# HOW TO BUILD, OPERATE AND MAINTAIN HVDC CONVERTER STATIONS WITH SUSTAINABILITY IN MIND

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**Abstract:** Achieving sustainability advancements in power transmission requires an integrated approach that combines cutting-edge technology, operational expertise, and power system's research which are core values of the CIGRE community. This paper explores a collaborative initiative by the Italian National Study Committees B4 and C3 by involving a technology provider, a transmission utility and a power system research centre, aimed at advancing the sustainability of modern power grids with specific focus on HVDC systems. As global energy demands increase and environmental concerns mount, this paper seeks to address key sustainability challenges through targeted advancements in transmission technology and operational green practices. In the first section a technology outlook is provided including a list of focus points from sustainability perspective. It is provided a comparison of LCA and circularity between HVDC and HVAC systems, offering insights into manufacturing, operation, and end-of-life phases. This analysis addresses key circularity aspects to improve material reuse and minimize environmental footprints throughout the technology's lifecycle. By establishing a structured comparison, the paper explores how HVDC technology can advance sustainable practices across design and operational stages. The second section contributes to the study by focusing on the integration of large infrastructure projects into the environment, specifically addressing mitigation strategies for visual impacts, interference with priority habitats both at sea and on land. These considerations are essential as HVDC systems require significant physical volumes. A general framework of regulatory and policy needs is given, including EU and national guidelines, to balance the possible environmental impacts and translate the short, medium and long-term results in KPIs not measurable with traditional economical frameworks. The final section includes a comprehensive LCA study, drawing from recent data from updated and improved environmental impact estimates according to the life cycle methodology of the current Italian electricity mix and 2030 scenarios. Although most expertise come from HVAC experience, similar methodology can be translated to the HVDC context, utilizing PNIEC (National Integrated Energy and Climate Plan) targets and projections through 2030. This time-based LCA perspective highlights how the environmental impact of the kWh evolves, emphasizing that as time progresses, the role of power losses becomes more pronounced, with manufacturing and end-of-life impacts relatively diminishing in the overall footprint. This interdisciplinary approach underscores the value of combining technology, utility operations, and research to establish HVDC as a sustainable backbone for future energy grids, providing a replicable model for responsible and effective deployment of advanced transmission systems.

**Keywords:** Energy Transition, High Voltage Direct Current, HVDC, Sustainability, Life Cycle Assessment

## 1. TECHNOLOGY OUTLOOK AND SUSTAINABILITY PERSPECTIVE ON HVDC SYSTEMS

High-voltage Direct Current (HVDC) technology is a significant advancement in electrical power transmission, utilizing direct current to efficiently transmit electricity over long distances. This technology is particularly beneficial for connecting remote renewable energy sources to urban centers with high electricity demand. HVDC systems enhance grid stability, improve transmission efficiency, and facilitate the integration of different AC networks. Considering sustainability performance in HVDC systems is crucial as the global community aims to mitigate climate change and transition to a low-carbon economy. Evaluating the sustainability of HVDC involves assessing environmental, economic, and social impacts throughout their lifecycle. Life Cycle Assessments (LCAs) provide a systematic approach to quantify the environmental footprint of HVDC projects from raw material extraction to end-of-life disposal.

Several assessments have been done following LCA methodology complying to ISO 14040 and 14044, CO2 equivalent, and it is proven that HVDC has a lower climate

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impact than HVAC when combining Converter Stations manufacturing Vs. HVAC stations, HVDC Cables Vs HVAC Cables, Total Losses, and End of Life considerations, above certain transmission distances [1]. This efficiency is attributed to the lower transmission losses of HVDC which contributes to overall energy conservation and reduction of the need for additional power generation, as well as its more efficient material utilization across manufacturing, operation, and end-of-life phases as shown in Figure 1 and Figure 2 [1]. Another LCA performed of HVAC vs HVDC systems, revealse that a continental multiterminal network with HVDC exhibits a lower climate impact compared to equivalent network extensions with HVAC technology. This result should be considered in efforts to achieve ambitious European climate targets [2].

