R&I Brief

MANUFACTURING FOR CLEAN ENERGY TRANSITION

EFFRA

EUROPEAN FACTORIES OF THE FUTURE RESEARCH ASSOCIATION

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1 Executive Summary

Europe's energy system is undergoing a decisive transformation. To meet the climate neutrality targets of 2030 and 2050, **the continent must accelerate electrification, cut emissions, and expand the deployment of clean energy technologies.** Through the decarbonization of energy-dependent activities, Europe's landscape will be transformed in terms of sustainability. Furthermore, a growth in competitiveness, resilience, and sovereignty is expected with that shift.

On the one hand, the adoption of **clean technologies** will drive the energy transition. The systems, components and products that make possible clean energy generation, together with the equipment to fabricate them are essential for that transition. Manufacturing is therefore at the backbone of clean technologies and represents a unique opportunity for Europe to gain leadership in this emerging sector. However, despite the initial technological advantage, European manufacturers are not currently ahead of the clean technologies market.

On the other hand, the manufacturing activity is on its own a relevant actor in energy consumption, with a growing impact either directly through consumption of its processes or indirectly through all the IT products and services linked to its activity.

Definitely, manufacturing needs a redefinition in terms of its energy efficiency. For that purpose, digitalization, smart grids, or AI techniques together with the integration of clean technologies and the development of their equipment show the potential to transform the sector and still ensure profit.

The outlined areas of interest are aligned with the priorities and guidelines from the **Clean Industrial Deal** and the **Net Zero Industrial Act** (NZIA) prepared by the European Commission (EC). Based on this, the EFFRA WG on Manufacturing for the Clean Energy Transition aims through this white paper to align advanced manufacturing research and innovation with Europe's clean energy ambitions by identifying gaps, fostering collaboration and shaping a coherent industrial strategy.

As a first step, the present state and rationale of the scenario of manufacturing for the clean energy transition have been set. Several energy generation technologies with different degrees of maturity and global market share fall under the clean technologies umbrella. For the most mature ones, one step forward in competitivity is mandatory to keep or even gain for the first time a relevant market position.

This could be achieved through **investment in innovative technology variants or remanufacturing solutions** to create a specific value added for the European products.

Regarding the generation technologies which show lower TRLs, Europe's initial technology leadership is threatened by rapid development of competitors through massive investments. A rapid upscale of the technologies is in this case crucial. The fragmented nature of the future cleantech market, both in terms of technologies and project types, is an important feature to keep in mind for the development and deployment of these technologies.

In a future with accelerated demand growth and a larger variety in energy sources, the manufacturing sector is also likely to be affected by an energy market featuring higher dynamics. Therefore, **reducing the footprint of industrial energy usage will go in the direction of growing both in sustainability and competitiveness**. For that purpose, solutions rooted on digitalization and cleantechs, expected to play a key role.

The transition to a clean, resilient, sovereign and competitive energy system in Europe presents a complex set of challenges that span scientific, technical, economic, and societal dimensions. These challenges must be addressed urgently to ensure that manufacturing can effectively support both the manufacturing of clean technologies and the transformation of industrial energy consumption. The identified challenges to address have been grouped according to a short and medium and long-term perspective.

In the short term, the mastering of new manufacturing processes and the development of specific assets for them, the development of advanced automation solutions and the deployment and exploitation of mature digital and data infrastructures are key for upscaling, productivity gain, cost reduction or optimal usage of the energy. Remanufacturability must be addressed for both new and more mature products as an enabler of sustainability, cost efficiency, resilience and sovereignty. Finally, standardization and personnel skilling will promote uptake of the new technologies and will alleviate problems associated to the workforce aging and shortage.

In the medium and long-term, achieving a net-zero manufacturing sector will require from the redesign of the manufacturing systems, the factory and the entire value chain for an optimal usage of energy, the deployment of cleantechs as the main power source and the assurance of a cross-sectorial integration of the new manufacturing reality. The involvement of local communities and stakeholders and alignment of both national and EU-level initiatives will be key for successful innovation and a definitive joint transformation of the manufacturing and energy sectors.

