UDK 620.28: 332.142.6: 502.174.1
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
Mater. Tehnol.

THE ROLE OF MATERIALS IN THE GREEN TRANSITION: OPPORTUNITIES, CHALLENGES, BARRIERS AND CONSEQUENCES

VLOGA MATERIALOV PRI ZELENEM PREHODU – PRILOŽNOSTI, IZZIVI, OVIRE IN POSLEDICE

Bojan Podgornik[1,2]

[1]Institute of Metals and Technology, Lepi pot 11, Ljubljana, Slovenia
[2]Faculty of Industrial Engineering, Šegova ul. 112, Novo Mesto, Slovenia

Prejem rokopisa – received: 2025-03-07; sprejem za objavo – accepted for publication: 2025-04-23

doi:10.17222/mit.2025.1420

Europe aims to achieve climate neutrality by 2050. Transitioning to a net-zero society requires research and innovations in energy, transport, manufacturing, and sustainable practices globally, as emissions and climate change are transboundary issues. Materials play a key role in this transition, which also increases Europe's dependence on the import of critical raw materials. These are crucial for green technologies. While the shift to green energy offers climate benefits, the irresponsible sourcing of raw materials for the transition can lead to environmental harm, human-rights violations, and supply challenges, particularly as most critical materials are sourced and produced outside Europe. To ensure sustainability and energy self-sufficiency, Europe must aim for greater reliance on recycling, circular-economy practices, and strategic sourcing.
While electric vehicles can significantly reduce emissions, their environmental benefits depend heavily on the electricity mix used for charging, as well as the energy-intensive processes involved in battery production. The transition to electric vehicles is essential for decarbonizing transport, which however is not without challenges. Solar panels do provide renewable energy, but their production is energy-intensive and may have significant environmental impacts. Also, in the case of wind turbines, essential for green energy, the limited sources and energy-intensive production of rare-earth elements combined with issues such as local climate impacts present ongoing environmental and societal challenges. Finally, in the case of green hydrogen the main challenges revolve around the source of energy for production, storage, and transportation, with all presenting significant energy and material challenges.

Keywords: green transition, materials, renewable energy, recycling, sustainability

Europa se je namenila postati klimatsko nevtralna do leta 2050. Prehod na družbo z neto ničelno emisijo toplogrednih plinov zahteva raziskave in inovacije na področju izdelave in porabe energije v transportu, proizvodnji ter globalni trajnostni praksi. Emisije in klimatske oziroma podnebne spremembe so medsebojno povezane in globalne. Materiali igrajo ključno vlogo pri tem prehodu, ki prav tako povečuje odvisnost Evrope od uvoza kritičnih (strateških) osnovnih surovin. Te so ključne za zelene, okolju prijazne tehnologije. Medtem, ko prehod na zeleno energijo prinaša podnebne koristi, lahko neodgovorno pridobivanje surovin za ta prehod lahko povzroči okoljsko škodo, kršitve človekovih pravic in izzive pri dobavi, zlasti ker se večina kritičnih materialov pridobiva in proizvaja zunaj Evrope. Za zagotovitev trajnosti in energetske samozadostnosti si mora Evropa prizadevati za večjo odvisnost od recikliranja, praks krožnega gospodarstva in strateškega pridobivanja osnovnih surovin.
Medtem, ko lahko električna vozila znatno zmanjšajo emisije, so njihove okoljske koristi močno odvisne od načina pridobivanja električne energije, ki se uporablja za polnjenje vozil, pa tudi od energetsko intenzivnih procesov znotraj proizvodnje baterij. Prehod na električna vozila je nujen za razogljičenje prometa, ki pa ni brez izzivov. Fotovoltaika in sončni kolektorji sicer zagotavljajo obnovljivo energijo, vendar je njihova proizvodnja energetsko intenzivna in lahko pomembno vpliva na okolje. Tudi problemi vezani na vetrne turbine, ki so bistvenega pomena za pridobivanje zelene energije, omejeni viri in energetsko intenzivna proizvodnja elementov redkih zemelj v kombinaciji z vprašanji, kot so lokalni podnebni vplivi, predstavljajo nenehne okoljske in družbene izzive. Nazadnje, tudi v primeru da bo prišlo do večje uporabe zelenega vodika so glavni izzivi, kakšno energijo bomo uporabljali za njegovo proizvodnjo, kako ga bomo shranjevali in transportirali. Pri tem pa so seveda vsi ti izzivi tudi vezani na pomembne energetske in materialne izzive.

Ključne besede: zeleni prehod, materiali, obnovljiva energija, recikliranje, trajnost

1 ENVIRONMENTAL IMPACT

Europe has set a very ambitious climate target, aiming to become the world's first climate-neutral continent by 2050. That means a zero-carbon footprint, achieved by balancing the amount of released carbon dioxide (CO_2) with the carbon removed from the atmosphere or fixed by plants.[1] When talking about fighting climate change and becoming climate neutral, we mainly refer to reducing the carbon footprint and cutting greenhouse-gas (GHG) emissions. However, it is more than that. Becoming "climate neutral" means substantially reducing GHG emissions, but also compensating for any remaining emissions, which are unavoidable. Only in this way can a net-zero emissions balance be achieved.[2] The oceans and soil both absorb carbon dioxide from the atmosphere, but forests represent the most effective "carbon sinks" and the most effective way to make a difference. EU forests

*Corresponding author's e-mail:
bojan.podgornik@imt.si

© 2025 The Author(s). Except when otherwise noted, articles in this journal are published under the terms and conditions of the Creative Commons Attribution 4.0 International License (CC BY 4.0).

absorb the equivalent of nearly 10 % of all EU GHG emissions each year.[3]

Transition to a green, net-zero emissions society requires a lot of research and development to facilitate new technologies, materials and processes, as well as actions in many different areas, mainly related to five areas, i.e., energy, transport, manufacturing, consumerism and environment:

- our buildings and the production of materials and goods should be renovated and modernized to make them much more energy efficient
- the ways we travel – by road, air and sea – need to become drastically more independent of fossil fuels and more environmentally friendly, i.e., using "green" fuels
- electricity production must be entirely based on renewable resources
- in manufacturing no material should go to waste – it must be recycled, low carbon-footprint materials should be prioritized and we need to reduce our customer needs and demands. We, as consumers, can reduce our environmental footprint through our behavior and choices.
- food production should not rely on pesticides and fertilizers that are damaging the air, soil, water and wildlife
- carbon sinks, such as forests, are declining and the trend should be reversed and managed in a more sustainable way

Regardless of its origin, pollution, GHG emissions and climate change affect every single piece of earth and every single one of over 8 billion people living on our planet. It makes no distinction based on borders. Climate change is a global problem! To focus only on Europe would not do much to mitigate global warming, as Europe accounts for less than 10 % of global GHG emissions.[2] Worse, if the Green Deal simply displaces Europe's GHG emissions to other countries and trading partners, it will have no impact at all on climate change.[4] This is why we cannot ignore pollution and environmental impact at the origin of the material, energy, food and consumer goods production, even if it is happening thousands of miles from Europe, our country and homes. We need to prevent carbon leakage and get rid of the mentality "only my backyard matters". Even though the EU has been key in negotiating and upholding the landmark international agreements on the environment – the UN Climate Convention, the Kyoto Protocol and the Paris Agreement – still many materials and products are imported to facilitate the EU's green transition, although having a very high impact on the local environment and climate at its origin.[2]

Although Europe's economy grew by more than 50 % in the last 30 years, it managed to cut its emission by almost 30 % over the same period.[5] However, together with the worldwide economy increase, which grew by almost 90 % in the last 30 years, also global emissions increased by about 65 % in this period. Overall global GHG emissions increased from 38 to 55 billion tons and CO_2 emissions from 22.5 to 37 billion tons.[6] Currently the main GDP share of 37 % belongs to Asia, followed by North America (30 %) and Europe (24 %), while South America and Africa together accounts for less than 7 %.[7] This is also reflected in emissions and pollution distribution. While in 1990s Asia, Europe and North America each contributed about 30 % to global emissions, nowadays, Asia is the main polluter contributing about 60 % of annual CO_2 and GHG emissions, followed by North America (17 %) and Europe (14 %), and Africa and South America again having a negligible impact of about 6 %. In the last 150 years developed countries have emitted about 74 % of the total emissions, with the 10 top nations emitting more than 90 % of that.[8] Furthermore, among all the continents only Europe succeeded to cut its emissions in the last 30 years, while almost all the others show substantial increase. North America managed to keep its emissions at the same level, while Asia shows the biggest increase of over 200 %, followed by Africa (110 %) and South America (75 %).[9]

Divided by sectors, electricity and heat production in recent years (2020-2023) represent the largest contributors to global emissions with over 20 billion metric tons of CO_2 equivalent (GtCO2e) per year and over 36 % share. This is followed by manufacturing and industry (21 %), agriculture, land use and forestry (18 %), and transportation (14 %) where road-transport emissions accounted for more than 70 % of total transport-related emissions. However, when considering the primary source of emissions, energy-related emissions account for almost three-quarters of these emissions (**Figure 1**). So, first of all we need to decarbonize our electricity supply, before we fully electrify all of our heating and road transport. But even then, we would still have emissions from shipping and aviation to deal with.[10]

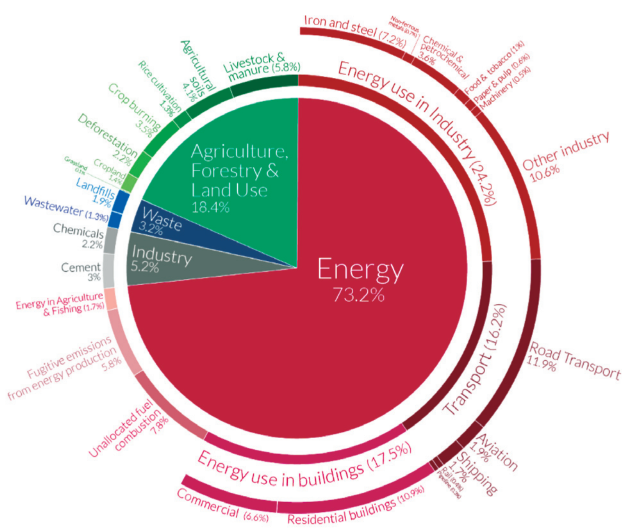

Figure 1: Global GHG emissions in 2020 by sectors[10]

1.1 Manufacturing & Industry

Currently, industries in Europe and North America account for about 20 % of their GHG emissions. Decarbonization efforts in this segment must first focus on an improved sustainable character and duration of products, thus alleviating the pressure on natural resources. This includes product reusability, reparability and recyclability, with the need to integrate high, preferably 100 % recycled contents[11] and successful use of material side-streams.[12] As of the end of 2020, only 12 % of secondary materials and resources were brought back into the economy of the EU.[13] In this respect materials efficiency and circular economy, which are based on the extraction and trading of resources, their transformation and their elimination, are regarded as crucial elements in the EU's green transition.[14]

Second, we need to ensure access to and supply of "clean" raw materials, especially strategic and critical raw materials (i.e. coking coal, rare-earth elements, lithium, manganese, copper, nickel, steel and aluminum[15]) required for clean technologies such as clean hydrogen, fuel cells, renewable electricity generation, energy storage, carbon capture, etc..[11] Finally, carbon-free renewable energy must be used as a source for driving industrial processes. The industry consumes about a quarter of the world's total primary energy, of which almost 70 % comes from fossil fuels.[14,16] Therefore, an important step in decarbonizing manufacturing and industry is through the decarburization of input materials and the energy required for their production.

In manufacturing, energy-intensive industries (EIIs), encompassing iron and steel, chemical and petrochemical, cement, aluminum, and pulp and paper industries, are responsible for more than two-thirds of industrial energy demands and sectoral emissions. Iron and steel alone are the largest CO_2 emitters of the industrial segment, representing 7 % of global emissions and 28 % of industrial emissions.[16] The cement industry is responsible for another 7 % of global GHG emissions, mainly contributed by clinker production, while the production of primary aluminum is the most energy-intensive and one of the most emission-intensive industrial materials today.[17] Thus, to transit the industry to a low-carbon economy, the decarbonization of EIIs is critical. However, specific factors such as high-temperature heat demand, process emission resulting from chemical reactions, and the long life of the industrial plants make it challenging to mitigate the emissions from EIIs. In short-to-medium terms, actions should be focused on increasing the use of zero-emission electricity from renewable resources, electrification in low/medium-temperature processes, improving energy efficiency and expanding the field of bioenergy, especially biomethane and H_2 for high-temperature heat demands. In the long term, additional strategic solutions are necessary for subsectors where emissions are central to production processing. Innovative technologies such as Direct Reduction Iron with H_2 as a reducing agent (DRI-H_2), electrolysis and electrowinning in iron and steel production, new inert-anode design in primary Al production, carbon capture utilization and storage, and bioenergy with carbon capture and sequestration are the most robust and promising technology options to reduce process-related emissions.[14] In parallel, the circular economy, utilization of side-streams and material efficiency are also crucial to facilitate the transition by reducing the demand for new materials.

