Renewable Power and Heat for the Decarbonisation of Energy-Intensive Industries

Authors:

Alessandro A. Carmona-Martínez, Alejandro Fresneda-Cruz, Asier Rueda, Olgu Birgi, Cosette Khawaja, Rainer Janssen, Bas Davidis, Patrick Reumerman, Martijn Vis, Emmanouil Karampinis, Panagiotis Grammelis, Clara Jarauta-Córdoba

Date Submitted: 2023-02-17

Keywords: energy-intensive industries, decarbonisation, renewable energies, Biomass, green hydrogen, heat pumps, Solar Thermal, geothermal

Abstract:

The present review provides a catalogue of relevant renewable energy (RE) technologies currently available (regarding the 2030 scope) and to be available in the transition towards 2050 for the decarbonisation of Energy Intensive Industries (EIIs). RE solutions have been classified into technologies based on the use of renewable electricity and those used to produce heat for multiple industrial processes. Electrification will be key thanks to the gradual decrease in renewable power prices and the conversion of natural-gas-dependent processes. Industrial processes that are not eligible for electrification will still need a form of renewable heat. Among them, the following have been identified: concentrating solar power, heat pumps, and geothermal energy. These can supply a broad range of needed temperatures. Biomass will be a key element not only in the decarbonisation of conventional combustion systems but also as a biofuel feedstock. Biomethane and green hydrogen are considered essential. Biomethane can allow a straightforward transition from fossil-based natural gas to renewable gas. Green hydrogen production technologies will be required to increase their maturity and availability in Europe (EU). EIIs' decarbonisation will occur through the progressive use of an energy mix that allows EU industrial sectors to remain competitive on a global scale. Each industrial sector will require specific renewable energy solutions, especially the top greenhouse gas-emitting industries. This analysis has also been conceived as a starting point for discussions with potential decision makers to facilitate a more rapid transition of EIIs to full decarbonisation.

Record Type: Published Article

Submitted To: LAPSE (Living Archive for Process Systems Engineering)

Citation (overall record, always the latest version):	LAPSE:2023.0051
Citation (this specific file, latest version):	LAPSE:2023.0051-1
Citation (this specific file, this version):	LAPSE:2023.0051-1v1

DOI of Published Version: https://doi.org/10.3390/pr11010018 *processes*

Review

Renewable Power and Heat for the Decarbonisation of Energy-Intensive Industries

Alessandro A. Carmona-Martínez [1,*], Alejandro Fresneda-Cruz [1], Asier Rueda [1], Olgu Birgi [2], Cosette Khawaja [2], Rainer Janssen [2], Bas Davidis [3], Patrick Reumerman [3], Martijn Vis [3], Emmanouil Karampinis [4], Panagiotis Grammelis [4] and Clara Jarauta-Córdoba [1]

1 CIRCE—Research Centre for Energy Resources and Consumption, Parque Empresarial Dinamiza, Ave. Ranillas 3D, 1st Floor, 50018 Zaragoza, Spain
2 WIP—WIP Renewable Energies, Sylvensteinstraße 2, 81369 Munich, Germany
3 BTG—BTG Biomass Technology Group, Josink Esweg 34, 7543 ES Enschede, The Netherlands
4 CERTH—Centre for Research and Technology Hellas/Chemical Process and Energy Resources Institute, Egialias 52, 15125 Marousi, Greece
* Correspondence: acarmona@fcirce.es

Abstract: The present review provides a catalogue of relevant renewable energy (RE) technologies currently available (regarding the 2030 scope) and to be available in the transition towards 2050 for the decarbonisation of Energy Intensive Industries (EIIs). RE solutions have been classified into technologies based on the use of renewable electricity and those used to produce heat for multiple industrial processes. Electrification will be key thanks to the gradual decrease in renewable power prices and the conversion of natural-gas-dependent processes. Industrial processes that are not eligible for electrification will still need a form of renewable heat. Among them, the following have been identified: concentrating solar power, heat pumps, and geothermal energy. These can supply a broad range of needed temperatures. Biomass will be a key element not only in the decarbonisation of conventional combustion systems but also as a biofuel feedstock. Biomethane and green hydrogen are considered essential. Biomethane can allow a straightforward transition from fossil-based natural gas to renewable gas. Green hydrogen production technologies will be required to increase their maturity and availability in Europe (EU). EIIs' decarbonisation will occur through the progressive use of an energy mix that allows EU industrial sectors to remain competitive on a global scale. Each industrial sector will require specific renewable energy solutions, especially the top greenhouse gas-emitting industries. This analysis has also been conceived as a starting point for discussions with potential decision makers to facilitate a more rapid transition of EIIs to full decarbonisation.

Keywords: energy-intensive industries; decarbonisation; renewable energies; biomass; green hydrogen; heat pumps; solar thermal; geothermal

check for updates

Citation: Carmona-Martínez, A.A.; Fresneda-Cruz, A.; Rueda, A.; Birgi, O.; Khawaja, C.; Janssen, R.; Davidis, B.; Reumerman, P.; Vis, M.; Karampinis, E.; et al. Renewable Power and Heat for the Decarbonisation of Energy-Intensive Industries. *Processes* **2023**, *11*, 18. https://doi.org/10.3390/pr11010018

Academic Editors: Carlos Herce, Benedetta de Caprariis and Yolanda Lara

Received: 18 November 2022
Revised: 7 December 2022
Accepted: 16 December 2022
Published: 22 December 2022

1. Introduction

The EU has set ambitious targets for decarbonisation by 2050 [1]. Part of this decarbonisation relies on the implementation of renewable energy (RE) technologies that replace the use of fossil-based energies. The second pillar of this decarbonisation path must be built on avoiding the emission of greenhouse gases (GHG) into the atmosphere by energy-intensive industries (EIIs). It is well known that EIIs were responsible for a third of the total of such emissions (>508 Mt CO2e) in the EU in 2014 [2,3]. In 2020, the European Union consumed around 2685 TWh of energy. The chemical and petrochemical sectors had the highest energy consumption (22%), followed by the non-metallic mineral (14%); paper, pulp, and printing (14%); and food, beverage, and tobacco (12%) sectors. These four industrial sectors alone consumed more than 60% of the total energy used by European industries (Figure 1) [4].

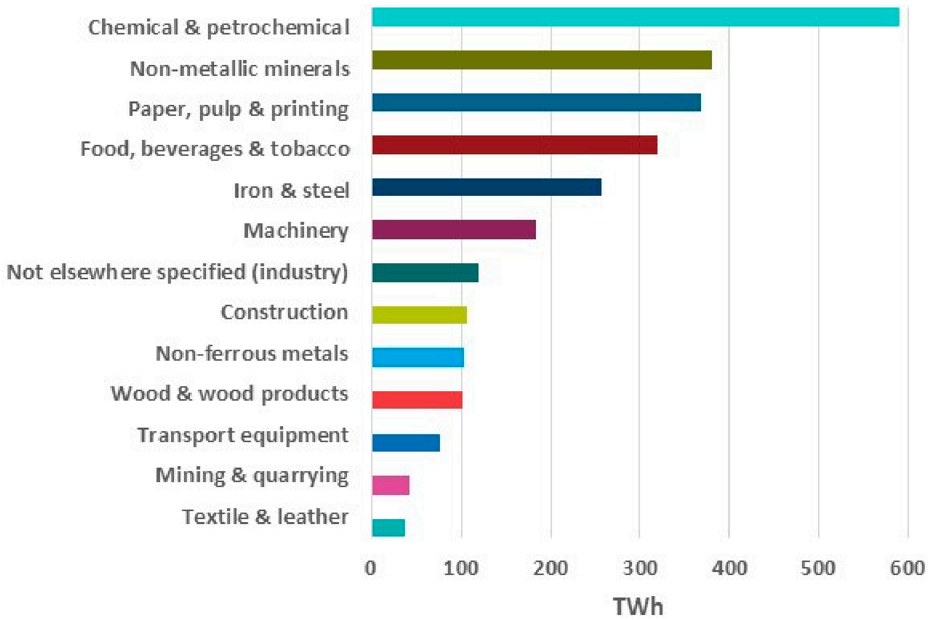

Figure 1. European energy consumption in 2020 by industrial sector. Plotted from information in the Eurostat database [4].

The present work provides an assessment of the most relevant technologies for renewable electricity and heat production as a replacement for fossil-based energy consumption by EIIs. Relevant RE technologies that can be deployed either in the short- (i.e., until 2030) or long-term (until 2050) have been analysed, as well as their integration into EIIs and in combination with other RE technologies. Within the 2030 scope, the analysis of relevant renewables based on their capacity to produce clean energy has been divided in the following two categories:

i. Replacement of existing fossil fuel-based electricity with clean renewable electricity sources such as wind, solar photovoltaic, and hydropower. This is a well-known group of relevant renewable technologies that are implemented in industries mainly through renewable Power Purchase Agreements (PPAs).

ii. Replacement of existing fossil fuel-based heat-produced heat with renewable heat production technologies such as solar thermal, heat pumps, geothermal energy, green hydrogen, and bioenergy such as solid biomass and liquid and gaseous biofuels. Currently, these REs show limited implementation in EIIs, even though they have been identified as a promising route for the decarbonisation of the sector.