The definition of priorities for research and recommendations for action is necessary as a continuation of the previous analysis. Concerning the priorities for research, in the short term the generic lines outlined so far include productivity enhancement, industrial scale-up, digital infrastructure, energy efficiency & net-zero factories, standards and skills. For the medium- and long-term priorities, modular and more integrated system concepts, the promotion of regional ecosystems and the creation of mindset & skill development programs have been outlined. In terms of recommendations, policymakers, industry, the research and scientific community and regions & clusters are the identified target audiences. Specific recommendations will be provided for each of these groups.

2 Introduction

Europe's energy system is undergoing a decisive transformation. To meet the climate neutrality targets of 2030 and 2050, the continent must accelerate electrification, cut emissions, and expand the deployment of clean energy technologies. This shift depends not only on advances in energy generation but also on the strength of the manufacturing systems that design, produce, and deliver underlying technologies. A resilient, competitive and adaptive manufacturing base is therefore essential, both to supply clean energy at scale and to reduce the energy footprint of industrial operations themselves.

The current global landscape exposes several vulnerabilities. Although the **EU** generates about **one-fifth of the world's clean energy patents,** when it comes to manufacturing clean technology, EU is behind. For example, it manufactures less than fifteen per cent of solar photovoltaic panels; in batteries, Europe accounts for less than 10 to 15 per cent of global cell production capacity compared with more than 80 per cent for China. High labour costs, fragmented supply chains, and limited automation contribute to this gap. At the same time, Europe remains fully dependent on imports of critical raw materials. This reliance on external suppliers creates strategic risks in a volatile geopolitical environment.

Industry is one of the major energy consumers, responsible for roughly one quarter of Europe's final energy demand, when both discrete manufacturing and process industry are included. Digitalisation, smart grids, AI-driven optimisation, and renewable integration could together save European industry around **€50 billion** annually while lowering emissions. Yet significant amounts of waste heat from industrial processes are still unused. Capturing this resource through recovery systems and deploying high-efficiency heat pumps, linked to district heating and cooling networks, could supply up to ten per cent of the EU's total heating demand. Combining industrial waste heat recovery with advanced thermal networks would not only reduce fossil fuel dependency but also lower operating costs and enhance energy resilience.

Through the Clean Industrial Deal, the European Commission (EC) has outlined the priority in transitioning towards a decarbonized yet competitive and resilient industry. Stemming from it, the Net-Zero Industry Act (NZIA) promotes a scaling up of the manufacturing capacity of technologies that will support the clean transition.

The NZIA supports in particular 8 strategic net-zero technologies:

- solar photovoltaic and solar thermal
- onshore wind and offshore renewables
- batteries and storage
- heat pumps and geothermal energy
- electrolysers and fuel cells
- sustainable biogas/biomethane
- carbon capture and storage (CCS)
- grid technologies.

Many of them have their interests represented at the European level in the form of a joint undertaking, partnership, or similar initiative. Other net-zero technologies, equally being supported though to a different degree, are sustainable alternative fuels, advanced technologies for nuclear processes, small modular reactors, and best-in-class fuels. Nevertheless, **most clean energy technologies continue to face obstacles in moving from prototypes to large-scale production.** The inability to scale remains one of the most pressing barriers to competitiveness.

The EFFRA Working Group on Manufacturing for Clean Energy Transition was created to respond to these systemic issues. Its role is to align advanced manufacturing research and innovation with Europe's clean energy ambitions by identifying gaps, fostering collaboration and shaping a coherent industrial strategy.

The group works across two complementary dimensions:

- manufacturing for clean technologies,
- energy for manufacturing, targeting the decarbonisation and digitalisation of industrial processes.

Both dimensions are reinforced by advanced manufacturing technologies, digital infrastructure, data-driven decision-making and workforce skills that enable intelligent, adaptive and sustainable production.

The group calls for coordinated action at the European level to accelerate the development and deployment of advanced manufacturing solutions. Priorities include strengthening the maturity of the involved manufacturing processes and the supply chain resilience, investing in automation and standardisation, developing devoted equipment, embedding digital intelligence into factories, and building a skilled workforce capable of supporting green and digital transitions. Alignment between national and EU policies is also essential to overcome fragmentation and ensure a unified industrial response.

Manufacturing for clean energy transition is about more than producing technologies: it is central to Europe's climate strategy, its economic sovereignty, and its global competitiveness.

A robust and future-ready manufacturing ecosystem, able to harness opportunities from solar and hydrogen to waste heat and district energy, will be the foundation for a successful energy transition and Europe's long-term industrial leadership.

