GO! – Green and Digital Transition of Heavy Mobile Machinery for a Sustainable Society

Project name: GO! – Glocal interdynO Research Infrastructure (GO!-RI)

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1. Introduction and policy context

This impact story primarily addresses the Sustainable Society dimension by contributing to climate change mitigation, industrial digitalization and long-term emission reductions in non-road mobile machinery. In addition, it contributes to Sustainable Public Finances by strengthening industrial competitiveness and leveraging RRF investment into substantial follow-up funding.

The green and digital transition of European industry is a cornerstone of the European Green Deal, the Fit for 55 package, and the Recovery and Resilience Facility (RRF). These policy frameworks emphasize climate neutrality, digital transformation, productivity growth and the resilience of European industry. Heavy mobile machinery and non-road mobile machinery (NRMM) are essential to sectors such as construction, mining, forestry, logistics, and energy infrastructure. At the same time, these machines present significant decarbonization challenges due to high power demand, long lifecycles, and demanding operating environments. GO! (Glocal interdynO Research Infrastructure) was established to address these systemic challenges by developing a shared, open and interoperable research infrastructure that supports the development, testing and validation of low-emission and digitally enabled heavy mobile machinery. The infrastructure enables both system-level testing of complete machines and component-level testing, including high-power single electric motors, providing critical capabilities for the development of sustainable and energy-efficient industrial solutions.

2. Impact objectives

The impact objectives of GO! are to strengthen sustainable growth by measurably improving the research, development and innovation conditions for low-emission and digitally enabled heavy mobile machinery. These objectives are directly aligned with the Sustainable Society dimension through climate change mitigation and industrial digital transformation, and with Sustainable Public Finances through enhanced productivity, competitiveness and leverage of RRF investment.

First, GO! aims to reduce development-phase emissions by enabling virtualization and laboratory-based validation of heavy machinery systems. By replacing emission-intensive field testing with Vehicle-in-the-Loop and digital twin–based workflows, the project targets up to 50% reduction in development-phase testing emissions compared to conventional field-based approaches. This supports long-term lifecycle emission reductions in non-road mobile machinery.

Second, GO! aims to shorten industrial development and validation cycles by 10–25% through system-level laboratory testing, subsystem validation and early-stage digital twin integration. By enabling component-level and powertrain-level validation without full prototype construction, the project reduces technological and financial risks, thereby accelerating market readiness of electrified and energy-efficient solutions.

Third, GO! aims to leverage RRF investment into sustained research and innovation activity. A measurable objective has been to enable significant follow-up funding and ecosystem activation.

Fourth, GO! aims to strengthen European research and industrial interoperability by promoting open, vendor-neutral and scalable testing architectures. The objective is to increase cross-border collaboration, shared validation methodologies and reusable digital twin models across Finnish and EU research and industrial actors. This contributes to strengthening European strategic autonomy in high-power electrification and testing capabilities.

Finally, GO! aims to enhance human capital in electrification, automation and digital twin technologies. The measurable objective includes increasing the number of MSc and PhD theses utilizing the infrastructure and strengthening the availability of advanced skills required for the green and digital transition of heavy machinery sectors.

3.Implemented actions and measures

GO! focused on the systematic development of the Northern Utility Vehicle Laboratory (NUVE-LAB) into a state-of-the-art research infrastructure for heavy mobile machinery. The development work aimed to establish an integrated and flexible testing environment that supports electrification, and digitalization of heavy-duty machines under safe and repeatable laboratory conditions. In addition to research-oriented use, the infrastructure was explicitly designed to support applied research and industrial development relevant to real-world applications.

Before GO!, validation of electric and hybrid powertrains in heavy mobile machinery typically required building full physical prototypes. Companies often had to integrate complete drivetrains into machines before meaningful performance and efficiency testing could begin. This approach was expensive, time-consuming and associated with high technical and financial risks, especially in early-stage development. For SMEs in particular, access to high-power testing facilities was limited, and the threshold for entering electrification research was therefore high.

One of the central implemented measures in GO! was the establishment of high-power electric driveline and single motor testing capabilities. These capabilities enable subsystem-level validation of electric motors, inverters and control strategies without requiring a fully assembled machine. Now, validation is possible at the powertrain or component level, significantly reducing the need for costly full-prototype builds. This change lowers development risk and accelerates iteration cycles, particularly for emerging and smaller companies.

