

INDUCT

**Inductive heating using magnetic nanoparticles for energy
efficient glass delamination in circular windows**

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Inductive heating using magnetic nanoparticles for
energy efficient glass delamination in circular windows

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1 Summary

The INDUCT project developed an innovative approach for the lamination and delamination of glass using inductive heating of nanoparticle-enhanced polymer interlayers. The project addresses a key challenge in laminated glass recycling, where current end-of-life treatments are energy-intensive and prevent recovery of intact glass sheets. By embedding magnetic nanoparticles in thermoplastic interlayers such as polyolefin elastomers (POE), the process enables localized, on-demand heating of the polymer layer creating a novel pathway for more efficient glass recycling.

The project aimed to demonstrate the technical feasibility of inductive (de)lamination, assess its technical, economic and environmental benefits, and advance the technology from proof-of-concept towards higher readiness levels. Activities covered the full value chain, including the development and functionalisation of magnetic nanoparticles, their integration into polymer interlayers, the production of laminated glass, and the design of an industrial inductive heating concept.

Experimental work demonstrated that the heating performance of nanoparticles is highly dependent on their size, structure, and composition, with optimized particles of size 56nm magnetite achieving temperatures sufficient for polymer softening and debonding (76°C). Integration of these nanoparticles into POE films enabled inductive heating at low loading levels. Glass laminates were successfully produced and tested, including the development of a demonstrator insulating glass unit (IGUs) that possessed visible light transmission of 71.5%.

In parallel, a TRL5 concept for an industrial inductive heating system was developed, including process design, equipment specifications, and system integration within a standard window production line. The concept enables both inline lamination and circular delamination of end-of-life glass. Key design requirements were identified, including the need for inductive heating systems operating at both high power and high frequency. The combination of these requirements currently exceeds commercially available capabilities and represents a critical development area for future scale-up.

The techno-economic assessment indicates strong potential for industrial application. The INDUCT process is estimated to reduce the cost of glass by approximately 25% compared to conventional production of new laminated glass, while also lowering CO₂ emissions and enabling true circularity through the recovery of intact glass sheets. Key barriers remain in inductive heating equipment development, process integration, and industrial adoption. However, the technology aligns strongly with circular economy and electrification objectives, and a follow-up project is being prepared to advance the technology towards industrial demonstration.

2 Project Background and Objectives

Laminated glass is increasingly applied in the building and automotive sectors due to its safety and performance benefits. However, end-of-life management of laminated glass remains a major challenge. Current recycling routes are energy-intensive and rely on mechanical shredding and chemical separation, which prevent reuse of intact glass sheets and lead to downcycling or landfilling. Since glass production is highly energy- and carbon-intensive, circular recycling solutions are required to reduce CO₂ emissions and raw material demand.

Selective heating of the polymer interlayer offers a promising route for energy-efficient lamination and delamination of laminated glass. This can be achieved through inductive heating by embedding magnetic nanoparticles in thermoplastic interlayers. Inductive heating enables localized, on-demand heating of the polymer without heating the full glass stack, drastically reducing energy consumption and enabling electrification of the process.

The advantages of inductively heated glass lamination and delamination compared to conventional processes are:

- › High energy efficiency, as only the polymer interlayer is heated, enabling energy reductions of up to 90%;
- › Full electrification, eliminating fossil fuel-based ovens and autoclaves and enabling integration with renewable electricity;
- › Fast and selective heating, with no warm-up or cooldown losses and increased process throughput;
- › Enabling true circularity, by allowing recovery and reuse of intact laminated glass sheets;
- › Compatibility with existing materials; although PVB is the typical interlayer for laminated glass, POE is still known and used in industry
- › Industrial scalability, as inductive heating is a mature technology with efficiencies of 70–90%;
- › Strong sustainability impact, through reduced CO₂ emissions, energy use and material waste.