Both groups of RE technologies considered in this analysis, renewable electricity and renewable heat, are being assessed on the basis of their technical feasibility, firstly by taking into consideration their availability by 2030. Secondly, the considered renewable solutions are being analysed in terms of what is required for their implementation. Renewable energy solutions for EIIs for the 2050 horizon are also being analysed. Some have already been identified, including e-fuels or renewable synthetic fuels from, e.g., the hydrogenation of captured CO_2, among others.

2. Renewable Electricity

Solar Photovoltaic, Concentrating Solar Power, and On/Offshore Wind

Renewable power can be obtained from different sources: solar photovoltaic, concentrating solar power, and on/offshore wind. The last decade has seen price improvements in these technologies for power production. According to a recent analysis by IRENA [5], the price of these sources of renewable power has steadily decreased (Figure 2). In comparison, fossil-based energy sources such as coal-fired power plants have operating costs that are higher than their renewable counterparts. IRENA's analysis—focused on Europe, North

America, and South Asia—indicates that the costs of these renewables vary, in part due to the price imposed on CO_2 emissions. Figure 2 indicates that renewable technology power production prices have experienced a considerable decline since 2010. This shows the competitiveness of renewable power generation and that the electrification process required for the decarbonisation of energy-intensive industries could experience a similar cost-declining trend.

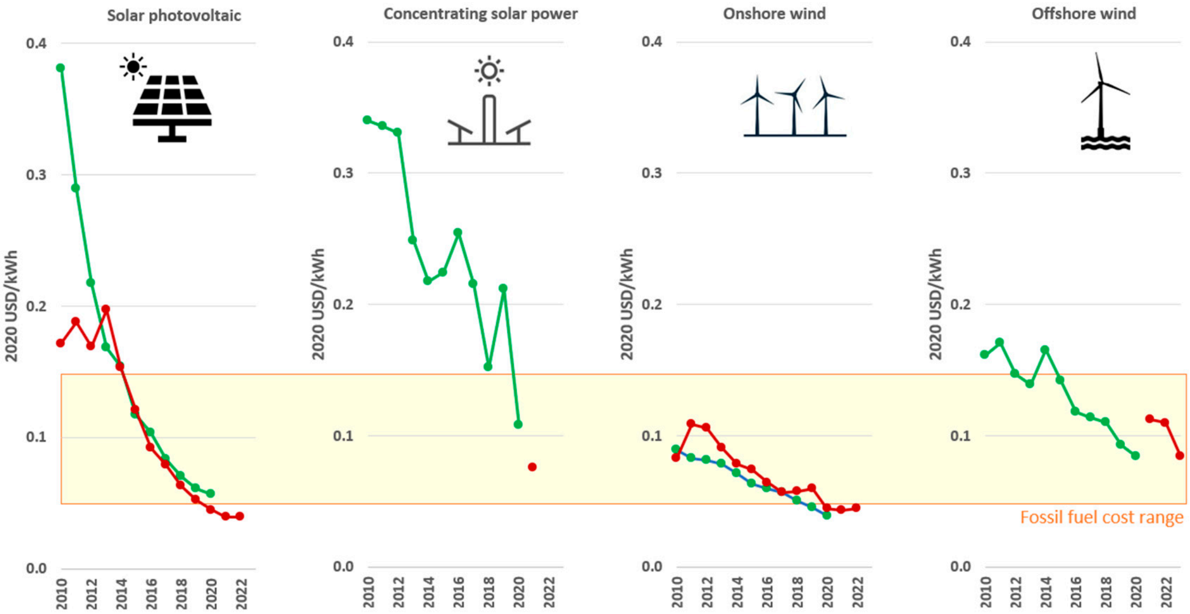

Figure 2. Global weighted-average levelised costs of energy (green) and power purchase agreement auction (red) prices for solar photovoltaic, on/offshore wind, and concentrating solar power between 2010 and 2023. Plotted from the original source [5].

The main advantage of renewable power is its flexibility in terms of implementation. Grid-connected installations harvest electricity for self-consumption and the surplus can be given to the network. However, off-grid facilities operate in isolation. These are placed in remote locations to meet local electricity demands. Off-grid facilities require the installation of batteries to store surplus electricity. By 2021, the European Union had installed around 26.8 GW of photovoltaic capacity [6]. The largest European market was Germany (21%), followed by Spain (19%), France (14%), the Netherlands (13%), Poland (13%), Greece (4%), and Italy (4%). The current worldwide photovoltaic power capacity is expected to grow from 900 GW (EU share of 25%) to 3000 GW (EU share of 5%) by 2050 according to the IEA Roadmap [7].

There are two main pathways for the implementation of renewable electricity produced either from solar photovoltaic, concentrating solar power, or on/offshore wind. The most straightforward pathway is the direct substitution of fossil-based electricity in current industrial processes. The second pathway involves the electrification of current processes based on a heat supply obtained from the use of non-renewable fuels such as natural gas and coal, among others [8].

Electrically powered technologies cover the broad temperature spectrum required by industries [9]. Applications that require low and medium temperatures, such as electric boilers and heat pumps that supply heat and cooling, are not sector-specific and can thus be implemented transversally. Table 1 presents a portfolio of electrically powered technologies expected to substitute conventional fossil-based energy (either non-renewable electricity or gas) for renewable heating and cooling.

Table 1. Renewable electricity-based technologies for the electrification of industrial processes.

<table>
<tr><th colspan="4">Process Temperature Range in °C</th><th rowspan="2">Technological Maturity</th><th rowspan="2">Applications</th><th rowspan="2">Electrification Stages</th></tr>
<tr><th><100</th><th>100–400</th><th>400–1000</th><th>>1000</th></tr>
<tr><td colspan="2">Compression heat pumps and chillers</td><td>N.A.</td><td>N.A.</td><td>Established in industries (only <100 °C)</td><td>Space heating
Hot water
Low-pressure steam
Drying
Cooling and refrigeration</td><td>1</td></tr>
<tr><td colspan="2">Mechanical vapour recompression (MVR)</td><td>N.A.</td><td>N.A.</td><td>Established in industries</td><td>Energy recovery
Distillation
Evaporation
Steam generation
Process heat</td><td>1</td></tr>
<tr><td colspan="3">Electric boilers</td><td>N.A.</td><td>Established in industries</td><td>Space heating
Hot water
Thermal oil
Steam</td><td>1</td></tr>
<tr><td colspan="4">Infrared heaters</td><td>Established in industries</td><td>Drying
Paint curing
Plastic treatments
Food processing</td><td>1</td></tr>
<tr><td colspan="4">Microwave and radio-frequency heaters</td><td>Established in industries, except for cement and ceramic firing/sintering</td><td>Drying
Ceramic firing
Ceramic sintering
Cement treatment
Food processing</td><td>1</td></tr>
<tr><td colspan="4">Induction furnaces</td><td>Established in industries</td><td>Metal melting
Reheating
Annealing
Welding</td><td>1</td></tr>
<tr><td colspan="4">Resistance furnaces</td><td>Established in industries</td><td>Metal melting
Smelting
Chemical heating
Ceramic firing
Glass melting
Calcination</td><td>2, 3</td></tr>
<tr><td colspan="4">Electric arc furnaces</td><td>Established in industries</td><td>Metal melting
Partial refining</td><td>2, 3</td></tr>
<tr><td colspan="4">Plasma technology</td><td>Established in industries only for metal and waste treatment</td><td>Waste treatment
Metal treatment
Welding
Sintering
Cement production</td><td>2, 3</td></tr>
</table>

Notes: Electrification stages: (1) Includes thermal processes that are common to all industries and therefore considered potential entry points for electrification; (2) corresponds to a more advanced stage of electrification with sector-specific technologies; and (3) explores the maximum achievable electrification potential when considering technologies with higher uncertainties and lower technological readiness levels. Table modified from the original source [9].

3. Renewable Heat

3.1. Solar Thermal

Solar thermal heat is the energy produced by converting solar energy into usable heat. Solar thermal collectors are the devices used for this purpose. They absorb the incoming solar radiation, convert it into heat, and transfer this heat to a medium (usually air, water, or oil) flowing through the collector. The solar energy collected is transported by the circulating fluid to be used directly or stored in a thermal energy storage tank [10].

There are two types of solar collectors: non-concentrating or stationary and concentrating. A non-concentrating collector has the same area for intercepting and absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's radiation on a smaller receiving area, thereby increasing the radiation flux [11]. Table 2 shows the most common types of collectors and the temperature ranges that they can deliver.

Table 2. Common types of collectors and the temperature ranges they can deliver.

Motion	Collector Type	Absorber Type	Temperature (°C)
Stationary non-concentrating	Flat plate collector (FPC)	Flat	30–80 [12]
	Evacuated tube collector (ETC)	Flat	50–200 [12]
Concentrating (single-axis tracking)	Parabolic trough collector (PTC)	Tubular	60–375 [13]
	Linear Fresnel collector (LFC)	Tubular	60–400 [14]
Concentrating (two-axis tracking)	Parabolic dish collector (PDC)	Point	750–1000 [15]
	Power tower receiver	Point	500–1500 [16]

Non-concentrating solar heaters are already in use on a commercial scale. Parabolic troughs have also reached commercial maturity, with well-documented references concerning their availability and reliability [13]. Linear Fresnel collectors are less mature than troughs, but they are also available on a commercial scale [17]. Parabolic dish and power tower receivers also exist on a commercial scale but they are still at the initial stage of commercialisation in Europe. The total overall production of solar thermal energy in the EU-28 countries in 2016 was around 50 TWh, representing a 2% share of renewable energy [18].