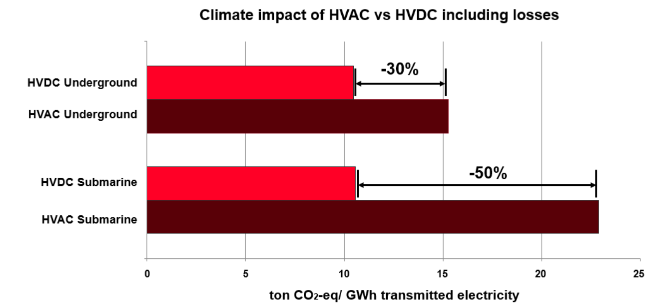


Figure 1: Climate impact of HVDC vs HVAC

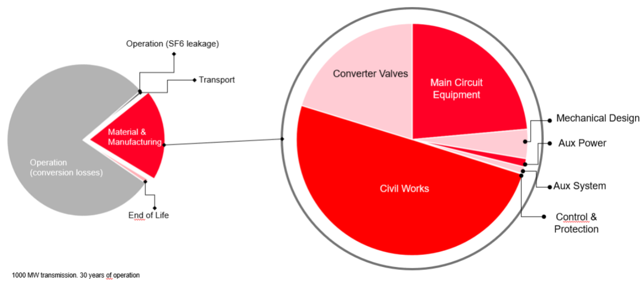


Figure 2: Climate impact of HVDC converter stations, 1000MW transmission, 30 years of operation, and with the Danish electricity mix.

While nowadays the largest climate impact by HVDC converter stations is due to conversion losses, technology advancement is leading to significant improvements over time. The latest HVDC technology iterations have already demonstrated improvements, with the latest generation converter systems achieving a 67% reduction in environmental impact compared to older designs. Figure 3 shows the environmental performance of different generations of power electronic components. In recent years, Modular Multilevel Converters (MMC) have emerged as the preferred topology for HVDC applications due to their scalability, modularity, superior performance in active/reactive power controllability and quality of the output waveform that reduces the need for extensive filtering, thereby improving overall system efficiency. Each MMC comprises numerous submodules containing power electronic components that enable the conversion process between AC and DC. The construction of MMCs involves a variety of materials, i.e. metals (steel, copper and aluminum), power semiconductors (BIGTs), dielectric insulation materials and each contributing to the converter's functionality and performance. Advancements in material science hold the potential to further reduce the environmental footprint of HVDC systems. Developing alternative materials with lower environmental impacts, enhancing the recyclability of semiconductors, and implementing comprehensive LCA practices are critical steps toward sustainable HVDC infrastructure. By embracing these strategies, HVDC technology can continue to evolve, contributing to the development of a sustainable and resilient energy system.

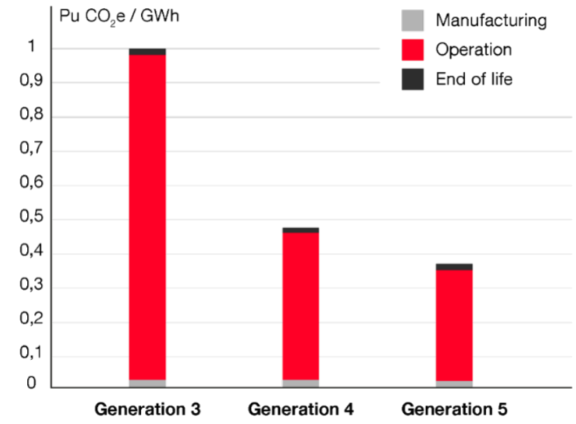


Figure 3: Environmental performance over time

The transition to a fossil-free society and advancements in grid technologies will significantly boost the demand for both commonly used and new metals and minerals. This surge is driven by the need for materials in fossil-free energy, and electrification technologies. Additionally, the global demand for metals and minerals is rising due to population growth, electrification, and expansion of electricity networks, expecting an increase with 4-6 times by 2040, compared to 2022[3]. Consequently, the supply and efficient use of these resources have become a critial global issue. Circularity considerations are particularly relevant for the sustainability of HVDC systems, such as including recycled materials in the high-voltage (HV) equipment, and considering end-of-life recyclability. Strategies such as enhancing the recycled content and recyclability of key components are crucial for minimizing environmental impact and promoting sustainability, in example:

- Recycled content: Primary metals like copper, aluminum, and steel, retain their intrinsic properties after recycling [4]. This characteristic makes recycled metals ideal for inclusion in products and buildings, to reduce environmental impact.
- Design for separability: By consider the end-of-life separability already in the research and development (R&D) phase, an efficient disassembly can be facilitated, which is an enabler in order to enhance end-of-life recyclability.