In parallel, multi-channel battery emulation systems were deployed to allow safe and reproducible simulation of different energy storage configurations without reliance on physical battery packs. This capability makes it possible to test energy management strategies and powertrain behavior under realistic load conditions while avoiding the cost, safety concerns and logistical complexity of large battery systems. It also enables rapid comparison of different battery chemistries and configurations within the same experimental setup.

The infrastructure was further strengthened through advanced measurement, data acquisition and analysis systems. High-resolution synchronized logging enables detailed efficiency mapping, energy flow analysis and system-level optimization. These capabilities support reproducibility, data reuse and lifecycle-oriented design approaches, which are essential for both scientific research and industrial validation.

Vehicle-in-the-Loop testing environment were implemented to integrate physical test systems with real-time digital twins and simulation models. This integration enables realistic work-cycle testing under laboratory conditions and allows early-stage validation of energy-optimized functions. By linking physical components with digital models, the infrastructure supports iterative refinement without the need for repeated full-scale field tests.

Connectivity to complementary virtual laboratory environments, including augmented reality and virtual reality visualization laboratories at the University of Oulu, was implemented and validated. This enables the reuse of recorded test data, remote collaboration and distributed experimentation. It also lays the foundation for future national and international cooperation with similar facilities, strengthening interoperability and scalability.

To ensure long-term usability and openness, the project explored open-source interfaces and evaluated the Arrowhead interoperability framework. Although full-scale integration remains a longer-term objective, the evaluation demonstrated the feasibility of secure, vendor-neutral and scalable communication between heterogeneous systems. This approach reduces technological lock-in and supports multi-actor use of the infrastructure across research organizations and industry.

Together, these implemented measures transformed NUVE-LAB from a traditional testing laboratory into a cyber-physical research and development platform. The shift from full-prototype dependency toward subsystem-level validation and digital twin–enabled workflows represents a structural change in how electrified heavy mobile machinery can be developed, tested and optimized.

4. Successes and challenges

A central success of the GO! project was the successful deployment of a nationally distinctive high-power research infrastructure that integrates electrification, digital twins and cyber-physical testing into a unified laboratory environment. NUVE-LAB became operational within the RRF funding period and was rapidly utilized in national and international RDI projects, doctoral research and industrial validation activities. The infrastructure demonstrated a strong leverage effect by enabling multiple follow-up projects and attracting significant additional funding, confirming its relevance and long-term sustainability. The collaboration between the University of Oulu and Oulu University of Applied Sciences proved particularly valuable, combining scientific excellence with applied, industry-driven validation and strengthening both academic credibility and industrial impact.

At the same time, the project encountered several structural, technical and market-related challenges that provided important learning experiences.

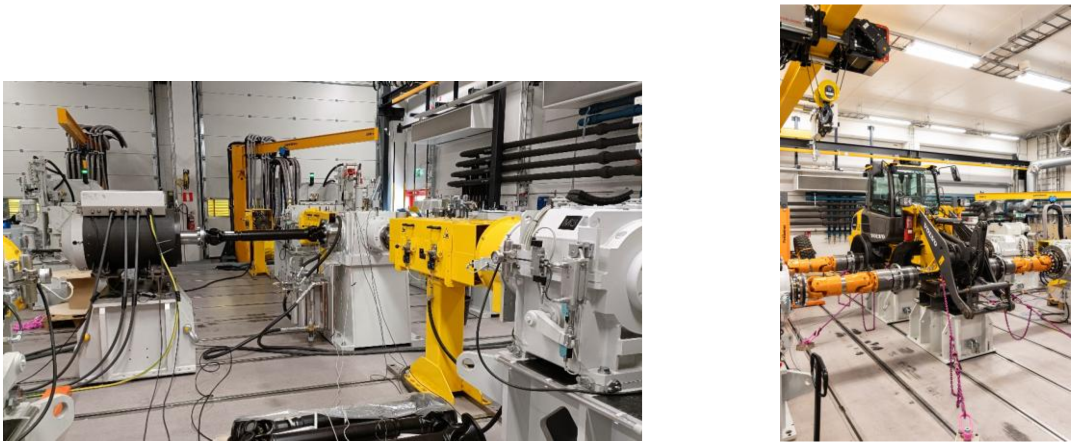
One key challenge was the rising cost of specialized high-power equipment and the limited availability of suitable commercial off-the-shelf solutions. As electrification technologies for heavy mobile machinery are still evolving, many required components—particularly in high-power driveline testing, real-time simulation integration and battery emulation—were either not readily available or required significant customization. Global supply chain constraints and increasing demand for power electronics and high-capacity testing systems further increased procurement costs during the project period. These challenges were addressed through adaptive prioritization of investments, phased implementation strategies and close technical coordination within the consortium. By continuously reassessing technical specifications against strategic impact objectives, the consortium ensured that the most impactful and future-proof capabilities were delivered within budgetary constraints.