In terms of circularity and recycling, steel is one of the most sustainable construction materials. Its strength, durability and ability to be recycled, again and again, without ever losing quality makes it the only true cradle-to-cradle building material, ideally suited to the green transition. It is also the world's most recycled material, with the secondary steelmaking process being based on high electric current (electric arc furnaces) and thus having 75 % lower carbon intensity than traditional steelmaking from iron ore by blast furnaces.[18] A similar situation is true for aluminum. It is infinitely recyclable, with almost three quarters of all the aluminum that has ever been produced still in use. Recycling aluminum scrap requires 95 % less energy than primary production with no loss of quality or volume[19] and can be nearly carbon neutral if powered by renewable electricity. However, the main obstacles for the increased secondary production of steel and aluminum, especially in Europe, is increased consumption and demand, scrap outflow and low collection rates, as well as a lack of high-quality scrap due to inadequate separation and treatment techniques.[14]

Another very important aspect of green manufacturing is the effective utilization of end-of-life materials and industrial side-streams as inputs to create new raw materials. There is a lot of underutilized material and energy potential in industrial side-streams, which are too often treated as waste.[20] Besides the required cooperation of multiple actors, inconsistent quality, fluctuating supply, cost of storage and logistics, the main challenge in the effective utilization of industrial side-streams is the lack of knowledge and the lack of new value-chain development for commercialization. For example, the lack of quality standards and product descriptions imposes challenges to side-stream producers and users as well as authorities and legislators. Furthermore, insufficient knowledge makes the assessment of long-term environmental impacts of the particular side-stream utilization difficult, causing rigidity of legislative decision-making. In many countries legislation is one of the main obstacles to efficient industrial side-stream utilization.[21]

With very ambitious GHG emission-reduction targets, the EU is facing the risk of "carbon leakage". This may and does occur if, to reduce costs related to climate policies, businesses relocate production to other countries with laxer emission regulations.[22] This involves transferring the production from the EU to other countries with lower ambitions for emission reduction, and EU materials and products being replaced by more carbon-intensive and environmentally unfriendly imports. This, although having positive short-term effects, inevitably leads to an increase in global GHG emissions and environmental impact. To prevent carbon leakage, the EU is implementing the Carbon Border Adjustment Mechanism (CBAM), a landmark tool to ensure consistent consideration of direct and indirect (embedded) emissions, and that the EU's climate objectives are not undermined.

1.2 Transport

Transport is one of the main pillars of modern society and economy, connecting people, cultures, cities and countries, and allowing products to be delivered and people to travel across the world. Transport networks also ensure access to key public services, thus contributing to a better quality of life, boosting the economy and spreading wealth. However, transportation also has a substantial negative impact on the environment, not only causing air pollution and GHG emissions, but also noise pollution and habitat fragmentation.[23] Although overall energy efficiency and emissions of new passenger cars, vans, trucks, planes and ships have been substantially improved in the last two decades, increased demands on all types of transport accelerate transport activity and its share volume, thus representing one of the main and the fastest grooving source of global GHG emissions and the largest in Europe.[13] Between 2000 and 2019 transport demand in the EU in passenger travel increased for about 20 %, in air travel by over 85 %, in passenger car transport by 18 % and in freight transport by 22 % (road freight by 31 %), and this is expected to increase even further.[24] The International Energy Agency (IEA) expects global transport to double, car ownership rates to increase by 60 %, and demand for passenger and freight aviation to triple by 2070.[25]

While in general GHG emissions in the European Union have decreased across most sectors since 1990, increased demands, growing reliance on road transport, denser traffic and more frequent congestions make transportation the only major economic sector showing an increase (**Figure 2a**). In 2022, domestic EU transportation emissions amounted to over 800 $MtCO_2e$, roughly 18 % higher than in 1990 and still more than 10 % higher than in 2000 (5.8 % from passenger cars and 5.5 % from heavy goods vehicles[23]). Globally transport is responsible for nearly 8 $GtCO_2e$, which is still lower than in 2019, demonstrating the lingering effects of the COVID-19 pandemic on passenger and cargo activity, but over 12 % higher than in 2020 and more than 70 % higher compared to 1990, **Figure 2b**.[26] Recent European Environment Agency (EEA) projections suggest that, even with all the measures planned, EU domestic transport emissions will only drop below the 1990 level in 2032.[23] To reach a long-term European strategy for low-emission mobility a reduction of more than two-thirds of emissions as compared to current levels is required. On the other hand, as not being prioritized by national policies, international transport emissions are projected to continue increasing.

Globally transport contributes about a quarter of the GHG emissions. And while aviation often gets the most attention in discussions on action against climate change, it emits just under one billion tons of CO_2 each year and thus accounts for less than 12 % of transport emissions and around 2.5 % of total global emissions. However, emissions from this sector still show an average increase rate of about 2 % per year,[24] with its global emission share likely to rise as other sectors are easier to decarbonize. A similar is true for international shipping. On the other hand, road transport is responsible for more than three-quarters of transport-bound emissions, **Figure 3**.[27] Most of this (60 %) comes from passenger cars and buses and the rest from trucks carrying freight. While emissions in the EU from domestic navigation, domestic aviation and railway have decreased since 1990 and are projected to remain relatively stable in the coming years, road transport keeps showing upward trends. Millions of cars, vans, buses and trucks are used, which still mostly use internal combustion engines and rely on petrol and diesel, thus substantially contributing to air pollution and GHG emissions.[23] However, in recent years a positive

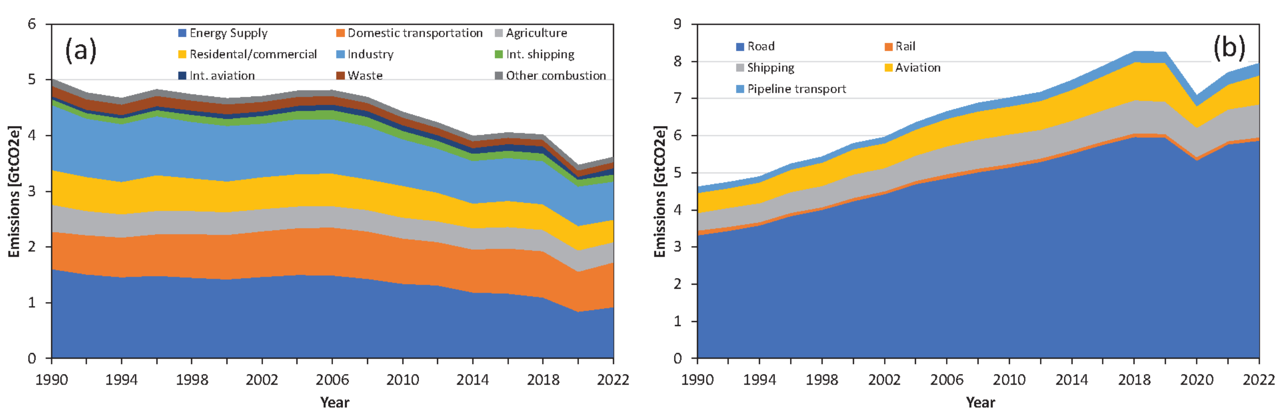

Figure 2: GHG emission: a) by sector in EU[28] and b) by transport globally[26] from 1990 to 2022

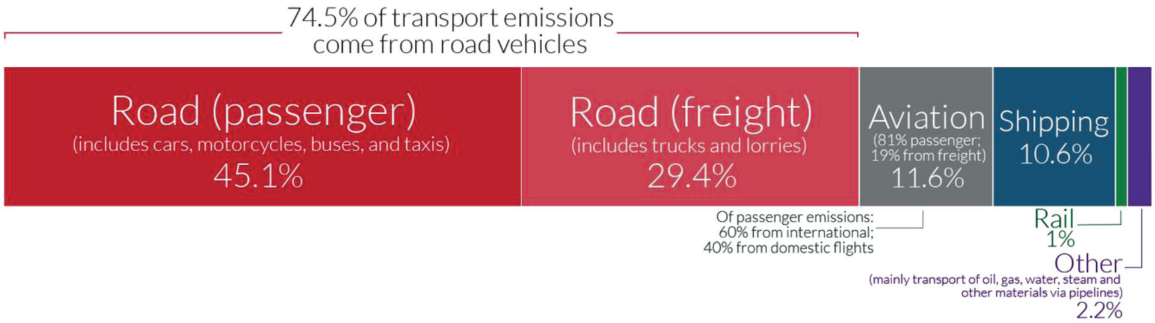

Figure 3: Global transport bound emissions in 2020[25]

trend and a shift towards electric vehicles has been observed, which can play a massive role in reducing transport tailpipe emissions and meeting the EU Green Deal goals. With different technological innovations and the shift towards lower-carbon electricity sources, the rise of electric vehicles offers a viable option to reduce emissions from passenger vehicles. Electrification and hydrogen technologies (i.e., fuel cells) also offer the potential to decarbonize sub-sectors such as motorcycles, buses, rail and small trucks. It is expected that many regions, including the European Union, United States, China and Japan will phased-out conventional vehicles as early as 2040. On the other hand, other transport sectors, including large trucks, aviation and shipping will be much more difficult to decarbonize, being mainly limited by the range, power, and the size and weight of batteries or hydrogen fuel tanks required.[25]

The number of new electric cars registered in the EU (battery electric vehicles – BEV and plug-in hybrid electric vehicles – PHEV) increased from only 600 in 2010 to over 2 million in 2022, which represents 21.6 % of all newly registered passenger cars in EU. The increase in 2022 alone was over 10 %, mainly in the BEV segment. A similar situation is observed for electric vans, reaching a share of 5.5 % of new registrations in 2022. To further facilitate the transition to electric vehicles, the EU aims to expand the recharging stations network,[11] targeting one million public charging points available by 2025.[23] But despite this huge growth and efforts we are still far away from the EU target of having 30 million zero-emission cars in operation on European roads by 2030.[11] Currently BEVs represent only 1.2 % and BEVs and PHEVs together still less than 2.5 % of the European car fleet.[29] Globally, electric vehicles sales in 2022 exceeded 10 million passenger cars, over 300.000 light commercial vehicles, about 65.000 buses and almost 60.000 medium- and heavy-duty trucks, with 14 % of all new passenger cars sold being electric and more than 26 million electric cars roaming global roads. However, this still represents less than 2 % of the global passenger cars fleet, not yet following the overall growth and 95 % of electric vehicles being restricted to China, Europe and North America, as shown in **Figure 4**.[30] By 2050 the global vehicle fleet is set to double, with more than 90 % of future vehicle growth projected to take place in low- and middle-income countries.[31] It is essential that low- and middle-income countries are part of a global shift to zero-emission transport. Unfortunately, analyses demonstrate that consumer uptake and use of electric cars are directly linked to country's GDP per capita, indicating that affordability remains a major issue.[32]

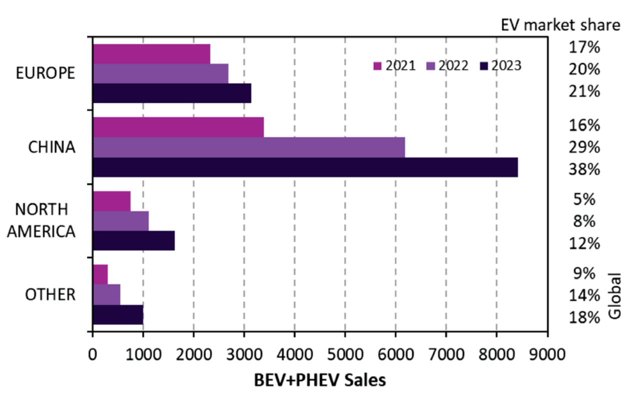

Figure 4: Electric cars sales and market share[30]

