installed only if the mean annual wind velocity in the industrial site is satisfactory
3	High initial capital cost for wind turbines, foundations, and grid integration
4	Large land and space requirements for installation of wind farms in industries
5	Grid integration and stability issues, especially for industries requiring continuous power
6	Maintenance and operational challenges, including wear, corrosion, and mechanical failures
7	Noise, environmental, and aesthetic concerns, which may limit installation locations

Source: own estimations

6. USE OF SOLAR THERMAL HEATING AND COOLING IN INDUSTRIAL DECARBONIZATION

A large portion of industrial emissions arises from the use of fossil fuels for process heating and cooling. Solar thermal heating and solar thermal cooling technologies offer effective, low-carbon solutions to address these energy demands, particularly in industries with significant thermal energy requirements. Solar thermal heating systems capture solar radiation and convert it into usable heat through collectors such as flat-plate, evacuated tube, or concentrating solar collectors. This heat can be used directly in industrial processes, including drying, washing, pasteurization, and preheating, which commonly operate at low to medium temperatures. Industries such as food and beverage, textiles, chemicals, and pharmaceuticals are especially well suited for solar thermal integration. By replacing fossil-fuel-fired boilers with solar thermal systems, industries can significantly reduce carbon dioxide emissions and fuel consumption. For applications requiring higher temperatures, concentrating solar thermal technologies, such as parabolic troughs and solar towers, can generate heat at temperatures exceeding 400°C. These systems can support more energy-intensive processes and can be combined with thermal energy storage to provide a stable heat supply even when solar radiation is unavailable. Thermal storage, using materials such as molten salts or pressurized water, enhances system reliability and enables greater fossil fuel displacement. In addition to heating, solar thermal cooling plays an increasingly important role in industrial decarbonization. Solar thermal cooling systems use heat from solar collectors to drive thermally activated cooling technologies, such as absorption or adsorption chillers. These systems are particularly attractive because cooling demand often coincides with periods of high solar availability. Industrial facilities that require refrigeration, air conditioning, or process cooling—such as food processing plants, cold storage facilities, and chemical industries—can benefit from solar-driven cooling solutions. One of the key advantages of solar thermal technologies is their ability to directly supply thermal energy without intermediate electricity conversion, resulting in high system efficiency. This makes solar thermal heating and cooling especially valuable for reducing emissions from industrial heat, which accounts for a majority of industrial energy use globally. Moreover, these technologies can be integrated into existing industrial energy systems, often as hybrid solutions that operate alongside conventional boilers or chillers, allowing for gradual decarbonization without disrupting operations. Despite their potential, challenges remain in the widespread adoption of solar thermal systems. These include high upfront capital costs, space requirements for collectors, and the variability of solar resources. However, declining technology costs, improved system designs, and supportive policy frameworks are helping to overcome these barriers. Advances in thermal storage and digital energy management further enhance the feasibility and performance of solar thermal solutions. Therefore, solar thermal heating and solar thermal cooling are powerful tools for industrial decarbonization, offering efficient, renewable, and scalable solutions for industrial thermal energy needs. When integrated with other low-carbon technologies, they can play a critical role in reducing fossil fuel dependence and advancing the transition toward a sustainable industrial energy system. The challenges related with the use of solar thermal heating and cooling in industries are presented in table 3.

Table 3. Challenges regarding the use of solar thermal heating and cooling in industries

1	High initial capital cost of solar collectors, storage tanks, and associated equipment
2	Intermittency of solar energy, leading to unreliable supply during cloudy days or at night
3	Large space requirements for solar collectors and installation in industrial sites
4	Integration challenges with existing heating, cooling, or process systems
5	Maintenance and operational issues, such as scaling, corrosion, or dirt on collectors
6	Economic feasibility and long payback period, especially in regions with low solar irradiance

