Sustainable and Reliable **Value for our Clients**

Helping our clients and suppliers evolve to operate within planetary boundaries

The **metals and mining industries** must evolve to significantly **reduce their carbon emissions** and limit global warming to internationally agreed limits. Tenova Group is helping drive this transformation by developing **innovative technologies** that not only support our clients in delivering **better products** but also drastically **reduce** their **environmental impact**.

In this section, we report on how we support our clients in reducing their environmental impact with our portfolio of products, technologies, and services, with a focus on digital transformation.

Driving Sustainable Solutions

Our portfolio of solutions is primarily dedicated to the sustainable transformation of the metals and mining industries. We create value for our clients by providing innovative technologies that ensure efficiency, resulting in improved performance, reduced waste, and lower carbon emissions. These technologies support the transition to cleaner fuels, enhance energy efficiency, and facilitate the recovery and reuse of previously wasted materials.

In developing these solutions, we not only serve our clients but also work hard to accelerate our sector's transition to a lower environmental impact.

Energy Transition

The iron and steel industry is one of the largest emitters of CO_2, responsible for around 7% of global direct energy-related CO_2 emissions. To address this, the steelmaking sector is undergoing a radical transformation to accelerate pathways to decarbonization, rethinking the energy sources that drive its industrial processes, **moving from carbon-based iron reduction processes to natural gas-based and hydrogen-based** ones. This shift is part of a broader energy transition in the metals and mining industries, driven by three key trends in which Tenova Group plays a pivotal role through its advanced solutions: decarbonization & hydrogen, electrification, and digitalization.

All these trends not only demand increased metal production, but also require that production itself evolves in alignment with them. To meet these challenges, Tenova positions itself as a leading figure in fostering a **shift in the metals industry energy paradigm** by promoting **hydrogen-ready technologies** to its clients for the transformation process of their business. This is further achieved through partnerships and collaborations with gas supply operators, electrolyzer manufacturers, and other third parties that support a green energy transition.

In this context, the following section presents key products, research cases, and partnerships that are driving the Group's shift in the energy paradigm.

Electrical Steel

As the world[2] invests in electric vehicles (EVs), improving and expanding the electrical grid infrastructure, the appetite for electrical steel grades is growing substantially. **Electrical steels** are specialty steel grades **containing silicon** as its primary alloying element. They are prized for their ability to conduct magnetic fields, and as such are used for the expansion of electricity infrastructure, for rotating machines such as wind turbines and electrical motors. Tenova's portfolio includes silicon steel processing lines that enable our customers to more efficiently produce metals that will be critical in facilitating the energy transition, including electrical steel (silicon steel), which is estimated to make up roughly 1-2% of total crude steel production globally. Tenova has developed numerous **technological advancements to improve the performance of electrical steel**, including innovations in the annealing, pickling, decarburization, flattening, and coating operations required in strip processing lines.

Improvements in silicon steel

As demand for magnetic steel (a special steel alloyed with carbon and other elements that exhibit magnetic properties and is used in electric machines) and silicon steel continues to grow, the need for more efficient production methods is increasing. Thus, Tenova's R&D team has been working intensively to develop technologies that improve the silicon steelmaking process. In addition to our **suite of technologies for silicon steel**, we are improving the **magnetic properties of silicon steel**, hot and cold rolling, and new descaling processes, like laser and other mechanical descaling. Our research intends to find the optimal process to improve surface finishing and enhance magnetic properties.

[2] International Energy Agency (IEA), Iron and Steel Technology Roadmap: Towards more sustainable steelmaking (2020).

DRI and ENERGIRON

The global steel industry community agrees that the partial or total use of hydrogen for **DRI (Direct Reduced Iron)** production is the most effective route for the decarbonization of the industry. More and more steelmakers are adopting this solution for the installation of **new green steel plants** or for the **decarbonization of integrated steel mills** (i.e., steelmaking from ores as raw materials).

Our **ENERGIRON** technology, jointly developed with Danieli, is at the forefront of sustainable steel production. By utilizing innovative DRI processes, ENERGIRON can reduce carbon emissions by up to 80% compared to traditional steelmaking methods.

This technology has been designed to use **different types of reducing gas sources including pure hydrogen** to reduce iron ores into metallic virgin iron to produce a wide range of **high-quality steels**. ENERGIRON plants efficiently reduce any iron unit into "energized" hot or cold DRI or hot briquetted iron with controlled metallization and carbon levels. ENERGIRON offers unparalleled flexibility: even with the same process scheme configuration, the client can select the best energy source - natural gas, reformed gas, syngas from a coal gasifier, coke oven gas or even hydrogen - without any process modification and can control the amount of embodied carbon during operations.

ENERGIRON plants meet the **most stringent environmental regulations**. Thanks to its unique features, it has the lowest carbon footprint of any ironmaking technology, with the further advantage that the selectively removed CO_2 can be sold. Additionally, the water byproduct of the reduction reaction, easily condensed and removed from the gas stream, can be used as cooling water in a zero-water consumption circuit.

DRI plants are typically coupled with **Electric Arc Furnaces (EAF)** for the melting of the DRI and its transformation into sellable iron or steel. The use of electrical energy substitutes chemical energy, which creates CO_2 emissions. We are proud that **the world's most productive DRI-fed EAF was produced by Tenova at Tosyali Bethioua plant**.

ENERGIRON technologies have concretely contributed to global steelmaking innovation over the course of 2024. Indeed, during the year, **Tenova successfully embarked on building a second DRI-fed EAF** for Baosteel Zhanjiang Iron & Steel Co., Ltd, working with Sinosteel Engineering & Technology Co. Ltd to successfully complete the performance test for the new **hydrogen-based 1,000,000 tons/year ENERGIRON Direct Reduction (DR) plant**.

With a full capacity of 1 million tons per year and installed at Baosteel – a Baowu Group company – it will be **China's largest hydrogen-based DRI facility**. The plant, which uses natural gas enriched with hydrogen, leveraging coke oven gas as the process gas, is **an industry first**. **It is also equipped to capture CO_2** for commercial use, further cutting emissions and creating an additional revenue stream. The **strength of our design** lies in the fact that the transition to better gases is possible while keeping the plant open, without requiring fundamental changes to its functional structure.

In **February 2024,** our ENERGIRON technology was also selected by **LKAB**, an international mining and minerals group, for the basic engineering of its 100% hydrogen-based Direct Reduced Iron (DRI) plant **in Gällivare**, **Sweden**.

The Gällivare demonstration plant, with a capacity of 1.35 million Mtpy (metric tons per year) of **fossil-free DRI**, will combine LKAB's **HYBRIT** and Tenova's **ENERGIRON technologies**, drawing on shared expertise in DRI production. Results from the HYBRIT pilot plant show that DRI made with **pure hydrogen** as a reducing agent **outperforms fossil-based alternatives** like natural gas.

Similarly, in **August 2024**, our US client **Nucor Steel Louisiana** reached **world record production** with 330.3 tons/hour of cold direct reduced iron (CDRI), **thanks to its pioneering ENERGIRON technology**.

SAF and Open Slag Bath Furnace

Open Slag Bath Furnace (OSBF) is the perfect solution for melting high-carbon DRI to produce hot metal.

Tenova joins RINA's 100% hydrogen-fueled Hydra project

We partnered with RINA on the Hydra project, funded by NextGenerationEU and supported by the Italian Ministry of Enterprises and Made in Italy. The project aims to enable European steelmakers to test 100% hydrogen fuel for greener steel production. Tenova will provide a **30 meter high DRI tower**, using **ENERGIRON** technology, and an **Electric Arc Furnace (EAF)**. By 2025, the pilot plant will produce up to seven tons of steel per hour with reduced carbon emissions. The project will help test various hydrogen-natural gas blends and iron ores, providing valuable insights for future investments. The EAF can also process residual materials from steelmaking and other sectors, such as plastics, biochar, and construction by-products, supporting more sustainable resource use.

The electric furnace, a **Submerged Arc Furnace (SAF)** in this case, works using Søderberg electrodes operating "submerged" in the slag or with a very short electrical arc or "brush arc". The OSBF can tap hot metal into torpedo cars. The resulting slag produced is similar to blast furnace slag and can be sold to the cement industry. The work done on OSBF slag treatment has identified a potential alternative processing route for the treatment of EAF slag, which is discussed in more detail in the Circular Economy section (p. 31)

Mineral Wool Applications

Historically, the **mineral wool flow sheet** has included Cupola furnace technology, a process with high carbon emissions. Tenova has identified the **use of Tenova's bespoke hybrid SAF design** (using graphite electrodes) to replace Cupola furnaces. This technological innovation has the potential to **reduce mineral wool carbon emissions** by up to 90% depending on the electrical energy carbon footprint. Tenova offers this technology to existing mineral wool producers (as a retrofit) or producers planning to expand their mineral wool production capacity.

iBLUE®

Conventional blast furnace-basic oxygen furnaces or oxygen converters **(BF-BOF)** dominate global steel production, producing **two tons of CO_2 for each ton of steel** produced (as a comparison, the EAF route from scrap produces 80% fewer emissions). Modifying their technology is the best route to CO_2 reduction for the steelmaking industry. As of 2023, 57% of global steel was produced via the BF-BOF route, while only 43% was produced via the electric (EAF) process. Tenova's technology to **substitute any Blast Furnace** is iBLUE®, which enables the **production of Liquid Pig Iron via the BF-BOF route** while massively reducing emissions. iBLUE® combines the production of high-carbon DRI with an electric arc melter to produce hot metal and granulated slag. It can also utilize BF grade pellets as raw material, making it the perfect substitute for blast furnace technology. The use of green hydrogen in the reduction process can further **minimize greenhouse gas emissions**. This represents a less costly option to produce hot metal with a minimal carbon footprint and results in minimal disruption to the operations of an integrated steel plant that plans to shift towards green steel production.

In 2023, Tenova started a pilot project on an industrial-sized submerged arc furnace for the production of hot metal, and achieved positive results. iBLUE® is increasingly confirmed as the sustainable alternative to blast furnaces to convert integrated steel mills with existing BOFs into "green metal plants". In addition to its environmental advantages, iBLUE® allows steelmakers to maintain existing steel grades production procedures and quality control: from this perspective, implementing iBLUE® does not require the qualification of the production process, and is highly recommended for high-quality steel grades, exposed automotive parts, etc.

A number of projects and studies with steelmakers in different parts of the world kicked off in 2023, and will result in the construction of new iBLUE® plants. The relevance of the technology was further confirmed in 2024 with a successful test conducted in a Swedish laboratory in February.

Tulum Energy S.A.

On October 31, 2024, Tulum Energy S.A. was established and incorporated in Luxembourg, with equal ownership by Tenova S.A. and Tech Energy Ventures. Tulum Energy is developing an **innovative technology**, initially conceived at Tenova, for the **production of low-carbon hydrogen from methane pyrolysis ("Turquoise hydrogen")**. Tulum subsequently raised venture capital from a **consortium of institutional, strategic, and financial investors**, as part of a capital increase successfully completed in July 2025.
Tulum's technology aims to produce low-carbon hydrogen (90% CO2 reduction compared to traditional technologies) on an industrial scale and at **competitive costs**. In particular, Tulum's technology can play a significant role in decarbonizing the steel industry. Tulum is currently developing its first demonstration plant in Mexico, at Ternium's site.