3 Present State and Rationale

Europe's energy sector is undergoing a rapid and complex transformation, driven by the twin imperatives of climate neutrality and industrial competitiveness. This transformation is deeply intertwined with manufacturing, which must evolve to support both the manufacturing of clean energy technologies and the energy needs of industrial operations themselves.

The energy transition encompasses a wide array of technologies, each with distinct maturity levels and manufacturing requirements. These include solar panels, batteries, wind farms, hydrogen systems, heat pumps, carbon capture and storage (CCS), carbon capture and utilization (CCU), nuclear, and oil & gas. Some technologies, such as solar and onshore wind, are relatively mature and already deployed at scale. Others like offshore wind, hydrogen, CCS, and CCU—are still in early stages of market development and require significant innovation in manufacturing processes, assets and systems, in infrastructure, and in supply chains. Europe's manufacturing capabilities are strong in research and prototyping but face challenges in scaling up production. High labor costs, fragmented supply chains, and limited automation contribute to lower productivity compared to global leaders, particularly in photovoltaics and battery manufacturing. There is an urgent need to strengthen the European manufacturing ecosystem—from raw material sourcing to end-of-life decommissioning—and to develop resilient, flexible, and adaptive production systems.
The working group adopts a dual perspective to address the full scope of manufacturing needs.
From the side of manufacturing equipment for clean technologies, the landscape varies depending on the technology maturity level.

For the most **mature generation technologies** (eg. PVs, wind energy, batteries) the lack of competitiveness represents a major threat for European manufacturers. Higher labor costs justify the problem only partially.

Other economies have been more agile in gaining high productivity both through massive investments while the technologies were still emerging and heavy automation so now European manufacturers' efforts must be oriented to retain, regain, or even gain for the first time the market leadership.

Nevertheless, **new opportunities are arising with alternative technologies** better aligned with the current market demands of efficiency, sustainability, and resilience in both energy generation and equipment manufacturing. Solutions for batteries, either reducing or skipping the use of critical raw materials, extension of generation overseas through offshore windfarms, and floating PVs are some examples in this sense.

Also, the adoption of **remanufacturing practices** is expected to make a significant contribution to the improvement of European manufacturers' competitiveness.

Regarding less mature technologies such as **hydrogen**, the initial technological advantage should not be overestimated, and lessons from the past must be learnt. Massive and early investment in technologies and automation is starting to make products from competing countries flourish, and their quality is rising quickly. For European manufacturers, the upscaling of equipment manufacturing remains their workhorse today. Tailored manufacturing to each project or application, complex and long value chains, and manufacturing processes that are not robust enough yet are the main difficulties that manufacturers must face today.

Another key aspect to consider is the shift of paradigm in energy generation with the adoption of clean technologies. Large, centralized manufacturing sites will transform into more distributed networks where large, medium, and small generation capacities are combined, involving different generation technologies.

This new paradigm represents for the equipment manufacturers a more fragmented market of systems not only for generation but also for the transportation and storage of energy.

- **On the other hand, European manufacturing itself can be a significant energy consumer.**

R&D&I efforts are increasingly focused on reducing the footprint of industrial energy use.

- Integration of net-zero technologies and renewable energy, sensor networks connected to AI-driven energy management systems for real-time optimization, smart production planning that incorporates energy efficiency as a core metric, carbon capture and storage (CCS) and hydrogen storage solutions to mitigate emissions and enhance energy flexibility, carbon capture and utilization (CCU) technologies that transform CO_2 into valuable materials and contribute to circularity are some of the considered solutions.

These innovations are reshaping manufacturing systems, requiring new infrastructure, digital capabilities, and regulatory frameworks. Workforce development remains a key enabler, ensuring that operators, engineers, and managers can adapt to energy-efficient practices and emerging technologies. Energy consumption regulations across Europe are evolving, but inconsistencies persist. A unified approach is needed to support industrial decarbonization while maintaining competitiveness.

The intersection of energy and manufacturing is central to Europe's strategic autonomy, sustainability, and global competitiveness. A resilient and strong energy supply is key to economic development.

Furthermore, manufacturing for clean technologies represents not only a huge new market segment but also supports climate goals, reduces dependency on external suppliers, and creates high-value jobs. At the same time, energy-efficient manufacturing enhances productivity, lowers operational costs, and contributes to sustainability.