Furthermore, the share of energy from renewable resources used for transport in the EU is still very low, being less than 9 % in 2022, although the Renewable Energy Directive set a 10 % share of renewable energy in the transport sector's final energy consumption to be reached by each Member State already in 2020. At the EU level, the trend in renewable share remains well below the target path with only two Member States reaching the goal of a 10 % share of energy from renewable sources in transport by 2020.[33] Globally, 95 % of the world's transport energy still comes from fossil fuels and for 45 % of countries transport is the largest source of energy related emissions, while for the rest it still comes second according to the UN Sustainable Transport Conference report.[34] Electric vehicles are anticipated to be a key component of Europe's and the world's mobility system, helping reduce road transport's impact on climate change and air quality. However, this will greatly depend on the electricity mix (i.e. sources and fuels used to produce electricity). BEVs charged with coal-generated electricity have higher life-cycle emissions than an equivalent internal combustion engine vehicle (ICEV).[33] Therefore, to reach climate-neutrality targets a comprehensive sustainable mobility system is required, not focused only on electric cars, electrification and electrical grid upgrade, but being based on cleaner and more active transport modes, more efficient engines, cleaner fuels, electricity from renewable resources as well as reduced need for mobility. The industry that is being created to produce electric vehicles and batteries also needs to be implemented with reduced emissions, environmental impact and sustainability in mind. And measures need to be implemented world-wide.[31] Users will also have to be provided with different transportation options and services to encourage them to change their usual means of travel for more sustainable ones.[13] In this respect shift in the EU as well as globally from air and road travel by petrol or diesel-powered cars, especially if traveling alone, toward automated public and high-speed rail travel is essential. Apart from walking and cycling, rail travel is the most sustainable mode of travel, emitting less than 1 % of all transport-bound emissions.[23]

1.3 Energy

Energy production and use is a part of every aspect of our lives, from our walls and windows and our electric appliances, to the way we travel and production methods.[3] It is responsible for 75 % of EU GHG emissions. One of the largest energy consumers in Europe is the buildings sector, which is responsible for more than one-third of the EU's GHG emissions, followed by manufacturing.[1] Therefore, the decarbonization of the energy sector is a crucial step towards a climate-neutral EU. In line with that, energy supply emissions have decreased by approximately 44 % since 1990 to just over 900 $MtCO_2e$.[35] However, the climate ambition of zero-emission by 2050 and 55 % reduction by 2030 is unachievable if no action is taken regarding the current energy model,[13] and emissions from fossil fuels bound energy production not offset by 'negative emissions' (e.g., the capture and storage of carbon from bioenergy or direct air capture) from other parts of the energy system.[25] The Clean Energy policy aims to address these challenges by developing a power sector based largely on renewable sources and an integrated, interconnected and digitalized EU energy market.[11]

Currently almost three-quarters of the EU energy system still relies on fossil fuels. Oil dominates the EU energy mix (with a share of 30.9 %), followed by natural gas (26.7 %) and coal (13.1 %). According to European Commission projections, fossil fuels will still provide about half of the EU's energy in 2030.[4] Renewables are growing in terms of share but their role remains limited (17.9 %), similarly to nuclear (12.0 %).[36] Globally, the situation is even worse, with fossil fuels in North America representing 79.7 % (renewables 13.4 %), in Asia 85.2 % (12.6 %), Africa 89.8 % (9.8 %) and in the Middle East even 97.5 % (1.6 %). The leader in the use of renewable resources is Central and South America, with 35.4 % of energy coming from renewable resources, mainly from hydropower.[37]

Limited resources and possibilities will require Europe to largely rely over the next decades on imports of solar and wind electricity from neighboring regions. The Middle East and North Africa, in particular, benefit from some of the best solar irradiation and wind-energy locations. However, these renewable resources will probably be primarily exploited to meet their own rapidly growing energy demands.[4] An alternative is offshore renewable energy, with the investment of almost €800 billion into offshore wind and ocean energy infrastructure and research planned between now and 2050.[11] This should increase the EU's offshore capacity from its current level of a few GW to about 350 GW by 2050.[38]

While renewable electricity is expected to decarbonize a large share of the EU energy system by 2050, green hydrogen represents a way to decarbonize other parts, not directly connected to the electricity grid. Furthermore, high renewable electricity production during peak times (sunny and windy weather) accompanied by low energy demand produces excess of energy, which can't be directly used. The European Green Deal includes a green-hydrogen strategy, aimed at installing 40 GW of renewable hydrogen electrolyzes by 2030 and from excess of renewable energy producing up to 10 million tons of green hydrogen in the EU.[6,11]

Thus, cleaner energy-related actions must focus on 6 key points:[13]

- Tapping into and uptake of renewable energy sources, including solar, wind and offshore power
- Phasing out of coal as a resource for energy production.
- Use of renewable gases such as biogas or hydrogen.
- Green-hydrogen production from excess of sun- and wind-based electricity
- Prioritizing energy efficiency and developing an interconnected energy infrastructure via EU energy corridors.
- Developing smart infrastructures and solutions for carbon capture, storage and utilization, to maintain crucial activities such as steel and cement production and reduce their emissions and environment impact.

However, by focusing on clean renewable energy Europe, which is the second-largest net importer of oil, is becoming more dependent on the import of "clean" energy as well as products and raw materials that serve as inputs for clean energy and clean technologies. For example, the import of minerals and metals, especially rare-earth elements (REEs) from a few resource-rich and processing countries is essential for the manufacturing of solar panels, wind turbines, lithium-ion batteries, fuel cells, and electric vehicles. These minerals and metals have particular properties and few to no substitutes. Europe itself has practically no mining and processing capacities for these critical raw materials. It produces only about 3 % of the overall raw materials required in lithium-ion batteries and fuel cells, while it has no mining or processing capacities for REEs. Currently, the EU list of critical raw materials includes 34 materials [39] judged critical because of their importance to high-tech and green industries, their scarcity, or the risk of supply disruption.[4]

China is a leading producer of the most critical raw materials and Europe dependency on the import of REEs from China is probably the most critical issue. As the demand for green technologies increases dependency of Europe on China will further increase. It is estimated that the EU's annual critical raw material demand for solar panels, wind turbines and Li-ion batteries will increase between 4 and 20 times over the next three decades. Overall, Europe's demand for raw materials is expected to at least double by 2050.[40]

2 KEY MATERIALS IN GREEN TRANSITION

Currently, our efforts to preserve the environment and secure the green transition are predominantly focused on reducing carbon foot-print and emissions, thus being mainly related to technology development and use of clean renewable energy. However, an energy system powered by clean-energy technologies differs profoundly from one fueled by traditional hydrocarbon resources[41] and being much more material intensive.[42] A typical electric-vehicle battery requires six times the mineral inputs of a conventional car and an onshore wind plant requires nine times more mineral resources than a gas-fired plant. In general, the average amount of minerals needed for a new unit of renewable power generation capacity has increased by 50 % over the last two decades. Thus, the shift to a green manufacturing, electrical mobility and clean-energy system is set to drive a huge increase in minerals requirements, with the energy sector becoming a major player in mineral market. Over the next decade increase to over 40 % for copper and REEs, 60-70 % for nickel and cobalt, and almost 90 % for lithium is expected. However, current energy policies suggest that the world is on track for doubling overall mineral requirements for clean energy technologies by 2040, while goals to hit net-zero emissions globally will require six times more mineral inputs than today.[41] And there are minerals required to make the actual technologies and materials required for supporting and integrating the technology into the grid.

Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance, longevity and energy density. Rare-earth elements, i.e., neodymium, dysprosium and praseodymium, are essential for permanent magnets vital for wind turbines and EV motors. Silicon and silver are used in solar panels to generate and carry electricity, and zinc to enhance energy conversion.[43] Photovoltaics also require indium, gallium, tellurium, germanium and cadmium. The use of hydrogen as an energy carrier increases the demand for nickel and zirconium for electrolyzes, and for iridium and platinum-group metals for fuel cells, where they are used as catalysts.[44] These could be replaced by lanthanum or cobalt nitride with near identical efficiency to platinum. Furthermore, electricity networks need a huge amount of copper and aluminum, and high-strength steels, aluminum and titanium alloys and composites being vital in terms of support structures and weight reduction.[41]

The average EV battery (from 2020/21) with a 60-kWh capacity contains roughly 185 kilograms of minerals (**Table 1**). Graphite for the anode, aluminum, nickel, manganese, cobalt, lithium and iron for cathode, copper and aluminum for current collectors, and steel and aluminum for the casing. The cathode, the most important component of the battery, contains the widest variety of minerals. Its composition is a major determinant in the battery's performance, with each element offering a unique benefit. In NMC batteries, accounting for the majority of batteries currently used in BEVs (~80 %) the nickel content determines energy density or the amount of energy stored per volume and thus the driving range of the vehicle. Cobalt and manganese on the other hand, act as stabilizers improving battery safety.[45] However, lithium iron phosphate (LFP) batteries do not use any nickel, but rather cheaper alternatives of iron phosphate and lithium carbonate and thus offer lower energy densities at better value.[46] Due to relatively low cost, abundance, and long cycle life, the most common anode ma-

Table 1: Content of minerals in different lithium-ion car batteries[45]

	Amount in kg (% of total amount)				
Mineral	NMC811*	NMC523	NMC622	NCA+	LFP
Graphite	45 kg (26.6 %)	53 kg (27.9 %)	50 kg (27.8 %)	44 kg (27.7 %)	66 kg (31.6 %)
Aluminum	30 kg (17.8 %)	35 kg (18.4 %)	33 kg (18.3 %)	30 kg (18.9 %)	44 kg (21.1 %)
Nickel	39 kg (23.1 %)	28 kg (14.7 %)	32 kg (17.8 %)	43 kg (27.0 %)	/
Copper	20 kg (11.8 %)	20 kg (10.5 %)	19 kg (10.6 %)	17 kg (10.7 %)	26 kg (12.4 %)
Steel	20 kg (11.8 %)	20 kg (10.5 %)	19 kg (10.6 %)	17 kg (10.7 %)	26 kg (12.4 %)
Manganese	5 kg (3.0 %)	16 kg (8.4 %)	10 kg (5.6 %)	/	/
Cobalt	5 kg (3.0 %)	11 kg (5.8 %)	11 kg (6.1 %)	2 kg (1.3 %)	/
Lithium	5 kg (3.0 %)	7 kg (3.7 %)	6 kg (3.3 %)	6 kg (3.8 %)	6 kg (2.9 %)
Iron	/	/	/	/	41 kg (19.6 %)
Total	**169 kg**	**190 kg**	**180 kg**	**159 kg**	**209 kg**

terial is graphite, representing the single-largest mineral component of the battery.

In the case of solar panels, several critical raw materials play an important role in transforming the Sun's energy to electricity. Besides silicon, which is the most common semiconductor material used in solar cells (95 % of the modules sold today), arsenic, gallium, germanium, indium and tellurium are required. High-purity arsenic and gallium are used to produce gallium-arsenide semiconductors, gallium and indium for copper-indium-gallium-diselenide thin-film solar cells and tellurium for cadmium-tellurium thin-film solar cells. On the other hand, germanium-based solar cells are commonly used in satellites.[47] Just like solar cells, wind turbines also rely on a few critical raw materials, including aluminum, cobalt and REEs. Aluminum plays a role in most parts of a wind turbine, particularly in the nacelle, where the transfer of wind power to electricity occurs. However, REEs are responsible for the most powerful and efficient magnets, enabling wind turbines to have smaller, lighter generators. Wind turbines also use neodymium-iron-boron magnets in their construction and operation.[47]

The most common metal used as catalysts in fuel cells nowadays is platinum. It absorbs reactants strongly enough to create a reaction yet not so strong that it becomes blocked. It is also selective and incredibly stable, preventing any undesirable reactions.[44] However, it is extremely expensive, with around 60 % of the price of a fuel-cell stack being the cost of the platinum for the catalyst. Also, palladium, belonging to the same group in the periodic table as platinum and being known for its stability, selectivity and durability has been used as a catalyst in fuel cells for decades. However, in recent years the price of palladium has surpassed even that of platinum, thus not being considered as a viable catalyst for future fuel-cell development.[44] Lately, it has been realised that platinum and palladium could potentially be replaced by transition-metal nitrides (TMNs) derived from cobalt, manganese, iron. They can have the same qualities and near identical efficiency as platinum, but cost a fraction of the price.[48] This would make fuel cells far cheaper and help speed up the transition to renewable energy. Another inexpensive metal found to potentially play a key role in the future of fuel cells is nickel, while researchers from the Chinese Academy of Sciences developed a pioneering binding method for creating low-cost fuel catalysts using lanthanum.[49]

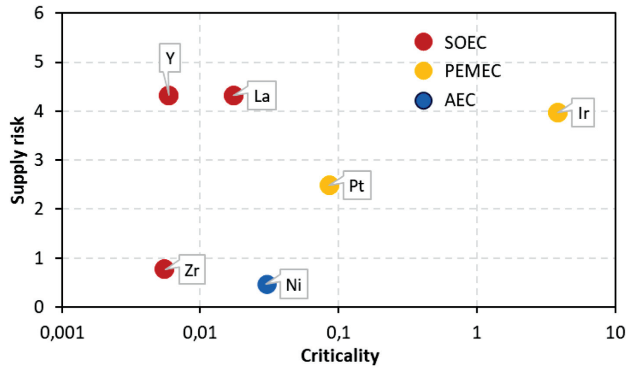

Figure 5: Critical minerals for low-carbon hydrogen electrolysis[52]

Low-carbon or green hydrogen also plays an important part in the green transition. In hydrogen production, nickel is widely used across water-electrolysis technologies (Alkaline Electrolyzer Cells – AEC). It has a lower criticality score (< 1; **Figure 5**) than other minerals and has a low supply risk.[50] However, a 1-GW electrolyzer uses as much as 1,000 tons of nickel and combined with its wide usage across other energy applications such as car batteries, may result in considerable future price increases. Other important electrolysis materials are iridium and platinum. Iridium, being far scarcer than platinum, has excellent catalytic activity in highly acidic conditions, but a very high criticality score (> 1; **Figure 5**), thus presenting the biggest bottleneck in meeting the projected 2050 Proton Exchange Membrane Electrolysis Cell (PEMEC) installations.[51] Finding promising alternatives thus poses quite a challenge, with platinum representing a crucial mineral for PEMECs to flourish in the future.[52] However, platinum also has a relatively high supply risk. The final group of minerals important in Solid Oxide Electrolyzer Cells (SOEC) technology are zirconium, yttrium and lanthanum. While zirconium is a non-critical mineral, yttrium and lanthanum have a high supply risk. Nearly 95 % of these mineral reserves are in China. A lack of strong alternatives adds to the criticality of yttrium and lanthanum (**Figure 5**).