- Recycling Metals: Metals such as copper, aluminum, and steel have established recycling processes. Recovering these materials from decommissioned MMCs and other HVDC main circuit equipment can significantly reduce the demand for virgin resources and lower environmental burdens associated with mining and refining.
- Semiconductor Recovery: Recycling semiconductor components is more challenging due to the complexity of devices and the presence of materials that require careful handling. However, advancements in recycling technologies are enabling the extraction of valuable materials from electronic waste, contributing to resource efficiency.

Moreover, lifecycle assessments indicate that reducing the material footprint of civil infrastructure, especially concrete and steel, which contribute over 80% of HVDC station mass, can further optimize sustainability metrics, such as reducing CO2-eq emissions. In example, the preference for sandwich panel construction over reinforced concrete (CLS) can result from several advantages, depending on the specific requirements of the project: reduced material waste and construction site waste, reduced construction time, improved acoustic insulation, improved thermal insulation (i.e. panels with insulating materials such as non-combustible, recycled glass or rockwool that improve the energy efficiency of buildings by reducing energy consumption for heating and cooling), improved wear and water resistance and improved seismic response.

Transitioning towards lead-free and SF6-free alternatives, and implementing strict environmental standards for suppliers play a fundamental role in mitigating the ecological footprint of HVDC technology. While HVDC systems generally use air-based insulations, there can be cases where gas-insulated switchgear (GIS) is required. The use of SF6 in GIS, a potent greenhouse gas with a global warming potential 23,500 times higher than $CO_2$, poses a significant environmental concern. Current HVDC designs can contain over one ton of SF6 per converter station, amounting to an equivalent potential impact of 25,600 tons of $CO_2$ over the system's lifetime, if released to the atmosphere, reinforcing the urgency of transitioning towards alternative insulation technologies. In response to stricter environmental policies and incentives, industries are exploring alternatives to SF6 to maintain the characteristics of conventional high-voltage equipment while minimizing the environmental impact. Lifecycle assessments (LCAs) on SF6-free GIS solutions show varied results. One study reports a 72% reduction in climate impact over 40 years for a GIS 145 kV using a carbon dioxide, oxygen and fluorinated gas mixture compared to conventional SF6 GIS [5]. Another LCA, verified by the Swedish Environmental Research Institute (IVL), evaluated conventional SF6 GIS and two SF6-free solutions – one with a carbon dioxide, oxygen and fluorinated gas mix, and another using technical air insulation and vacuum interrupter technology. The study found a 65% GWP reduction with vacuum interrupter technology and technical air, and a 71% reduction with the fluorinated gas mixture [6]. Considering the substantial advancements in SF6 alternatives, this represents a significant measure to mitigate the environmental footprint of converter stations, whenever technology solution is commercially available.

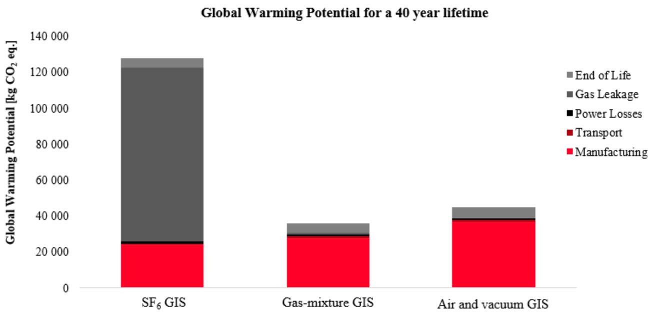


Figure 4: Environmental performance for GIS based on different insulation materials.