Globally, **competition** is intensifying, particularly **from regions with lower labor costs**, **integrated supply chains, and secure access to raw materials.** This EFFRA Working Group on Manufacturing Needs for the Energy Sector aims to identify R&D&I priorities, bridging gaps, and aligning stakeholders toward a cohesive and forward-looking strategy.

4 Challenges and Needs

The transition to a clean, resilient, and competitive energy system in Europe presents a complex set of challenges that span scientific, technical, economic, and societal dimensions. These challenges must be addressed urgently to ensure that manufacturing can effectively support both the manufacturing of clean technologies and the transformation of industrial energy consumption.

Europe's clean energy manufacturing sector faces a range of short-term and long-term challenges that must be addressed to ensure competitiveness, scalability, and sustainability.

In the short term, **high production costs and low levels of automation** in production continue to hinder the industrialization of technologies such as **offshore wind, hydrogen systems, batteries, and solar panels.** European manufacturers struggle with high labor costs and limited automation, which reduce their global competitiveness.

On the other side, clean energy technologies, like **offshore wind turbines, hydrogen electrolysers, and carbon capture and utilization (CCU) technologies still require significant research**, development, and innovation to transition from lab-scale prototypes to industrial-scale production.

Bridging this gap is a critical need. Furthermore, many European factories lack the digital maturity and data infrastructure needed to support AI-driven optimization, predictive maintenance, and lifecycle management, creating a barrier to intelligent and adaptive manufacturing.

Another pressing issue is the **lack of standardization and interoperability across components, systems, and data architecture.** Without **common standards**, manufacturing new products for clean or seamless integration of the clean technologies into manufacturing environments becomes difficult, slowing innovation and deployment.

At the same time, the sector is grappling with skill shortages and workforce gaps. The energy transition demands very **interdisciplinary expertise** in:

- **automation**
- **artificial intelligence**
- **lifecycle design,**
- **energy systems integration**.

Accelerating workforce development through targeted education, reskilling programs, and cross-sector collaboration is essential.

From a product-oriented vision, manufacturing for the more mature clean technologies demands a significant leap forward in productivity to keep, regain, or gain the European manufacturers' positioning.

Higher levels of automation and intelligence at all factory levels are needed.

It is equally important to ensure the **highest quality at minimum waste,** to introduce new designs with longer durability and higher performance or to develop new business models which deploy conventional manufacturing, repairing and remanufacturing under different families of products.

At the same time, products with lower maturity levels that have demonstrated their potential must be scaled up from now on at a high pace to ensure Europe's positioning in the emerging segments. Upscaling demands an important effort in mastering the manufacturing processes and design of both equipment and systems.

For the success of a competitive upscaling, the solutions must show not only robustness and efficiency, but also the flexibility to address a diversified demand depending on the specific application.

Automation, digitalization, and standardization are expected to play here as well a key role in accelerating upscaling. Special attention should be paid to those products particularly favourable to the European manufacturing ecosystem, thanks to resilient material supply chains or design for remanufacturing and recyclability.

Looking ahead, long-term challenges revolve around transforming industrial processes to be energy-efficient and climate-neutral. **Achieving net-zero manufacturing requires a fundamental redesign of manufacturing systems to minimize energy use, integrate renewable sources, and embed energy efficiency into every layer of operations.** The manufacturing activity also has an impact on the raw materials extraction and processing, and the lifecycle of the fabricated products (Scopes 1&3, respectively, according to the GHG protocol).

Thus, equally important is the design of products with the entire lifecycle in mind, from manufacturing and assembly to reuse and recycling. Embracing design-for-X principles will help reduce costs, improve quality, and enable circularity. Strengthening supply chain resilience and developing a robust energy manufacturing ecosystem across Europe is vital for the same reason

- This includes *securing access to critical raw materials, localizing manufacturing sites, and building networks that can withstand geopolitical and economic shocks.* Moreover, the energy transition extends beyond the energy sector itself, impacting transport, construction, ICT, and more verticals. Manufacturing systems must therefore support cross-sector integration, enabling shared infrastructure, collaborative innovation, and community-level engagement.

Involving local communities and stakeholders is key to ensuring social acceptance and long-term sustainability.