How much and which minerals are required in kilograms per MW of electrical generation from different renewable energy source is indicated in **Figure 6**. Further-

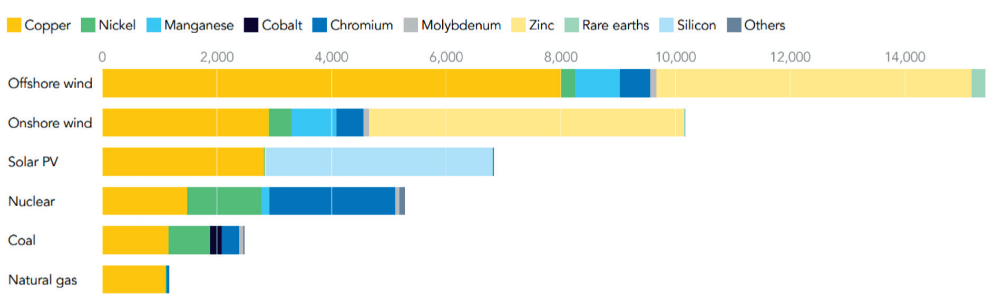

Figure 6: Minerals required in kilograms per MW of electrical generation from different energy sources[42]

Table 2: Green technologies material and energy requirements

	Green technology				
Requirements*	*60 kWh lithium-ion EV battery*	*3 MW offshore windmill*	*3 MW onshore windmill*	*400 W Solar panel*	*400 kW PEM Fuel Cell*
Ore processed	5.5–7.0 tons	2000–2200 tons	1000–1600 tons	45–75 kg	4–7 tons
Energy	11–12 MWh	4.4 GWh	3.3 GWh	0.6–0.8 MWh	7.5–8.5 MWh
Lifespan	10–15 1000–1500 charges	20–25 years	20–25 years	25–30 years	5,000–10,000 operating hours
Efficiency / Capacity factor	85–95 %	40–50 %	25–35 %	18–22 %	50–60 %
Electricity prod. annually		10–12 GWh	7.0–9.0 GWh	500–700 kWh	

* Data obtained by ChatGPT 4.0 (October 2024) and considering 100 % use of raw materials

more, in **Table 2** data on mining, ore processing and manufacturing-related energy demands for different renewable-energy production and storage technologies are listed. These are simplified estimates, obtained with AI. Actual values can vary based on ore quality, extraction efficiency, type of process and technology, etc. Furthermore, the use of recycled material significantly impacts indicated values, reducing material and energy requirements by as much as 10-times.

Up to now, we are mainly focused on the clear benefits of reducing reliance on fossil fuels and how this will mitigate climate change. However, if the raw materials required for the green transition are not sourced responsibly, we are facing many problems. Besides increased demands and the limited availability of raw materials, we are also facing negative impacts on materials sourcing and extraction. These go from environmental pollution and biodiversity losses, carbon emissions from plant and soil disruption to significant health, ethical and human rights concerns around extracting and refining materials in the third world, e.g., cobalt mining.[53] Supplies of required materials and minerals also present a particular challenge, with a majority of the production of critical raw materials taking place outside the EU (**Figure 7**). This requires further investments to ensure that these materials are fairly available to all and provide energy self-sufficiency. The EU has set clear targets on providing strategic raw materials,[39] which include:

- at least 10 % of EU annual usage extracted in the EU
- at least 40 % of annual usage processed within the EU
- at least 15 % of annual usage being recycled

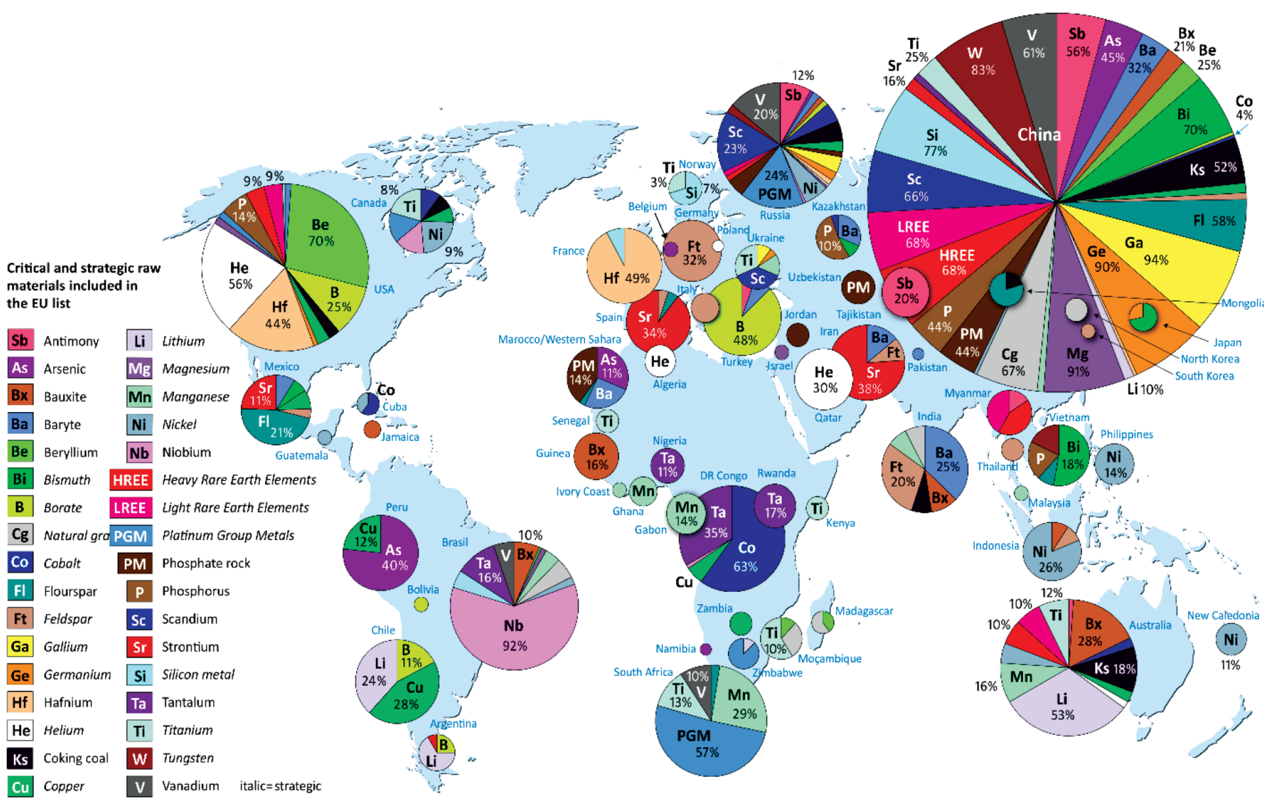

Figure 7: Global distribution of critical and strategic raw materials[15]

- no more than 65 % of annual usage shall originate from one single third country, in any relevant part of the chain.

Making Europe self-sufficient in strategic materials requires the full employment of circular-economy principles, scaling up recycling and reducing the use of critical materials. A circular economy emphasizes the need for the recovery of valuable minerals from existing products, technologies and processes, the reuse of materials, the better utilization of material side-streams, extending product lifetimes and finding new ways of using hard-to-recycle components, e.g., old wind-turbine blades. We also need to aim for waste elimination through green design, systems thinking and developing innovative sustainable materials and designs.[54] Another option of reducing the need for critical raw materials is to simply reduce their use by replacing them with others, more readily available.

Of all the industry-related decarbonization options, using recycled materials is probably the most readily available, providing high-quality renewable materials as replacements for extracted resources. The production of recycled materials, using different processes and consuming less energy than primary production, emits fewer greenhouse gases. For instance, the production of recycled aluminum is more than 95 % less CO_2 intensive than primary production, and for steel, it is about 65 %. However, it needs to focus on high-quality recycled materials. Recycling is currently insufficient, both in terms of quality and quantity,[55] as well as in many countries limited by legislation and bureaucracy. A large share of end-of-life materials are still disposed of in landfills, burnt for energy, lost in recycling processes, or never even enter the waste-collection system. Most natural resources are still made into products, used, and disposed of when no longer needed. Especially for metals, recovery rates are complicated due to the inefficient collection and processing of metallic end-of-life goods and the accessible supply of certain metal reserves.[56] On the other hand, quality losses are due to mixing different material grades and various forms of contamination during the recycling process. This results in the downcycling of recycled materials into lower-price materials, being mainly reused in lower-grade applications.

3 CONCERNS AND LIMITATIONS

3.1 E-mobility

Electric vehicles are anticipated to be a key component in decarburizing transport and reaching zero-emission targets. However, this will greatly depend on the electricity mix, i.e., sources and fuels used to produce electricity. Whereas the life-cycle emissions of a BEV using electricity generated from renewable sources can be almost 90 % lower than an equivalent ICEV, BEVs charged with electricity generated from coal or gas have higher life-cycle emissions than ICEV.[33] Current world electricity requirements are around 30,000 TWh, of which only about 40 % is currently produced from renewable resources globally and about 60 % by using fossil fuels (coal, oil and gas). Global electricity requirements are expected to more than double by 2050, with the demanded switch to electromobility requiring an additional 15,000–20,000 TWh.[57] This would require up to 7-times more installations for the exploitation of renewable resources, which currently simply is not feasible.[58] Consequently, the use of fossil fuels till 2050 may increase to about 75 % to cover all global electricity demands. Taking such energy mix into account (60–75 % coal), a typical middle-sized BEV, making 4.9–5.6 km/kWh[59] would be responsible for a generation from 100 to 125 g of CO_2/km.[60] Similar gasoline or diesel ICEV (2020 onward) produces less than 100 g of CO_2/km.[61] Thus, BEV is as green as the electricity produced to charge its battery and would need to be charged by electricity solely produced from renewable resources to be regarded as a near-zero-emission vehicle.

Even in such cases, vehicle body, engine and battery production and recycling-related emissions need to be considered. In particular, batteries for BEVs contain a lot of minerals that need to be mined, with the demand for batteries expected to grow by more than ten-fold in the next decade. On one hand we have problem of metals mining, extraction and supply, with a typical BEV battery requiring even up to 500 kg of metals. On the other hand, also handling, storage and recycling of waste batteries need to be properly addressed, including all stages of the battery's lifecycle, from design to waste treatment.[11,61] All BEVs entering the roads nowadays will source waste batteries in 15 to 20 years. It is estimated that by 2030, the world will produce around 15 million metric tons of discarded batteries, without an effective waste-batteries management plan for such volumes in place yet.[63] Furthermore, the battery packs are very unique, thus requiring special recycling and handling, consequently being energy intensive, with low efficiency and up to 5-times more expensive than the recycling of an ICEV.[64] This poses a high risk that in poor countries many may end up in landfills.