Combustion Systems for Furnaces

Traditional hot rolling and heat treatment processes utilize fossil fuels, resulting in a high carbon footprint for final products like long or flat steel products. Tenova is committed to developing and deploying **highly efficient low-emissions combustion systems** for reheating and heat treatment furnaces. Since 2008, we have specialized in the development of **regenerative and self-regenerative burners** that provide at least a **10% reduction in CO_2 emissions** using fossil feedstock. Furthermore, Tenova's regenerative burners are also **hydrogen-ready**: whenever green hydrogen becomes readily available, our clients can immediately use variable amounts of hydrogen blended with more standard fuels and drastically reduce their carbon emissions without any additional investment.

In 2021, we reached a key milestone in this endeavor by developing the first burners for heat treatment furnaces using up to **100% hydrogen**, while keeping NOx below the strictest emission limits. Tenova's regenerative flameless burners combine the lowest NOx emission level with high temperature combustion air preheating, thus combining a drastic reduction of CO_2 emissions with high combustion efficiency. That means our products provide clients with improved plant sustainability even before cleaner fuels such as green hydrogen become readily available.

We believe hydrogen will play a key role in the future of combustion systems. However, many countries and markets are not yet structurally prepared to adopt this technology. Therefore, over the coming years, we are committed to providing our clients with reliable and sustainable solutions that serve as incremental steps toward the energy transition.

While we and our clients look forward to the necessary developments in the hydrogen distribution infrastructure, **in 2024, we developed a basic concept study for hybrid burners**, which will support steelmakers in pursuing their emission-reduction targets by directly utilizing renewable electricity to cut standard fossil fuel consumption. During the year, we filed relevant patents so that this medium-term solution will **allow our clients to use the clean electricity already available to reduce their emissions potentially up to 25%**[3] while keeping the hydrogen-ready feature.

We have also integrated digital solutions into our line of **SmartBurners** to provide up-to-the-minute data on the operating efficiency and processes of our burners, easing inspections and maintenance. Our **Industrial Internet of Things (IIoT)** framework offers a complete set of process diagnostics KPIs to control key parameters like combustion ratio, and KPIs to monitor critical components such as switching valves.

Our multi-megawatt TSX SmartBurner family for reheating furnaces can be fed with variable mixtures of natural gas and hydrogen – potentially up to 100% hydrogen. Our 200-kilowatt TRKSX (Tenova Self-ReKuperative Flameless) SmartBurner also uses variable mixtures of natural gas and hydrogen and works both in flame and flameless modes, keeping **NOx emissions well below the strictest limits**.

[3] This emission reduction percentage is an estimate based on a case-study burner, representative of our designs.

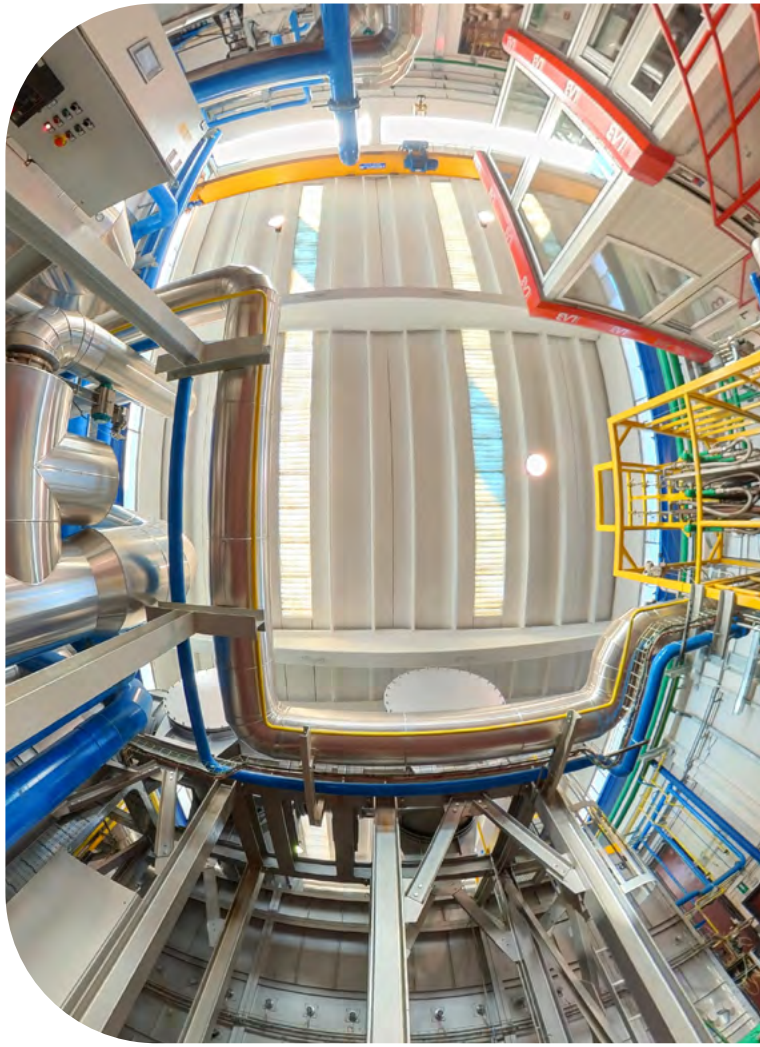
In a collaborative project with **thyssenkrupp Hohenlimburg GmbH**, Tenova LOI Thermprocess proceeded with advanced heating hoods, featuring our patented Ultra-low NOx HPH®-flameless concept and increasing air preheating temperatures to 600°C. It achieved up to 12% energy and CO_2 savings. In production trials, the project aimed to decarbonize steel production by gradually shifting the fuel gas supply for the heat treatment of hot-rolled narrow strips from natural gas to 100% hydrogen. Despite the higher combustion temperature, the flameless concept resulted in low NOx emissions.

To assess the impact of increased hydrogen use on the overall system, we employed a mobile natural gas/hydrogen mixing station. This allowed us to test different gas mixtures during annealing cycles. To this end, Tenova developed the THSQ Burner family that can work with any hydrogen/natural gas mixture while maintaining consistent thermal performance and NOx emissions. The tests consistently confirmed that Tenova LOI Thermprocess's ultra-low NOx HPH®-flameless bell-type annealing plant is well-suited for hydrogen use.

TenovaLAB

We continuously invest in new research and development activities to create cutting-edge technologies that provide low-carbon solutions to our clients in the metals and mining industries. For this reason, between 2023 and 2024, Tenova invested in its own R&D facilities by installing an **experimental laboratory at our headquarters in Castellanza**. Our TenovaLAB (T-LAB) carries out experimental industrial activities for the development and testing of all burner technologies. Equipped with **four test furnaces** of varying thermal power, T-LAB allows our R&D team to close the loop between our in-house modeling and simulation capabilities and the engineering of industrial products. On-site product testing, such as thermal and emissions measurement, enables us to fine-tune product specifications, minimizing technology risks for our clients. Furthermore, T-LAB allows our customers to see our products in action in real operating conditions.

During 2024, after we expanded our facilities at T-LAB with preparatory works, we completed the installation of a 1.5 MW **water electrolysis unit** directly connected to the solar panels' roofing of our Pomini Workshop. This expansion is partially financed through a Horizon EU grant to demonstrate the green hydrogen production/utilization chain at full industrial scale, from the generation of hydrogen to blending with natural gas in the combustion systems of the different test furnaces at T-LAB.



Case Study: Partnering with Clients for a Low-Carbon Future

As our economies move towards net-zero emissions, metals companies have a major role to play in emissions reduction. Tenova is constantly innovating to develop low-carbon solutions for the metals industry. In 2024, Tenova embarked on a number of projects including:

We partnered with **Snam**, Europe's largest energy infrastructure operator, to conduct joint strategic studies and market analyses to implement green hydrogen projects in the metals industry. We aim to bring integrated, turnkey commercial solutions tested in industrial plants to implement a substantial reduction of CO_2 and NOx emissions in metals production processes, from melting to thermal processing of long and flat products.

Under a joint agreement between Tenaris, Snam S.p.A. and Tenova, the pipe mill of TenarisDalmine carried out industrial tests of hydrogen generation and use, with the aim of evaluating the performance and reliability of generating and using hydrogen as a fuel in steel heating processes. The goal has been achieved during long term industrial tests in which the hydrogen produced on site by an electrolizer was used to feed a Tenova HydrogenReady burner installed in a furnace for seamless pipes, confirming the industrial feasibility of Tenova HydrogenReady solutions.

We signed a Cooperation Agreement with **Power Conversion** (a **GE Vernova** business) to develop innovative medium voltage power feeding solutions for EAFs and SAFs. The partnership combines our metallurgical expertise with Power Conversion's Direct Feed technology to improve energy efficiency, process stability, and grid compatibility, supporting the decarbonization of high-power electric furnaces.

We signed another Cooperation Agreement with **Inductotherm**, for the joint proposal and commercialization of the 'Hybrid Furnace' solution. The hybrid furnace combines Inductotherm's induction heating systems with Tenova's high-efficiency, low-carbon combustion technologies, including our HydrogenReady burners. The goal is to support decarbonization in rolling mills by integrating high thermal efficiency, direct electrification through induction, and the potential use of green hydrogen. By bringing together both companies' technological expertise and track records in induction and combustion systems, we offer a state-of-the-art solution to rolling mills worldwide.

Energy Efficiency

In cases where it is not yet feasible to transition to cleaner fuels, we have developed a suite of technologies to help our clients use their existing fuels more efficiently or adapt their existing processes to reduce their emissions.

Metals Advancements

Consteel® & EMS

In use for over 30 years and on 80 sites across all continents, our Consteel® Electric Arc Furnace (EAF) has proven its value to clients around the world. Consteel® is a process which preheats and continuously charges raw feed materials, in particular **scrap**, into an EAF, melting them by immersion in the liquid steel present in the furnace. The EAF operates in constant flat bath conditions, a key advantage over conventional batch processes, where scrap is melted by the direct action of the electric arc. The EAF off-gases are used to preheat the incoming scrap and feed materials. Their composition is controlled and sent to a fume-cleaning plant in conditions suitable for the complete combustion of carbon monoxide and other pollutants without any fuel consumption. This process produces liquid steel with high productivity, a short and adjustable heat cycle, and a lower power cost compared to other EAF installations using conventional or other alternative steelmaking technologies. To further improve its Consteel® Electric Arc Furnace (EAF), Tenova introduced additional features, like the **Electro Magnetic Stirring technology**, such as **Consteerrer®**, which improves energy consumption and refractory lining life.

