Long term impacts of liquid electronics

Redefining liquid electronics through data and collective intelligence

Deep technology breakthrough poised to reshape the foundations of electronics, robotics and sustainable innovation

PNO INNOVATION

Executive summary

Liquid electronics represent a radical shift in how devices can sense, compute, heal, and adapt. Emerging from EU-funded initiatives, these deep technologies blend intelligent materials, energy harvesting, and adaptive computing within a liquid, self-healing, and environmentally conscious platforms.

While traditional electronics rely on rigid architectures and energy-intensive production, liquid-state systems enable a new generation of flexible, resilient, and potentially circular devices—capable of operating in extreme environments, interacting safely with biological systems, and reducing dependency on scarce raw materials.
Yet, their development must be guided by sustainability, safety, responsibility, and fairness.

> The organisations that integrate innovation with responsible governance will define the future of liquid intelligence.

The landscape in transition: from rigid chips to adaptive matter

The global shift toward materials that compute, sense, and self-organise reflects a broader transformation in electronics. Liquid-based devices—combining **colloidal cybernetic systems (CCS), liquid memory, in-memory computing, soft energy harvesters**—demonstrate how intelligence can be embedded into reconfigurable, fault-tolerant systems.
These innovations address structural limitations of traditional silicon electronics:

- **High energy demand**
- **Dependence on critical raw materials**
- **Rigid architectures vulnerable to damage**
- **Limited interoperability with biological environments**

Liquid electronics open pathways to more sustainable, low-energy, circular, and versatile systems [1].

From scientific insight to emerging applications

Successful translation of deep tech research into real-world potential is possible by unifying materials science, cybernetics, and responsible innovation [2]. This approach integrates four dimensions—mirroring the strategic alignment seen in leading European initiatives:

Vision and Design

Embedding sustainability, safety, and fairness into early-stage material and system architecture.

Responsible Development

Ensuring REACH-compliant nanomaterial production, ethical sourcing, and circular end-of-life strategies.

System Integration

Advancing liquid processors, self-healing polymer skins, and thermo galvanic energy harvesters into functional cybernetic modules.

Governance & Foresight

Applying Responsible Research and Innovation (RRI), life cycle thinking, and stakeholder-driven recommendations.

When these dimensions align, organisations achieve faster adoption, measurable efficiency, and improved outcomes—turning foresight into execution.

Innovation scales when materials, intelligence, and sustainability converge.