A second challenge was the complexity of aligning university-based scientific research timeframes with applied industrial development cycles. Academic research often follows longer-term investigative trajectories focused on publication and theoretical advancement, whereas industrial partners operate under shorter development and commercialization timelines. Balancing these rhythms required structured communication, transparent prioritization and expectation management, particularly when synchronizing experimental campaigns with project milestones.

A third challenge related to interoperability integration. Although the Arrowhead interoperability framework was evaluated and demonstrated as a promising approach for secure and vendor-neutral system integration, full-scale implementation required more time than anticipated. Integrating heterogeneous hardware and software components while ensuring real-time performance, cybersecurity and scalability proved technically demanding. This experience underlined the importance of incremental implementation, governance of digital architectures and long-term ecosystem coordination.

Finally, integrating digital twins into routine industrial workflows required a cultural as well as technical transition. While Vehicle-in-the-Loop environments and simulation models were technically operational, companies needed support in adapting internal validation procedures and data practices to model-based, data-driven development. Iterative collaboration, joint experimentation and competence development were essential to build confidence in these new methods.

Despite these challenges, the project successfully delivered strategically critical testing and validation capabilities aligned with its sustainable growth objectives. The adaptive management of rising equipment costs, limited commercial availability and interoperability complexity strengthened the consortium's resilience and reinforced NUVE-LAB as a mature, scalable and future-oriented research infrastructure. Despite these challenges, the experience strengthened the consortium's ability to manage complex interdisciplinary infrastructures and provided valuable lessons for future large-scale RDI environments. The challenges themselves became part of the systemic learning process, reinforcing the long-term resilience and maturity of the research infrastructure.



Picture 1. NUVE-LAB customized gears for single electric motor testing capability (left) and full electric mobile work machine testing set-up (right) in NUVE-LAB.

5. Impact mechanisms

GO! generates impact through a reinforcing causal chain that links advanced testing capability to faster electrification, measurable emission reductions and ultimately to EU climate targets. The first mechanism begins with the establishment of high-power, subsystem-level testing capability within NUVE-LAB. By enabling safe, repeatable and data-driven validation of electric motors, power electronics, battery systems and integrated powertrains in a controlled laboratory environment, the infrastructure significantly lowers technological and economic risks. Instead of requiring full-scale prototype builds and emission-intensive field trials, companies can validate performance, durability and efficiency at component and subsystem levels. This reduction in development risk and cost directly accelerates electrification pathways, as companies can move more confidently and rapidly from concept to validated solution. Resource sharing further strengthens this effect, since SMEs and emerging companies gain access to capabilities that would otherwise be financially unattainable.

The second mechanism connects faster validation to improved energy efficiency and lower emissions. The close integration of digital twins with physical testing allows system-level and lifecycle optimization early in the design process. By directly linking component-level simulation models, including traction battery systems and control strategies, to physical experiments, the infrastructure enables early identification of inefficiencies and suboptimal configurations. This leads to improved powertrain architectures, optimized energy management strategies and reduced reliance on fossil-based propulsion systems. In the short term, measurable emission reductions occur through the replacement of emission-intensive field testing with virtualization and Vehicle-in-the-Loop workflows. In the medium and long term, electrified and energy-efficient solutions validated in the laboratory contribute to reduced lifecycle greenhouse gas emissions when deployed in construction, forestry, mining and logistics operations.