Other environmental benefits of HVDC systems, important to mention, are the lower generation of electromagnetic fields compared to AC systems, better suitability for underground or underwater transmission reducing visual and environmental impact, reduced right-of-way requirements and land consumption reducing the environmental footprint and potential impact on ecosystems.

Finally, to accelerate the scale up of the HVDC industry, repeatability will support fast world-wide HVDC deployment at highest quality and environmental standards. In example, the use of functional requirement specifications, seeking repeatability in sequential projects and adaptation to well established global base solutions and best practices based on global experience and incrementally optimized engineering, are leading the industry to perfected quality and HSE safety by design.

Additionally, operational improvements such as modular converter station designs and predictive maintenance techniques are being introduced to maximize energy efficiency while minimizing waste. By leveraging digital twin technology and real-time monitoring [14], HVDC systems could further reduce losses, extend the lifespan of critical components, and enable more effective recycling strategies at the end of operational life. Furthermore, retrofitting aging equipment with energy-efficient components enhances overall system efficiency, leading to lower energy consumption, reduced carbon emissions, and minimized resource depletion. These enhancements, alongside industry-wide efforts to standardize circularity practices, suggest that ongoing technological developments will continue to shape HVDC's environmental profile in the coming years.

## 2. INTEGRATION OF LARGE INFRASTRUCTURE PROJECTS INTO THE ENVIRONMENT – LAND CASE STUDY

It is important to recognize that landscapes have always been changing due to the interaction between human actions and natural processes and the sedimentation of these events is still contributing to shape it. Among these events it is possible to find deep traces of the relation between territorial and energetic dynamics: the landscape of energy is a recent concept with old roots connecting society, environment and territory [10].

Electricity transmission system operators (TSO) ensure the reliability, efficiency, security and cost-effectiveness of the transmission system. Within their responsibilities, TSOs develop and maintain transmission infrastructure assets, bearing in mind that new electrical infrastructure influences the landscape.

Figure 4: An existing HVDC Converter Station characterized by its exclusive architectural design

It is essential to address this impact to ensure that the transformation is not disruptive but rather fosters a seamless integration between the new infrastructure and the environment. It can be ensured by embracing a sustainable landscape approach during the entire process of planning a new electrical infrastructure. Following this direction a primordial approach has been applied to some new HVDC Converter Stations through important architectural design carried out by architects with high professional competences. This inspired the next step, combining architecture and biodiversity in order to create a deep integrated approach. Paying close attention to the integration of the new infrastructure into the environment has a double meaning. On one side it reveals the attention to the geographical aspects of the territory including all its physical and spatial peculiarities; on the other much attention is paid to the social aspects of the territory represented by the local communities (including their authorities) and by their needs. To achieve this goal, Terna (Italian TSO) presents and shares development projects to the communities since the early stages of development in order to receive feedback and try to incorporate them into the project. This dialogue, combined with technical knowledge, helps to execute large infrastructure projects while not introducing any fragmentation or vulnerability into the landscape, instead boosting its harmonious relation with the landscape.

One of the keywords of this process is “equilibrium”, coming to a point of agreement considering all these elements is strongly challenging. A powerful and realistic way to achieve this goal is resorting to the architecture and to the natural capital. For example, the process of planning a new converter or substation starts by mapping the main buildings, halls and external areas which can be reserved for green planning. As any other planning process of a new building or of a new green area, it is imperative to understand where the new is going to be placed; analyzing the existing is the first essential step. It means to investigate the landscape system in a deep way and at different scales [11]. For example, based on an architectural perspective, it is important to examine the local pre-existing buildings, including the volumes, shades, and construction materials. Concerning the natural aspect of the environment, it is essential to analyze the shapes and the natural structure of the landscape the patterns of land use, and the vegetation in the surrounding area along with its distribution. Additionally, specific features such as climate and soil must be studied to gain a comprehensive understanding. Simultaneously it is necessary to carry out territorial research at larger scales, for example the visibility analysis. All these investigations should be based on different acquisition methods: on-site inspections, library and cartographic research and so on in order to delineate an overview of the local context as exhaustive and complete as possible.