The solar process heat installations applied to industrial sectors are similar to those used in residential buildings, especially for those applications where low (<150 °C) to medium (150 °C–400 °C) temperatures are required. For higher temperatures (>400 °C), more advanced or concentrated solar collectors are required. Almost all industrial processes with a heat demand require temperatures that can be provided by a solar thermal system. Among the EIIs, the chemical sector has a high percentage of low- and medium-temperature heat requirements in its production processes (>50%) and is the most suitable industrial sector (among the EIIs) for the effective use of solar thermal heat. The selection of an appropriate solar collector depends on several factors including operating temperature, thermal efficiency, energy yield, and costs, among others [19].

3.2. Heat Pumps

A heat pump (HP) is a technology that provides heating, cooling, and hot water. There are multiple known applications of heat pumps focused on district heating [20,21]. However, the use of heat pumps for industrial applications is gaining interest due to their potential to aid in the decarbonisation of processes. Heat pumps convert energy from air, ground, and water to useful heat using a refrigerant cycle. Such a cycle runs thanks to a special fluid that undergoes phase transitions and circulates in a closed circuit, which is normally composed of four parts: an evaporator, compressor, condenser, and expansion valve [22].

Air-source heat pumps use the heat of the surrounding ambient air as their primary energy source. These types of heat pumps are considered less expensive compared to other existing heat-pump-based technologies. Air-source heat pumps are installed above ground. Another type of air-source heat pump applied to industrial processes is the so-called exhaust heat pump. It uses the exhaust heat from manufacturing processes. Exhaust heat is typically warmer than the surrounding air. This causes the evaporation-to-condensation process to be more effective. These types of heat pumps are very suitable for the industrial sector due to the available heat streams that could potentially be recovered.

Underwater heat pumps require a water source as the heat-exchange medium, which could be obtained either from the ground, surface, or seawater [23]. These types of heat pumps extract heat from the water source, making the heat available for other applications such as heating, cooling, and the preparation of hot water. Water heat pumps are considered highly efficient due to the excellent temperature characteristics of water as an energy carrier. Additionally, the underwater temperature remains stable throughout the year. This type of heat pump is especially interesting for locations where extreme weather does not cause a drop in performance.

The implementation of heat pumps in EIIs is limited for multiple reasons. There are not enough manufacturers of equipment based on the concept of heat pumps. The available equipment is not able to deliver the broad range of process temperatures typically required by industries. Most commercial manufacturers provide equipment able to supply heat with temperatures up to 90 °C. Above such temperatures, the available options in the market are constrained. Only a few providers offer equipment that is able to deliver heat in the range of 120 to 165 °C. Fortunately, several ongoing projects have demonstrated heat delivery in the range of 160 to 200 °C [24]. EIIs have a large heat demand, requiring temperatures up to 200 °C. Table 3 provides an overview of the potential of heat-pump applications in several industrial sectors [25].

Table 3. Overview of heat-pump applications and temperature ranges in selected industrial processes.

Industrial Sector	Industrial Process	Process Temperature in °C										T in °C
		20	40	60	80	100	120	140	160	180	200	
Paper	Drying											90–240
	Boiling											110–180
	Bleaching											40–150
	De-inking											50–70
Food and Beverage	Drying											40–250
	Evaporation											40–170
	Pasteurisation											60–150
	Sterilisation											100–140
	Boiling											70–120
	Distillation											40–100
	Blanching											60–90
	Scalding											50–90
	Concentration											60–80
	Tempering											40–80
	Smoking											20–80

Table 3. *Cont.*

Industrial Sector	Industrial Process	Process Temperature in °C										T in °C
		20	40	60	80	100	120	140	160	180	200	
Chemicals	Distillation											100–300
	Compression											110–170
	Thermoforming											130–160
	Concentration											120–140
	Boiling											80–110
	Bioreactions											20–60
Metals	Drying											60–200
	Pickling											20–100
	Degreasing											20–100
	Electroplating											30–90
	Phosphating											30–90
	Chromating											20–80
	Purging											40–70
Plastic	Injection moulding											90–300
	Pellet drying											40–150
	Preheating											50–70
Textiles	Colouring											40–160
	Drying											60–130
	Washing											40–110
	Bleaching											40–110
Wood processing	Glueing											120–180
	Pressing											120–170
	Drying											40–150
	Steaming											70–100
	Cocking											80–90
	Staining											50–80
	Pickling											40–70
Automotive	Resin moulding											70–130
Mechanical engineering	Surface treatment											20–120
	Cleaning											40–90
Technology Readiness Level (TRL) indicated above:			Conventional HP (<80 °C), established in industries									
			Commercially available HP (80 to 100 °C), key technology									
			Prototype status, high-temperature HP (100–140 °C)									
			Laboratory research status, very-high-temperature HP (>140 °C)									

Table modified from the original source [25,26].

3.3. Geothermal

Geothermal energy is increasingly seen as an energy source that will aid in the decarbonisation of European industries. There are projections that by 2050, around 100 to 210 TWh/year will be available using geothermal energy [27]. The main applications of geothermal energy have been in the residential and commercial sectors in the form of district heating [28,29]. However, applications in the agricultural and industrial sectors are also expected [30]. In industries, geothermal energy can be directly employed to supply heat or steam for processes as diverse as pasteurisation, drying, and evaporation, among others. Geothermal heat and steam could be implemented in industries such as the food-processing industry, chemical production, and material mining. Additionally, the benefits of geothermal energy sources include the provision of local, flexible renewable energy; diversification of the energy mix; reduction in fossil-based fuel imports; and protection against volatile fossil fuel prices [31].

Geothermal energy applications are highly dependent on the below-surface water temperature. According to Dalla Longa and colleagues [31], practically all regions in Europe show an economical potential for geothermal energy applications depending on the depth (Figure 3). Except for Iceland and a few other European regions with clear volcanic activity, the potential to produce electricity from geothermal energy is limited to reservoirs of depths less than 2 km. Direct geothermal applications, such as in agricultural greenhouses or industries, can be developed when reservoirs with depths of less than 2 km are available.

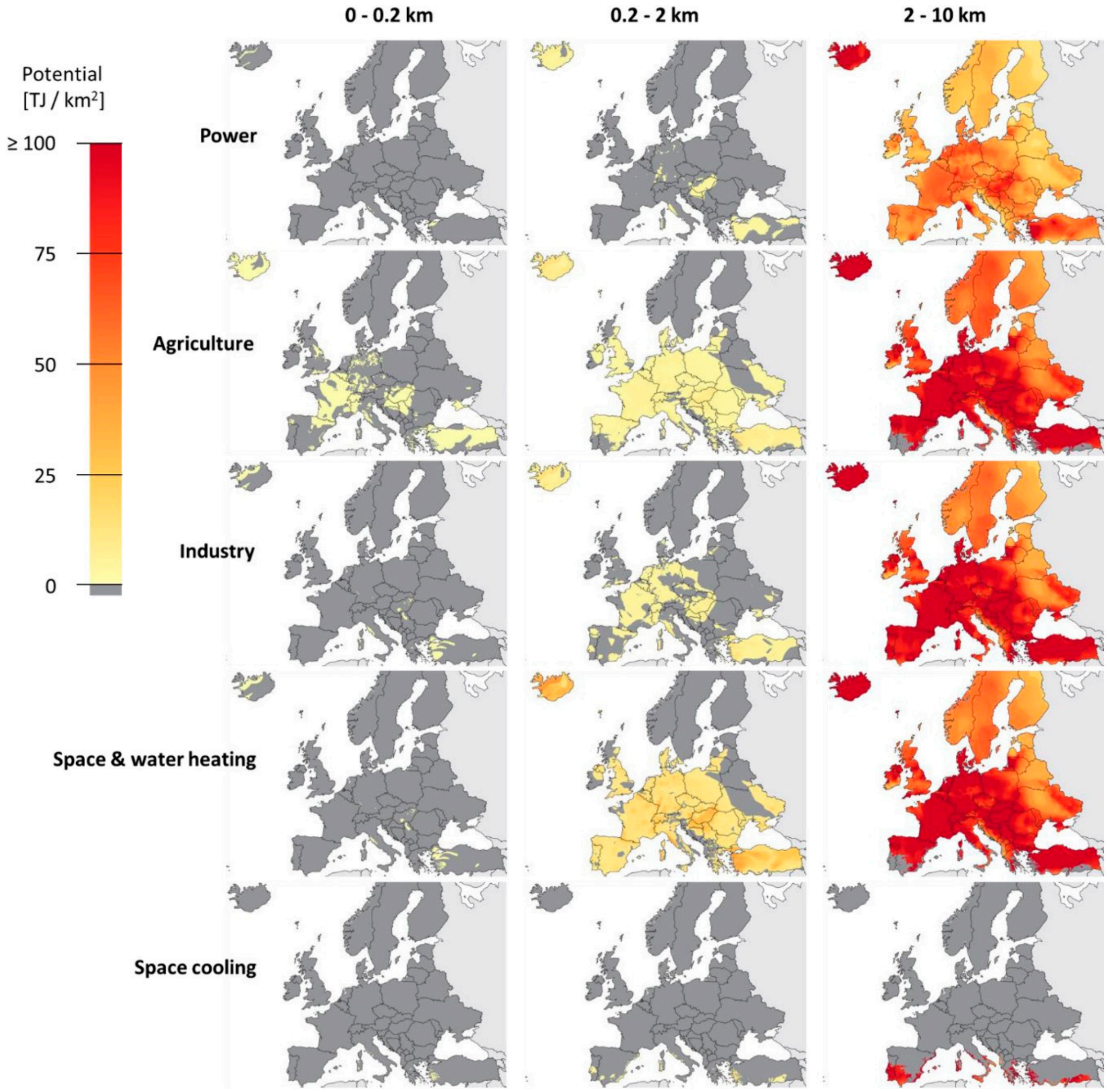

Figure 3. Long-term economic potential for various geothermal applications in Europe at three different ranges. Taken from the original source [28] (license: CC by 4.0).