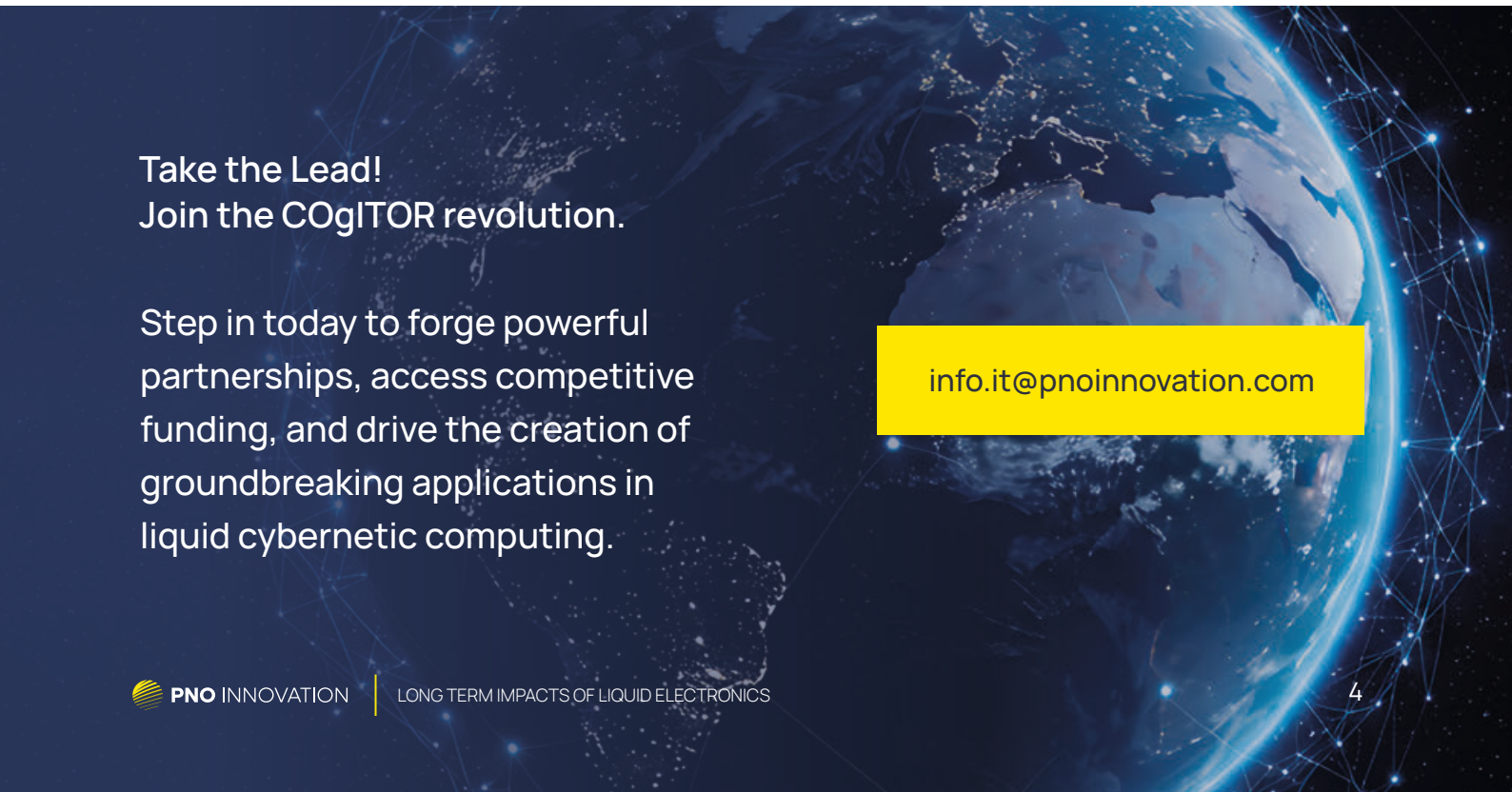
Case examples in action

Across Europe, coordinated innovation is translating research into real-world impact.

The COgITOR initiative exemplifies this shift. By combining data mapping, stakeholder engagement, and policy integration, it has supported the systemic development of liquid electronics. A survey targeted to stakeholders highlighted fields where liquid electronics may become transformative:

- **Robotics & Automation.** Self-healing actuators, adaptive sensors, and fluidic intelligence for harsh or remote environments.
- **Healthcare & Implants.** Biocompatible, flexible, and low-energy systems for monitoring, prosthetics, and future biohybrid interfaces.
- **Energy Harvesting & Storage.** Soft thermos galvanic cells and adaptive materials for sustainable power in resource-constrained settings.
- **Environmental & Space Exploration.** Fault-tolerant systems capable of operating where traditional electronics fail—pressure, radiation, or temperature extremes.
- **Future Computing Architectures.** Liquid memory and in-memory computation enabling low-power, analog, reconfigurable information processing.

When collaboration meets insight, innovation scales from pilot to system-level impact.



Take the Lead! Join the COgITOR revolution.

Step in today to forge powerful partnerships, access competitive funding, and drive the creation of groundbreaking applications in liquid cybernetic computing.