iRecovery® Captures and Reuses Thermal Heat

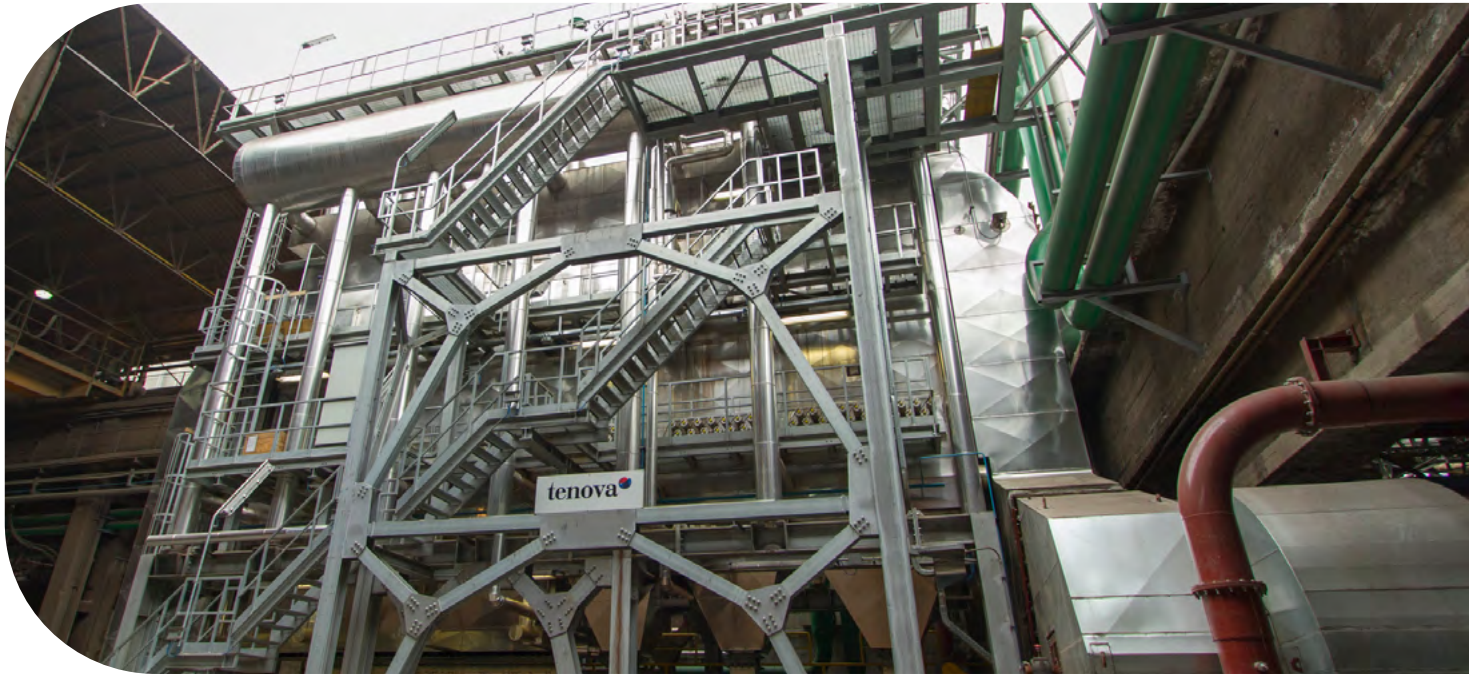
Today, process optimization and energy efficiency to reduce emissions are more important than ever for steel producers. Tenova began working on this over a decade ago, well before other companies were thinking about sustainability in the industry. In the past ten years, we developed the iRecovery® system for recovering thermal power from EAF waste flue gas and using it as an energy source. This energy comprises the biggest fraction of the primary energy input in the EAF process, yet it typically goes to waste. iRecovery® captures the thermal energy created by the off-gas and uses it to produce steam to power steelmaking and other activities. In Brescia, for example, our client ORI Martin uses the heat captured with iRecovery® to heat 2,000 homes in winter and power 700 homes in summer, reducing 10,000 tons of CO_2 every year.

In 2023, Tenova developed the iRecovery solution for application at high pressure, up to 60bar(g). This solution increases the applicability of iRecovery in the transformation process of steelmaking from BF-BOF to DRI-EAF through integration into the existing steam network. We coupled Consteel and iRecovery® in order to improve the effectiveness of our technologies: while the high temperature thermal power contained in the waste gases (up to 800°C) is first used in scrap preheating by Consteel, the Waste Heat Boiler (WHB) **uses the recovered residual waste gas energy**. This combination can produce about 90-140 kg/tls of steam.

In 2024 Tenova signed a contract with Voeastalpine Donawitz for the supply of two iRecovery plants for their new electric arc furnaces to be supplied by Danieli. Each of the systems is sized to produce around 50 tph of steam from each of the 75t EAF.

Multiple Pre-heater for Ferroalloys production

In 2023 Tenova, together with one of the world's largest ferrochrome producers, successfully reached full performance of Tenova's patented multiple pre-heating system. The system utilized the chemical energy contained in the furnace off-gas as a fuel to pre-heat the chromite feed materials. This technology reduces the electrical energy requirement (directly decreasing the operating cost per ton product) and it has the added advantage of improving furnace stability.



Mining advancements

In-Pit Crushing & Conveying (IPCC)

IPCC systems represent an innovative and more sustainable approach to materials handling in surface mining. Instead of relying on diesel-powered haul trucks to transport run-of-mine material from the pit to the processing facility, the IPCC system crushes the material directly at or near the mine face and transports it via **energy-efficient conveyors**. This system **increases safety while also significantly reducing emissions** and **lowering operational costs**, furthering the mining industry's **global green transition** and decarbonization goals.

High-Pressure Grinding Rolls (HPGRs)

This technology is increasingly recognized as a key technology for **improving energy efficiency in ore processing** – comminution is the most energy-intensive of mining processes. HPGRs use high pressure to compress and fracture ore particles between two rotating rolls, which significantly reduces the energy required, especially when processing hard materials. This energy-efficient technology allows for a reduction in process energy intensity and, at the same time, enhances downstream flotation efficiency by improving particle size distribution and mineral liberation.

DELKOR BQR Flotation Cells

Efficient and reliable flotation is essential for maximizing mineral recoveries, and DELKOR's BQR Flotation Cells are designed with this goal in mind. DELKOR's BQR Flotation Cells, boasting DELKOR's proprietary MAXGen mechanism, improve the recovery rate of valuable minerals while using less energy, thereby increasing overall processing efficiency.

Circular Economy

Industrial processes inevitably generate a variety of waste byproducts. At Tenova Group, we are committed to supporting the circular economy by developing technologies that enable the recovery, reuse, and valorization of these materials, reducing their environmental impact. In the metals business, our solutions focus on the efficient treatment and transformation of steelmaking byproducts, such as slag, into valuable secondary materials. In the mining business, our comprehensive portfolio of dewatering equipment is designed to reduce freshwater usage and manage tailings and waste more effectively. Together, these efforts help our clients operate more sustainably across the entire metals and mining value chain.

Metals advancements

Auto Catalyst and Battery Recycling

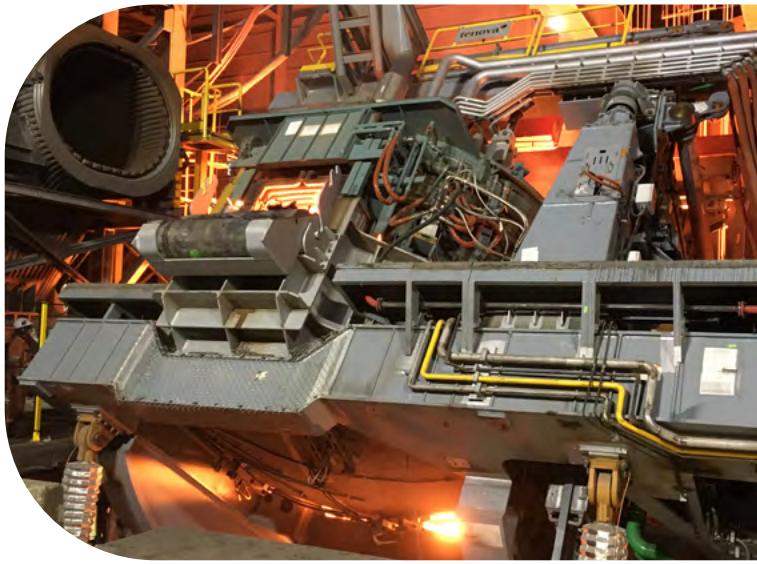
Melting furnace technology is used to recycle the PGM's (Precious Group Metals) contained in spent auto catalysts. As the first generation of electric cars reaches the end of its cycle, there is a **real opportunity to recover valuable materials contained in various electric car systems** (primarily the battery and auto catalyst). Tenova offers both **hydro and pyrometallurgy process paths to recover these materials**.

EAF-LF (Electric Arc Furnaces - Ladle Furnace)

The primary production of steel from virgin iron ore is highly energy intensive. This can be mitigated without loss in quality by using ferrous scrap mixed with DRI/HBI and other virgin iron units (pig iron / hot metal) when necessary. Quality and availability of steel scrap are therefore important factors, especially considering the decreasing quality of world steel scrap. To this end, we are conducting research and implementing **new Industry 5.0 technologies** to manage low-quality scrap in furnaces, improve EAF flexibility, and achieve cost savings while enhancing environmental performance. EAF steel production is already an integral part of the circular economy.

Tenova is implementing innovative approaches to increase the recycling process, replacing the use of injected coal in the EAF with alternative materials that are byproducts from other industrial processes, like polymers from waste plastic and by treating EAF process residues, such as slag and fume dust to recover both metal and mineral fraction for internal use or application in other industries.

In October 2024, we secured a contract with **Tata Steel UK** to supply a **high-productivity Electric Arc Furnace (EAF)** and associated equipment for their **Port Talbot plant**. By **replacing** the current **blast furnaces**, the new state-of-the-art production line will significantly **reduce carbon emissions** while ensuring the continued production of **high-quality flat steel**. This project is a key element of the joint agreement between Tata Steel and the **UK government**, aimed at the decarbonization of steelmaking in the UK, with an **estimated reduction of 50 million tons of direct carbon emissions** over the next decade.[4]



[4] For further information about this project, please visit: tenova.com

Tenova Goodfellow Inc.'s NextGen® for Dongkuk Steel Mill in Korea

In 2024, Dongkuk Steel Mill Co. Ltd. contracted Tenova Goodfellow Inc. to supply and install its **NextGen® System** at their Incheon Plant in **South Korea**. Designed for a 120-ton AC shaft furnace, the system includes advanced sensors for off-gas measurement, featuring two sampling stations and a central cabinet. With hybrid laser/extractive off-gas analysis, the system offers **fast response times and monitors CO, H_2O, CO_2, O_2, and H_2,** enabling real-time control and improving efficiency. Its low maintenance needs also lead to cost savings in hardware and installation. Unlike other laser technologies, **Tenova's patented NextGen® system offers full-spectrum analysis**, enabling complete control without compromising dynamic burner, lance, and fume system suction management. It also provides enhanced water detection and real-time mass and energy balance, essential for controlling both chemical and electrical energy inputs to the **EAF**. In contrast to in-situ systems, which offer only intermittent off-gas analysis, **NextGen® delivers continuous, simultaneous analysis from all sample locations**. The system uses a high-velocity pump to extract, filter, and clean off-gas before it enters the sample station laser cells, ensuring uninterrupted laser beam transmission. Key components include the gas probe, heated sample line, sample station cabinet, control cabinet, and analyzer server. A key characteristic of the system installed at the Dongkuk Steel mill is the "zero maintenance" design, which was created to significantly simplify the management and handling of this equipment.

Dry Slag Granulation

The **capture and reuse of currently wasted materials**, such as ladle furnace slag, is a critical step in the decarbonization of the steel industry. In 2016, the European steel industry generated about 43 million metric tons of slag, of which about 7% — or 3 million metric tons — is not being reused, posing not only a serious environmental problem in Europe, but representing a **huge amount of available material for potential recycling**. Today, slag handling is a costly and time-consuming operation that poses significant safety and operational risks, requires water, and is a potential source of fugitive dust and fumes.