Historically, European countries that have taken advantage of geothermal energy, such as Iceland, Italy, France, and Hungary, among others, have been the first to develop applications based on this energy source. However, applications based on the use of geothermal energy can also be developed in other low- and medium-enthalpy areas [32]. In regions with lower-temperature geothermal sites, applications make use of heat pumps [31].

One challenge concerning the use of geothermal-based energy is related to the financing and development of the infrastructure for a new heat grid [33]. Retrofitting is seen as an alternative to the implementation of geothermal energy not only for its most common application—urban district heating—but also as an energy source for energy-intensive industries.

3.4. Solid Biomass

Solid biomass has been identified as a key fuel for the transition to renewable energies in Europe. It is by far the main feedstock (91%) for bioheat production [34]. There are many conversion processes needed to transform biomass into useful forms of energy, which can be categorised into three main conversion pathways: thermochemical, physicochemical, and biochemical. Renewable heat can be produced using technologies that are characterised as thermochemical conversion processes.

Figure 4 illustrates the main thermochemical conversion technologies able to produce renewable heat and power from solid biomass. One of the main advantages of these technologies is their versatility, which makes it possible to take advantage of a wide variety of raw materials that can be used as fuels. Another advantage is that the energy generated is non-intermittent, which means that the required quantities can be generated when needed.

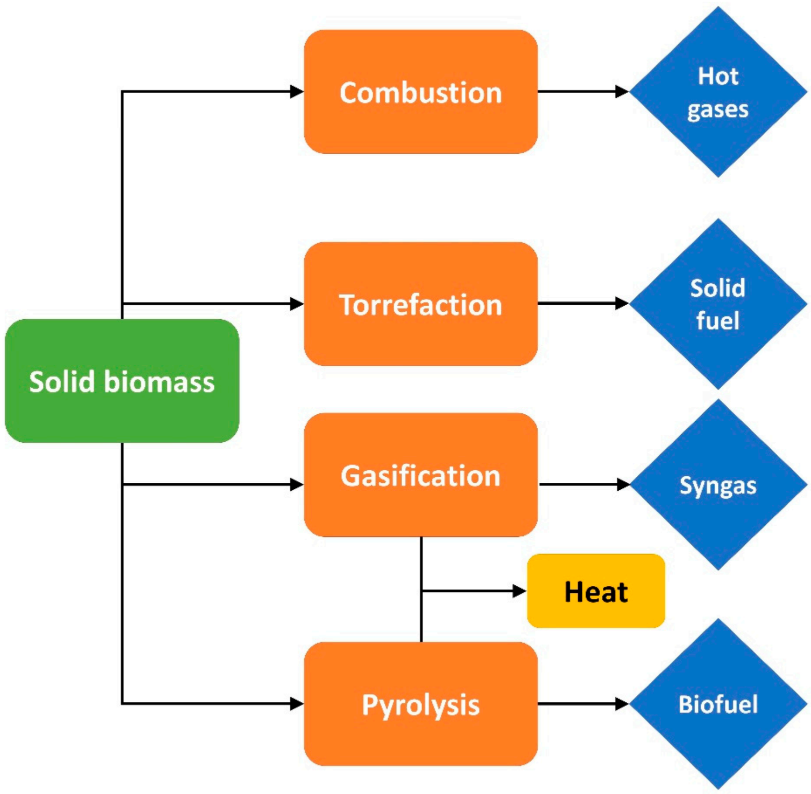

Figure 4. Main biomass thermochemical conversion technologies. Own design, based on information from [35–37].

Essentially, all thermochemical conversion technologies are available on a commercial scale, depending on the feedstock in use, although it should be noted that combustion is more widely applied than other technologies. Examples of commercial facilities that produce each thermochemical pathway are shown in Table 4.

Table 4. Examples of commercially available thermochemical technologies.

Pathway	Reactor Type	Capacity	Developer
Torrefaction	Fluidised bed	60,000 ton/a	Topell Energy
Gasification	Updraft	2–15 MW	DTI
(Fast) Pyrolysis	Fluidised bed	24,000 ton/a	BTG Bioliquids

As of 2018, the pulp and paper sector, as well as the wood and wood product industries, used a combined 81% of the biomass used in EU industries for energy consumption. The non-metallic minerals sectors, including glass, ceramics, and cement, are by volume, the third largest industrial users of biomass. Other EII sectors, including the chemical and petrochemical, iron and steel, and non-ferrous metals sectors, use 0.64%, 0.04%, and 0.03% of the biomass for energy consumption, respectively [38].

Biomass combustion to produce heat in combination with electricity is widely applied in several EII sectors. One example is the Polaneic Green Unit in Poland, where the older pulverised coal boiler was replaced with a biomass-fired circulating fluidised bed boiler [39]. Torrefied biomass was applied in the iron and steelmaking industry in existing blast furnaces. Steelmaker ArcelorMittal, Belgium, has started the construction of a new facility called the Torero plant. The produced torrefied biomass will partly substitute pulverised coal and be used as an alternative carbon source [40]. Gasification plants are mainly dedicated to producing heat and electricity from which the heat is used for district heating. There are, however, a few examples of using 'producer gas' for pyro-processing systems in cement plants. One such example is in Germany at the Rüdersdorfer Zement GmbH cement plant [41].

Biochar as a by-product of biomass gasification and pyrolysis is of interest to energy-intensive industries as a substitute for fossil coal used in steel production [42]. Biochar in multiple formats has been tested and compared with anthracite reference coals. Melting tests in a pilot electric arc furnace have shown that biochar reacts in a similar way to reference coals. Thus, biochar shows great potential for use in industrial-scale electric arc furnace steelmaking as a substitute for fossil coal. Additionally, biochar obtained from pyrolysis and gasification can be carbon-negative by combining net carbon removal from industrial processes with the production of energy or other added-value products beyond sequestered carbon [43].

3.5. Liquid and Gaseous Biofuels

Biofuels are obtained via the conversion of an organic feedstock either into a liquid (most common), solid, or gaseous form of fuel [44]. Biofuels can be identified depending on the feedstock used for their production in conventional and advanced biofuels [45]. Although conventional biofuels (first-generation biofuels) are known to be produced from edible and land-consuming feedstocks, advanced biofuels (second-generation biofuels) make use of non-food and non-feed organic feedstocks [46]. Although most commercialised biofuels (e.g., biodiesel and bioethanol) are used in the transport sector [47], they are not extensively used in energy-intensive industries within the cement, iron, ceramic, and chemical sectors, to name a few. These sectors still rely on the use of conventional fossil fuels for their processes such as combustion-carbon-based electricity and natural gas for heat production. The former can be substituted more frequently with renewable electricity from variable sources. However, the combustion of natural gas could ideally be substituted by biomethane [48]. Not only is this renewable gas obtained via the anaerobic digestion of multiple renewable organic feedstocks but its use in industries also does not require any modification of current industrial processes. The similarity between the compositions of natural gas and biomethane is very high (Table 5).

Table 5. Comparison of natural gas, biogas, and biomethane.

Compound	Natural Gas (%) [49]	Biogas (%) [50]	Biomethane (%) [51]
Methane	87.0–98.0	50–75	>90
Ethane	1.5–9.0	N.A.	N.A.
Butane	0.1–1.5	N.A.	N.A.
Pentane	<0.4	N.A.	N.A.
N_2	5.5	0–10	N.A.
CO	0.05–1.0	25–50	N.A.
O_2	<0.1	0–2	N.A.
H_2	N.A.	0–1	<5

Independent of the technical feasibility of biomethane, one of its implementation challenges is deeply linked to its availability [52]. It is expected that biomethane will only replace around 8% of the total natural gas consumption in the EU by 2030 [53].

3.6. Green Hydrogen

Hydrogen is an energy carrier that can be produced from fossil fuels and biomass, water, or a mixture of both. At present, roughly 95% of worldwide hydrogen production comes from fossil fuels [54]. Hydrogen is considered renewable or green when the full life-cycle greenhouse gas emissions of the production process are close to zero. The most common method of producing green hydrogen is through the electrolysis of water (in an electrolyser powered by electricity), and with the electricity stemming from renewable sources, it can also be produced through other pathways. FCH JU—The Fuel Cells and Hydrogen Joint Undertaking—investigated 11 different green hydrogen pathways besides electrolysis, and 6 pathways were considered sound for 2030 [55]. Figure 5 presents these different pathways based on the three feedstocks that can be used to generate hydrogen: renewable electricity, biomass and biogas, and solar irradiation. The figure also shows their technological readiness levels (TRL) on the horizontal axis. The steam reforming of biomethane/biogas with or without carbon capture and utilisation/storage is also a mature and well-established technology. Less mature pathways include biomass gasification [56] and pyrolysis [57], thermochemical water splitting [57], photocatalysis [58], the supercritical water gasification of biomass [59], combined dark fermentation [60], and anaerobic digestion.