info.it@pnoinnovation.com

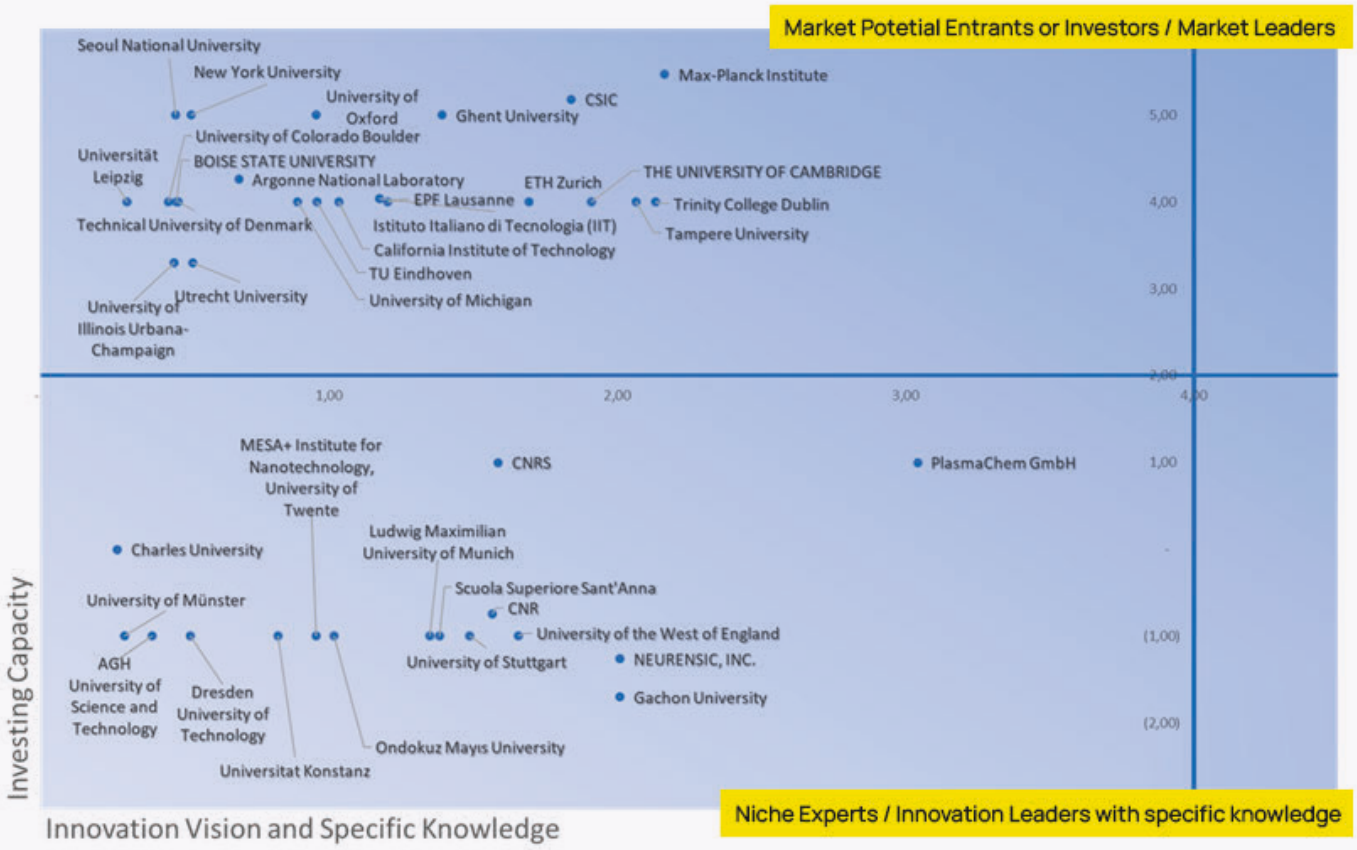
Mapping europe's innovation network

Using the Wheesbee analytics platform, Europe's liquid electronics innovation ecosystem was analysed to explore how funding, research, and partnerships interact. Insights from initiatives such as COgITOR show how interconnected ecosystems produce the strongest systemic outcomes.

By visualising the distribution of expertise, partnerships, and investment flows, this mapping helps policymakers and investors identify high-impact collaboration zones, anticipate emerging hubs, and target resources for maximum return.

Institutions such as Istituto Italiano di Tecnologia (IIT) has resulted as an organization "high potential entrant or investor", thus with medium/high investing capacity. Others as PlasmaChem GmbH has resulted as a "niche expert" with high innovation vision and specific knowledge in the field.

> Collaboration remains Europe's greatest advantage in shaping the global liquid electronics landscape.



PNO Innovation's elaboration.

Regulatory opportunity: shaping the rules of a new material era

Current EU regulations do not yet acknowledge liquid-state electronics as a formal product category, leaving major gaps in safety evaluation, recyclability standards, AI/adaptive-material oversight, and certification for hybrid electronic–chemical systems [3].

This regulatory vacuum is a strategic opportunity: a coordinated European initiative—such as a **Liquid Technologies Observatory**—could establish new standards and position Europe as the global leader in safe, sustainable, and ethical liquid electronics.

> Regulation is an accelerator for innovation done right.

Europe's innovation network and future leadership

Liquid electronics has stemmed from potential to performance—delivering measurable efficiency gains, improved outcomes, and distinct market advantages.

The next phase of leadership will belong to organisations that operationalise data strategies while ensuring collaboration, transparency and shared infrastructure.

- Cross-disciplinary teams spanning materials, robotics, computing, and ethics
- Industrial partners advancing circular nanomaterial production
- Public engagement through surveys and workshops
- A commitment to open innovation as the top governance priority identified by stakeholders

Leaders are now merging governance and business strategy to create value through efficiency and market differentiation.

> A connected ecosystem will turn liquid electronics from laboratory success into societal transformation.

Outlook: the coming era of liquid intelligence

Europe's liquid electronics landscape is entering a new era—defined by responsible AI, connected ecosystems, and measurable outcomes. Continued progress relies on integrating data, policy, and foresight to achieve sustainable transformation.

Initiatives such as COgITOR and others demonstrate how collective intelligence translates deep tech research into tangible benefits. As EU funding and AI governance frameworks evolve, new opportunities for collaboration will shape the next wave of adoption.

Over the next 20 years, experts foresee [4]:

- Emergence of **fully liquid computing prototypes**
- **Self-healing, adaptive systems** integrated into wearables, implants, and robots
- **Low-power liquid processors** for edge AI
- **Soft, eco-friendly sensors** embedded in natural and biological environments
- **Circular materials pipelines** reducing reliance on scarce resources

The future risks—privacy, dual use, leakage, uncontrolled adaptation—are real, but manageable through governance and transparency.

The next generation of electronic intelligence will be fluid, sustainable, and deeply intertwined with both environment and industry.

References

1 European Commission (2020). Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability.

2 Chiolerio, A., & Quadrelli, M. B. (2017). Smart fluid systems: The advent of autonomous liquid robotics. Advanced Science, 4(6), 1700036.

3 European Commission (2023). Critical Raw Materials Act: Ensuring a Secure and Sustainable Supply of Critical Raw Materials in Europe. Brussels.

4 COgITOR D6.9 – Long-term ethical and social implications of liquid electronics

Contributors

Chandra Gracia Anweta
Consultant
@ gracia.anweta@pnoinnovation.com
in /chandra-gracia-anweta-932b3534

Chiara Zocchi
Consultant
@ chiara.zocchi@pnoinnovation.com
in /chiarazocchi1

For inquiries or collaboration opportunities, contact PNO Innovation.

info.it@pnoinnovation.com

Connecting innovation and meaningful impact.

PNO INNOVATION

www.pnoinnovation.com