Finally, **fragmented manufacturing policies across Europe create inefficiencies** that must be addressed through a coordinated industrial strategy.

Aligning national and EU-level initiatives will support innovation, enhance strategic autonomy, and ensure that manufacturing for the clean energy transition contributes meaningfully to Europe's competitiveness on the global stage.

Overall, the manufacturing sector must stay attentive to the clean technologies sector to identify well in advance changes in its evolution and adapt to them.

Progression towards a decarbonised industrial activity and the capability of digital technologies an control their energy requirements can have a significant impact on the global energy demand and their generation systems.

The challenges outlined above are interconnected and urgent. Addressing them requires coordinated action across research institutions, industry, policymakers, and civil society. The implications extend beyond the energy sector, impacting climate policy, economic resilience, digital transformation, and social equity.

The EFFRA Working Group on Manufacturing Needs for the Energy Sector serves as a platform to identify these challenges, prioritize solutions, and foster collaboration. By tackling both short-term bottlenecks and long-term systemic issues, the group aims to accelerate Europe's energy transition and build a manufacturing ecosystem that is sustainable, competitive, and future-ready.

5 Research & Innovation Priorities and Recommendations

Europe's manufacturing sector must evolve to meet the demands of the energy transition. The clean technology sector is a huge potential market for European manufacturing.

This section outlines short- and long-term research and innovation priorities and recommendations that support the development of European manufacturing for the clean transition. These priorities are aligned with EU policy frameworks such as:

- the Net-Zero Industry Act (NZIA)
- the Green Deal Industrial Plan,
- the Critical Raw Materials Act (CRMA)
- the Ecodesign for Sustainable Products Regulation (ESPR)
- the Energy Efficiency Directive (EED).

They also build on **Horizon Europe** partnerships, including Made in Europe, Clean Hydrogen, Batt4EU, Processes4Planet, Clean Steel, Built4People, Clean Aviation, and Europe's Rail.

Guiding Principles for the R&I Priorities

To ensure effective and impactful innovation, the following principles should guide the R&I agenda:

- Accelerate industrialisation through scalable manufacturing systems, leveraging NZIA instruments such as strategic project status and acceleration valleys.
- Enhance productivity and competitiveness by investing in automation and zero-defect manufacturing approaches.
- Promote circularity and material security by embedding ESPR and CRMA requirements into product and process design.
- Strengthen workforce capabilities through coordinated skills development, supported by NZIA academies and EU partnerships.
- Align with emerging standards, particularly in AI, to ensure conformity and interoperability across manufacturing systems.

R&I priorities can be built upon the following cross-cutting Enablers and Infrastructure Needs:

- Establish a network of open pilot lines for key clean technologies, federated under Made in Europe and equipped with traceability services, providing a foundation for industrial scale-up and innovation.
- Deploy Manufacturing Data Space nodes using DSSC Blueprint components to support data sharing and optimisation.
- Fund pre-normative research to accelerate harmonised standards development through CEN-CENELEC.
- Support skills development through NZIA academies and partnership-based curricula in automation, digitalisation, and circular manufacturing.

Short-Term R&I Priorities

- **Productivity:** enhancing manufacturing output and efficiency through automation, advanced process control, and zero-defect production systems.
- **Industrial scaling up:** rapidly transitioning clean technologies from pilot to mass production by deploying modular, flexible and adaptive manufacturing systems.

- **Digital infrastructure:** developing data spaces, digital twins, AI-driven platforms and secure connectivity to enable real-time optimization and interoperability across manufacturing systems.
- **Energy efficiency and net-zero factories:** implementing renewable integration, energy monitoring and optimization and waste heat recovery technologies to reduce the energy consumption of manufacturing system.
- **Standards:** Establishing harmonized technical and sustainability standards to accelerate market adoption and ensure conformity across supply chains.
- **Skills – training (from identifying skills needs to reskilling-upskilling):** building a cleantech-ready workforce through targeted training programs that address emerging digital and energy-focused competencies.