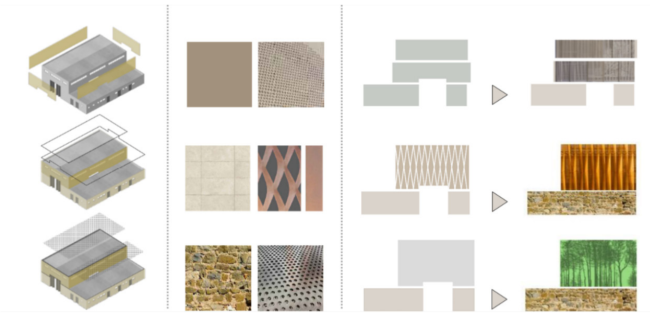

Figure 5: Carrying out territorial reasearches means studying local volumes, materials and colors, too.

Once strengths, resources and needs of the specific area where the new infrastructure is to be developed have been outlined, they have to be involved into the creative process. It is more advisable that the designer plan more than one design concept to reflect the different possibilities to approach the landscape. For example, it can plan an architecture for the purposes of evoking the historical heritage through traditional materials or colors or it can suggest revisiting the local heritage through contemporary shapes or materials.

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Figure 6: – An example of architectural concept and green planning for a new HVAC Station in rural area using traditional materials, local colors and native species (render).

Figure 7: The same new HVAC Station above mentioned planned using contemporary materials, local colors and native species (render).

Furthermore, a future trend will be to relate these ideas to the bio-architecture in order to establish a complete and balanced relationship between the natural environment and new constructions. Regarding the green areas, the principles of the naturalistic engineering [12] are the foundation of our green planning, for example all our projects provide the use of native species. The choice to plan through the naturalistic engineering underlines our main focus: the protection of the local ecosystem, the improvement of its resilience and of its biodiversity (both vegetation and fauna), the restoration of ecological balance [13].

Figure 8: An example of green planning based on naturalistic engineering principles improving local biodiversity.

These design concepts are just the starting point of the process. They are undoubtedly susceptible to several integrations throughout the planning process. Some integrations are related to the above-mentioned dialogue with the Communities and the Authorities, others are related to technical aspects. It is fundamental that the project respects the technical and electromechanical constraints to ensure the feasibility of the new infrastructure and address all safety concerns. The design approach, here summarized, highlights that the connection between electrical infrastructure and environment is not restricted to a basic reduction of visual impacts or to classic mitigation actions, but it is related to concrete examples of enhancement strategies.

Figure 9: An example of a sustainable landscape approach applied to a new HVAC Station: it shows the harmonic integration between the new infrastructure and the environment (render).

## 3. INTEGRATION OF LARGE INFRASTRUCTURE PROJECTS INTO THE ENVIRONMENT – MARINE CASE STUDY

Terna is committed to reconciling the need to build HVDC electricity infrastructure with the need to protect the environment and biodiversity. For years, the company has prioritized the protection of marine ecosystems in its strategies, a focus that has become increasingly relevant given the strong push for HVDC marine cable infrastructure.

To guarantee an adequate level of protection and safety for HVDC submarine cables, it is essential to ensure that they are buried on the seabed. The extensive distribution of marine phanerogams, such as Posidonia oceanica and Cymodocea nodosa, along the Italian coasts make these plants and their protection one of the drivers in the process of designing and building HVDC submarine cables. These marine plants exert a significant action in protecting coastlines from erosion, act as nurseries for many animal species, and contribute to the accumulation of $CO_2$ and the release of $O_2$. They are considered ecological resources of great importance and are therefore protected under European Directives such as the Habitats

Directive (1992/43/EEC), the Bern Convention (All. I) and the Barcelona Convention (SPA/BIO Protocol).

Alongside design, Terna is constantly implementing innovative approaches and solutions to minimize the environmental impact of HVDC infrastructures. These efforts ensure the sustainable coexistence of marine cables and seagrasses, highlighting the positive integration of advanced technology with ecological preservation.