The INDUCT project has built upon laboratory-scale proof-of-concept work at TNO, where magnetite nanoparticles embedded in POE films were successfully heated inductively to temperatures above 160°C, enabling polymer softening and delamination. The consortium brings complementary expertise in nanoparticle synthesis, polymer compounding, film extrusion, inductive heating equipment and industrial glass processing. Further development is required in INDUCT to progress towards industrial application. Key challenges include optimization of nanoparticle properties, integration into POE films while maintaining optical and mechanical performance, validation of inductive lamination and delamination at representative scale, and development of an industrially compatible inductive heating concept.

The overall INDUCT project objectives were to:

- › Demonstrate the concept of energy efficient glass lamination and delamination via inductive heating.
- › Assess and verify technical, economic and environmental advantages of implementing the lamination and delamination process in a renewable-dominated energy system.
- › Advance the TRL of inductive heating for glass (de)lamination from TRL3 (established proof of concept) to TRL4 (lab testing of prototype components and process).
- › Provide a concept for an industrial inductive heating setup tailored for glass (de)lamination.
- › Provide a roadmap for scale up to pilot scale, with a perspective towards commercialization.

3 Results

3.1 Work Package 1 - Development of magnetic nanoparticles, films and laminates

Magnetic nanoparticles were successfully developed and tailored for application in inductively heated laminated glass by Nano Hybrids, UvA and TNO. Multiple synthesis routes were explored to control particle size, composition, and magnetic properties, enabling alignment with the requirements for efficient induction heating and compatibility with polymer interlayers.

Initial nanoparticle systems based on iron/iron oxide core-shell structures showed stable and well-controlled compositions, but exhibited limited heating performance due to relatively low magnetic response. To overcome this, an alternative synthesis route was developed, enabling improved control over particle structure and crystallinity. This resulted in nanoparticles with significantly enhanced magnetic properties and heating performance, reaching temperatures in the range of 200–250 °C under inductive heating conditions.

In parallel, magnetite nanoparticles with controlled particle sizes were produced, demonstrating a strong dependence of heating performance on particle size and magnetic behaviour. An optimal particle size was identified, showing improved magnetic properties and achieving rapid heating rates and temperatures well above those required for polymer softening.

These nanoparticles were subsequently incorporated into polyolefin elastomer (POE) matrices via compounding and extrusion. The resulting nanocomposite materials retained their functional heating performance, even at low particle loadings. Heating experiments demonstrated that the polymer melting temperature could be reached within minutes, confirming the feasibility of inductive heating for (de)lamination applications.

Finally, nanocomposite films were successfully produced at both laboratory and pilot scale. Different material configurations were evaluated, including variations in particle distribution within the film, to optimise performance while maintaining optical and mechanical requirements. These results demonstrate the technical feasibility of integrating inductively heatable nanocomposites into laminated glass systems and provide a foundation for further scale-up and industrial validation.

3.2 Work Package 2 - Production of glass laminates, and investigation of lamination/delamination

Nanocomposite films developed in WP1 were successfully integrated into glass laminates by Yparex and TNO, and then evaluated for their performance in lamination and delamination applications. Both small-scale and larger demonstrator laminates were produced to assess feasibility under representative conditions.

Initial proof-of-principle experiments by TNO and Ambrell demonstrated that inductive heating of nanocomposite interlayers can achieve temperatures sufficient for glass lamination. Successful bonding of glass samples was achieved at relatively low nanoparticle loadings,

confirming that only limited amounts of magnetic material are required. In addition, reheating enabled separation of the bonded samples, demonstrating the feasibility of inductively driven delamination using the same material system.

Further experiments with thin films highlighted the importance of film thickness, heat losses to the glass, and the performance of the induction setup. While thinner films showed reduced heating efficiency under the available laboratory conditions, these limitations were identified as being primarily related to the experimental setup rather than fundamental material constraints.