7. USE OF SOLID BIOMASS AND BIOGAS IN INDUSTRIAL DECARBONIZATION

While electrification and renewable electricity are key strategies, they are not always sufficient for high-temperature and continuous industrial processes. In this context, solid biomass and biogas offer important low-carbon alternatives, particularly for industries that require thermal energy and gaseous fuels. Solid biomass, including wood pellets, agricultural residues, and forestry by-products, can be used directly as a fuel to generate heat and electricity. When sourced sustainably, biomass is considered nearly carbon-neutral, as the carbon dioxide released during combustion is offset by the carbon absorbed during plant growth. Many industries, such as pulp and paper, food processing, cement, and district heating systems, already use solid biomass to replace coal or fuel oil in boilers and combined heat and power (CHP) plants. This fuel substitution can significantly reduce lifecycle carbon emissions while utilizing locally available resources and waste materials. Biogas, produced through the anaerobic digestion of organic waste such as agricultural residues, food waste, sewage sludge, and industrial by-products, provides another valuable pathway for industrial decarbonization. Biogas typically consists of methane and carbon dioxide and can be used directly for heat and power generation or upgraded to biomethane by removing impurities. Biomethane can be injected into existing natural gas grids or used on-site as a low-carbon substitute for fossil natural gas, making it especially attractive for industries with existing gas-based infrastructure. One of the key advantages of solid biomass and biogas is their suitability for high-temperature and continuous processes, where electrification may be technically challenging or economically prohibitive. Industries such as ceramics, glass, steel, and chemicals often require stable thermal energy that biomass boilers and biogas-fired systems can reliably provide. Additionally, biogas and biomethane can serve as feedstocks for producing renewable hydrogen and other bio-based chemicals, further expanding their role in industrial decarbonization. Beyond emissions reduction, biomass and biogas contribute to a circular economy by valorizing waste streams and reducing landfill use. Industrial symbiosis—where waste from one process becomes fuel for another—can enhance resource efficiency and reduce environmental impacts. Moreover, the use of locally sourced biomass and biogas can improve energy security and stimulate rural economic development. Despite their benefits, challenges remain. Unsustainable biomass harvesting can lead to deforestation and biodiversity loss, while biogas production requires careful management to avoid methane leakage. Therefore, robust sustainability criteria, efficient technologies, and strong regulatory frameworks are essential to ensure genuine climate benefits. Therefore, solid biomass and biogas play a vital role in industrial decarbonization by providing renewable, flexible, and dispatchable energy solutions. When sustainably managed, they complement electrification and renewable electricity, enabling deeper emission reductions and supporting a resilient, low-carbon industrial future. The challenges related with the use of solid biomass and biogas in industries are presented in table 4.

Table 4. Challenges regarding the use of solid biomass and biogas in industries

1	High initial capital costs for biomass boilers, gasifiers, and biogas plants
2	Unreliable and seasonal feedstock supply, leading to fuel insecurity
3	High transportation and storage costs due to bulky and low-density biomass
4	Technical and operational complexities, especially in biogas systems
5	Lack of skilled manpower and technical expertise for operation and maintenance
6	Policy, regulatory, and financing barriers, including unclear standards and limited incentives