Another limitation of BEVs is a limited driving range on a single charge as compared to ICEVs, typically ranging between 300 and 450 km per full charge,[59] about half of the comparable ICEV. This is further escalated by th limited availability of charging stations (about 1/5 of available gas filling units in EU and USA per 1000 km)[65] and the fact that the charging of BEVs can take quite some time. Depending on the charging method/power (Level 3 to Level 1) anywhere from 20 minutes (DC fast charging to 80 %) to a few hours, while an ICEV tank is filled in just a few minutes. However, overnight recharging gives some extra convenience. An inadequate charging infrastructure and its development, especially in rural and remote areas, is caused by high installation, expansion and land-acquisition costs, but mainly due to an outdated and undersized distribution network. This is proving to be the major bottleneck. In the last decades huge investments were made in terms of renewable energy installation, but very minor to modernize, expand and increase capacity of the grid. The development timeline for grid infrastructure is up to seven times slower than that of renewable-energy and charging-station installations. As global electricity and charging points demand surges, the importance of grid resilience and reliability is necessitating grid transformation for a cleaner future.[66] And finally, car batteries, especially the most typical lithium-ion batteries, are subjected to a drop in performance with time, temperature and way of usage, which shortens the car's driving range and reduces the battery's charging capacity. Degradation typically ranges between 2 % and 3 % per year. Aggressive driving and excessive energy use, frequent discharging and recharging cycles, especially under high-power fast DC charging to 100 % (not recommended for everyday use) and use in hot climates, further stress the battery and have a cumulatively negative effect over the years.[67]

Finally, there are also battery-material mining-related issues. The tremendous increase in renewable-energy and rechargeable-battery demands will inevitably lead to a boom in mining for the required raw materials, especially lithium and cobalt, which undoubtedly raises environmental and social concerns.[68] The demand for lithium is expected to grow annually by about 25 % and for cobalt by about 10 %, reaching as much as 3 million and 0.4 million metric tons by 2030, respectively,[69] with the production of BEVs requiring the major part. Though emissions deriving from mining two essential minerals, lithium and cobalt, are currently considerably lower than those deriving from fossil-fuels production (one tenth), the extraction methods for lithium and cobalt can be very energy intensive, potentially causing air and water pollution, land degradation and groundwater contamination.[70] It has been shown that 40 % of the total environment impact of lithium-ion batteries comes from the mining process itself. Furthermore, the lion's share of the main two minerals is concentrated in a few countries, mainly developing countries.[15] Thus, the dirty aspects of the production process are often out of our sight and not properly addressed. More than half of the world's lithium resources lies beneath the salt flats in the Andean regions of Argentina, Bolivia and Chile, one of the world's driest regions. Nearly half of world cobalt reserves are in the Democratic Republic of the Congo, which accounts for over two-thirds of its global production. Furthermore, about 20 % of cobalt sourced from central Africa comes from artisanal mines, where child labor and slave-like conditions are still exploited.[71]

Lithium is typically sourced through brine mining, which involves extracting lithium from underground salt-water reserves through evaporation or by direct extraction, with massive quantities of freshwater used to flush out the lithium. There are considerable risks in polluting local water sources and causing desertification. Estimates show that from 0.5 to 2 million liters of water are needed to produce one ton of lithium. In Chile's Salar de Atacama and Salar de Uyuni, lithium and other mining activities consumed 65 % of the water, causing groundwater depletion, water sources and soil contamination and other forms of environmental degradation.[72] Lithium mining also generates large quantities of mineral waste. In the case of cobalt, the dust from excavation may contain toxic metals including uranium that are linked to health problems such as respiratory diseases and birth defects.[73] On the other hand, cobalt mining sites may contain sulphur minerals that can generate sulfuric acid when exposed to air and water, leading to acid mine drainage, and river and stream devastation.[70]

As reserves of lithium and cobalt will most certainly not meet future demands, further research and investment in sustainable mining techniques and technologies that can effectively recycle critical materials from used lithium-ion batteries is needed. The industry also needs to find ways to reduce the need for mining these minerals in the first place, focusing on more environmentally friendly substitutional materials like iron, silicon and sodium,[74,75] or even organic materials.[76] Full-scale electrification of the passenger car and van industry is mandatory, but a rather long-term goal. Reaching that target will take many years and extensive effort. However, at the moment Toyota's 1:6:90 rule represents the best compromise between maximizing positive environmental impact while leveraging the existing energy mix and the shortage of renamable resources, infrastructure, traveling preferences and average purchasing power. 1:6:90 rule points out that a single BEV contains enough precious minerals to build six plug-in hybrids or 90 hybrids. At its core, this rule asserts that the environmental impact achieved by 90 hybrid vehicles over their lifespan surpasses that of a single EV by a staggering 37 times,[77] highlighting the current superiority of hybrid technology in the short-term mitigation of carbon emissions.[78]

3.2 Solar Panels

Solar-panel technology's constant progress and prevalence results in the integration of solar power into commercial facilities and homes nearly everywhere. However, solar power's renewable and "green" carbon-free character of energy supply is not the only factor to consider.[79] Manufacturing is rather expensive, energy intensive (about 500 kWh/m^2 for monocrystalline, 350 kWh/m^2 for polycrystalline and 150 kWh/m^2 for thin-film solar panels) and not without environmental impacts. Solar panels contain photovoltaic (PV) cells made up of semiconductors (i.e., silicon), which absorb photons from the sun's rays and release electrons. Beside silicon, glass, coper and aluminum are the main materials used in solar panels production. The mining of materials and the production of solar panels, especially semiconductors, have a significant ecological footprint. It consumes substantial energy and water while emitting toxic chemicals (i.e., fluorinated gases, hydrogen peroxide, sulfur acid, etc.) and greenhouse gases.[80] In terms of GHG emissions, it may take up to four years of solar-panel use to compensate for production-bound emissions.[81] On the other hand, the use of fluorinated gases, which are flammable and highly toxic, pose serious health hazards upon inhalation. Fluorinated gases also have a much higher global warming potential than CO_2, and thus a high climate footprint.[82] Liquid chemicals containing Per- and PolyFluoroAlkyl Substances (PFASs), also known as forever chemicals also require special disposal and cleaning technologies to prevent hazardous substances accumulation and exposure, which, however, generate hazardous toxic wastewaters.[83] Consequently, the semiconductor industry generates a considerable amount of waste, including chemical sludge, contaminated water and silicon dust, which can cause respiratory diseases, and require responsible purification, recycling and disposal practices for sustainable production.[84]

In terms of efficiency, up to 40 % of crystalline silicon is wasted as silicon-cutting waste during the wafer production process. However, with a proper recycling approach as much as 60 % of this can be recovered and used in the production of aluminum alloys, steels and silicones.[85] When it comes to the conversion of solar energy, the efficiency of a single solar cell can reach 42 %, but drops to between 15 % and 22 % for an assembled solar panel.[86] It turns out that most of the sunlight hitting PV cells gets lost during the conversion process. It is either reflected or turned into heat. Solar panels also degrade over time due to thermal cycling, UV radiation, wear and exposure to severe weather conditions (heat & humidity), at an average rate of 0.5–1 % per year.[87] The typical productive life of a solar panel is 25 years, meaning a final efficiency of not more than 15 %. On the other hand, the efficiency of solar panels also depends on other factors not being dependent on the material and design itself. Those include the amount of light reflected away from the panel's surface, the intensity of the sun and space constraints, the temperature and the panel's heat build-up.[88] All this requires the installation of a large number of solar panels and covering a considerable surface area to increase the electricity production potential and harvest enough energy.[79] A 1-MW solar PV power plant needs an area of 1–2 hectares. While some areas (urban areas) are more conducive to solar-panel installation than others, any area that has been cleared and developed for this purpose is considered lost habitat, with an impact on local ecosystems. It can fragment habitats, degrade land, disturb wildlife, and introduce non-native species.[89]

The installation of PV power plants also raises a concern about inducing a heat-Island effect (PVHI), similar to Urban Heat Island effects in cities. While the dark surfaces of the solar panels absorb most of the sunlight that reaches them, only a fraction (~15 %) of that incoming energy is converted to electricity. The rest is returned to the environment as heat. Empirical and experimental examinations show that temperatures over a PV plant can be 3–4 °C warmer than wildlands at night.[90] Large PV power plants induce a landscape change, which is darker and less reflective, thus altering the energy balance of absorption, storage, and release of radiation. PV installations shade a portion of the ground, thus reducing heat absorption in the surface soil, they emit thermal radiation, reflect and absorb upwelling longwave radiation, while removal of the vegetation reduces the amount of cooling due to transpiration. If these effects are only local, they do not necessarily result in a detrimental effect. However, building large PV power plants, i.e., solar farms, and covering tens or even thousands of square kilometers would result in a considerable amount of heat, which redistributed by the flow of air in the atmosphere could have regional and even global effects on the climate. As shown by Zhengyao Lu,[91] covering the Sahara Desert with solar farms could raise temperatures across the globe and cause devastating droughts in the Amazon. Covering 20 % of the Sahara would raise local temperatures by 1.5°C and world's average temperature by 0.16 °C, while 50 % coverage would result in 2.5 °C and 0.39 °C rises, respectively. The massive new heat source in the Sahara would also reorganize global air and ocean circulation, affecting precipitation patterns worldwide and more frequent tropical cyclones along North American and East Asian coasts.

Finally, panel disposal has an impact on the environment. Solar panels contain some environmentally harmful substances, also found in many consumer and industrial electronics, so proper disposal is critical. However, at present, recycling options for solar panels remain limited, especially in terms of an adequate infrastructure to collect and facilitate the recycling process on a large scale.[79] It also costs 10 to 30 times more to recycle than to send panels to the landfill. So, the majority of used solar panels nowadays ends up in landfills or are send to developing countries, where they pose serious threat to people who scavenge recyclable materials by hand.[92] It is estimated that by 2050 nearly 80 million tons of solar-panel waste will be generated globally.[93] However, taking into account the new regulations, initiatives, trends and customer habits, solar-panel replacements will take place far sooner than every 30 years, resulting in far more waste than anticipated.[94] Already in 2031, the number of discarded panels may surpass that of new installations, and by 2035 outweigh the new units sold by up to 3 times, thus greatly impacting the renewable character of solar panels.

3.3 Wind turbines

High-performance onshore and offshore wind turbines rely heavily on critical materials, particularly REEs like neodymium [Nd], praseodymium [Pr], and dysprosium [Dy], for the production of permanent-magnet electric generators. Those REEs are critical to the efficiency of wind turbines, but are relatively scarce and have a vulnerable global supply chain from only a few countries. Furthermore, a significant increase in REE demand driven by the ambitious green deal and global wind-power targets cannot be achieved without 10- to 25-fold expansion in REEs production, escalating problems of REEs availability, monopoly, excessive mining and environmental concerns.[95] Similar to EV batteries and solar panels' minerals mining and production, production of magnets for wind turbines is burdened with REEs environmental issues, including lengthy and energy-intensive processing, the use of large amounts of water and toxic chemicals, the scarcity of deposits and the inefficiency of separation, as well as the production of large amounts of hazardous waste containing radioactive elements and toxic byproducts.[96] All that requires more reuse and recycling of existing REEs at the end of life to reduce the need for new mining and processing. However, at the moment there are not enough spent rare-earth materials available for recycling and the supply problem will only grow as demand increases.