Tenova has developed a Ladle Furnace (LF) **slag granulation solution**, which uses forced air flow to rapidly cool and solidify slag. The fast cooling transforms the slag from liquid to solid, enabling the reuse of slag as raw material in the construction industry. Our solution decreases workers' exposure to harmful chemicals in slag, reducing water use, and the need for virgin lime. Furthermore, we extended our dry granulation technology to EAF slag generated during high alloy steel production via the DRI/EAF process.

In 2023, Tenova was awarded the first contract for the installation of an LF dry slag granulation solution system in Italy, which will process more than 20,000 tons/year of slag. The first of its kind, the plant will be equipped with the latest artificial intelligence algorithms to assist production optimizing the granulation process. The granulated product will then be utilized for the preparation of chemicals for the construction industry.

Lithium Recovery

Lithium is widely used in metallurgical processes for **metal melting**, to **eliminate the formation of oxides**, **and absorb impurities**. Its growing use in clean energy technologies, like solar arrays and electric vehicle batteries, make it a **critical metal for a net-zero future**. Building on this potential, Tenova's engineers have studied a number of processes to produce lithium more efficiently. **Tenova Advanced Technologies (TAT)** adapted its Solvent Extraction (SX) technology for producing **lithium from primary sources** to produce **lithium recycled from batteries**. For this project, Tenova Advanced Technologies secured funding from the Israel Innovation Authority to complete the process development from both brine and battery sources. One of the main uses of the funds was the purchase of the LiEL™ Electrolysis skid for the TAT Research and Development (R&D) Center in Israel. The new process can be applied across all feed streams, originating from any source, including solar, hard rock, waste recycling, and process waste streams, to produce high-quality lithium hydroxide. The key characteristic of this process is the **high efficiency of extraction**, superior to the traditional process, and a **lower use of water.**

Rare earths

Rare earth elements are among the most **sought-after chemicals** worldwide, **essential to modern technology** and everyday life. They are found in devices like smartphones, computers, electric vehicles, wind turbines, and solar panels. Recognized as critical raw materials by both the European Commission and the US Department of Energy, rare earths are vital for **advancing the energy transition** and achieving global decarbonization goals. Tenova offers a range of solutions to better **manage rare earths**.

Black Mass and Rare Earth Solvent Extraction

TAT specializes in both innovative technology development and robust process equipment for solvent extraction. Our experience and expertise in all aspects of SX includes the development of SX processes utilizing an in-house R&D center and detailed design, supply and construction of SX plants.

Tenova Turbulent Technologies Mixing System is a new mixing technology which enables significant reduction of entrainment levels without changing the process flow. It can be easily retrofitted to most existing mixer settlers or installed in new SX plants. The main advantage of this technology is the reduction of entrainment of expensive extractants, organic contamination in the product stream, aqueous contamination in the loaded organic stream, ecological impact of organics in the raffinate stream, operation, and maintenance costs. It further enables increased settling flux and eliminates the need for after-settlers. Thanks to this technology, our clients are able to recoup precious metals such as lithium, nickel and manganese from battery forms.

Rare earths are also the main components of our latest product, **NdFeB magnets** made from neodymium-praseodymium (NdPr) metal. This stable and powerful magnet can contribute to powering electric vehicles, further demonstrating how big an impact our innovations can make in this industry.

The World's Strongest Permanent Magnet

Tenova has designed, manufactured, and commissioned **advanced electrolytic cells** for the efficient commercial production of NdPr metal. Equipped with cutting-edge automation and an automatic tapping system, **these cells ensure operational efficiency, stability, and high product quality**. Our proprietary sensors and integrated control system optimize performance and reliability, supported by auxiliary equipment to enhance plant operations.

This technology has been deployed by MP Materials, marking the **first commercial-scale production of rare earth metals in the USA** in decades. MP has an agreement with **General Motors** to supply permanent magnets to make **electric cars** in the US, and, to date, it is the only manufacturer of these magnets. At this facility, NdPr metal will be used to produce NdFeB magnets—among the most powerful permanent magnets essential for vehicles, drones, robotics, electronics, aerospace, and defense. Tenova Group, which initially developed this technology with the University of Toronto, is proud to contribute to this milestone, **reflecting our dedication to innovation and the energy transition**.

Twin-chamber Furnaces for Aluminum

Aluminum's many useful qualities have made it ubiquitous across all areas of modern life. Additionally, its recyclability makes it a highly valuable waste material. **Recycling aluminum uses up to 95% less energy than it would take to mine virgin material**, creating fewer emissions. Tenova has created new technologies to further enhance the environmental benefits of recycling aluminum. Our **Twin-Chamber Melting Furnace (TCF®)**, **a Tenova LOI Thermprocess technology**, enables the remelting of up to 6% organically contaminated aluminum or other scrap metal without pre-treatment. Its dual-chamber design includes a post-combustion process to completely incinerate contaminants and use the resulting energy generated for furnace processes, thus reducing consumption of external energy. Our TCF® technology has **30 installations worldwide**, producing approximately 1,500,000 MT of liquid aluminum every year. And for existing casthouses, the application of TCF® to the recycling of post-consumer scrap can significantly reduce the overall CO_2 emissions of the plant, as the process generates only 80 kg of additional CO_2 per ton of liquid aluminum.

Magnesium Production from Coal Ash

As global demand for magnesium metal rises, **Latrobe Magnesium Limited (LMG)** in Australia uses Tenova's technology to **harvest this metal from fly ash byproduct** – a hazardous waste material deriving from brown coal power generation. Originally developed to have a zero-waste pickling process during steelmaking, our pyrohydrolysis process was adapted to suit LMG's unique situation to **recover magnesium**. The related emissions from this technology are roughly half of those of conventional magnesium production plants. Launched in 2022, LMG is currently building its 1,000 tons per annum magnesium demonstration plant in the Latrobe Valley of Victoria integrating the Tenova Spray roaster unit. From the production experience acquired through this initiative, LMG eventually intends to develop a commercial scale operation producing 10,000 to 40,000 tons of magnesium metal per year.

Mining advancements

DELKOR Thickeners

In 2024, DELKOR secured a significant contract to supply equipment to the world's largest thickened tailings project, located in Chile. DELKOR's thickener technology provides a **safe and sustainable dewatering solution for tailings management**. As part of this key project, DELKOR will supply seven 60 meter diameter DELKOR High-Density Thickeners, together with a multitude of DELKOR Shear Thinning Systems to the copper tailings facility. This important project represents a long-term strategy for the safe and effective disposal of copper tailings, establishing what will become the **largest thickened tailings project globally**.

The use of DELKOR thickeners will enable **significant water recovery**, allowing water to be reused in processing. This approach greatly reduces freshwater consumption and will ensure continued mining operations for all the client's northern mining sites, which would otherwise face significant challenges in securing sufficient water for the concentrator plant operation.

The current copper tailings from two large mining sites are discharged into an existing tailings dam whose lifespan, though extended, is nearing the end of its useful life. To meet projected production demands, the new facility is scheduled to commence operation in the first half of 2027, enabling more effective and improved tailings storage, higher water recovery rates, and a reduction in particulate emissions.

DELKOR's high density thickener technology will help the mining operation reduce freshwater intake and operate more safely. Its position as a leading global provider of high-performance dewatering solutions is essential for water recycling, for increasing safety and for reducing the environmental footprint of tailings facilities in arid regions such as Antofagasta, Chile.

DELKOR Horizontal Belt Filters (HBFs)

In line with circular economy principles, **DELKOR horizontal belt filters (HBFs)** offer an efficient solution for resource recovery and waste reduction across various industrial processes. These high-capacity vacuum filtration systems are capable of dewatering a wide range of materials, enabling both **water reuse** and more **sustainable residue management**. DELKOR pioneered the application of belt filters in acid filtration, and this technology is now widely used for tailings filtration as well. By supporting closed-loop processes and reducing the need for fresh water, HBFs help improve overall operational efficiency and environmental performance across sectors.

DELKOR Filter Presses

DELKOR Filter Presses offer an effective solution for reducing waste and enhancing the reuse of water in both mining and industrial operations. By applying **high pressure** to dewater a wide range of commodities, these systems produce a dry filter cake that can be safely handled, stored, or even reused, depending on the application. Commonly deployed downstream of mineral processing plants, as well as in chemical, fertilizer, and wastewater treatment facilities, DELKOR filter presses support the **sustainable management of tailings and sludge**. Their ability to recover water and significantly reduce waste volumes contributes directly to greater resource efficiency and a lower environmental footprint.

Impact Monitoring

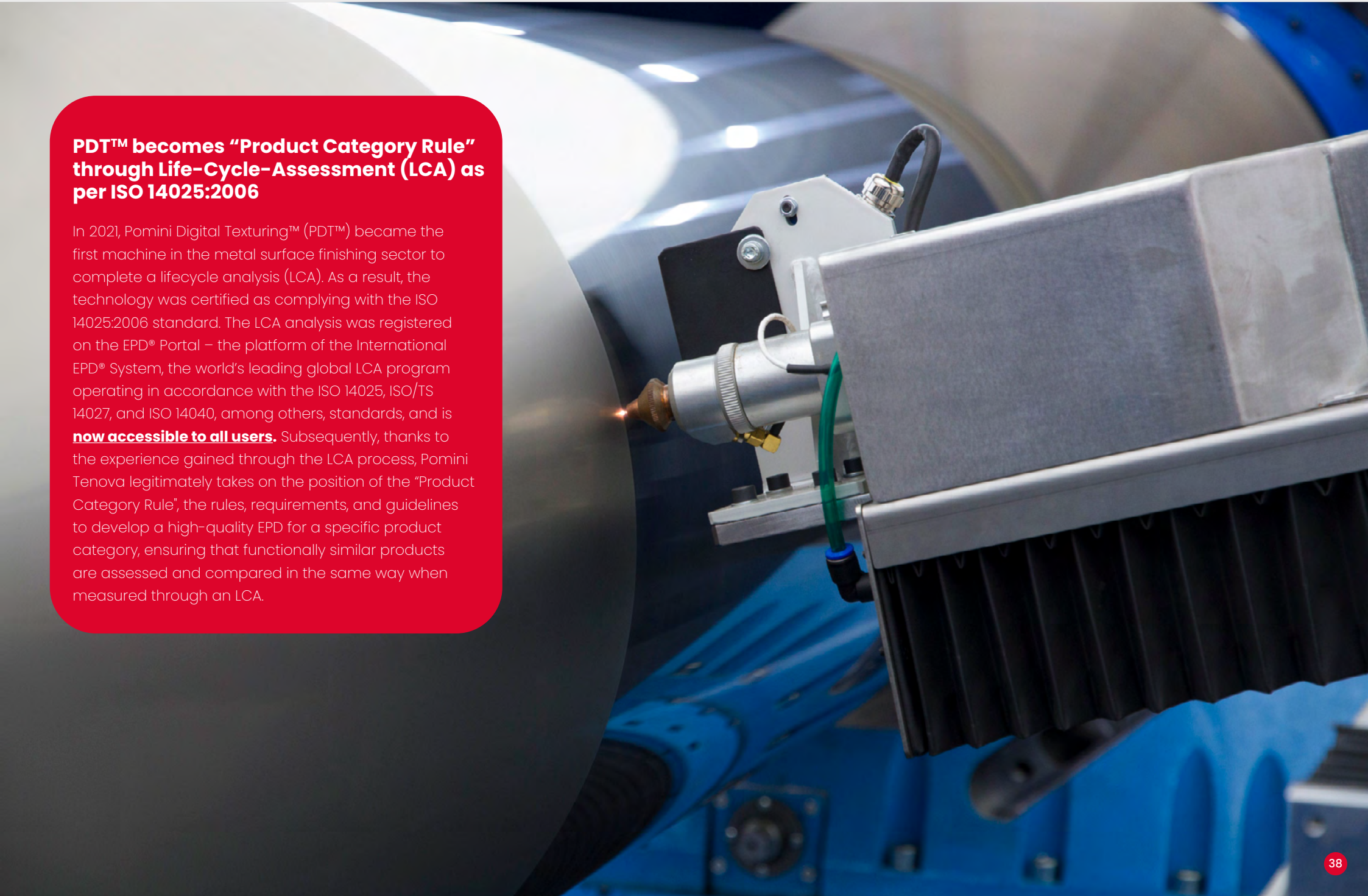
As a responsible company, we recognize the importance of monitoring the impact of our products and services on the environment and human health. We commit to improving our processes and products to ensure their impact is accounted for throughout their entire life cycle.