When it is not possible to avoid or minimize interference with valuable seagrass meadows, compensatory measures are adopted to offset the impact. The most typical one is the transplanting of seagrasses carried out according to procedures that consider, in agreement with the relevant scientific authorities, specific site parameters such as depth, water conditions, temperature, etc. In order to ensure the protection of marine biodiversity, as a compensatory measure for the Tyrrhenian Link a 1000 MW HVDC project that will connect Sicily to Sardinia and to the Italian peninsula. It was precisely that Terna carried out, as a part of this project, for the first time in Europe, an experimental transplantation of Cymodocea nodosa, a marine plant of significant ecological value. The transplantation project, in collaboration with CoNISMa, ECON srl, Poliservizi srl and SUBONICA srl, is purely experimental, having never been carried out for this species on such a large scale and in the open sea. In detail, the transplant will involve the reintegration into the marine ecosystem of about 20.000 cuttings on about 1.200 m² of seabed using experimental techniques that pursue the highest standards of environmental sustainability and allow the best possible results to be achieved. This intervention will lead to results of high scientific value, laying the foundations for new developments in the environmental restoration of marine phanerogams.

Figure 10: Illustration of the Cymodocea n. Transplant activities.

In addition, in the contex of Tyrrhenian Link project, a transplantation of Posidonia oceanica, another marine plant of relevant ecological role, will be carried out. This activity will regards a transplantation over a designated area of about 1500 m². The operation aims to restore the ecological integrity of the posidonia habitat by ensuring regeneration of this key marine species, which plays a crucial role in coastal ecosystems.



Figure 11: Illustration of the Cymodocea n. Transplant activities.

## 4. LIFECYCLE ASSESSMENT OF ITALIAN ELECTRICITY NETWORK - SCENARIO WITH HVDC TECHNOLOGY IMPLEMENTATIONS

The development of large network infrastructures, particularly HVDC systems, is closely tied to the energy transition in the electricity generation sector. On the one hand, HVDC connections enable more efficient integration of large renewable energy plants in remote areas (such as offshore wind farms), thereby increasing the share of renewables in the energy mix. On the other hand, as observed, a significant portion of the environmental impact of network infrastructures is linked to the energy they dissipate. However, the impact associated with the production of this electricity is rapidly evolving, precisely due to the increasing penetration of renewable energy sources made possible by these new network infrastructures.

To address the critical question of effectively evaluating the true sustainability of the energy transition towards an energy system based on renewable sources, it is not sufficient to focus solely on the direct emissions occurring during the energy generation or consumption phases. A holistic approach is deemed necessary, considering the entire life cycle of the energy technologies involved, including an in-depth analysis of the overall environmental impacts, ranging from the extraction of raw materials required for technological components to their manufacturing, installation, maintenance, and ultimately, their end-of-life disposal or recycling. Within this context, Life Cycle Assessment (LCA) emerges as a fundamental and rigorous methodological tool. LCA, regulated by the ISO 14040 standard, provides a structured framework for quantifying and comparing the environmental burdens associated with products, processes, or services throughout their entire life cycle.

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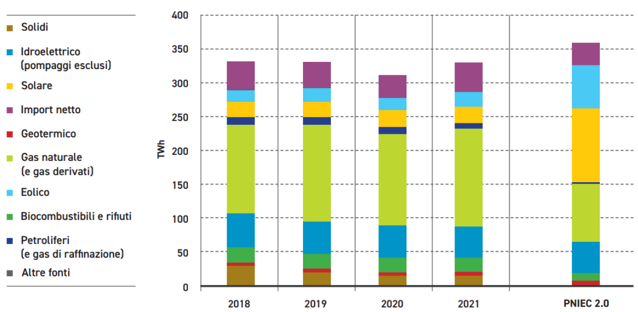


Figure 12: Trend in gross domestic electricity (GIEC) in Italy divided by source and forecast for 2030