Based on these findings, multilayer nanocomposite films were produced at larger scale with optimised thickness and particle distribution. These films achieved the required balance between heating performance and optical quality. Optical transmission values above 70% were obtained, although additional processing steps were required to further reduce haze and meet application requirements.

Glass laminates prepared with these optimised films were successfully manufactured and processed into insulating glass units (IGUs), resulting in full window demonstrators. The final demonstrators confirmed the technical feasibility of integrating inductively heatable interlayers into laminated glass systems, providing a basis for further optimisation and industrial validation.

3.3 Work Package 3 - Design of industrial inductive heating setup

A conceptual TRL5 design for an industrial inductive heating system was developed by TNO and Ambrell (with input from all project partners), targeting integration into standard glass manufacturing lines for both lamination and end-of-life delamination. The design was based on a representative scale-up case for 1 m × 1 m glass plates, reflecting a realistic next step towards industrial implementation. System requirements were determined through modelling of thermal and magnetic behaviour, leading to the identification of key operating conditions for effective heating of the polymer interlayer. The results indicate that inductive heating performance is governed by hysteresis losses in the magnetic nanoparticles, with higher operating frequencies enhancing heating rates.

A coil-based heating concept was developed, with a multi-layer pancake-type geometry selected to achieve a sufficiently uniform magnetic field over the target area as shown in Figure 1.

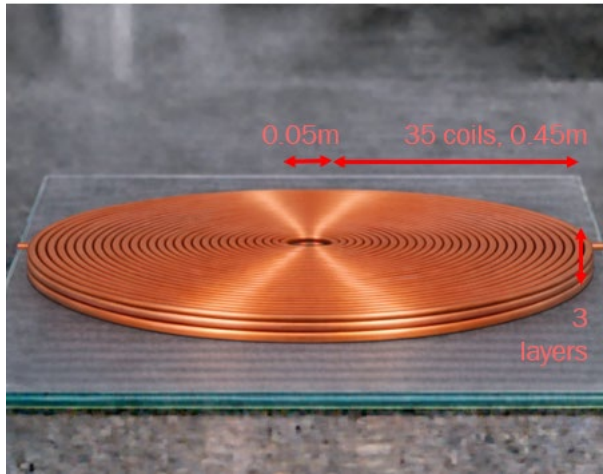


Figure 1: Representation of coil geometry in proposed TRL5 design

The required magnetic flux density for effective heating was estimated to be in the range of 0.2–0.3 T. To achieve this over the specified area, high power input is required, with total system demand exceeding 1.2 MW at 500kHz.

The analysis further showed that the required heating performance can be achieved with relatively low nanoparticle loadings in the polymer interlayer, provided that sufficient magnetic field strengths are reached. However, the combination of high power and frequency requirements exceeds the capabilities of currently available commercial induction systems, highlighting a key challenge for further scale-up.

In parallel, a full process concept was developed, including process flow design, equipment definition, safety considerations, and system layout. Based on this design, the total installed equipment cost for a system capable of processing 1 m × 1 m glass plates was estimated at approximately € 1.5 million. Overall, the results demonstrate the technical feasibility of scaling inductive heating for laminated glass applications, while also identifying key technological gaps that must be addressed to enable industrial deployment.

3.4 Work Package 4 - Roadmap

An initial techno-economic assessment was performed to evaluate the potential of the INDUCT concept for both laminated glass production and recycling applications. The analysis compared the conventional production route with the inductive (de)lamination approach and identified the key technical, economic and implementation factors influencing feasibility.

The results indicate that the INDUCT concept has strong potential as an alternative to conventional laminated glass production, primarily due to its fundamentally different process route. By enabling the recovery and reuse of existing glass, the INDUCT approach avoids several energy- and capital-intensive upstream steps associated with virgin glass production.

The INDUCT process is estimated to reduce the cost of glass by approximately 25% compared to conventional production of new laminated glass, while also lowering CO₂ emissions and enabling true circularity through the recovery of intact glass sheets. This highlights a strong value proposition for the technology as it matures.