Source: own estimations

7. USE OF ENERGY STORAGE IN INDUSTRIAL DECARBONIZATION

As industries increasingly adopt renewable energy sources such as solar and wind power, energy storage has become essential for ensuring reliability, flexibility, and deep emissions reductions. By balancing energy supply and demand, storage technologies enable the effective integration of low-carbon energy into industrial operations. One of the primary roles of energy storage in industrial decarbonization is addressing the intermittency of renewable energy. Solar and wind generation fluctuate based on weather and time of day, while industrial processes often require continuous and stable energy supply. Electrical energy storage systems, particularly batteries, can store excess renewable electricity during periods of high generation and release it when production declines. This allows industries to maximize the use of clean energy while reducing dependence on fossil-fuel-based backup power. Beyond electricity, thermal energy storage plays a crucial role in decarbonizing industrial heat, which accounts for a large share of industrial energy use. Thermal storage systems can capture and store heat from renewable sources such as solar thermal collectors, electric heaters, or waste heat recovery systems. Stored thermal energy can then be used for process heating at later times, improving energy efficiency and reducing fuel consumption. Technologies such as molten salt storage, phase-change materials, and hot water tanks are increasingly being deployed in industrial applications. Energy storage also supports industrial electrification and load management. By shifting energy use to off-peak periods or times of abundant renewable supply, storage systems help reduce peak electricity demand and associated emissions. This flexibility not only lowers operational costs but also reduces strain on power grids, facilitating higher shares of renewable energy at the system level. In some cases, industries can participate in demand response and ancillary service markets, creating additional revenue streams while supporting grid stability. In addition, long-duration energy storage solutions, including hydrogen storage, compressed air energy storage, and advanced battery technologies, are gaining attention for their potential to decarbonize energy-intensive and continuous industrial processes. These systems can store energy over hours, days, or even seasons, making them especially valuable for industries with constant energy demands or limited grid access. Despite their benefits, energy storage technologies face challenges related to cost, scalability, and technological maturity. However, rapid innovation, economies of scale, and supportive policies are driving cost reductions and expanding deployment. Therefore, energy storage is a critical enabler of industrial decarbonization. By enhancing renewable energy integration, improving efficiency, and providing operational flexibility, energy storage technologies help industries reduce emissions while maintaining reliability and competitiveness in the transition to a low-carbon economy. The challenges related with energy storage in industries are presented in table 5.

Table 5. Challenges regarding the energy storage in industries

1	High capital and installation costs of large-scale energy storage systems
2	Limited storage capacity and energy density, especially for long-duration needs
3	Efficiency losses during charging, storage, and discharging cycles
4	Safety and reliability concerns (thermal runaway, fire risks, system failures)
5	Integration challenges with existing industrial power systems and processes
6	Short lifespan and degradation of storage technologies, leading to replacement costs

Source: own estimations

8. USE OF GREEN HYDROGEN IN INDUSTRIAL DECARBONIZATION

Green hydrogen, produced through the electrolysis of water using renewable electricity, has emerged as a promising solution for reducing emissions in hard-to-abate industrial sectors. Unlike conventional hydrogen produced from natural gas or coal, green hydrogen generates little to no greenhouse gas emissions over its lifecycle. One of the most significant roles of green hydrogen in industrial decarbonization is as a substitute for fossil-based feedstocks. Industries such as ammonia, methanol, and oil refining currently rely heavily on grey hydrogen derived from natural gas, resulting in substantial carbon emissions. Replacing grey hydrogen with green hydrogen can dramatically reduce emissions while allowing existing industrial processes to continue with minimal modification. This makes green hydrogen a particularly attractive option for sectors where direct electrification is not feasible. Green hydrogen also has strong potential as a clean energy carrier for high-temperature industrial heat. Industries such as steel, cement, and glass require extremely high and continuous heat, which is difficult to achieve using electricity alone. Hydrogen combustion can provide these high temperatures without direct carbon dioxide emissions. In the steel industry, for example, green hydrogen can be used in direct reduced iron processes, replacing coal and significantly lowering emissions from steel production. In addition to its role in heat and feedstock substitution, green hydrogen supports the broader integration of renewable energy into industrial systems. Hydrogen can be produced during periods of excess renewable electricity generation and stored for later use, addressing the intermittency of solar and wind power. This flexibility enhances energy system resilience and enables deeper penetration of renewable energy in industrial operations. Despite its promise, the widespread adoption of green hydrogen faces several challenges. High production costs, limited infrastructure for storage and transport, and efficiency losses during conversion remain significant barriers. However, rapid technological advancements, declining renewable electricity costs, and increasing policy support are steadily improving the economic viability of green hydrogen. Many governments and industries are investing in hydrogen strategies, pilot projects, and international supply chains to accelerate deployment. Therefore, green hydrogen is a critical enabler of industrial decarbonization, particularly for sectors that are difficult to electrify or require hydrogen as a feedstock. While it is not a standalone solution, green hydrogen complements renewable electricity, energy efficiency measures, and other low-carbon technologies. Its strategic integration into industrial energy systems will be essential for achieving deep emission reductions and building a sustainable, low-carbon industrial future. The challenges related with the use of green hydrogen in industries are presented in table 6. The zero-carbon options for on-site electricity generation in industries are presented in table 7 while the zero-carbon options for on-site heat generation in industries in table 8.