Currently, there is no significant hydrogen production from renewable sources; green hydrogen has been limited to demonstration projects [54] but is expected to be developed in the coming years. In low- and medium-grade heat industrial segments, using renewable electricity is the primary way to decarbonise industrial processes according to FCH JU [62]. However, electric heaters, boilers, and furnaces become less efficient when higher temperatures are required, and their use may necessitate major adaptations of existing production processes. For industrial processes in the high-grade heat segment, hydrogen may, therefore, offer benefits due to its ability to generate high temperatures using process setups similar to those used today. As more than 30% of the industries' CO2 emissions stem from high-grade heat, these uses have an essential role to play in decarbonisation, certainly for as long as CCS or other innovations are not competitive. Besides its use in high-grade heat processes, EIIs can use green hydrogen for chemical and synthetic fuel production and as a reduction agent (steel industries).

The production of green hydrogen is generally not yet carried out on a commercial scale. It can be used directly for heat and/or power generation, for material use (in the chemical and refinery industries), in production processes to avoid the production of CO_2 emissions (in the steel industry), or in CCU processes (in the lime and cement industries). In the steel industry, some companies are exploring the use of hydrogen in their production processes. The three Swedish steel-sector companies, steel manufacturer SSAB, mining company LKAB, and energy company Vattenfall, collectively work on HYBRIT (Hydrogen Breakthrough Ironmaking Technology) and are developing a pilot plant at the SSAB site in Luleå, Sweden. In Germany, the multinational steel production company ArcelorMittal is taking steps to reduce its carbon emissions by retrofitting a production plant to use hydrogen for iron ore reduction. ArcelorMittal partnered with the University of Freiberg to test a hydrogen-based process at its Hamburg steel production plant [63].

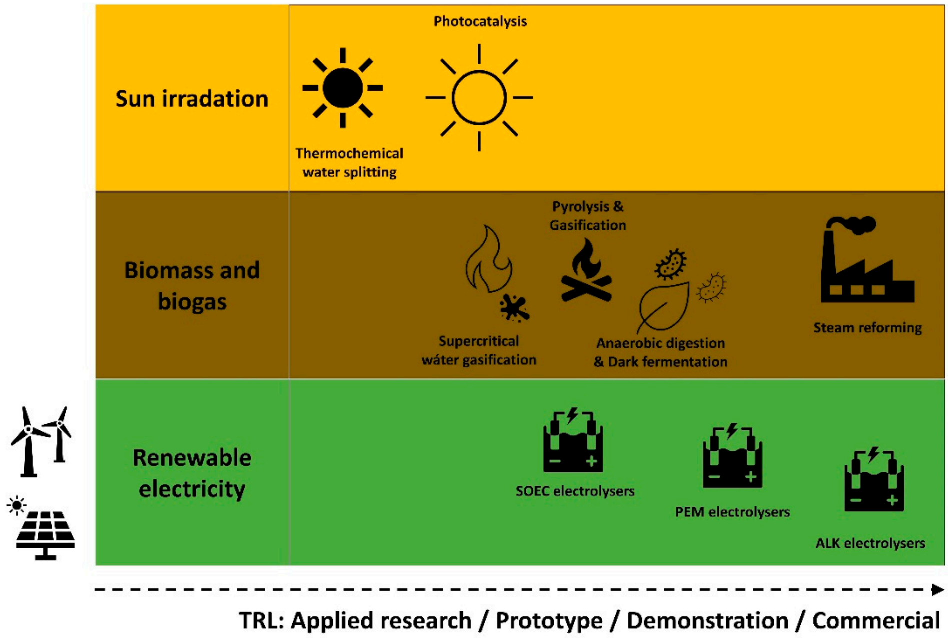

Figure 5. Renewable hydrogen pathways and current levels of maturity. TRL stands for technology readiness level (redrawn from the original source [61]).

Regarding green hydrogen, biological hydrogen production via dark fermentation, photosynthesis, or photofermentation could also be considered [64]. Biohydrogen production is of interest to the scientific community and represents an additional route to green hydrogen production [65]. In the current European context, there exist ambitious goals for green hydrogen produced from electrolysers powered with renewable electricity (6 GW by 2024, 40 GW from 2025 to 2030, and green hydrogen deployment on a large scale by 2030). It seems unlikely that biological hydrogen production processes could cope with such goals [66], especially when biological hydrogen production has only been demonstrated at a low TRL [67].

4. Assessment of Renewables

Table 6 shows an overview of REs' potential for the decarbonisation of EIIs. The integration of electrified processes is widely applied in industries such as secondary steel and non-ferrous metals production [68]. In high CO_2-emitting industries, such as ceramics, glass, and paper, the electrification of the processes will contribute to the reduction in emissions. In other industrial sectors that rely significantly on the use of (fossil-based) heat for the conversion of raw feedstocks, the use of renewable power can be part of the decarbonisation pathway. Renewable power in these highly heat-dependent sectors will have to be used in combination with other renewable solutions.

Table 6. Overview of renewable energies' potential for the decarbonisation of the top GHG-emitting and energy-intensive industries.

Sector	Renewable Power for Process Electrification		Renewable Heat and Its Sources				CCUS Technologies	
	Heat and Mechanical	Electrochem. Processes (Excl. H_2)	Biomass Combustion (and Biofuels Feedstock)	Other RE (Geotherm. and Conc. Solar)	Green H_2 (Electrolysis/Gasification)	Biomethane (Anaerobic Digestion)	Carbon Capture and Storage	Carbon Capture and Utilisation
Steel	XXX	XX	X	XXX	XXX	XXX	XXX	XXX
Chemicals	XXX	XXX	XXX	XX	XXX	XX (**)	XXX (*)	XXX
Fertilisers	XXX	XXX	XXX	XX	XXX	XX (**)	XXX (*)	XXX
Cement	XX	O	XXX	XX	X	XX (**)	XXX	XXX
Lime	X	O	XXX	XX	X	XXX	XXX	XXX
Refining	XX	O	XXX	XX	XXX	XXX (**)	XXX	XXX
Ceramics	XXX	O	X	XXX	XX	XXX	O	X
Paper	XX	O	XXX	XX	O	XXX (**)	O	O
Glass	XXX	O	XXX	XXX	X	XXX	O	O
Non-Fe metals	XXX	XXX	XXX	XX	XX	XXX	X	X
Alloys	XXX	XXX	XXX	XX	XX	XXX	X	X
Notes	O: Limited or no significant application foreseen X: Possible application but no main route or wide-scale applications XX: Medium potential XXX: High potential				XXX: Sector already applies the technology on a large scale (it can be expanded in some cases) (*) In particular for ammonia and ethylene oxide (**) In particular as feedstock for added-value products			

Table adapted from the original source: [69].

One of the main opportunities for renewable power in sectors where heat is required, especially low-temperature heat, will be the use of electric boilers capable of providing heat application below 300 °C. Industrial applications, such as electric arc, infrared, induction, dielectric, direct resistance, microwave, and electron beam heating, which require temperatures below 1000 °C, can be powered with renewable electricity [69]. Above 1000 °C, there is a need for further research to fulfil the requirements of industrial sectors such as the cement and glass sector [68].

Apart from the electrification of heat with renewable power, this will be widely employed in conventional electrochemistry-based technologies [70] and novel electrochemistry-based fermentations for high-added value products from CO_2 [71]. The non-ferrous, ferro-alloys and silicon, and chemical industries make use of these technologies that will continue to be powered with electricity. However, there will be a gradual increase in the use of renewable power to replace fossil-based power. Examples of the use of renewable power in the steel and chemical industries are high-temperature steel electrolysis/iron ore reduction with plasma and electricity-based processes (plasma, microwave, and ultrasounds).

Multiple and diverse industrial processes in the steelmaking and refining sector (e.g., feedstock for ammonia production) can utilise (renewable) hydrogen. Today, most global H_2 production relies on the steam reforming of methane (SMR), which is a process that leads to high CO_2 emissions [72]. Thus, low CO_2-emitting routes such as electrolysis are attracting attention worldwide. However, other alternative routes, such as methane pyrolysis [73], water photolysis, and standard SMR with CCSU, should also be considered.

Applications of hydrogen obtained using the above-mentioned routes will continue to be for the refining of chemicals (for low-CO_2 ammonia, methanol, olefins, or (bio)synthetic fuel production [74]) and in the steel sector (as a reducing agent in the direct reduction of iron or in smelting processes) [75].

Biomass (wood, agricultural, and forestry waste) will be a key feedstock in the decarbonisation of industries independent of its origin [76]. Biomass is used and will continue to be used not only as a fuel for heat production in the paper and silicon industries but also as a feedstock for other types of biofuels. For example, biomass is used as a partial replacement for coal as a reducing agent in the steelmaking industry [40]. In recent years, lignocellulosic ethanol production technologies have reached the commercialisation stage [77]. Furthermore, algae biomass has successfully been used for the production of biofuels such as biogas [78]. An issue regarding the use of biomass, either as a direct source of heat via combustion or as a feedstock for biofuels, is its availability. Although worldwide biomass is the largest renewable energy source with a significant 13% share of the global energy mix (considering all types of energy sources) [79], it is estimated that only half of both the energetic and non-energetic final consumption of biomass by the chemical sector can be covered [69].