Italy is actively engaged in the energy transition, with the electricity sector at the forefront of increasing the utilization of renewable energy sources and becoming a sustainable energy vector for other key sectors, including industry, transportation and heating. The Italian electricity system decarbonization process is characterized by an increasing integration of renewable energy sources such as solar and wind power. The goal outlined in the National Integrated Plan for Energy and Climate (NIEPC) is ambitious, aiming to achieve 63% of electricity generation from renewable sources by 2030. In the frame of this work, the impact on the environment of the electricity system is evaluated with reference to the Gross Inland Electricity Consumption (GIEC), defined as the gross production of electricity, including pumped hydro, plus the balance of international exchanges. Results are systematically presented per unit of energy (1kWh) of GIEC on the High Voltage transmission system. The evolution of GIEC in recent years and its targets for 2030 are described in Figure 12. The mix in 2030 must cope with a higher electricity demand than today (360 TWh compared to 330 TWh in 2021), with renewables contributing 66%. The penetration of renewables is led by solar, which will account for 30% of total consumption, followed by wind (18%) and finally hydro, whose production remains comparable to today (46 TWh).

The approach adopted for the evaluation of environmental impacts is the EF3.1 (Environmental Footprint version 3.1 adapted for SimaPro using impact categories having robustness I or II, except for the use of minerals and metals for which a robustness of III is also considered). Lacking any official comprehensive information about the production mix as a function of the energy source and conversion technology used, the LCA has been conducted based on statistical data published on a yearly base of electricity generation by source and fuel category (Eurostat) and by conversion technology (Terna for thermoelectric, GSE for renewables), fuel consumption for thermoelectric generation and installed capacity for renewables (Eurostat), annual direct emissions for thermoelectric plants (EMAS). The present Italian thermoelectric mix has been reconstructed for each plant considering the type of fuel (natural gas, coal, refinery gas, diesel, biofuels, etc.) and the related processing technologies. For renewable energy sources, a similar method is applied, associating the source with the conversion technologies, and in particular:

- for PV, difference is made among system configuration (roof-mounted or ground-mounted), module types (Poli-Si, Mono-Si, a-Si, CdT, CIS etc.)[1], type of technology (Al-BSF, PERC, HJT, IBC), size of plant and inverter rated power. Equivalent hours for 2021 were updated: 998 equivalent hours on roofs and 1308 equivalent hours on the ground installations.
- For wind power, plants are differentiated by size (plants smaller than 1 MW, plants between 1 and 3 MW, plants greater than 3 MW). The equivalent hours are evaluated in 1840h
- For hydropower, the distinction is made between reservoir plants (seasonal reservoir duration, greater than 400 hours), reservoir (weekly or daily reservoir duration, less than 400 hours and greater than 2 hours) or run-of-river plants;
- a single technology is considered for geothermal: i.e. the Ecoinvent database “Electricity, high voltage {IT}| electricity production, deep geothermal | Cut-off, U”.

As for the energy mix 2030, thermoelectric plants in 2030 are modelled in the same way as for 2021; efficiencies have been adjusted according to the assumptions made for the PNIEC scenario, equivalent hours for rooftop and ground base PV have been assumed as 1230 hours and 1468 respectively; all new installed PV between now and 2030 will be monocrystalline silicon modules; a progressive evolution of the technologies of PV panels has been introduced in our hypothesis, based on the assumptions of the International Technology Roadmap for Photovoltaic (ITRPV), 2021. Equivalent hours were also adjusted for wind power plants: 2,197 for onshore and 3,047 for offshore), and technologies not currently present were added to the mix, such as concentrated solar power and offshore wind power.

As can be seen from Figure 13, almost all impacts are more than halved, except for the consumption of mineral and metal resources, which is more than double the 2021. The issue if resource consumption will be the main concern of the decarbonisation process, if appropriate circularity measures are not implemented.