Table 6. Challenges regarding the use of green hydrogen in industries

1	High production cost of green hydrogen due to expensive electrolyzers and renewable electricity
2	Limited availability of renewable power for large-scale, continuous hydrogen production
3	Storage and transportation difficulties because of hydrogen's low volumetric energy density
4	Lack of infrastructure (pipelines, refueling stations, storage facilities)
5	Safety concerns related to hydrogen leakage, flammability, and embrittlement of materials
6	Integration challenges with existing industrial processes and equipment

Source: own estimations

Table 7. Zero-carbon options for on-site electricity generation in industries

Energy source/fuel	Technology
Solar energy	Photovoltaic systems
Wind energy	Wind turbines
Biogas/biomethane	Cogeneration of heat and power
Green hydrogen	Gas or steam turbines

Source: own estimations

Table 8. Zero-carbon options for on-site heat generation in industries

Energy source/fuel	Technology
Solar energy	Solar thermal collectors
Ambient temperature and green electricity (provided by solar photovoltaics)	Heat pumps
Green electricity (provided by several systems)	Electrothermal equipment (electric boilers)
Solid biomass	Burning
Biogas/biomethane	Burning/cogeneration of heat and power
Green hydrogen	Burning

Source: own estimations

9. DISCUSSION

Existing studies have indicated that the use of several renewable energy sources and technologies can facilitate the elimination of carbon emissions in industries. Although the use of these sustainable energy technologies in industries has many advantages there are several barriers that do not favor their broad adoption. Several studies have analyzed the advantages and drawbacks in using different sustainable energy sources and technologies in various industrial sectors in several countries. Among them, solar photovoltaic electricity, wind power, solar thermal energy for heating and cooling, solid biomass and biogas, green hydrogen and energy storage. These sustainable energy technologies can replace conventional energy sources and fuels which are currently used in industries. They can generate electricity, heat and cooling meeting the industrial energy demand while many of them are mature, reliable, well-proven and cost-efficient. However, there are several challenges in using these sustainable energy sources and fuels in industries particularly in hard-to-abate industrial sectors. The intermittent nature of solar and wind energy does not match with the industrial requirements for constant energy supply and energy storage is necessary. The current study explores the possibility of using various sustainable energy sources and technologies in industries promoting their decarbonization highlighting the challenges that prevent their adoption. Our work is limited in the analysis of using the abovementioned sustainable energy technologies in industries without studying the use of additional green energy technologies such as, cogeneration of heat and power, reuse of waste heat, fuel cells et cetera. Future work should be focused on exploring several other zero-emissions energy sources and technologies that can be used in industries analyzing their advantages and the challenges preventing their adoption.

10. CONCLUSIONS

Various aspects of using several renewable energy sources and technologies in industries, such as solar photovoltaics, wind turbines, solid biomass and biogas systems, solar thermal heating and cooling systems, energy storage systems and green hydrogen have been studied. The challenges that hinder their broad adoption have been identified. The main findings can be summarized as follows.

a) Several sustainable energy sources and technologies can be used for energy generation in industries reducing their scope 1 and scope 2 carbon emissions.
b) Solar photovoltaics can be used for electricity generation in industries replacing the grid electricity use. However, their intermittency nature requires power storage while their installation requires large space which might not be available.
c) Wind turbines generating electricity can be installed only if the mean annual wind velocity in the industrial site is satisfactory while the intermittency of wind requires power storage.
d) The intermittency nature of solar energy results in unreliable heat and cooling supply during the cloudy days while solar thermal collectors require large space for their installation which might not be available in industries.
e) The cost of transporting and storing biomass might be high while the unreliable feedstock supply might result in fuel insecurity.
f) The capital and installation cost of energy storage systems in industry might be high while the short lifespan and degradation of storage technologies lead to high replacement cost.
g) The cost of producing green hydrogen is currently high while its storage and transportation have many difficulties.

Conclusively, several mature and reliable sustainable energy technologies can be used in industries promoting their decarbonization provided that the existing challenges hindering their adoption will be overcome.

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