Renewable gases such as hydrogen and biomethane will become increasingly relevant for the replacement of natural gas [80]. Biomethane as the result of biogas upgrading from the anaerobic digestion of organic matter and via thermochemical methanation processes is considered a renewable gas that can be injected into the gas grid and used to substitute fossil-based natural gas without the need to adapt or change equipment. Green hydrogen produced via renewable power requires replacement of the burners and part of the gas installation to ensure connection tightness. However, biomass-based solutions face challenges with respect to availability. It is expected that biomethane will only replace around 8% of the total natural gas consumption in the EU by 2030. On the other hand, only 40 GW of green H_2 will be available in the EU by 2030 [81].

Finally, carbon capture use and storage (CCUS) will bring further opportunities to industries for decarbonising their processes. Currently, 40 Mt CO_2 is captured each year in industries and fuel transformation [82]. There exists a plethora of robust CO_2 capture technologies that are applied in pre- and post-combustion processes in industries [83]. Once CO_2 has been captured, the main route should be its valorisation in added-value products, for example, in the fertiliser and chemical industries. In the latter, CO_2 as a feedstock can be used to produce a broad range of products from basic chemicals to fine chemicals and synthetic fuels [69]. Here, the intervention of renewable H_2 will be essential. Interest in the use of CO_2 has increased in different industrial sectors. Specifically, CO_2 contained in waste gases coming from iron and steel production can be used to produce ethanol thanks to the action of specialised microbial cultures [84]. In addition to the microbial production of ethanol from CO_2, multiple compounds could potentially be produced from industrial CO_2 such as acetate, methanol, and butyrate, among others [85,86]. These simple compounds could lead to multiple value chains thanks to additional post-processes to convert carboxylates into bulk fuels or solvents [87].

Carbon capture and storage (CCS) will be an alternative mitigation route for large industrial CO_2 emitters such as the cement and lime, steel, chemical manufacturing, and refining sectors [88]. Highly CO_2-concentrated gas streams can be easily processed since these streams do not require the technologies that currently capture CO_2 from diluted streams. Examples of this are the exhaust streams found in ammonia production via the steam methane reforming process (95–100% CO_2) and in ethylene production (30–100% CO_2) [69].

An industrial example of carbon capture bioconversion into synthetic fuels is currently being developed by ArcelorMittal. Carbon from the blast furnace is captured and taken to a bioreactor. There, the gas is pressurised and injected into a microbial broth where microorganisms consume CO and H_2 to produce ethanol, which is continuously distilled from the broth [89]. Some characteristics that make this technology relevant for the decarbonisation of steel production are (i) the microorganisms used in this process are driven by CO and H_2; in case of a lack of H_2, the microorganisms can perform the water shift reaction by "picking up" H_2 from the water; (ii) there is no need for a strict cleaning of the blast furnace gas since the microorganisms can easily adapt to trace impurities such as CO_2 and nitrogen; (iii) thanks to the use of different specialised microbial cultures, the production of multiple chemicals can be accomplished; and (iv) the energy conservation in the system has been hypothesised to be relevant; around 70% could be converted into alcohol and approximately 30% could be converted into biomass that could be further valorised.

5. Conclusions

EIIs' decarbonisation will occur through the progressive use of an energy mix that allows the EU industrial sectors to remain competitive on a global scale. Each industrial sector will require specific renewable energy solutions, especially the top GHG-emitting industries. This work provides a catalogue of renewable energy technologies that are currently available (regarding the 2030 scope) and that will be available in the transition towards 2050. These renewable options have been classified into technologies based on the use of renewable electricity and those used in industries to produce heat for multiple processes. Process electrification will be the key to the decarbonisation of industries. Although the costs of producing renewable electricity will gradually decrease, current natural gas-dependent processes will need to be converted to take advantage of the increasing availability of renewable power. Industrial processes that are not viable for electrification will still need a form of renewable heat. Multiple renewable technologies are and will become available in the coming years to supply a broad range of temperatures needed by industries ranging from concentrating solar power and heat pumps to geothermal energy. Biomass will be a key element in decarbonisation not only in coal-based combustion systems but also as a feedstock for biofuels. The contribution of renewable gases such as biomethane from anaerobic digestion and green hydrogen from electrolysis is expected to be essential in the coming years. Biomethane could allow a "smooth" transition due to its chemical composition and remarkable renewable origin. Green hydrogen will not only require technological adaptations but also several years to increase its availability all over Europe. The present work also serves as an initial point of discussion with potential decision makers to jointly draft a vision of renewable energy solutions for the development of short- and long-term strategies for the full decarbonisation of EIIs.

Author Contributions: Conceptualisation, A.A.C.-M., R.J., P.R., E.K. and C.J.-C.; Writing—original draft preparation, A.A.C.-M., A.F.-C., C.K., R.J., B.D., P.R. and M.V.; Writing—review and editing, A.A.C.-M., A.F.-C., A.R., O.B., R.J., B.D., P.R., M.V., E.K. and C.J.-C.; Supervision, A.A.C.-M., A.R. and C.J.-C.; Project administration, A.R.; Funding acquisition, C.K., P.R., E.K., P.G. and C.J.-C. All authors have read and agreed to the published version of the manuscript.

Funding: The RE4Industry project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 952936.

Acknowledgments: A.C. acknowledges DALL-E 2 for generating digital images for the graphical abstract.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Filipović, S.; Lior, N.; Radovanović, M. The Green Deal—Just Transition and Sustainable Development Goals Nexus. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112759. [CrossRef]
2. European Environment Agency. EU Emissions Trading System (ETS) Data Viewer. Available online: https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1 (accessed on 14 November 2022).
3. Rissman, J.; Bataille, C.; Masanet, E.; Aden, N.; Morrow, W.R.; Zhou, N.; Elliott, N.; Dell, R.; Heeren, N.; Huckestein, B.; et al. Technologies and Policies to Decarbonize Global Industry: Review and Assessment of Mitigation Drivers through 2070. *Appl. Energy* **2020**, *266*, 114848. [CrossRef]
4. European Comission. *Energy Balances*; European Statistical Office: Luxembourg, 2022.
5. *Renewable Power Generation Costs in 2020*; IRENA: Abu Dhabi, United Arab Emirates, 2021.
6. Jäger-Waldau, A.; Donoso, J.; Kaizuka, I.; Masson, G.; Bosch, E. *IEA PVPS Reporting Countries*; Becquerel Institute: Wallonia, Belgium, 2022; pp. 1–23.
7. IEA. Technology Roadmap—Solar Photovoltaic Energy 2014—Analysis. Available online: https://www.iea.org/reports/technology-roadmap-solar-photovoltaic-energy-2014 (accessed on 14 November 2022).
8. Lechtenböhmer, S.; Nilsson, L.J.; Åhman, M.; Schneider, C. Decarbonising the Energy Intensive Basic Materials Industry through Electrification—Implications for Future EU Electricity Demand. *Energy* **2016**, *115*, 1623–1631. [CrossRef]