Pomini Digital Texturing™

Our **Pomini Digital Texturing™** (PDT™) equipment covers an extensive range of **surfaces for work roll texturing** in cold rolling mill applications for both the steel and aluminum sectors. With up to four state-of-the-art lasers and no need for ancillary equipment, the process requires **minimal power** consumption. A simple digital process, based on modern **fiber-optic laser** heads, PDT™ enables an unparalleled range of surface possibilities compared to any other existing texturing technology.

PDT™ offers **benefits beyond energy efficiency**. It does not have adverse impacts on human health. Other texturing technologies may require, as a post-process in many applications, the use of significant quantities of hexavalent chromium, a highly carcinogenic material which can be difficult to remove from the environment. PDT™ makes it possible to significantly reduce, and even completely **eliminate hexavalent chromium**, making it a much safer and less toxic alternative.

Looking ahead, Pomini Tenova foresees **several impactful potential uses** for the revolutionary PDT™ technology. One potential use we are currently exploring is in the field of electrolyzers - machines that convert water into hydrogen to be used as a clean-burning fuel, a key enabler of a low-carbon future. A second area of development is in electric vehicle batteries. We are exploring the use of PDT™ on aluminum foil to obtain a reduction in intrinsic resistance characteristics through texturing. We look forward to sharing more about these and other potential applications in the future.

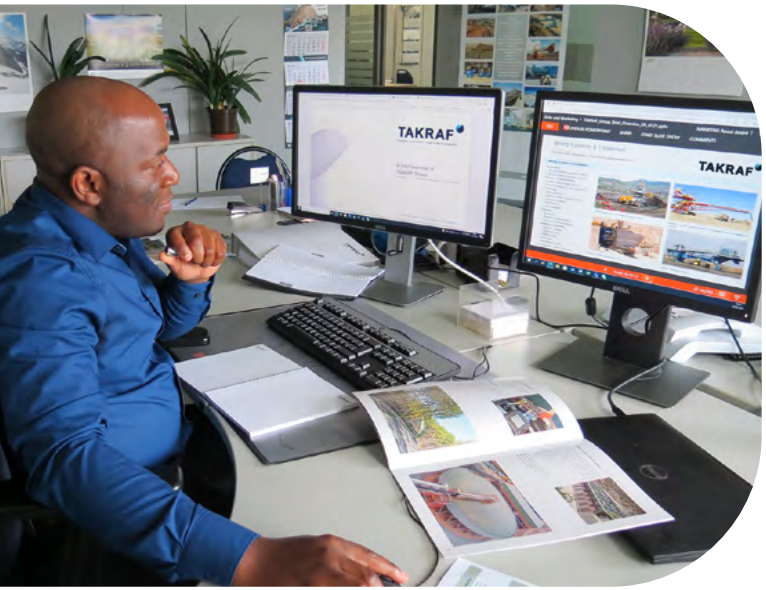


PDT™ becomes "Product Category Rule" through Life-Cycle-Assessment (LCA) as per ISO 14025:2006

In 2021, Pomini Digital Texturing™ (PDT™) became the first machine in the metal surface finishing sector to complete a lifecycle analysis (LCA). As a result, the technology was certified as complying with the ISO 14025:2006 standard. The LCA analysis was registered on the EPD® Portal – the platform of the International EPD® System, the world's leading global LCA program operating in accordance with the ISO 14025, ISO/TS 14027, and ISO 14040, among others, standards, and is **now accessible to all users.** Subsequently, thanks to the experience gained through the LCA process, Pomini Tenova legitimately takes on the position of the "Product Category Rule", the rules, requirements, and guidelines to develop a high-quality EPD for a specific product category, ensuring that functionally similar products are assessed and compared in the same way when measured through an LCA.

Delivering **Safe Products by Design**

Tenova Group encourages employees at every level to focus on eliminating potential dangers before they emerge. This means **safety starts at the design stage**, leveraging the experience, know-how, and innovative approaches of our experts and engineers to **build safety directly into products** from the start. This unwavering attention to detail has enabled us to build an extensive, multi-decade track record of safe and high-performing products, systems, and facilities.



Safe Technology for Clients

A tech-forward approach, focused on digital technologies, data gathering, data analysis, and dedicated training, enables us to deliver products with considerable safety advantages. We build monitoring features, including robotics, smart sensors, and AI, directly into our products. We collect digital data on facility performance and production errors and compile digital report cards for maintenance effectiveness and troubleshooting. These innovations provide real-time and predictive analytics to **enable clients to prevent accidents** and reduce potential harm to their employees.

Metals – Safe Technologies

Our **iBOF Intelligent iSDS® Slop Detection System** closely **monitors vibrations** in the BOF route and **alerts technicians** when the risk of slopping, or an overflow, increases past a set threshold. iSDS® technology significantly reduces the number of slopping events through effective prediction of such occurrences and advanced alarming to the furnace operators. Accurate slop prediction is a critical tool in the BOF operation that provides an additional protective system to increase yield and productivity while reducing operating costs and minimizing fugitive emissions. Preventing slopping reduces potential harm to workers from direct contact or slop emissions, while reducing product loss. Three iSDS® systems have been successfully commissioned by ArcelorMittal South Africa between 2023 and 2024, and all three have been in continuous operation, steadily achieving expected performances.

Our **Water Detection System (WDS)** enables EAF process monitoring optimization by measuring the sound of the water flowing in the water-cooled sidewalls. Additionally, our WDS monitors leaks and alerts plant operators when higher-than-normal water conditions are present in the EAF. Tenova's WDS is the only commercially available system that is capable of continuously interconnecting with the EAF off-gas for both H2 and H2O vapor. The real-time EAF process information and NextGen® off-gas hardware include full spectrum analysis of the water conditions in the EAF, which are evaluated for abnormalities.

Our **Submerged Arc Furnaces (SAF)** provide more **reliability and safety** when processing **Platinum Group Metals (PGMs)** concentrates than other furnaces. Because they use electricity as an energy source, our SAFs provide high process efficiency at low energy utilization levels. Furthermore, Tenova has developed a patent that covers the use of graphite with copper cooling to prevent the sulfide corrosion of the copper cooling elements in a furnace sidewall. The use of graphite helps to protect the copper cooler from corrosion caused by free sulfur present in the furnace sidewall adjacent to the concentrate feed layer. Advances in robotics have enabled Tenova to develop an automated casing addition solution for Søderberg electrode. Poor casing addition practices are one of the main contributors to electrode failure; the new development therefore has multiple benefits – not only does it remove personnel from a potentially hazardous environment, but it also contributes to more stable and safer plant operation with higher quality standards for electrodes casing welding.

MEGtec™, Tenova's alternative cooling medium system, drastically **reduces the risk of explosions** caused by leaks from furnace equipment such as sidewall coolers, taphole block, and electrodes. Minimal equipment changes to the existing equipment are needed, and the technology is well suited to adoption in existing operations. In 2024 tests were conducted using this technology, showing that no explosion in liquid metal occurs - even with substantial leaks from the side walls or copper coolers that use this system.

Pomini Digital Texturing™ (PDT™), presented in the "Impact monitoring" paragraph (p. 37), is inherently fire risk-free and fully enclosed, thus reducing the exposure of workers to internal processes.

Our **SAFE+ (Safe Plus) EAF configuration** allows **operators to remain in a comfort area** and **detect several possible critical situations**, like water leakage. The introduction of several robotized operations and remote control of the furnace improves the working conditions of operators in the melt shop, particularly in the area surrounding the furnace.

Tenova, through its Business Unit Tenova Material Handling (TMH), is developing some main R&D projects with the aim of improving the value for clients in terms of safety and workers' wellness.

SafeForPorts is a **pioneering initiative** that leverages **Virtual Reality (VR) and AI** to revolutionize **port operations**, prioritizing **safety** in the maritime industry. The project is part of the Istituto Italiano di Tecnologia's (IIT) RAISE (Robotics and AI for Socio-economic Empowerment) and is implemented under the Italy's National Recovery and Resilience Plan, funded by the **European Union – NextGenerationEU**, highlighting its significance in driving innovation and safety within the maritime sector.

A combination of digital twins and VR allows company stakeholders to immerse themselves in port operations and fully understand data, providing solutions. Digital twins enable companies to show their technical teams the global layout of the equipment and train for the operation that will be required. All of this can be presented concisely through the interlinking digital twins with virtual and augmented reality. This allows the **operators to train** without the stress of incidents and builds confidence for when they will operate on real machines.

Thanks to **remote control**, **the TMH machine** can be operated **remotely**, typically in a building. This allows operators to work in more comfortable conditions and increases machine availability, reducing the time for shift changing and allowing the machines to work in poor weather conditions.

The project has gained significant momentum thanks to the **synergies** between **automation teams** in Tenova. A pilot system has been implemented to assess the confidence level of a skilled operator while **driving the ship unloader remotely**, i.e., without a direct view of the working area. The goal is to determine whether the working environment reproduced at the remote station provides a **sensory experience comparable to direct view** operation. The evaluation focused on key factors such as visual details, granularity, and realistic perception of each piece of equipment as well as dimensions and sounds. Thanks to all the sensors and cameras installed, the operator is allowed to experience optimized visibility from a remote station as if he were on board the unloader.

Full Automation represents the most ambitious goal that TMH wants to achieve. The target is to reach **unmanned operation of TMH Port Machines**. The expected results are: an **optimization** of the **operation sequences** with a consequent **energy consumption reduction, better operating conditions for operators** who will have to supervise the activities but in less stressful conditions, and a **reduction** of overall operating time.

Mining – Safe Technologies

Tenova Group prioritizes safety in all its designs, including the mining industry: both **TAKRAF and DELKOR promote a holistic maintenance philosophy** that enhances safety, operational efficiency, and reduces the total cost of ownership by integrating maintenance requirements from the earliest engineering stages.