The third mechanism extends these technological improvements into systemic and EU-level impact. The open and interoperable design of the infrastructure strengthens collaboration and scalability across organizations and national borders. Companies and research organizations can co-develop and test electrified solutions through shared interfaces without technological lock-in. This accelerates diffusion of validated electrification concepts across the European industrial ecosystem. As faster electrification reduces greenhouse gas emissions in the non-road mobile machinery sector, an area historically less regulated than road transport, the cumulative effect contributes to the EU's Fit for 55 objective of reducing greenhouse gas emissions by at least 55% by 2030 and supports the long-term climate neutrality target of the European Green Deal.

In summary, the causal pathway can be described as follows: advanced high-power testing capability lowers development risk; lower risk accelerates electrification and digital optimization; accelerated electrification leads to measurable emission reductions at development and operational levels; and scaled industrial adoption of validated solutions contributes to EU-wide climate targets and sustainable growth objectives

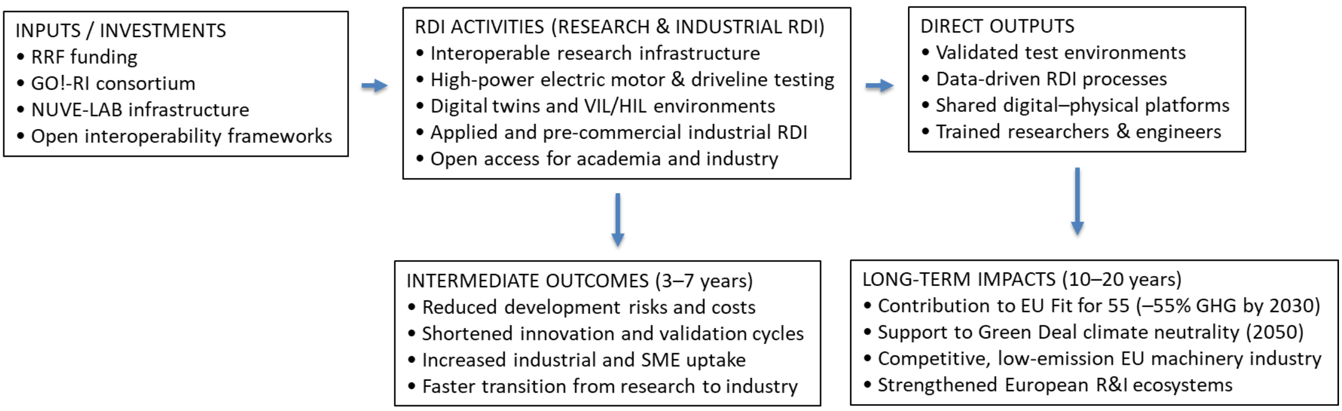


Figure 1. Impact pathway of the GO! project.

6. Medium- and long-term impacts and systemic effects

In the medium term (3–7 years), GO! is expected to translate validated testing environments and data-driven RDI processes into reduced development risks and costs, shorter innovation and validation cycles, and an accelerated transition from research to industrial application.

Through open access to interoperable testing and simulation capabilities, the project supports increased uptake by industrial actors, including SMEs, and strengthens research and innovation capacity in electrified and automated heavy machinery.

In the long term (10–20 years), GO! contributes to systemic change in industrial research, development and innovation practices by promoting data-driven, interoperable and ecosystem-based innovation models that integrate physical testing with digital twins and real-time simulation. Existing research on electrification, automation and digital twin–enabled development indicates that such models can support significant lifecycle emission reductions and improved resource efficiency, particularly when combined with supportive regulation, standardization, and coordinated innovation policies at national and EU levels. By accelerating the uptake of electric, energy-efficient and digitally enabled solutions for non-road mobile machinery, GO! contributes to the EU Fit for 55 target of reducing greenhouse gas emissions by at least 55 % of NUVE-LAB testing compared to traditional field tests by 2030, and supports the European Green Deal objective of climate neutrality by 2050. At the same time, the project strengthens European research and innovation ecosystems by promoting interoperable, scalable and cross-border RDI practices.