9. Madeddu, S.; Ueckerdt, F.; Pehl, M.; Peterseim, J.; Lord, M.; Kumar, K.A.; Krüger, C.; Luderer, G. The CO_2 Reduction Potential for the European Industry via Direct Electrification of Heat Supply (Power-to-Heat). *Environ. Res. Lett.* **2020**, *15*, 124004. [CrossRef]
10. Anastasovski, A.; Raskovic, P.; Guzovi'c, Z.; Sedić, A. A Systematisation of Methods for Heat Integration of Solar Thermal Energy in Production Processes: A Review. *J. Sustain. Dev. Energy Water Environ. Syst.* **2020**, *8*, 410–437. [CrossRef]
11. Kalogirou, S.A. Chapter Three—Solar Energy Collectors. In *Solar Energy Engineering*; Academic Press: Boston, MA, USA, 2009; pp. 121–217. ISBN 978-0-12-374501-9.
12. Wang, R.; Ge, T. *Advances in Solar Heating and Cooling*; Woodhead Publishing: Sawston, UK, 2016; ISBN 0081003021.
13. Belessiotis, V.; Kalogirou, S.; Delyannis, E. *Thermal Solar Desalination: Methods and Systems*; Elsevier: Amsterdam, The Netherlands, 2016; ISBN 0128097825.
14. Fresnel Collector LF-11 Datasheet. 2021. Available online: https://mb.cision.com/Public/17705/3013997/8f88fef06bc27025.pdf (accessed on 1 June 2022).
15. Berrada, A.; El Mrabet, R. *Hybrid Energy System Models*; Academic Press: Cambridge, MA, USA, 2020; ISBN 012821404X.
16. Qazi, S. *Standalone Photovoltaic (PV) Systems for Disaster Relief and Remote Areas*; Elsevier: Amsterdam, The Netherlands, 2016; ISBN 0128030410.
17. Buscemi, A.; Panno, D.; Ciulla, G.; Beccali, M.; Lo Brano, V. Concrete Thermal Energy Storage for Linear Fresnel Collectors: Exploiting the South Mediterranean's Solar Potential for Agri-Food Processes. *Energy Convers. Manag.* **2018**, *166*, 719–734. [CrossRef]
18. Eurostat Primary Production of Renewable Energy by Type. Available online: http://ec.europa.eu/eurostat/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=ten00081&language=en (accessed on 1 September 2022).
19. Sornek, K.; Filipowicz, M.; Jasek, J. The Use of Fresnel Lenses to Improve the Efficiency of Photovoltaic Modules for Building-Integrated Concentrating Photovoltaic Systems. *J. Sustain. Dev. Energy Water Environ. Syst.* **2018**, *6*, 415–426. [CrossRef]
20. Østergaard, P.A.; Andersen, A.N. Booster Heat Pumps and Central Heat Pumps in District Heating. *Appl. Energy* **2016**, *184*, 1374–1388. [CrossRef]
21. Waite, M.; Modi, V. Potential for Increased Wind-Generated Electricity Utilization Using Heat Pumps in Urban Areas. *Appl. Energy* **2014**, *135*, 634–642. [CrossRef]
22. RHC-ETIP. Strataegic Research and Innovation Agenda for Heat Pumps: Making the Technology Ready for Mass Deployment. 2021. Available online: https://www.rhc-platform.org/sria_heatpumps/ (accessed on 1 April 2022).
23. Wołoszyn, J.; Gołaś, A. Coefficient of Performance Stabilisation in Ground Source Heat Pump Systems. *J. Sustain. Dev. Energy Water Environ. Syst.* **2017**, *5*, 645–656. [CrossRef]
24. Zühlsdorf, B.; Bühler, F.; Bantle, M.; Elmegaard, B. Analysis of Technologies and Potentials for Heat Pump-Based Process Heat Supply above 150 °C. *Energy Convers. Manag. X* **2019**, *2*, 100011. [CrossRef]
25. Nowak, T. *Heat Pumps: Integrating Technologies to Decarbonise Heating and Cooling*; European Copper Institute: Woluwe-Saint-Pierre, Belgium, 2018.
26. Arpagaus, C.; Bless, F.; Uhlmann, M.; Schiffmann, J.; Bertsch, S.S. High Temperature Heat Pumps: Market Overview, State of the Art, Research Status, Refrigerants, and Application Potentials. *Energy* **2018**, *152*, 985–1010. [CrossRef]
27. Dalla Longa, F.; Nogueira, L.P.; Limberger, J.; van Wees, J.-D.; van der Zwaan, B. Scenarios for Geothermal Energy Deployment in Europe. *Energy* **2020**, *206*, 118060. [CrossRef]
28. Østergaard, P.A.; Lund, H. A Renewable Energy System in Frederikshavn Using Low-Temperature Geothermal Energy for District Heating. *Appl. Energy* **2011**, *88*, 479–487. [CrossRef]
29. Barkaoui, A.-E.; Boldyryev, S.; Duic, N.; Krajacic, G.; Guzović, Z. Appropriate Integration of Geothermal Energy Sources by Pinch Approach: Case Study of Croatia. *Appl. Energy* **2016**, *184*, 1343–1349. [CrossRef]
30. Urbancl, D.; Trop, P.; Goričanec, D. Geothermal Heat Potential-the Source for Heating Greenhouses in Southestern Europe. *Therm. Sci.* **2016**, *20*, 1061–1071. [CrossRef]
31. Partners, G.P. Developing Geothermal Distric Heating in Europe. 2014. Available online: http://geodh.eu/wp-content/uploads/2012/07/GeoDH-Report-2014_web.pdf (accessed on 1 February 2022).
32. Kalogirou, S.A.; Florides, G.A.; Pouloupatis, P.D.; Panayides, I.; Joseph-Stylianou, J.; Zomeni, Z. Artificial Neural Networks for the Generation of Geothermal Maps of Ground Temperature at Various Depths by Considering Land Configuration. *Energy* **2012**, *48*, 233–240. [CrossRef]
33. Somogyi, V.; Sebestyén, V.; Nagy, G. Scientific Achievements and Regulation of Shallow Geothermal Systems in Six European Countries—A Review. *Renew. Sustain. Energy Rev.* **2017**, *68*, 934–952. [CrossRef]
34. Calderón, C.; Gauthier, G.; Jossart, J.-M. *AEBIOM Statistical Report 2017*; European Bioenergy Outlook: Brussel, Belgium, 2017.
35. McKendry, P. Energy Production from Biomass (Part 2): Conversion Technologies. *Bioresour. Technol.* **2002**, *83*, 47–54. [CrossRef]
36. Islas, J.; Manzini, F.; Masera, O.; Vargas, V. Chapter Four—Solid Biomass to Heat and Power. In *Resources, Technologies, Sustainability and Policy*; Lago, C., Caldés, N., Lechón, Y., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 145–177, ISBN 978-0-12-813056-8.
37. Malico, I.; Nepomuceno Pereira, R.; Gonçalves, A.C.; Sousa, A.M.O. Current Status and Future Perspectives for Energy Production from Solid Biomass in the European Industry. *Renew. Sustain. Energy Rev.* **2019**, *112*, 960–977. [CrossRef]
38. Calderón, C.; Avagianos, I.; Jossart, J.-M. *Bioheat Statistical Report*; Bioenergy Europe: Brussels, Belgium, 2020.

39. BIOFIT: Technical Options for Retrofitting Industries with Bioenergy: A Handbook. 2020. Available online: https://www.biofit-h2020.eu/publications-reports/BioFitHandbook-2020-03-18.pdf (accessed on 1 February 2022).
40. Hingsamer, M.; Jungmeier, G.; Van Der Stricht, W.; Van De Casteele, S. Environmental Assessment of Biofuel Production Using Waste Wood Integrated in a Large-Scale Steel Mill. 2021. Available online: http://programme.eubce.com/2021/abstract.php?idabs=18806&idses=1175&idtopic=21 (accessed on 1 March 2022).
41. *Large Industrial Users of Energy Biomass*; IEA Bioenergy: Didcot, UK, 2013.
42. Demus, T.; Reichel, T.; Schulten, M.; Echterhof, T.; Pfeifer, H. Increasing the Sustainability of Steel Production in the Electric Arc Furnace by Substituting Fossil Coal with Biochar Agglomerates. *Ironmak. Steelmak.* **2016**, *43*, 564–570. [CrossRef]
43. Brown, R.C. The Role of Pyrolysis and Gasification in a Carbon Negative Economy. *Processes* **2021**, *9*, 882. [CrossRef]
44. Suurs, R.A.A.; Hekkert, M.P. Competition between First and Second Generation Technologies: Lessons from the Formation of a Biofuels Innovation System in the Netherlands. *Energy* **2009**, *34*, 669–679. [CrossRef]
45. Heyne, S.; Harvey, S. Assessment of the Energy and Economic Performance of Second Generation Biofuel Production Processes Using Energy Market Scenarios. *Appl. Energy* **2013**, *101*, 203–212. [CrossRef]
46. IRENA. *Advanced Biofuels, What Holds Them Back?* IRENA: Abu Dhabi, United Arab Emirates, 2019.
47. Ajanovic, A.; Haas, R. On the Future Prospects and Limits of Biofuels in Brazil, the US and EU. *Appl. Energy* **2014**, *135*, 730–737. [CrossRef]
48. Corbellini, V.; Kougias, P.G.; Treu, L.; Bassani, I.; Malpei, F.; Angelidaki, I. Hybrid Biogas Upgrading in a Two-Stage Thermophilic Reactor. *Energy Convers. Manag.* **2018**, *168*, 1–10. [CrossRef]
49. Arinelli, L.d.O.; Teixeira, A.M.; de Medeiros, J.L.; Araújo, O.d.Q.F. Supersonic Separator for Cleaner Offshore Processing of Natural Gas with High Carbon Dioxide Content: Environmental and Economic Assessments. *J. Clean. Prod.* **2019**, *233*, 510–521. [CrossRef]
50. Matuszewska, A.; Owczuk, M.; Zamojska-Jaroszewicz, A.; Jakubiak-Lasocka, J.; Lasocki, J.; Orliński, P. Evaluation of the Biological Methane Potential of Various Feedstock for the Production of Biogas to Supply Agricultural Tractors. *Energy Convers. Manag.* **2016**, *125*, 309–319. [CrossRef]
51. Cavaignac, R.S.; Ferreira, N.L.; Guardani, R. Techno-Economic and Environmental Process Evaluation of Biogas Upgrading via Amine Scrubbing. *Renew. Energy* **2021**, *171*, 868–880. [CrossRef]
52. EBA. EBA Statistical Report 2020. 2020. Available online: https://www.europeanbiogas.eu/wp-content/uploads/2021/01/EBA_StatisticalReport2020_abridged.pdf (accessed on 1 June 2021).
53. Eurogas. *The Sustainable Credentials of Gas*; Eurogas: Brussels, Belgium, 2019.
54. IRENA. *Hydrogen: A Renewable Energy Perspective*; IRENA: Abu Dhabi, United Arab Emirates, 2019.
55. Fuel Cells and Hydrogen 2 Joint Undertaking; Fraile, D.; Altmann, M.; Barth, F.; Pschorr-Schoberer, E.; Albrecht, U.; Lanoix, J.; Bünger, U.; Zerta, M.; Zittel, W.; et al. *Study on Hydrogen from Renewable Resources in the EU: Final Report*; Publications Office: Luxembourg, 2016.
56. Mikulandrić, R.; Lončar, D.; Böhning, D.; Böhme, R.; Beckmann, M. Artificial Neural Network Modelling Approach for a Biomass Gasification Process in Fixed Bed Gasifiers. *Energy Convers. Manag.* **2014**, *87*, 1210–1223. [CrossRef]
57. Medrano, J.A.; Oliva, M.; Ruiz, J.; García, L.; Arauzo, J. Hydrogen from Aqueous Fraction of Biomass Pyrolysis Liquids by Catalytic Steam Reforming in Fluidized Bed. *Energy* **2011**, *36*, 2215–2224. [CrossRef]
58. Colón, G. Towards the Hydrogen Production by Photocatalysis. *Appl. Catal. A Gen.* **2016**, *518*, 48–59. [CrossRef]
59. Rönnlund, I.; Myréen, L.; Lundqvist, K.; Ahlbeck, J.; Westerlund, T. Waste to Energy by Industrially Integrated Supercritical Water Gasification—Effects of Alkali Salts in Residual by-Products from the Pulp and Paper Industry. *Energy* **2011**, *36*, 2151–2163. [CrossRef]
60. Muñoz-Páez, K.M.; Alvarado-Michi, E.L.; Moreno-Andrade, I.; Buitrón, G.; Valdez-Vazquez, I. Comparison of Suspended and Granular Cell Anaerobic Bioreactors for Hydrogen Production from Acid Agave Bagasse Hydrolyzates. *Int. J. Hydrog. Energy* **2020**, *45*, 275–285. [CrossRef]
61. IRENA. *Hydrogen from Renewable Power, Technology Outlook for the Energy Transition*; IRENA: Abu Dhabi, United Arab Emirates, 2018.
62. FCHEA. Hydrogen Roadmap Europe—A Sustainable Pathway for the European Energy Transition. 2019. Available online: https://www.h2knowledgecentre.com/content/researchpaper1125 (accessed on 1 December 2021).
63. FCHEA. Hydrogen as a Clean Alternative in the Iron and Steel Industry. 2019. Available online: https://www.fchea.org/transitions/2019/11/25/hydrogen-in-the-iron-and-steel-industry (accessed on 1 December 2021).
64. Mohanakrishna, G.; Mohan, S.V. Multiple Process Integrations for Broad Perspective Analysis of Fermentative H2 Production from Wastewater Treatment: Technical and Environmental Considerations. *Appl. Energy* **2013**, *107*, 244–254. [CrossRef]
65. Mohan, S.V.; Chiranjeevi, P.; Mohanakrishna, G. A Rapid and Simple Protocol for Evaluating Biohydrogen Production Potential (BHP) of Wastewater with Simultaneous Process Optimization. *Int. J. Hydrog. Energy* **2012**, *37*, 3130–3141. [CrossRef]
66. European Commission. *A Hydrogen Strategy for a Climate Neutral Europe*; European Commission: Brussels, Belgium, 2020.
67. Osman, A.I.; Deka, T.J.; Baruah, D.C.; Rooney, D.W. Critical Challenges in Biohydrogen Production Processes from the Organic Feedstocks. In *Biomass Conversion and Biorefinery*; Springer: Berlin/Heidelberg, Germany, 2020. [CrossRef]
68. Nadel, S. Electrification in the Transportation, Buildings, and Industrial Sectors: A Review of Opportunities, Barriers, and Policies. *Curr. Sustain. Renew. Energy Rep.* **2019**, *6*, 158–168. [CrossRef]