Although REEs receive a lot of attention, they represented only a very small share of all the materials used for offshore and onshore wind turbines (0.01–0.03 *w*/%). On the other hand, concrete and steel are the main materials used in building onshore and offshore windmills, with concrete on average accounting for 75 *w*/% and 40 *w*/% and steel for 23 *w*/% and 26 *w*/%, respectively.[97] Concrete reinforced with steel is mainly used to construct the foundations, steel for towers, gearbox and as ballast, while blades are made of fiberglass and epoxy resins. All these materials, regarded as non-critical, require energy-intensive processes and account for a considerable amount of GHG emissions with a large carbon footprint. The CO_2 emissions of non-critical materials are 20- to 40-times higher than of REEs in windmills production, contributing about 380 tCO2e/MW for onshore and about 675 tons tCO2e/MW for offshore turbines. The major impact is coming from steel and iron production, representing up to 85 % of the overall carbon footprint of wind turbines.[97]

Typical wind turbines are designed for a period of 20–25 years. When decommissioned, between 85 % and 95 % of a turbine's materials, such as steel, aluminum and copper, can be easily recycled. However, blades, designed to withstand a harsh environment for years are a different story. Made of fiberglass and covered with a tough epoxy resin makes their separation and recycling nearly impossible. Traditional solutions include shredding old blades into fillers or adding pieces to cement production. They can also be repurposed and downgraded into utility poles, park benches, bike sheds or used in bridge construction. All these are solutions effective at a local level.[98] Globally, old blades are most commonly disposed of in landfill sites, where they do not pose any environmental hazard but take up a great deal of space. With up to 43 million tons of wind-turbine-blade waste predicted by 2050 and with a number of countries, notably Germany, Finland and the Netherlands, banning this practice, we need more efficient recycling on a large scale. In June 2021 Wind Europe called for a Europe-wide landfill ban on decommissioned wind-turbine blades by 2025 and Europe's wind industry actively committing to re-use, recycle, or recover 100 % of decommissioned blades in the near future.[99]

Wind farms also have a negative effect on the landscape,[100] they cause noise pollution[101] and can have negative effects on the local climate.[102] The sheer size of wind turbines, combined with the very large exposed areas required to build wind farms, make them particularly visible in the landscape from a very large distance, thus potentially affecting sensory experiences, perceptions and sense of place. Wind farms typically use between 10 and 60 hectares per MW of power output capacity, but less than 0.4 ha/MW is disturbed permanently and less than 1.5 ha/MW temporarily during construction.[103] Wind turbines also make rhythmic noise in audible and lower (infrasound) frequencies produced by the rotating blades, which can extend several hundred meters away from the wind turbine. There is also mechanical sound generated by the turbine itself. The noise and vibrations generated by wind turbines are raising questions about their potential impact on human health and well-being. Prolonged exposure to turbine noise is associated with sleep disturbances, annoyance and stress.[104] Noise, vibrations and visual impacts are often assumed to lead to decreases in property values and seen as a significant negative economic impact of wind farms. Although individual wind turbine has practically no effect on the local climate, wind farms have been proven to affect the climate within a radius of a few kilometers and the problem may well become global with more wind power development.[105] By capturing the energy of air movement, wind turbines weaken the wind and cause increased turbulence with the development of higher area's climate contrasts.[106] The air has time to warm up more in summer, and cool down more in winter. The rotation of the blades also causes dryer air at a higher elevation to mix with moist air at the surface, thus lowering the relative humidity close to the ground by as much as 3 % and potentially increasing the surface evaporation. Experimental observations combined with numerical simulations have revealed that large wind farms affect atmospheric humidity to a considerable extent with the decrease in near-surface humidity extended in the shadow of the wind farm for a relatively long distance, even up to 30 km.[107] Beside drying out, air also warms up as it mixes throughout the wind farm during overnight and early morning hours. Wind turbines mix the cold air near the surface, thus preventing the surface from cooling. While an individual wind turbine has a negligible effect on the temperature increase, big wind farms can result in about 0.5 °C higher local temperatures. Furthermore, analyses of satellite data over a region of the world's largest wind farms show a significant warming trend of up to 0.7 °C per decade, particularly at night-time, which may have noticeable impacts on regional weather.[108]

3.4 Fuel Cells

In the case of fuel cells, the major issue is related to hydrogen production, storage and transportation. Hydrogen is the most abundant element in the universe, being present in 75 % of all matter. It is light, can be stored, and does not generate any pollution by itself. However, chemical processing is needed to extract it and turn it into fuel. In terms of extraction process hydrogen is color classified, with the most common types of hydrogen being grey, blue, and green hydrogen.[109] Grey hydrogen produced from natural gas by steam methane reforming process is the most common, and the cheapest form of hydrogen production. To produce 1 kg of grey hydrogen, which can generate up to 23 kWh in a fuel cell, "only" 8.5 kWh of energy is needed, but releases about 10 kg of CO_2. Blue hydrogen is extracted using the same steam reforming process, but utilizes carbon capture and storage technology to reduce emissions in the atmosphere. Blue hydrogen requires 50 % more energy (~12 kWh), but theoretically reduces CO_2 emissions by up to 3 times. However, taking into account also the energy required for heating and to power carbon capture, and typical energy mix, emissions reduction can be very minor, only in the range of 10 %.[110] Green hydrogen is the cleanest option, made by electrolyzing water and splitting it into hydrogen and oxygen, without any carbon emissions being released within the process. It is aimed at using electricity generated by renewable energy sources (hydro, wind and solar). While green hydrogen results in little to no direct CO_2 emissions, and indirect ones (carbon footprint) being 10 times lower as for grey hydrogen, it requires about 6 times more energy (~50 kWh) and a significant investment in a renewable-energy infrastructure. Furthermore, green hydrogen can only be green if enough direct renewable sources are available to power the hydrogen production, rather than using the current grid and questionable energy mix involving a different share of fossil fuels.[111] This is important, because the CO_2 emissions from green hydrogen are nearly all embedded emissions from materials, equipment and energy production. If relying on electricity predominantly produced from CO_2-intensive coal and natural gas, hydrogen will no longer be "green".

To guarantee that hydrogen production is carbon-free for everything beyond the carbon embodied in the materials needed for power generation and electrolysis, electricity must come from dedicated renewable power arrays, such as wind or solar farms, or a renewable-heavy electricity grid. For the majority of European countries, except Norway and Sweden, with a lot of hydropower, the potential of green hydrogen production using grid electricity is greatly constrained due to a reliance on fossil fuels, imported electricity or nuclear power.[112] A Rocky Mountain Institute (RMI) analysis shows that green hydrogen produced on today's fossil-heavy grid (50–60 %) would have an average annual carbon intensity of over 20 kg CO_2 per kg H_2. That would nearly double the emissions footprint of grey hydrogen made from natural gas with no carbon capture and storage.[113]

1 kg of hydrogen contains 33.33 kWh of usable energy, but only 0.003 kWh per liter under ambient conditions. Petrol and diesel on the other hand carry around 8.8 kWh/L and 10 kWh/L, respectively. This poses a challenge when hydrogen must be transported and stored. Pressurized hydrogen contains about 0.5 kWh/L at 200 bar and 1.4 kWh/L at 700 bar, while liquid hydrogen achieves more than 2.3 kWh/L[114] and represents the best way of transporting and storing hydrogen. The drawback of liquid hydrogen is the amount of energy (7–12 kWh/kg) required to condense, liquefy and store it at cryogenic temperatures of -252.8 °C. On the other hand, pressurizing hydrogen to 700 bar requires about 3 times less energy, but faces high-pressure-related material problems (diffusion, corrosion, H-embrittlement, etc.).

3.5 Implications of the Green Transition for Metallurgy

The green transition poses substantial challenges and transformative pressures on the metallurgical sector, particularly in the context of ferrous and non-ferrous metals such as steel and aluminum. These two materials are essential to industrial infrastructure and green technologies alike, yet their primary production processes are among the most energy- and emission-intensive globally. Conventional steel production via a blast furnace–basic oxygen furnace (BF–BOF) route is responsible for approximately 7 % of global CO_2 emissions, largely due to its reliance on coking coal.[115] In response to EU climate objectives and regulatory instruments such as the Emissions Trading System (ETS) and CBAM,[116] the sector is increasingly shifting toward alternative, low-carbon production pathways. The deployment of electric arc furnaces (EAFs), if powered by renewable electricity and using scrap-based feedstock, offers significant emissions reductions – up to 75 % lower than traditional routes. However, such a transition is constrained by the limited availability and inconsistent quality of scrap, but mainly by electricity-price volatility and grid-decarbonization rates. The hydrogen-based direct reduction of iron ore (H-DRI) is emerging as a promising long-term solution, but it is still in its early industrial stage.[117] It demands massive investment in a green-hydrogen infrastructure, a secure renewable-energy supply, and plant retrofitting to meet new standards. This structural transformation necessitates not only massive capital investments, but also workforce upskilling, raw-material strategy revision, and regulatory adaptation.

Similarly, primary aluminum production remains among the most energy-intensive industrial activities, predominantly driven by electrolysis in Hall-Héroult cells, consuming roughly 14–16 MWh of electricity per ton of metal produced.[118] To address the environmental footprint of Al alloys production, research is advancing the development of inert anodes as replacements for conventional carbon-based anodes in electrolytic cells,[119] but largely focusing on recycling. While Europe sources a significant share of its aluminum from secondary production, which requires only around 5 % of the energy used in primary production and is nearly carbon-neutral when powered by renewable energy, the circular potential is far from being fully realized. Challenges include the outflow of scrap, insufficient collection and sorting infrastructure, and quality degradation due to alloy mixing and contamination during recycling. Moreover, the EU's reliance on imported bauxite and alumina, combined with limited domestic smelting capacities, raises concerns regarding energy security, strategic autonomy, and embedded emissions.[120]

In this context, the green transition of metallurgy not only necessitates a decarbonization of primary production routes but also calls for a systemic enhancement of recycling rates, scrap quality, and material circularity. The successful transformation of steel and aluminum production in Europe will thus be pivotal for achieving climate-neutrality targets, enhancing resource resilience, and underpinning the decarbonization of downstream sectors such as construction, mobility, and energy infrastructure.

4 CONCLUSION

Climate change is accelerating, and the evidence of our impact – through industrial activity, transportation, and energy production – is increasingly undeniable. The resulting environmental consequences, including more frequent and severe storms, floods, droughts, biodiversity loss, and ecosystem degradation, have profound and direct effects on human society. As demonstrated throughout this work, we already possess the tools and technologies required to address these challenges. More importantly, we bear the responsibility to apply them wisely through a deliberate and sustainable green transition, safeguarding both the environment and future generations.

In this transition, materials play a pivotal role. From critical raw materials such as rare-earth elements and lithium, to high-volume industrial materials like steel and aluminum, their availability, sourcing, production methods, and recyclability will determine the success and sustainability of the transformation. The shift toward renewable energy, electrified transport systems, hydrogen-based energy storage, and circular material flows presents not only opportunities but also considerable challenges and unintended consequences. Every green technology, despite its environmental promise, entails trade-offs – including emissions from material extraction, energy use in manufacturing, and end-of-life disposal impacts. Therefore, a prudent, well-planned, and scientifically grounded implementation of green technologies is essential. This must be guided by comprehensive life-cycle assessments that span raw-material extraction, processing, production, energy mix, operational use, decommissioning, and recycling.

In this context, the metallurgical sector, particularly steel and aluminum production, will be at the forefront of industrial transformation. If the green transition in metallurgy proves successful, it could position Europe as a global leader in sustainable production – enhancing circularity, minimizing dependence on imported fossil fuels, and supporting decarbonization across key downstream sectors such as construction, mobility, and manufacturing. Achieving this will require coordinated action across research, industry, and policy, supported by investments in low-carbon technologies and robust recycling systems.

Ultimately, however, the green transition cannot succeed without a fundamental shift in consumer behavior. Societal sustainability must be anchored in individual responsibility – through more conscious consumption, reduced demand for resource-intensive goods, and support for environmentally sound practices. This transformation must be global in scope, with equitable collaboration across borders, ensuring that the solutions we implement benefit not only our own communities but the planet as a whole.

Acknowledgement

The author acknowledges the financial support from the Slovenian Research and Innovation Agency (research core funding No. P2-0050.

5 REFERENCES

[1] European Green Deal, European Council, https://www.consilium.europa.eu/en/policies/green-deal/ ; accessed 22.10.2024

[2] 5 facts about the EU's goal of climate neutrality, European Council, https://www.consilium.europa.eu/en/5-facts-eu-climate-neutrality/ ; accessed 22.10.2024

[3] T. Belardo, What you need to know about the European Green Deal - and what comes next, World Economic Forum, https://www.weforum.org/agenda/2021/07/what-you-need-to-know-about-the-european-green-deal-and-what-comes-next/ ; accessed 22.10.2024

[4] M. Leonard, J. Pisani-Ferry, J. Shapiro, S. Tagliapietra, G. Wolff, The geopolitics of the European Green Deal, European Council on Foreign Relations, https://ecfr.eu/publication/the-geopolitics-of-the-european-green-deal/ ; accessed 22.10.2024

[5] European Union Carbon (CO2) Emissions 1990-2024, Macrotrends, https://www.macrotrends.net/global-metrics/countries/EUU/european-union/carbon-co2-emissions ; retrieved 24.10.2024

[6] H. Ritchie, P. Rosado, M. Roser, Greenhouse gas emissions, Our World in Data, https://ourworldindata.org/greenhouse-gas-emissions ; accessed 24.10.2024

[7] List of continents by GDP, Statistics Times, https://statisticstimes.com/economy/continents-by-gdp.php ; retrieved 24.10.2024

[8] Sarin Abraham, K. Ganesh, A. Senthil Kumar, Yves Ducqd, Impact on Climate Change Due to Transportation Sector – Research Prospective, Procedia Engineering, 38 (**2012**), 3869–3879, doi:10.1016/j.proeng.2012.06.445.