Medium- and Long-Term R&I Priorities

- **Modular and adaptive manufacturing:** developing highly flexible and modular manufacturing systems that can rapidly adapt to accommodate evolving market changes, clean technologies and product lifecycles.
- Integrated systems – from materials to manufacturing to energy use: Creating and end-to-end integrated systems that optimize material sourcing, product manufacturing and energy consumption holistically to improve sustainability and resilience.
- **Industrial clusters development**: establishing regional ecosystems and valleys that co-locate manufacturers, suppliers, R&D centers, and energy-efficient infrastructure to enable collaborative innovation, shared resources and accelerated deployment.
- **Mindset and skill development programs**: Fostering long-term workforce readiness through continuous and higher education initiatives that support digitalisation, sustainability and innovation-driven manufacturing.

Recommendations

For Policymakers

- More joint-partnership calls combining Made in Europe with clean technology-related partnerships (Battery4EU, Hydrogen Europe…)
- Finalise NZIA secondary legislation and apply it consistently across Member States.
- Operationalise ESPR/DPP and CRMA benchmarks with clear guidance and investment support.
- Implement EED obligations with support for industrial energy management and district heating planning.
- Use public procurement to create stable demand for sustainable EU-made products.

For Industry

- Invest in modular, data-driven factories with in-line analytics.
- Participate in Manufacturing Data Spaces to enable multi-party optimisation.
- Embed circularity and material strategies into product and process design.
- Collaborate through EU partnerships to accelerate innovation and workforce development.

For RTOs and Universities

- Bridge TRL gaps through joint pilot lines and open datasets.
- Conduct pre-normative research to support standards and circularity metrics.
- Develop micro-credentials and training aligned with NZIA academies.
- Structuring R&D objectives in line with use-case technology requirements at different TRL levels, planned in parallel, will ensure a coherent and efficient innovation pathway.

For Regions and Clusters

- Create vibrant ecosystems that enable collaboration and accelerate deployment.
- Establish Net-Zero Acceleration Valleys that co-locate manufacturers, suppliers, RTOs, and training centres.
- Align permitting processes with NZIA single contact points and support SMEs through local data infrastructure.

Europe's ability to lead the clean energy transition depends on decisive action to scale manufacturing capabilities, integrate sustainability and digitalisation, and build a skilled workforce. These priorities and recommendations provide a roadmap for transforming Europe's manufacturing landscape into a competitive, resilient, and future-ready ecosystem.

6 Conclusions

Europe is entering a critical decade in which manufacturing will determine its ability to lead the global clean energy transition, safeguard strategic autonomy, and generate high-value industrial growth. This white paper has shown that clean energy technologies are not only essential to achieving climate neutrality but also represent a golden opportunity to revitalise Europe's industrial base, create resilient value chains, and secure long-term competitiveness. Despite Europe's strong record in research, engineering excellence, and regulatory leadership, these advantages will only translate into industrial leadership if they are matched by rapid and coordinated action to scale manufacturing capabilities and reduce dependencies on external suppliers.

The manufacturing challenges faced by the energy sector are multidimensional. They require innovations in automation, digitalisation, standardisation, and circularity, but also new skills, new investments, and a more coherent policy framework. The window to act is narrowing: global competitors are rapidly scaling production, capturing market share, and securing access to critical raw materials. Europe must now shift from ambition to implementation, and from prototypes to full commercial deployment.

The conclusions of this working group underline the central message that Europe's energy transition will succeed or fail in the factory. Manufacturing is not an auxiliary activity; it is the foundation upon which clean energy deployment, economic resilience, and social prosperity will be built. Accelerating the industrialisation of solar, hydrogen, batteries, heat pumps, electrolysers, and grid technologies will generate significant opportunities for SMEs, large companies, and entire regional ecosystems. Equally, embedding energy efficiency, waste heat recovery, digital optimisation, and circular design into industrial operations will reduce costs, enhance productivity, and support Europe's objective of climate-neutral manufacturing.

Europe has the knowledge, the capacity, and the market power to become the global centre for clean energy manufacturing. What is needed now is decisive action to scale this capacity, accelerate deployment, and secure strategic autonomy in the technologies that will shape our future.

The call to action is clear: Europe must act with urgency, coordination, and ambition to transform its manufacturing landscape and lead the clean industrial revolution. The choices made in the next few years will determine whether Europe is merely a consumer of clean technologies—or the world leader in producing them.

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Chaired by: **Fabio Sgarbossa, NTNU - Mariluz Penalva Oscoz, Tecnalia - Taha Arbaoui Insa lyon**

Contact: Info@effra.eu