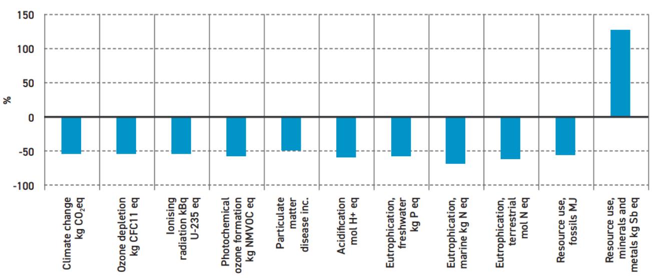


Figure 13: Percentage difference between expected mix impacts (2030) and current GIEC (2021) per unit kWh

[1] Poli-Si: polycristalline Silicium, Mono-Si: monocristalline Silicium, a-Si: amorphous Silicium, CdTe: Cadmium Telluride, CIS: Copper indium diselenide; Al-BSF: Aluminum Back Surface, PERC: Passivated Emitter and Rear Contact, HJT: Hetero Junction Technology, IBC: Interdigited Back Contact

Our analysis indicated that in 2021, the Italian electricity production and import contributed to climate change for 0.331 $kgCO_{2eq}$ per kWh. Projections for 2030 indicate a trend toward the reduction of most environmental impacts: this is the direct result of the increasing share of energy generated from renewable sources. For 2030, our forecast indicates a value as low as 0.149 kg CO2eq per kWh. The trend is shown in figure 14.

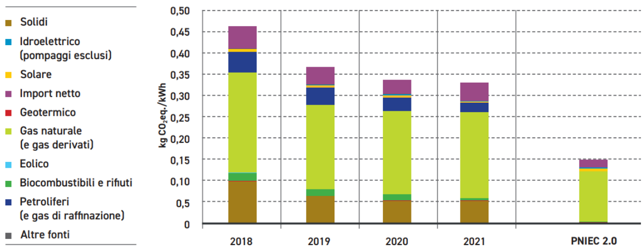


Figure 14: Environmental impacts in terms of GHG emissions for the Italian GIEC over the years

Despite this promising prospect of overall environmental improvement, LCA-based analysis has highlighted a potential trade-off associated with the decarbonization of the electricity sector. Specifically, a significant increase in the consumption of mineral and metal resources is anticipated. This increase is closely linked to the production of renewable energy technologies (such as solar panels and wind turbines) and energy storage systems (batteries), which require the use of a wide range of materials, often critical and with high environmental impacts associated with their extraction and processing.

The methodology accounts for all components of the electricity value chain in Italy, including transmission losses, based on the structure foreseen for the system in the reference years. The use of HVDC technologies in the transmission system have shown outstanding advantages in terms of overall energy efficiency. Past studies [8] reported that in HVAC systems, cable losses represent a substantial portion of the total system losses, with these losses becoming increasingly significant as transmission distances increase. Conversely, in HVDC systems, the losses associated with converters are found to be more predominant than those associated with cables. However, studies indicate that the advantages of HVDC systems surpass those of HVAC systems once the transmission distances reach a breakeven distance. In the case of transmission cables longer than 100km, the HVDC systems appears to have around 40% less losses on comparable basis to equivalent HVAC transmission [8]. The divergence between the losses becomes increasingly pronounced as the transmission cables are further extended. More recent studies [9] have confirmed that for an 880km transmission line, the power losses from the HVDC system are more than 50% lower than from the HVAC system. This significant gain in terms of efficiency is directly reflected in the environmental impact, with a corresponding reduction of the GHG emissions of the power system. Considering HVDC technologies on main corridors along the Italian peninsula could help to further reduce the greenhouse gas emissions of the Italian electricity grid below values foreseeable today.

## 5. CONCLUSION

In conclusion, the integration of LCA and circularity principles in the design, operation, and decommissioning of HVDC systems are very important tools and principles for minimizing environmental impacts and promoting resource efficiency. By focusing on material reuse and adopting sustainable practices, HVDC technology can play a significant role in advancing sustainable energy infrastructure.

The comprehensive appraoch to sustainability is crucial in modern infrastructure projects. This involves not only the integration of sustainable practices in building design and construction but also the preservation of marine ecosystems. HVDC technology plays a pivotal role in this conext by ensuring efficient and sustainable energy transmission.

In parallel, collaborations between technology providers, utilities, and research institutions are fostering a shared knowledge base for best practices in sustainable HVDC system design. These cooperative efforts ensure that advancements are aligned with long-term environmental goals, promoting a holistic and sustainable approach.

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