Chute maintenance is a typical high-risk task: replacing liners is hazardous and time-consuming. TAKRAF mitigates this by designing modular or rotatable chute sections, allowing maintenance to be performed in a much safer manner and reducing downtime from a full shift to just 60 minutes. Another smart solution TAKRAF has developed is the ability to replace liners safely from outside the chute. Techniques such as external ultrasonic wear measurement enable planned **maintenance without entry into confined and dangerous spaces**.

For elevated and/or steep belt conveyors, TAKRAF has developed a maintenance cart that can safely and quickly access any point along a conveyor. This solution has been successfully deployed at major copper projects in North and South America, significantly enhancing safety and efficiency, even in complex terrains with elevated sections and curves.

At Tenova Group, safety is a **non-negotiable** priority and prioritizing it can mean turning down opportunities that do not meet our standards.

In **2024**, TAKRAF declined to bid on an important project with a major global mining company **on grounds of safety**. TAKRAF engineers deemed the required technical operating parameters of the machine too extreme and outside of what would be considered safe parameters for slope steepness and technical feasibility. TAKRAF proposed an alternative solution to reduce slope steepness so as to arrive to suitably safe operating parameters, but this was rejected. At this point, **TAKRAF declined to bid, citing significant safety concerns** regarding the operation of such a machine within the required technical operating parameters and harsh operating conditions of the mine site.

The following content provides some further background on some of the **innovations and challenges** that TAKRAF continued to develop during 2024, proving that **safety and efficiency can complement one another**.

TAKRAF X-TREME Class Sizer: Redefining Maintenance, Safety and Productivity

As mining operations adopt more advanced equipment and face tougher conditions, there is an urgent need for maintenance concepts that are both safe and efficient to protect workers and minimize downtime. While traditional views suggest that increased safety complicates and slows down maintenance, TAKRAF's X-TREME Class Sizer challenges this assumption.

Designed according to TAKRAF's holistic maintenance philosophy, **the brand's X-TREME Class Sizer combines durability and abrasion resistance, together with a modular-type design to minimize wear and simplify maintenance**. Its components allow for quick and adaptable servicing, from replacing individual crushing teeth to roll segments or even entire rolls with reduced disassembly and downtime.

Key features such as a quick-release system, split housing for shaft removal, and integrated sliding units all contribute to increased safety and reduced maintenance times. **TAKRAF emphasizes that safety and efficiency in maintenance are complementary goals, with safer operations leading directly to higher productivity**.

The TAKRAF Sizer Hot-change Method

Another prime example of increased safety and efficiency is TAKRAF's sizer hot-change method, which allows for safe and quick swapping between an operational sizer and a spare on the same platform, minimizing downtime. For larger operational setups, a checker-type arrangement enables multiple sizers to share a common spare machine, which can be supported by an optional bridge crane for handling, further boosting efficiency.

These solutions allow maintenance activities to occur separately from operations, **improving safety and ergonomics while reducing time pressure that can lead to unsafe shortcuts**. While such systems may require higher initial investment, they ultimately reduce overall ownership costs by enabling safer and faster equipment reintegration, maximizing production time.

TAKRAF's commitment to separating operation from maintenance exemplifies how safety and efficiency can go hand-in-hand, proving that smarter maintenance solutions are able to combine both increased safety and increased efficiency, without compromise.

Innovative Tie Rod Replacement on a Ship Unloader: TAKRAF Brazil's Safe and Efficient Solution

A few years ago, TAKRAF Brazil was tasked with replacing the tie rods connecting the main boom to the counterweight boom of a Continuous Ship Unloader (CSU) commissioned in 2002. The challenge was to complete the work safely, efficiently, and within tight time and budget constraints.

Traditional tie rod replacement involves extensive scaffolding to support the machinery, but this method was unsuitable for the project's tight schedule. TAKRAF Brazil's engineering team devised an **innovative solution by employing a temporary tie rod to maintain stability, eliminating the need for scaffolding altogether**.

This approach allowed the project to be completed in less than 15 days, 60% faster than by using a traditional approach with scaffolding, and reduced costs by nearly 50%. Importantly, the work was carried out without any accidents and without disrupting other critical equipment, such as the jetty conveyor beneath the CSU.

This project is just one of many examples that highlight **TAKRAF's commitment to innovative, safety-first solutions that optimize efficiency**. This project exemplifies how creative maintenance strategies can simultaneously enhance safety and operational efficiency.

TAKRAF's Advanced Remote and Condition-Based Maintenance Systems

Bulk material handling systems are critical to mining operations, linking mines to processing plants, stockyards, and markets through reliable and efficient material movement and storage. Any disruption in this chain impacts productivity, making maintenance essential. To address this, **TAKRAF develops automated solutions that maximize safety and efficiency in maintenance across mining, material handling, and mineral processing equipment**.

TAKRAF's equipment features advanced Programmable Logic Controller (PLC)/ Distributed Control System (DCS)-based control systems with built-in protection to reduce operator errors and support troubleshooting. These systems integrate with clients' asset management, Enterprise Resource Planning (ERP), and Manufacturing Execution System (MES) platforms to plan preventive maintenance effectively. Remote access and support enable software updates and expert assistance via smart glasses, augmented reality tools, and web-based dashboards, showing key performance indicators and maintenance schedules.

Condition-oriented maintenance is facilitated through sensors and advanced monitoring tools that track component health, such as idler bearings and belt conditions. Additionally, intelligent lock-out procedures enhance safety by allowing maintenance teams to securely isolate power, increasing safety, and reducing downtime during troubleshooting and repairs.

R&D and Sustainable Innovation

At Tenova Group, we enhance existing technologies in the metals and mining sectors, while also designing and producing innovative solutions that minimize the environmental impact of our clients' facilities and boost their efficiency and performance. Our solutions reduce CO_2 emissions to some of the lowest levels in the metals industry. We create cutting-edge technologies that **reduce fine particles, NOx emissions, dioxins, and other hazardous substances**. We strongly believe in the potential of alternative and renewable energy sources, incorporating them into our solutions wherever possible. We have already put **hydrogen-ready technologies** on the market, and many of our solutions are designed around the concept of **recovery, reuse, and circularity**, from dispersed energy to reutilized residues and more, fostering an effective circular economy.

Our innovation process begins with **research, an open-ended, creative ideation phase**, and is followed by development, where ideas with high potential are turned into prototypes of future products. Finally, once tested and finalized, the product is produced and marketed to customers. This process cuts across a number of teams and business units, including engineering, functional units, sales, and more. Our attention to sustainability has been a successful driver of business growth for Tenova Group. We are coordinating our **R&D&I** (Research, Development, and Innovation) **efforts across Business Units and Product Lines**, to find integrated, synergistic solutions through collaboration.

Our R&D&I focus areas for 2022-2024 were **energy transition, local environment, process flexibility and efficiency, raw materials and residual valorization, safety, and final product quality**. We have identified how each of these focus areas contributes to the United Nations Sustainable Development Goals (UN SDGs). The UN SDGs serve as a useful guide for businesses and society to align on to advance sustainable development. To further our impact, we also participate in national and regional working groups, including EU ones, on sustainable topics like circular economy and decarbonization to generate projects, roadmaps, and partnerships.

Metals - 2024 R&D projects

Between 2023 and 2024, Tenova submitted 14 proposals for EU and Italian funding for projects covering several areas of interest and involving different business units. Of these, six were selected for funding and have kicked off:

iSteel Expert

Funded by the EU Research Fund for Coal and Steel (RFCS) program, it aims to **implement a remote virtual expert system to improve the management of steel production operations**. The IoT-based system will be used to monitor events and suggest actions, reducing the need for physical presence around the furnace area at the Pittini Siderpotenza plant in Potenza, Italy. Additionally, it supports the preservation and transfer of industrial knowledge through a knowledge-based tool that includes interactive training, fostering the continuous evolution of industry expertise.

SafeForPorts

Explored in the "Safe technology for clients" chapter, is funded by RAISE (Robotics and AI for Socio-economic Empowerment) with support from the Italian Ministry of University and Research (NextGeneration EU funding). It is a **Virtual Reality (VR) simulator for remote training** and on-field assistance for smart and sustainable ports.

AI DRAFT

Funded by the MADE Competence Center 4.0 with support from the Italian Ministry of Enterprise and Made in Italy (NextGeneration EU funding), it focuses on **AI-driven automation for technical design**. The project aims to apply AI and design of experiment (DoE) technologies to **improve EAF** shell design by:

- Enhancing energy efficiency, reducing CO_2 emissions, and minimizing energy and material consumption by revising component designs (e.g., cooled panels, injectors).
- Extending component lifespan and improving reliability.
- Reducing the time to market for innovative components.
- Minimizing residue generation.
- Preventing operational issues.

Simulation Driven Design for Tenova Consteel

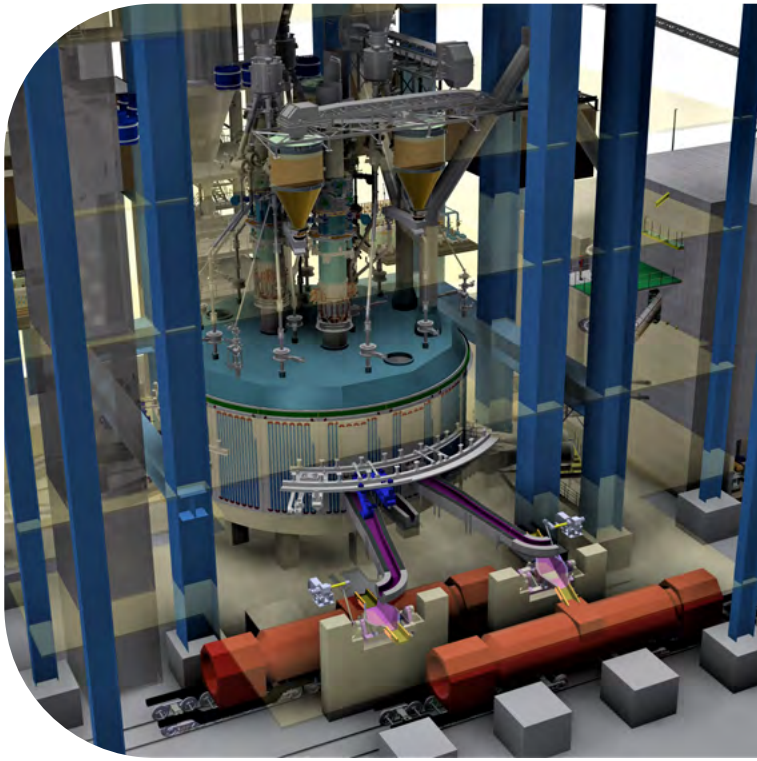
Funded by MADE Competence Center 4.0 with support from the Italian Ministry of Enterprise and Made in Italy (NextGeneration EU funding), it focuses on **developing a Reduced-Order Model (ROM)** for the Consteel® Conveyor. The aim is to simulate the behavior of the Consteel® Conveyor under repeated loads in a very short time, within a specific "design space." This design space represents the set of parameters or variables that define a system, product, or process, and includes all possible combinations of factors influencing the design or process outcome. By enabling these simulations, this project helps **reduce environmental impacts** related to trial-and-error testing, improving the overall sustainability and efficiency of our steelmaking technologies.