Table 1. Anticipated impacts across time horizons

Time horizon	**Type of impact**	**Expected effects**
Short-term (0–3 years)	Research and innovation capacity	Continuing and increased number of RDI projects utilizing NUVE-LAB; improved access to high-power testing
	Knowledge production	Continued peer-reviewed publications, MSc and PhD theses
Medium-term (3–7 years)	Industrial innovation	Shortened development cycles (estimated 10–25%)
	Emission reduction potential	Reduced testing-related emissions through simulation models and virtualization (VIL testing)
	Competitiveness	Improved market readiness of low-emission solutions
Long-term (10–20 years)	Climate impact	Contribution to significant lifecycle emission reductions in heavy machinery
	Systemic change	Shift towards data-driven, interoperable and ecosystem-based RDI models
	Economic resilience	Strengthened European industrial and research infrastructure base

7. EU-level impacts

GO! supports EU-level objectives under the European Green Deal and Fit for 55. GO! contributes to European climate and sustainability goals by helping to reduce emissions from non-road mobile machinery, such as work machines used in construction, forestry, mining and logistics. These machines are a significant source of emissions but are often outside the scope of road transport regulations. GO! provides research and testing environment where low-emission technologies, including electric and hybrid powertrains and energy-efficient control solutions, can be developed, tested and validated before being deployed in real-world applications.

The project strengthens European research capacity by establishing a shared research infrastructure that is accessible to multiple organizations across national borders. The testing methodologies, digital tools and system architectures developed within GO! are designed to be transferable and reusable, enabling other research institutions and companies to adopt similar approaches without the need to replicate identical facilities. This supports cross-border collaboration, reduces duplication of investments and accelerates the diffusion of new technologies across Europe.

In addition to its research-oriented impact, GO! contributes to EU-level industrial competitiveness by enabling applied research and pre-commercial development of key technologies for non-road mobile machinery. The NUVE-LAB infrastructure can be utilized by industrial actors for the research, development and validation of electric motors and associated powertrain solutions, including power electronics, control strategies and integrated electric driveline configurations. High-power testing capabilities, advanced measurement systems and real-time integration with digital twins allow industry-driven innovation to be carried out under controlled laboratory conditions. This reduces development risks and shortens innovation cycles, thereby accelerating the uptake of low-emission and digitally enabled machinery solutions across EU Member States.

Furthermore, GO! supports European industrial digitalization by combining physical testing with digital models and data-driven development methods. The use of open and interoperable interfaces enables different technologies, software tools and data sources to function together, facilitating data sharing and joint development activities between organizations. This interoperability makes it easier for companies and research organizations to connect their own solutions to the infrastructure and to collaborate in international projects. As a result, innovations developed within GO! can be scaled beyond individual organizations or countries, contributing to wider European efforts to modernize industry, strengthen research infrastructure capacity and reduce environmental impacts in line with EU strategic priorities.

8. Monitoring and evaluation

The monitoring and evaluation of GO! focus on assessing how the infrastructure advances sustainable growth, particularly through green transition, digitalization and strengthened research and innovation capacity. Both quantitative and qualitative indicators are used to evaluate progress along the impact pathway from testing capability to accelerated electrification, measurable emission reduction and contribution to EU climate and competitiveness objectives.

Quantitative monitoring includes the number of RDI projects utilizing NUVE-LAB, the cumulative volume of follow-up funding enabled (approximately €15.65 million during and immediately after the RRF period), and the number of registered infrastructure users (83 users). These indicators measure infrastructure utilization, ecosystem activation and leverage of the original RRF investment. The number of peer-reviewed publications, MSc theses and PhD theses completed using the infrastructure are tracked as indicators of knowledge generation and human capital development.

Climate-related indicators include model-based estimates of reduced development-phase emissions achieved through replacing emission-intensive field testing with Vehicle-in-the-Loop laboratory validation. In addition, lifecycle-based modelling is used to estimate the potential greenhouse gas reductions when electrified and energy-efficient powertrains validated in NUVE-LAB are deployed in real-world applications. Estimated reductions in development time (approximately 10–25%) and reduced need for full-scale prototyping are used as indicators of improved resource efficiency and productivity.

Industrial impact is monitored through the number and diversity of companies, including SMEs, using the infrastructure for testing and validation, as well as through the continuation of collaboration in follow-up RDI projects. Cross-border research cooperation and shared validation campaigns serve as indicators of strengthened European interoperability and strategic resilience.

Qualitative evaluation complements numerical metrics. Stakeholder feedback, workshops and consortium-level reviews are used to assess perceived reductions in technological risk, improvements in data-driven development practices and the integration of digital twin methodologies into industrial workflows. Together, these indicators provide a concise and structured basis for evaluating how GO! contributes to sustainable growth and long-term systemic transformation.