[9] Annual CO_2 emissions by world region, Our World in Data, https://ourworldindata.org/grapher/annual-co-emissions-by-region ; retrieved 24.10.2024

[10] H. Ritchie, Sector by sector: where do global greenhouse gas emissions come from?, OurWorldInData.org, 2020, https://ourworldindata.org/ghg-emissions-by-sector ; accessed 24.10.2024

[11] K. McDougall, The EU Green Deal explained, Norton Rose Fulbright, https://www.nortonrosefulbright.com/en/knowledge/publications/c50c4cd9/the-eu-green-deal-explained; accessed 22.10.2024

[12] T. Leppänen, J. Köpman, O. Rasila, P. Tervonen, Categorization of Industrial Side Streams for Reuse Potential Evaluation, International Journal of Management, Knowledge and Learning, 10 (**2021**) 253-265

[13] The European Green Deal - a roadmap to a sustainable economy, Public Agency Ihobe, 2020, https://www.ihobe.eus/news/the-european-green-deal-a-roadmap-to-a-sustainable-economy ; accessed 24.10.2024

[14] M. Rahnama Mobarakeh, T. Kienberger, Climate neutrality strategies for energy-intensive industries: An Austrian case study, Cleaner Engineering and Technology, 10 (**2022**) 100545, doi:10.1016/j.clet.2022.100545.

[15] Geological Survey of Sweden, Critical and strategic raw material, 2024, https://www.sgu.se/en/mineral-resources/critical-raw-materials/ ; accessed 24.10.2024.

[16] IEA, Energy Technology Perspectives 2020, 2020, https://www.iea.org/reports/energy-technology-perspectives-2020 ; accessed 24.10.2024

[17] Net-Zero Industry Tracker 2023, World Economic Forum, 2023, 75-85, https://www3.weforum.org/docs/WEF_Net_Zero_Tracker_2023_REPORT.pdf ; accessed 24.10.2024

[18] D. Toto, Study confirms EAF advantage in carbon emissions, Recycling today, July 2022, https://www.recyclingtoday.com/news/us-steelmaking-75-percent-less-carbon-emission/ ; accessed 24.10.2024

[19] R. Beheshti, Sustainable aluminium and iron production, Ph.D. Thesis, KTH Royal Institute of Technology, Sweden, 2017

[20] T. Leppänen, E. Mustonen, H. Saarela, M. Kuokkanen, P. Tervonen, Productization of Industrial Side Streams into By-Products, Journal of Open Innovation: Technology, Market, and Complexity, 6 (**2020**) 185, doi:10.3390/joitmc6040185.

[21] N. Pajunen, G. Watkins, K. Husgafvel, K. Heiskanen, O. Dahl, The challenge to overcome institutional barriers in the development of industrial residue based novel symbiosis products – Experiences from Finnish process industry, Miner. Eng., 46–47 (**2013**) 144–156, doi:10.1016/j.mineng.2013.03.008.

[22] EU Science HUB, Greenhouse gas emissions from manufacturing: what difference across countries?, Joint Research Centre, September 2023, https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/greenhouse-gas-emissions-manufacturing-what-difference-across-countries-2023-09-29_en ; accessed 25.10.2024.

[23] European Environment Agency, Transport and mobility, October 2024, https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility?activeTab=07e50b68-8bf2-4641-ba6b-eda1afd544be ; accessed 25.10.2024

[24] European Environment Agency, Transport and environment report 2021: Decarbonizing road transport – the role of vehicles, fuels and transport demand, February 2022, https://www.eea.europa.eu/publications/transport-and-environment-report-2021 ; accessed 25.10.2024

[25] H. Ritche, Cars, planes, trains: where do CO_2 emissions from transport come from?, Our World in Data, October 2020, https://ourworldindata.org/co2-emissions-from-transport ; retrieved 25.10.2024

[26] J. Teter, F. Voswinkel, Use of Energy – Transport, IEA, July 2023, https://www.iea.org/energy-system/transport ; retrieved 25.10.2024

[27] European Environment Agency, Greenhouse gas emissions from transport in Europe, October 2023, https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport ; retrieved 25.10.2024

[28] European Environment Agency, EEA greenhouse gases – data viewer, August 2024, https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers ; retrieved 25.10.2024

[29] European Alternative Fuels Observatory, European Commission, https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27/vehicles-and-fleet ; retrieved 26.10.2024

[30] The global electric vehicle market overview in 2024, VIRTA, https://www.virta.global/en/global-electric-vehicle-market ; retrieved 26.10.2024

[31] Supporting the global shift to electric mobility, UN environment programme, https://www.unep.org/topics/transport/electric-mobility/supporting-global-shift-electric-mobility-0 ; accessed 26.10.2024

[32] Electric cars: lower-income countries fall behind, with uptake linked to GDP per capita, Automobile Manufacturers' Association, https://www.acea.auto/press-release/electric-cars-lower-income-countries-fall-behind-with-uptake-linked-to-gdp-per-capita/ ; accessed 26.10.2024

[33] European Environment Agency, Progress of EU transport sector towards its environment and climate objectives, https://www.eea.europa.eu/publications/progress-of-eu-transport-sector-1 ; accessed 28.10.2024

[34] K. Platzer, Sustainable transport, sustainable development, Interagency report – second global sustainable transport conference, United Nations, 2021, https://sdgs.un.org/sites/default/files/2021-10/Transportation %20Report %202021_FullReport_Digital.pdf ; accessed 28.10.2024

[35] European Environment Agency, Greenhouse gas emission intensity of electricity generation in Europe, June 2024, https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1 ; retrieved 28.10.2024

[36] IEA, Energy supply, https://www.iea.org/regions/europe/energy-mix ; retrieved 28.10.2024

[37] H. Ritchie, P. Rosado, Energy Mix, Our World in Data, 2020, https://ourworldindata.org/energy-mix, retrieved 28.10.2024

[38] EU sets out vision for offshore power, Norton Rose Fulbright, December 2020, https://www.nortonrosefulbright.com/en/knowledge/publications/1863f32f/eu-sets-out-vision-for-offshore-power ; accessed 28.10.2024

[39] European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, M. Grohol, C. Veeh, Study on the critical raw materials for the EU 2023 – Final report, Publications Office of the European Union, 2023, doi/10.2873/725585

[40] Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, A., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D. and Christou, M., Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650, JRC132889.

[41] IEA, The Role of Critical Minerals in Clean Energy Transitions, 2023, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions, accessed 29.10.2024

[42] ICF, Securing raw material supply is critical to the green transition, August 2023, https://www.icf.com/insights/energy/securing-raw-material-supply-green-transition ; accessed 29.10.2024

[43] C. O'Brien, R. Barnett, The Minerals in Solar Panels and Solar Batteries, Palmetto, June 2022, https://palmetto.com/solar/minerals-in-solar-panels-and-solar-batteries ; accessed 29.10.2024

[44] E. Eikeng, A. Makhsoos, B.G. Pollet, Critical and strategic raw materials for electrolysers, fuel cells, metal hydrides and hydrogen separation technologies, International Journal of Hydrogen Energy, 71 (2024) 433-464, doi:10.1016/j.ijhydene.2024.05.096

[45] A.R. Carreon, The EV Battery Supply Chain Explained, RMI, May 2023, https://rmi.org/the-ev-battery-supply-chain-explained/ ; accessed 29.10.2024

[46] D. Versaci, R. Colombo, G. Montinaro, M. Buga, N. Cortes Felix, G. Evans, F. Bella, J. Amici, C. Francia, S. Bodoardo, Tailoring cathode materials: A comprehensive study on LNMO/LFP blending for next generation lithium-ion batteries, Journal of Power Sources, 613 (2024) 234955, doi:10.1016/j.jpowsour.2024.234955

[47] United States Geological Survey, Critical Mineral Commodities in Renewable Energy, June 2019, https://www.usgs.gov/media/images/critical-mineral-commodities-renewable-energy ; accessed 29.10.2024

[48] Rui Zeng, Yao Yang, Xinran Feng, Huiqi Li, Lauryn M. Gibbs, Francis J. DiSalvo, Héctor D. Abruña, Nonprecious transition metal nitrides as efficient oxygen reduction electrocatalysts for alkaline fuel cells, Science Advances, 8 (**2022**), doi: 10.1126/sciadv.abj158

[49] Siyuan Zhu, Liting Yang, Jingsen Bai, Yuyi Chu, Jie Liu, Zhao Jin, Changpeng Liu, Junji Ge, Wei Xing, Ultra-stable Pt_5La intermetallic compound towards highly efficient oxygen reduction reaction. *Nano Research,* 16 (**2023**) 2035–2040, doi:10.1007/s12274-022-4868-3

[50] S. Kiemel, T. Smolinka, F. Lehner, J. Full, A. Sauer, R. Miehe, Critical materials for water electrolysers at the example of the energy transition in Germany, International Journal of Energy Research, 45 (2021) 9914-9935, doi:10.1002/er.6487

[51] S. Godfrey Nnabuife, A.K. Hamzat, J. Whidborne, B. Kuang, K.W. Jenkins, Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production, International Journal of Hydrogen Energy, in press, 2024, doi:10.1016/j.ijhydene.2024.06.342

[52] A. Basu, R. Daliah, Critical Minerals for the Hydrogen Economy, LUX Research, http://luxresearchinc.com/wp-content/uploads/2022/07/executive-summary-critical-minerals-for-the-hydrogen-economy.pdf ; retrieved 30.10.2024

[53] M. Posner, To Meet Global Cobalt Demand, Companies Must Reform Mining Practices in the Congo, Forbes, February 2023, https://www.forbes.com/sites/michaelposner/2023/02/09/as-demand-soars-for-cobalt-used-in-electric-car-batteries-heres-what-companies-need-to-do-in-the-democratic-republic-of-congo/ ; accessed 6.11.2024

[54] Towards the circular economy: economic and business rationale for an accelerated transition, Ellen MacArthur Foundation, 2013, https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an ; accessed 6.11.2024

[55] R. Le Moigne, To reduce CO_2 emissions, the materials industry needs to transition to a circular economy, Circulate, Ellen MacArthur Foundation, May 2022 ; https://medium.com/circulatenews/to-reduce-co2-emissions-the-materials-industry-needs-to-transition-to-a-circular-economy-520d83620283

[56] D. Mulvaney, R.M. Richards, M.D. Bazilian, E. Hensley, G. Clough, S. Sridhar, Progress towards a circular economy in materials to decarbonize electricity and mobility, Renewable and Sustainable Energy Reviews, 137 (2021) 110604, doi:10.1016/j.rser.2020. 110604.

[57] Global Energy & Climate Scenarios Through 2050, EnerData, March 2024, https://www.enerdata.net/publications/reports-presentations/energy-climate-scenarios-2050.html ; retrieved 6.11.2024

[58] W. Zappa, M. Junginger, M. van den Broek, Is a 100 % renewable European power system feasible by 2050?, Applied Energy, 233–234 (**2019**) 1027–1050, doi:10.1016/j.apenergy.2018.08.109

[59] Electric Vehicle Database, Energy consumption of full electric vehicles, https://ev-database.org/cheatsheet/energy-consumption-electric-car ; retrieved 6.11.2024

[60] Planet Energies, Electricity Generation and CO2 Emissions, February 2016, https://www.planete-energies.com/en/media/article/electricity-generation-and-related-co2-emissions ; retrieved 6.11.2024

[61] European Commission: EU Action - Transport, CO2 emission performance standards for cars and vans, https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/co2-emission-performance-standards-cars-and-vans_en; accessed 6.11.2024

[62] J. Fleischmann, P. Schaufuss, M. Linder, M. Hanicke, E. Horetsky, D. Ibrahim, S. Jautelat, L. Torscht, A. van de Rijt, Battery 2030: Resilient, sustainable, and circular, McKinsey & Company, January 2023, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular#/ ; accessed 6.11.2024

[63] J.-P. Skeete, P. Wells, X. Dong, O. Heidrich, G. Harper, Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition, Energy Research & Social Science, 69 (2020) 101581, doi:10.1016/j.erss.2020.101581

[64] Xiaotu Ma, Luqman Azhari, Yan Wang, Li-ion battery recycling challenges, Chem, 7/11 (2021) 2843-2847, doi:10.1016/j.chempr.2021.09.013

[65] Gas Stations Vs. EV Charging Stations: Why Density Matters, NovaCharge, https://www.novacharge.net/blog/gas-stations-vs.-ev-charging-stations-density-matters ; accessed 6.11.2024

[66] S. Porter, J. Thomson, C. Grant, C. Rizzo, K. Hardin, J. Nagdeo, Expanding and modernizing the power grid for a clean energy transition, Deloitte Research Center for Energy & Industrials, May 2024, https://www2.deloitte.com/us/en/insights/industry/power-and-utilities/grid-modernization-and-expansion-critical-for-clean-energy-future.html ; accessed 6.11.2024

[67] C. Argue, How long do electric car batteries last? What 10,000 electric vehicles tell us about EV battery life, Geotab, October 2024, https://www.geotab.com/blog/ev-battery-health/ ; accessed 6.11.2024

[68] COMMODITIES AT A GLANCE, Special issue on strategic battery raw materials, No. 13, United Nations Conference on Trade and Development, Geneve 2020, https://unctad.org/system/files/official-document/ditccom2019d5_en.pdf ; accessed 6.11.2024

[69] Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, IEA, September 2023, https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach ; accessed 6.11.2024

[70] March Zheng, The Environmental Impact of Lithium and Cobalt Mining, Earth.org, March 2023, https://earth.org/lithium-and-cobalt-mining/ ; accessed 6.11.2024

[71] T. Gross, How 'modern-day slavery' in the Congo powers the rechargeable battery economy, NPR, February 2023, https://www.npr.org/sections/goatsandsoda/2023/02/01/ 1152893248/red-cobalt-congo-drc-mining-siddharth-kara ; accessed 6.11.2024

[72] A. Katwala, The devastating environmental impact of technological progress, Wired UK, October 2019, https://www.wired.com/story/lithium-copper-mining-atacama-desert/ ; accessed 6.11.2024

[73] M.P. Mills, 'Cobalt Red' Review: The Human Price of Cobalt, The Wall Street Journal, February 2023, https://www.wsj.com/articles/cobalt-red-review-the-human-price-of-cobalt-11675293373?reflink=desktopwebshare_permalink ; accessed 6.11.2024

[74] N.S.M. Hafiz, G. Singla, P. Kumar Jha, Next generation sodium-ion battery: A replacement of lithium, Materials Today: Proceedings, 2022, doi:10.1016/j.matpr.2022.11.245.