69. Tomas, W.; Gauri, K.; Isobel, R. Industrial Value Chain—Abridge Towards a Carbon Neutral Europe. 2018. Available online: http://www.old.caneurope.org/docman/members/gas-and-workshops/3430-long-term-target-energy-transition-value-chain/file (accessed on 1 January 2022).
70. Pletcher, D.; Walsh, F.C. *Industrial Electrochemistry*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 1990; ISBN 0412304104.
71. Schievano, A.; Pepé Sciarria, T.; Vanbroekhoven, K.; De Wever, H.; Puig, S.; Andersen, S.J.; Rabaey, K.; Pant, D. Electro-Fermentation—Merging Electrochemistry with Fermentation in Industrial Applications. *Trends Biotechnol.* **2016**, *34*, 866–878. [CrossRef]
72. Bassani, A.; Previtali, D.; Pirola, C.; Bozzano, G.; Colombo, S.; Manenti, F. Mitigating Carbon Dioxide Impact of Industrial Steam Methane Reformers by Acid Gas to Syngas Technology: Technical and Environmental Feasibility. *J. Sustain. Dev. Energy Water Environ. Syst.* **2019**, *8*, 71–87. [CrossRef]
73. Sánchez-Bastardo, N.; Schlögl, R.; Ruland, H. Methane Pyrolysis for CO2-Free H2 Production: A Green Process to Overcome Renewable Energies Unsteadiness. *Chem. Ing. Tech.* **2020**, *92*, 1596–1609. [CrossRef]
74. Jourdin, L.; Burdyny, T. Microbial Electrosynthesis: Where Do We Go from Here? *Trends Biotechnol.* **2021**, *39*, 359–369. [CrossRef] [PubMed]
75. *The Future of Steelmaking—How the European Steel Industry Can Achieve Carbon Neutrality*; Roland Berger GMBH: Munich, Germany, 2020.
76. Rehfeldt, M.; Worrell, E.; Eichhammer, W.; Fleiter, T. A Review of the Emission Reduction Potential of Fuel Switch towards Biomass and Electricity in European Basic Materials Industry until 2030. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109672. [CrossRef]
77. Raj, T.; Chandrasekhar, K.; Naresh Kumar, A.; Rajesh Banu, J.; Yoon, J.-J.; Kant Bhatia, S.; Yang, Y.-H.; Varjani, S.; Kim, S.-H. Recent Advances in Commercial Biorefineries for Lignocellulosic Ethanol Production: Current Status, Challenges and Future Perspectives. *Bioresour. Technol.* **2022**, *344*, 126292. [CrossRef] [PubMed]
78. Adeniyi, O.M.; Azimov, U.; Burluka, A. Algae Biofuel: Current Status and Future Applications. *Renew. Sustain. Energy Rev.* **2018**, *90*, 316–335. [CrossRef]
79. Tzelepi, V.; Zeneli, M.; Kourkoumpas, D.-S.; Karampinis, E.; Gypakis, A.; Nikolopoulos, N.; Grammelis, P. Biomass Availability in Europe as an Alternative Fuel for Full Conversion of Lignite Power Plants: A Critical Review. *Energies* **2020**, *13*, 3390. [CrossRef]
80. Kolb, S.; Plankenbühler, T.; Frank, J.; Dettelbacher, J.; Ludwig, R.; Karl, J.; Dillig, M. Scenarios for the Integration of Renewable Gases into the German Natural Gas Market—A Simulation-Based Optimisation Approach. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110696. [CrossRef]
81. Cuevas, F.; Zhang, J.; Latroche, M. The Vision of France, Germany, and the European Union on Future Hydrogen Energy Research and Innovation. *Engineering* **2021**, *7*, 715–718. [CrossRef]
82. IEA CCUS in Industry and Transformation. 2021. Available online: https://www.iea.org/reports/transforming-industry-through-ccus (accessed on 1 February 2022).
83. Wilberforce, T.; Olabi, A.G.; Sayed, E.T.; Elsaid, K.; Abdelkareem, M.A. Progress in Carbon Capture Technologies. *Sci. Total Environ.* **2021**, *761*, 143203. [CrossRef]
84. Takors, R.; Kopf, M.; Mampel, J.; Bluemke, W.; Blombach, B.; Eikmanns, B.; Bengelsdorf, F.R.; Weuster-Botz, D.; Dürre, P. Using Gas Mixtures of CO, CO_2 and H_2 as Microbial Substrates: The Do's and Don'ts of Successful Technology Transfer from Laboratory to Production Scale. *Microb. Biotechnol.* **2018**, *11*, 606–625. [CrossRef]
85. Mohanakrishna, G.; Vanbroekhoven, K.; Pant, D. Impact of Dissolved Carbon Dioxide Concentration on the Process Parameters during Its Conversion to Acetate through Microbial Electrosynthesis. *React. Chem. Eng.* **2018**, *3*, 371–378. [CrossRef]
86. Mohanakrishna, G.; Vanbroekhoven, K.; Pant, D. Imperative Role of Applied Potential and Inorganic Carbon Source on Acetate Production through Microbial Electrosynthesis. *J. CO_2 Util.* **2016**, *15*, 57–64. [CrossRef]
87. Agler, M.T.; Wrenn, B.A.; Zinder, S.H.; Angenent, L.T. Agler Waste to Bioproduct Conversion with Undefined Mixed Cultures: The Carboxylate Platform. *Trends Biotechnol.* **2011**, *29*, 70–78. [CrossRef] [PubMed]
88. Lamberts-Van Assche, H.; Compernolle, T. Economic Feasibility Studies for Carbon Capture and Utilization Technologies: A Tutorial Review. *Clean. Technol. Environ. Policy* **2022**, *24*, 467–491. [CrossRef]
89. De Maré, C. Why Both Hydrogen and Carbon Are Key for Net-Zero Steelmaking. 2021. Available online: https://www.aist.org/AIST/aist/AIST/Publications/Monthly/049-066_September-2021.pdf (accessed on 1 April 2022).