LIFE H2Reuse

Funded by EU LIFE-CLIMA, the project focuses on the **sustainable decarbonization** of the bright annealing process in the steel industry by **recovering and reusing hydrogen** (H2) as fuel in H2 burners. Specific goals include reducing CO_2 emissions, preventing H2 waste, lowering energy consumption, demonstrating the new process, and evaluating its cost-effectiveness and business potential. The innovations will be developed and tested in a real environment to assess their technical, environmental, and socio-economic impacts.

Extracting Value from Black Slag

Black slag is a by-product of the EAF steelmaking process. Due to the oxidizing operating mode of the EAF, the slag contains up to 30% FeO. An **Open Slag Bath Furnace** (OSBF) is the perfect solution for processing black slag, and due to the reducing environment of the OSBF, we are currently studying how the slag could be modified, producing **pig iron**, and a **white slag** that can be sold to the cement industry. The technology is complementary to the Direct Reduction Process-EAF (DRP-EAF) processing route and is not a substitute for the primary steelmaking process.



Moreover, three additional projects have been selected for funding, and now the administrative formalization is ongoing with the EU Commission:

- **EU Research funded by RFCS's Big Ticket call PRISMA** – PRISMA is pioneering sustainable practices in the European steel industry, aligning with the Green Deal and Twin Transition objectives. Central to PRISMA is the development of a Unified Environmental Data Model (UEDM), streamlining environmental reporting and analysis across the steel value chain. Leveraging modern digital infrastructure and platforms, PRISMA aims to quantify and mitigate steel production's carbon footprint through, for example, dynamic life cycle assessments (LCAs) and digital product passports (DPPs).
- **EU Research funded by RFCS's Big Ticket call SLAG2BUILD** - Forced air granulation of Ladle Furnace SLAG to enhance its hydraulic properties and allow its re-use as a replacement of Portland Cement in the Building sector.
- **EU Research funded by Horizon Europe - SYRIUS** - The Syrius project aims to integrate a SOEC (Solid Oxide Electrolyzer Cell) to produce green hydrogen within a real Electric Arc Furnace steel plant, advancing circularity in the steelmaking process. The system also incorporates heat and water recovery, as well as steam generation, to enhance efficiency.

Case Study: Tenova with TenarisDalmine and Snam for Hydrogen Testing in Nation First

On July 3, 2024, Italy began its first test of hydrogen use in steel production. The project, led by **Snam**, **TenarisDalmine**, **and Tenova**, aims to explore solutions for decarbonizing hard-to-abate industries by utilizing hydrogen to support the green energy transition. The primary goal is to use hydrogen produced on-site to fuel an H2-ready burner developed by Tenova and installed in a reheating furnace at Tenaris's plant in Dalmine, Bergamo. Over six months, the trial assessed hydrogen's performance in an industrial setting, focusing on the steel sector, while developing safety guidelines and plant management procedures to reduce CO_2 emissions.

TenarisDalmine provided the plant site and reheating furnace, contributing its expertise in steel plant operations. Snam supplied an alkaline electrolysis system to produce hydrogen and support its transportation. Tenova provided the hydrogen-powered burners, while Techint Engineering & Construction managed the installation, risk analysis, and safety compliance.

Snam also introduced its Hydrogen as a Service program, offering leasing options for electrolysis systems to help companies adopt decarbonized hydrogen with reduced risk. This collaboration strengthens Techint Group's expertise in decarbonization technologies for hard-to-abate industries.

Furthermore, in 2024 we have made significant progress on the following projects:

HyTecHeat

In 2022, Tenova was awarded a Horizon Europe project to demonstrate blended green hydrogen and fossil fuel firing in industrial furnaces. The HyTecHeat project aims to **advance hybrid heating technologies by evaluating their effects on steel product quality, refractories, and overall heating processes**. Industrial tests on real burners across three European sites will support the steel sector's transition to hydrogen. Tenova's demonstrator at T-LAB has been selected as a key example for hydrogen use in industrial reheating furnaces.

Initially, Tenova combined modeling and experimental testing to develop industrial burners capable of using hydrogen with conventional fuels in varying ratios. We will also provide an industrial-scale combustion system fueled by green hydrogen to validate its technical feasibility in industrial furnaces.

At T-LAB, existing equipment currently supports full-scale combustion systems using natural gas. Adapting the facility for hydrogen involves two approaches: hydrogen trailers or on-site hydrogen production. Due to capacity limitations of trailers, continuous on-site hydrogen production is preferred. Accordingly, Tenova plans to install a 1.5 MW alkaline electrolyzer, supplied by **De Nora's advanced Dragonfly® system**, **producing green hydrogen from renewable electricity**. The hydrogen is stored in pressurized buffer vessels at 30 bar, then expanded to 0.3 bar before feeding the hydrogen-ready TLX burner prototype (350 kW) installed on the test furnace. This burner operates under real industrial conditions with natural gas/hydrogen blends and oxygen-enriched air.

The combustion system's PLC integrates control and safety signals with the electrolyzer's PLC and hydrogen buffer pressure loop, decoupling hydrogen production from consumption. This design allows the hybrid burner to closely follow furnace thermal demands while overcoming electrolyzer turndown limitations.

Additionally, **the project integrates a comprehensive hydrogen storage system provided by Snam, ensuring safe and efficient handling of hydrogen produced on-site**. This setup is part of a broader HyTecHeat initiative, **funded with €3.3 million by the EU**, which includes multiple demo cases focused on hybrid burners and the progressive transition to 100% hydrogen use in steel reheating. The project targets significant reductions in Scope 1 CO_2 emissions, with potential EU-wide savings of 7.5 to 25 million tons annually.

The demonstrator highlights critical challenges in green hydrogen adoption at industrial sites, including:

- Flexibility of hydrogen production and consumption.
- Integrated control of combustion and electrolyzer systems.
- Efficient storage of surplus green hydrogen for later use.

By encompassing the entire production chain - from green energy generation via photovoltaics to hydrogen production, storage, and furnace operation - HyTecHeat sets a benchmark for safe, efficient, and scalable green hydrogen integration in sustainable steel manufacturing.

ReMFra Project: Recovering Metals and Mineral Fraction from Steelmaking Residues

The **ReMFra project**, part of the Clean Steel Partnership (Horizon Europe), aims to develop and validate an efficient industrial scale pyrometallurgical process for **recovering metals and minerals from various steelmaking residues**. The process consists of two main sub-processes: a plasma reactor for processing coarse residues like scale, sludge, and slag, and the RecoDust process for fine-grain residues. Tenova will develop the technological process for the plasma reactor and size the main equipment involved in the system, and will also participate in the dissemination and exploitation program by sharing research results with potential users. Some of the targets of this project include the development and implementation of highly efficient technologies for recovering metals and mineral fraction from steelmaking residues, enabling the use of obtained slag in higher value applications, and the reduction of CO_2 emissions.

iSlag

iSlag was a project started in 2020 and concluded in 2024, focused on improving the **valorization of slag from the electric steelmaking** route by promoting best practices and enabling industrial symbiosis. Slag, which makes up around 90% of steelmaking byproducts, plays a central role in the steel industry's efforts to align with the EU's circular economy goals, as emphasized by ESTEP and the Clean Steel Partnership.

Efficient slag recycling requires accurate knowledge of its chemical composition. However, steelworks generally prioritize the monitoring of steel quality over slag characterization. This oversight can result in missed opportunities for cost savings or environmental gains. A major barrier is the absence of affordable, real-time systems for analyzing both liquid and solid slag. While slags are often stored and later assessed for reuse, the lack of fast, specific tools, especially when slag from different steel grades is mixed, limits their full valorization potential. The challenge is even greater with uncommon steel grades, where slag properties are not prioritized. iSlag aimed **to address these gaps** by supporting technological advancements that enhance slag management and promote more effective reuse. Tenova played a crucial role in achieving these objectives, by designing and implementing **the diagnostic systems for real-time slag analysis**. In fact, we developed and field tested – at TenarisDalmine's EAF meltshops and **Sidenor Aceros Especiales Basauri** plants – the **Laser Induced Breakdown Spectroscopy (LIBS) system**, a powerful analytical technique used to determine the composition of materials by focusing a high-energy laser pulse onto the surface of a sample. To enhance the accuracy of the LIBS system and process the data collected by it, Tenova also developed a **Machine Learning (ML) workflow**. By using advanced algorithms like **Support Vector Regression (SVR) and Extreme Gradient Boosting Regression (XGBR)**, the ML workflow delivers precise and reliable predictions.

NGEN Project

The **ArcelorMittal Dofasco-led consortium**, in partnership with Tenova, developed a smart technology platform to digitally transform the secondary ladle metallurgy facility at ArcelorMittal Dofasco. The project enhanced the understanding of digitalization in heavy manufacturing, an area that often lags behind other industries. Key insights were gained in process execution for **implementing intelligence, establishing data flow standards, and understanding the impact on the workforce**, crucial as global industrial economies move toward digital transformation.

InSGeP

The InSGeP project, "Investigations of Slags from Next Generation Steel Making Processes," is a European research initiative co-funded by the EU Research Fund for Coal and Steel (RFCS), launched on July 1, 2023. As the steel industry shifts to low-emission processes like direct reduced iron, hot briquetted iron, hydrogen plasma smelting reduction (HPSR), and electrical smelting, understanding byproducts like slag is crucial for maintaining a zero-waste approach.
The project aims to **identify slags produced by future steelmaking processes** and explore their **valorization** within the **existing value chain**. It seeks to define innovative applications for slag to ensure a smooth transition without disrupting industries that rely on it, such as road construction and cement production.

The project involves 13 partners from Austria, Belgium, France, Germany, Italy, and Spain, including 5 steelworks, 6 research organizations, and 2 suppliers. It will use limited quantities of slags from next-generation steel production and conduct laboratory, pilot-scale, and industrial-scale tests. The slags will be evaluated for their chemical, mineral, environmental, and physical properties, with various cooling and granulation methods applied for different applications. Testing will include using slags in road construction, cement production, liming material, and 3D printing.

iSteel-Expert

iSteel-Expert is a remote virtual system that **monitors steelmaking operations 24/7**, analyzes data, and suggests actions to optimize the process. Acting as a human expert, it collects and analyzes furnace data, **improving maintenance and decision-making**. Powered by IoT, it enhances human management by detecting relevant events and identifying their impact. The system integrates a **knowledge-based approach** through an interactive, immersive training tool, helping preserve, transfer, and evolve the company's knowledge base. The main objectives pursued are the preservation and evolution of the company's knowledge, increasing process efficiency, improving equipment condition and maintenance, and reducing environmental impact.

LIFE H2Reuse

In the production of **seamless stainless steel and nickel alloy precision tubes**, bright annealing is crucial for achieving the desired properties. This process, conducted in a vacuum or controlled atmosphere with reactive gases, minimizes surface oxidation, resulting in a brighter surface, a thinner oxide layer, reduced hardness, increased ductility, and fewer internal stresses. It also lowers the risk of corrosion, cracking, and distortion. Bright annealing is performed in a hydrogen (100% H2) atmosphere at temperatures between 1,040°C and 1,200°C, followed by rapid cooling. In continuous plants like LOI's at SMSTI, hydrogen is dispersed after use, leading to wasted resources.