[75] K. Turcheniuk, D. Bondarev, V. Singhal, G. Yushin, Ten years left to redesign lithium-ion batteries, Nature, 559 (**2018**) 467–470, doi:10.1038/d41586-018-05752-3

[76] T. Chen, H. Banda, J. Wang, J.J. Oppenheim, A. Franceschi, M. Dinca, A Layered Organic Cathode for High-Energy, Fast-Charging, and Long-Lasting Li-Ion Batteries, ACS Central Science, 10/3 (**2024**), doi: 10.1021/acscentsci.3c01478

[77] S. Hey, Toyota's 1:6:90 Rule – The Case for Hybrids, EnergyMinute, June 2023, https://energyminute.ca/news/toyotas-1690-rule-the-case-for-hybrids/ ; accessed 6.11.2024

[78] P. Lyon, Total EV Adoption Is Not The Way Forward, Says Toyota Chairman, Forbes, March 2024, https://www.forbes.com/sites/peterlyon/2024/03/03/bucking-industry-trend-toyota-chairman-downplays-ev-growth-predictions/ ; accessed 6.11.2024

[79] C. Crail, C. Tynan, R. Akinwonmi, Solar Energy Pros And Cons: What Are The Advantages And Disadvantages?, Forbes, September 2024, https://www.forbes.com/home-improvement/solar/solar-energy-pros-and-cons/ ; accessed 6.11.2024

[80] J.C. Hess, Chip Production's Ecological Footprint: Mapping Climate and Environmental Impact, Interface, June 2024, https://www.interface-eu.org/publications/download/chip-productions-ecological-footprint ; accessed 6.11.2024.

[81] What is the energy payback for PV?, National Renewable Energy Laboratory, U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, https://www.nrel.gov/docs/fy04osti/35489.pdf ; accessed 6.11.2024

[82] European Commission: EU Action – Fluorinated greenhouse gases, About F-gases, https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/about-f-gases_en; accessed 6.11.2024

[83] A. Villard, A. Lelah, D. Brissaud, Drawing a chip environmental profile: environmental indicators for the semiconductor industry, Journal of Cleaner Production, 86 (**2015**) 98–109, doi:10.1016/j.jclepro.2014.08.061

[84] M.S. Leonova, S.S Timofeeva, Environmental and economic damage from the dust waste formation in the silicon production, IOP Conference Series: Earth and Environmental Science, 229 (**2019**) 012022, doi:10.1088/1755-1315/229/1/012022

[85] Donghui Wei, Jian Kong, Zhaoyang Zhang, Pengfei Xing, Yanxin Zhuang, Study on recycling Si from silicon diamond-wire saw cutting waste by a slag refining process in industrial scale, Journal of Cleaner Production, 398 (**2023**) 136557, doi:10.1016/j.jclepro.2023.136557

[86] A. Vourvoulias, How Efficient Are Solar Panels in November 2024?, GreenMatch, October 2024; https://www.greenmatch.co.uk/blog/2014/11/how-efficient-are-solar-panels ; accessed 6.11.2024

[87] D.C. Jordan, S.R. Kurtz, Photovoltaic Degradation Rates – an Analytical Review, Progress in Photovoltaics, 21 (**2013**) 12–29, doi:10.1002/pip.1182

[88] S. Kurpaska, J. Knaga, H. Latala, J. Sikora, W. Tomczyk, Efficiency of solar radiation conversion in photovoltaic panels, BIO Web of Conferences, 10 (**2018**) 02014, doi:10.1051/bioconf/20181002014

[89] The Environmental Impact of Solar Energy: Is It Truly Worth It?, Aspiration, February 2022, https://www.aspiration.com/resources/the-environmental-impact-of-solar-energy ; accessed 6.11.2024

[90] G.A. Barron-Gafford, R.L. Minor, N.A. Allen, A.D. Cronin, A.E. Brooks, M.A. Pavao-Zuckerman, The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures, Scientific Reports, 6 (**2016**) 35070, doi: doi:10.1038/srep35070

[91] Z. Lu, Giant desert solar farms might have unintended climate consequences, Trellis, March 2021, https://trellis.net/article/giant-desert-solar-farms-might-have-unintended-climate-consequences/ ; accessed 6.11.2024

[92] The Mounting Solar Panel Waste Problem, Institute for Energy Research, https://www.instituteforenergyresearch.org/renewable/solar/the-mounting-solar-panel-waste-problem/ ; accessed 6.11.2024

[93] S. Weckend, A. Wade, G. Heath, End-of-Life Management – Solar Photovoltaic Panels, International Renewable Energy Agency, June 2016, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf ; accessed 6.11.2024

[94] A. Atasu, S. Duran, L.N. van Wassenhove, The Dark Side of Solar Power, Harvard Business Review, June 2021, https://hbr.org/2021/06/the-dark-side-of-solar-power ; accessed 6.11.2024

[95] Jiashuo Li, Kun Peng, Peng Wang, Ning Zhang, Kuishuang Feng, Dabo Guan, Jing Meng, Wendong Wei, Qing Yang, Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions, One Earth, 3 (**2020**) 116–125, doi:10.1016/j.oneear.2020.06.009

[96] C. Gramling, Rare earth mining may be key to our renewable energy future. But at what cost?, Science News, 203, January 2023, https://www.sciencenews.org/article/rare-earth-mining-renewable-energy-future ; accessed 6.11.2024

[97] A. Farina, A. Anctil, Material consumption and environmental impact of wind turbines in the USA and globally, Resources, Conservation and Recycling, 176 (**2022**) 105938, doi:10.1016/j.resconrec.2021.105938

[98] M. Winrow, When wind turbine blades get old what's next?, BBC, March 2024, https://www.bbc.com/news/business-68225891 ; accessed 7.11.2024

[99] Wind industry calls for Europe-wide ban on landfilling turbine blades, Wind Europe, June 2021, https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/ ; accessed 7.11.2024

[100] T. Kirchhoff, K. Ramisch, T. Feucht, C. Reif, M. Suda, Visual evaluations of wind turbines: Judgments of scenic beauty or of moral desirability?, Landscape and Urban Planning, 226 (**2022**) 104509, doi:10.1016/j.landurbplan.2022.104509

[101] Y. Teff-Seker, O. Berger-Tal, Y. Lehnardt, N. Teschner, Noise pollution from wind turbines and its effects on wildlife: A cross-national analysis of current policies and planning regulations, Renewable and Sustainable Energy Reviews, 168 (**2022**) 112801, doi:10.1016/j.rser.2022.112801

[102] L. Burrows, The down side to wind power, The Harward Gazette, October 2018, https://news.harvard.edu/gazette/story/2018/10/large-scale-wind-power-has-its-down-side/ ; accessed 7.11.2024

[103] Future of Wind: Deployment, investment, technology, grid integration and socio-economic aspects, International Renewable Energy Agency, October 2019, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf ; accessed 7.11.2024

[104] J.H. Schmidt, M. Klokker, Health effects related to wind turbine noise exposure: a systematic review, PLoS One, 9 (2014) e114183, doi: 10.1371/journal.pone.0114183

[105] L.M. Miller, D.W. Keith, Climatic Impacts of Wind Power, Joule, 2 (**2018**), 2618–2632, doi:10.1016/j.joule.2018.09.009

[106] N. Bodini, J.K. Lundquist, P. Moriarty, Wind plants can impact long-term local atmospheric conditions. Scientific Reports, 11 (**2021**) 22939, doi:10.1038/s41598-021-02089-2

[107] K.A. Adkins, A. Sescu, Wind Farms and Humidity, Energies, 15 (**2022**) 2603, doi:10.3390/en15072603

[108] Liming Zhou, Yuhong Tian, Somnath Baidya Roy, Chris D. Thorncroft, Lance Bosart, Yuanlong Hu, Impacts of wind farms on land surface temperature, Nature Climate Change, 2 (20–12) 539–543, doi:10.1038/nclimate1505

[109] What Are The Colours Of Hydrogen And What Do They Mean?, Acciona, June 2022, https://www.acciona.com.au/updates/stories/what-are-the-colours-of-hydrogen-and-what-do-they-mean/ ; accessed 7.11.2024.

[110] R.W. Howarth, M.Z. Jacobson, How green is blue hydrogen?, Energy Science & Engineering, 9 (**2021**) 1676–1687, doi:10.1002/ese3.956

[111] N. Lakhani, Is hydrogen really a clean enough fuel to tackle the climate crisis?, The Guardian, March 2023, https://www.theguardian.com/environment/2023/mar/07/hydrogen-clean-fuel-climate-crisis-explainer ; accessed 7.11.2024

[112] Zilong Wang, Identifying green hydrogen produced by grid electricity, International Journal of Hydrogen Energy, 81 (**2024**) 654–674, doi:10.1016/j.ijhydene.2024.07.214

[113] T. Weiss, C. Gamage, T. Koch Blank, G. Lillis, A. Jardine Wall, Hydrogen Reality Check: All "Clean Hydrogen" Is Not Equally Clean, RMI, October 2022, https://rmi.org/all-clean-hydrogen-is-not-equally-clean/ ; accessed 7.11.2024

[114]J. Essler, C. Haberstroh, H. Quack, H.T. Walnum, D. Berstad, P. Nekså, J. Stang, M. Börsch, F. Holdener, L. Decker, P. Treite, Report on Technology Overview and Barriers to Energy- and Cost-Efficient Large Scale Hydrogen Liquefaction, IDEALHY project (FP7/2007-2013, grant agreement no. 278177), June 2012, https://www.idealhy.eu/

[115]J. Rodriguez Diez, S. Tome-Torquemada, A. Vicente, J. Reyes, G.A. Orcajo, Decarbonization Pathways, Strategies, and Use Cases to Achieve Net-Zero CO_2 Emissions in the Steelmaking Industry, Energies, 16 (**2023**) 7360, doi:10.3390/en16217360

[116]Carbon Border Adjustment Mechanism, https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en ; accessed 10.4.2025

[117]Yuzhang Ji, Zhongyuan Chi, Shufu Yuan, Yongxu Chen, Yujie Li, Tianchi Jiang, Weijun Zhang, Development and Application of Hydrogen-Based Direct Reduction Iron Process, Processes 12 (**2024**) 1829, doi:10.3390/pr12091829

[118]H. Mishchuk, Viktor Tryhuba, From energy intensity to sustainability: An analysis of trends in the aluminium industry, Journal of Management, 40 (**2024**) 51-56, doi:10.38104/vadyba.2024.2.05

[119]G.M. Haarberg, Electrowinning of Aluminum —Challenges and Possibilities for Reducing the Carbon Footprint, Electrochemistry, 92 (**2024**) 043002, doi:10.5796/electrochemistry.24-69019

[120]C. Windmark, L. Lattanzi, A. Månberger, A.E.W. Jarfors, Investigation on Resource-Efficient Aluminium Recycling – A State of the Art Review, Advances in Transdisciplinary Engineering, Ebook Volume 21: SPS2022, IOS Press, 2022, doi:10.3233/atde220122