The LIFE H2Reuse project aims to **mitigate the environmental impact** of bright annealing by recovering and reusing wasted hydrogen as fuel in hydrogen burners. This innovative solution, still under development, will be tested in real environments to meet technical, environmental, and socio-economic KPIs.

The process will be applied to Tenova's roller hearth furnace plants, which also use hydrogen-rich atmospheric gas, offering the potential for reduced carbon footprints, resource savings, and cost reductions. The main targets concern emission reduction, energy savings, and resource efficiency.

GHG Emissions:	Resource Efficiency:	Energy Savings:
Baseline: 990.23 tons of CO_2eq/year **Project-End**: 618.34 tons of CO_2eq/year **Savings**: 372.75 tons of CO_2eq/year	**Baseline**: 0 tons/year **Project-End**: 32.65 tons/year of hydrogen recovered	**Baseline**: 1.85 GWh/year **Project-End**: 0.98 GWh/year **Savings**: 870 MWh/year

Mining – 2024 R&D projects

In 2024, our mining business continued fostering a co-creation culture and bottom-up innovation through the **"Innovation Challenge"** open to all TAKRAF and DELKOR employees across all global business units. In consideration of the business's commitment and sustainability statement, the Innovation Challenge focuses on ESG-aligned themes, namely: energy-efficient technologies, environmental impact reduction, circular economy, and low-carbon transition.

An unprecedented 89 applications were received, highlighting the growing internal commitment to developing sustainable and forward-thinking solutions. Winning projects ranged from a **semi-mobile dewatering plant for Dry Stack Tailings (DST) to a modular and reusable platform for process plant design, and a portable pilot plant** to test the performance of DELKOR's BQR MAXGen-equipped Flotation Cells across various applications.

This initiative aims to support the business's sustainability goals and, at the same time, develop a culture of shared value creation where employees are the fuel of the business, and strengthen the alignment between people and vision.

TAKRAF Systems focused its R&D activities on the following internal projects:

- **SmartSpreader:** The aim of this project, which started in 2022 in collaboration with the University of Queensland (UQ) in Australia, is to drastically reduce costs for supplementary dozer operation by automating the continuous dumping process of a spreader.
- **Conveyability Test Rig:** For this project, the phases of development, design and detailed engineering were completed, with the device expected to become operational in 2025. The test rig, which is intended to define the conveyability of bulk materials on conveyor belts, is attracting great interest, particularly in the area of Dry Stack Tailing (DST). Since a DST system significantly reduces water consumption, this initiative directly contributes to our Environmental goals in the ESG framework.

TAKRAF products also focused its R&D activities on two internal projects:

• **Wearing Green:** The project, started in 2021 in collaboration with the Brandenburg Technical University in Germany, and was completed in 2024. It aimed at a specific **Finite Element Analysis (FEA)** model that represents the inhomogeneities of a structure that is built up of several welded layers. Whereas rolled or forged steel can be modelled in FEA by just a few mechanical parameters determined by standard tests, the project showed that for 3D-welded structures, the parameters of the welding process itself must also be considered. By enhancing the accuracy of structural modelling for complex welded components, the project supports material efficiency and contributes to product safety and reliability.

• **Crushing:** The newly developed concept of a **smooth roll sizer** was successfully tested in the field and has the potential to further enhance the application range of TAKRAF's sizers. Under specific conditions, a smooth roll sizer can achieve similar small product sizes within a **smaller footprint, improve energy efficiency, and at a lower CAPEX** compared to other fine crushing or grinding equipment.

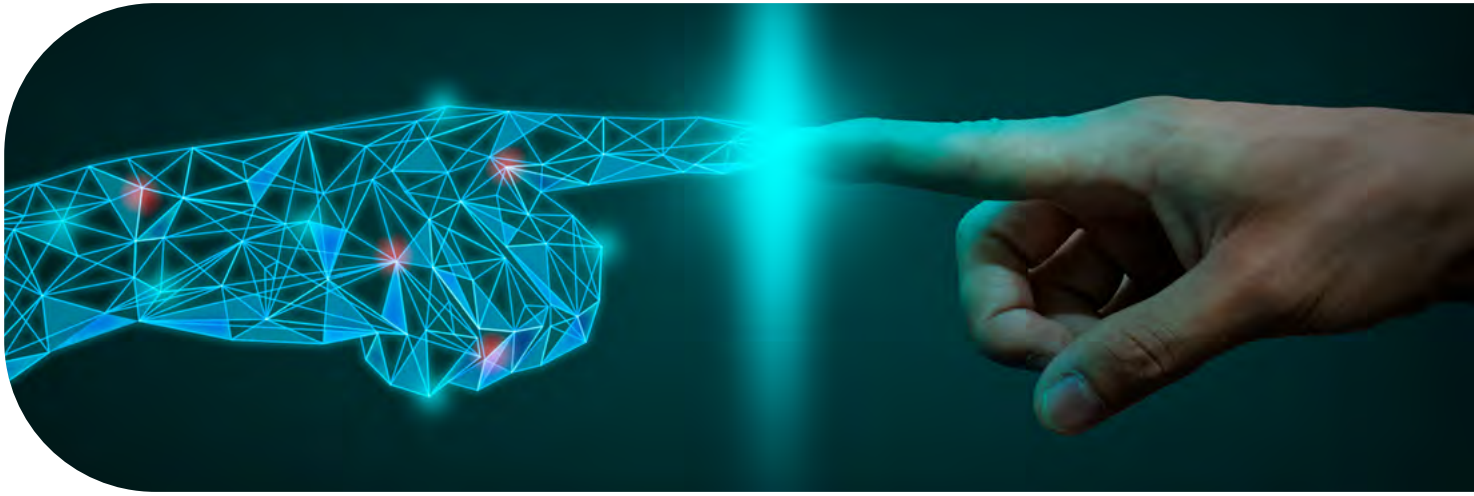
DELKOR continued with the great advances it made in the development of high-torque thickener drives, with this project now nearing completion. The project, which was launched in 2023, aims to support the industry in tackling one of the most pressing environmental challenges: **sustainable management of large tailings facilities and water conservation**. A testament to the good work carried out by DELKOR and the brand's R&D work was the recent award, by Codelco, the world's largest producer of copper, to supply seven DELKOR high-density thickeners to the world's largest thickened tailings project.

Furthermore, two internal projects were also launched:
• **Coarse Particle Recovery:** A research program was initiated to develop a method for **recovering valuable coarse particles** from diverse mineral slurries. Coarse particle recovery is currently receiving a lot of attention due to its advantage of rejecting unwanted minerals from the process circuit at an early stage. In doing so, the energy required to process material is lowered together with lowering the hydraulic capacities of downstream equipment, which results in further **energy efficiencies, decreased environmental impact, and improved sustainability**. The project has now entered the literature review stage, which will serve as a firm foundation for the subsequent stages of new product development.

• **Classification:** A classification project to return to basics and grasp the working principles of a specific type of particle classifier, to prepare for the inclusion of this equipment into the DELKOR product range..

Digital Transformation

Digital technologies have the potential to **revolutionize the metals and mining industries**. This is why Tenova Group not only integrates digital solutions into many of its technologies but has also created a digital strategy and team to stay ahead of the curve. Our strategy places customer value and sustainability at its center, helping us stay focused in this rapidly evolving space. It leverages technologies such as AI, machine learning, and data analytics to increase efficiency and reduce environmental impacts for our clients.



Adopting a Digital Mindset

To continue to optimize productivity through our new hybrid working model, we encourage our employees to adopt a **digital mindset**, seeking digital solutions to solve problems across categories from smart working to Industry 4.0 integration. The ambition of our digital mindset mentality is to **promote a deep cultural change** wherein our teams understand and harness the pioneering modern technologies that could revolutionize our industries.

Some of our activities to advance a digital mindset have been around the deployment of specific tools and technologies to educate employees and raise their awareness about digitalization processes. We have several technological systems in place to support remote collaboration in Tenova and with our business partners as well, including the **Project Collaboration Portal and the Supplier Portal**, all accessible on multiple, user-friendly devices.

Our project management platform provides an accessible central repository of all project information, such as relevant documents and procurement plans, which set up Tenova's teams for success. For the near future, we are planning to **enhance the platform with AI features** to reduce repetitive processes, therefore increasing efficiency.

We value the introduction of new tools and support our employees with **additional training** to familiarize them with these innovations, enhancing their connection with one another, while also emphasizing the importance of protecting sensitive information through high cybersecurity awareness and a thorough understanding of Tenova's procedures and guidelines. We have also successfully realized the **first pilot project using GenAI** (Generative Artificial Intelligence). The adoption of this transformative new technology will enable our employees to optimize their daily work and to focus on activities with real added value.

Support Client Engagement

In addition to the digital features embedded in our products, we want to provide the best possible customer service, so we have created several systems to help employees communicate effectively with customers. Customers have access to our **Tenova Digital Portal** where they can request support for specific products and order spare parts. The portal is regularly updated with new features. Among these services, the **ESPC (Electronic Spare Parts Catalog**) allows clients to browse and request spare parts efficiently through an interactive digital catalog. For Pomini customers, the **IPA (Inspektor Performance Analyzer)** service provides advanced data analysis derived from the Inspektor system. The **T-LAB Experiments section** offers access management and reporting functionalities for experiments conducted within the T-Lab research environment. Furthermore, the **Product Portal section** gives customers the ability to consult user and maintenance manuals for selected Tenova products. Lastly, **the Slag Granulation tool** allows users to perform detailed analyses of slag granulation potential based on its chemical composition, supporting a more informed and sustainable decision process.

Some of the proprietary digital tools we have developed include:

- **Tenova IIoT Platform** is the IIoT platform developed in partnership with Microsoft, which facilitates communication with our customers. Its purpose is to **retrieve plant data and analyze** it to develop new services and **AI applications** which help customers **use and maintain their equipment**.

- **Tenova EDGE** is the **field gateway** developed by Tenova, which allows the customer's plant to connect in a standard and secure way to our IIoT Platform. The EDGE device also has the capability to host and automatically **manage the update of developed machine learning** models and AI applications.

- **Tenova adVISOR** is a **virtual assistant** that provides suggestions on **product maintenance and operation**. It can be used on a mobile device and provides real-time updates. The tool's remote assistance feature, available on mobile and wearable devices, offers support to field operators.

- **Tenova Electronic Spare Parts Catalog** enables customers to easily **select spare parts** with fewer mistakes by connecting to the customer's portfolio database, accurately identifying the required part.

In addition to projects related to the digital transformation of processes, Tenova strives to develop digital solutions that reduce the environmental impact of our customers' plants and launch these solutions on the market. Notable launches have included the inauguration of **TenovaLAB in Castellanza**, established to conduct experiments and R&D in burner development, facilitating the completion of our Smart Burner platform.

Additionally, the adoption of the Tenova IIoT platform enables the application of our proprietary mathematical models, including those used for the thermal simulation of reheating furnaces. This innovative use of models also allows us to provide new services to our customers: for instance, the thermal model of reheating furnaces could be used by our customers as a simulator to gain insights on possible improvements in equipment operation.

One of the new features introduced to the Tenova IIoT Platform is the **Emission Impact Dashboard**. This tool is designed to track the emissions produced by the cloud services utilized by the platform. Consequently, it enables the monitoring and demonstration of the environmental impact of Tenova's products and technologies across the entire value chain, extending beyond the equipment installed at customer sites.