At the same time, the analysis showed that the INDUCT process introduces new cost drivers, including electricity demand for inductive heating, the use of nanoparticle-modified interlayers, and investment in specialised induction equipment. Sensitivity analysis highlighted that the INDUCT process is particularly influenced by electricity prices and the cost of induction equipment, whereas conventional production is more sensitive to raw material costs and high-temperature furnace operation.

Beyond economics, a broader evaluation of implementation aspects confirmed a strong fit of the INDUCT concept within circular glass value chains, particularly in regions with established glass collection and recycling infrastructure. Key challenges identified include the availability of high-power, high-frequency induction equipment and the need for process adaptation within existing glass manufacturing environments.

Finally, the roadmap analysis confirmed that the technology is well aligned with broader policy objectives related to electrification and circular economy. Continued development and demonstration at higher TRL levels were identified as critical next steps towards industrial deployment.

3.5 Work Package 5 - Project management

This work package ensured the coordination and integration of all activities across the consortium. Activities included planning, monitoring of technical progress, coordination between partners, and organisation of regular consortium meetings. This structured approach enabled effective integration of material development, process testing, and engineering design.

The project successfully achieved its main objectives, with all key work packages contributing to the demonstration of the INDUCT concept and the development of a clear pathway towards further scale-up.

4 Bottlenecks and follow-up

4.1 Technical and operational challenges

Several technical and operational challenges were encountered and overcome during the project. The implementation of inductive heating experiments was partially delayed due to the time required to install appropriate safety enclosures around the experimental setup. In addition, accurate temperature measurement during inductive heating proved challenging, as conventional thermocouples are affected by alternating magnetic fields. As a result, alternative measurement approaches, such as infrared imaging, were applied, although these introduced additional uncertainties related to measurement conditions and sample exposure.

Differences in heating behaviour between composite pellets and extruded films were observed, primarily due to increased heat losses in layered systems and the influence of surrounding materials. This complexity made it more difficult to directly translate material-level performance into laminate-level behaviour. Furthermore, limitations in small-scale production methods, particularly for multi-layer film configurations, constrained the ability to systematically optimise material composition and structure.

4.2 Changes to the project plan

During the course of the project, electromagnetic modelling was introduced as an additional activity to strengthen the technical basis of the system design. This activity was not included in the original project plan but was incorporated in response to the need for a more robust understanding of inductive heating behaviour at larger scales.

The inclusion of modelling enabled improved interpretation of experimental results and supported more informed design choices for the industrial concept. While this resulted in a modest shift in timeline for certain activities, it ultimately enhanced the quality and reliability of the TRL5 system design.

4.3 Follow up to the project plan

A follow up to the INDUCT project is currently being developed in order to build on and valorise the positive technical and strategic results achieved. The envisaged follow up aims to progress the technology towards a next stage of development, with a stronger focus on the development of an inductive heating generator and coil for this application, and demonstration within an industrially relevant context.

At this stage, it is anticipated that the follow up activities will be based in the Netherlands, allowing the project to leverage the existing glass recycling supply chain from the established collection and processing network of Recycling Vlakglas.

In the MOOI project “BIPV Circular Energy Buildings” (2025-2028), part of the work focuses on renewable debonding of PV panels at end of life by making use of an external stimulant. Induction heating is under investigation as one of the possible external stimuli, where ferrimagnetic particles could act as magnetic susceptors in the encapsulant matrix. As a PV panel consists of a polymer-glass interface at the top, the knowledge regarding debonding polymer-glass gathered during the INDUCT project can be used to branch out to an additional application area beyond safety glazing.

In the JTF project “Circutherm” (2026-2028), induction heating of magnetite nanoparticles is investigated as a platform technology for several use cases: circular bonding and debonding of safety footwear, circular packaging materials, and renewable syngas production through the reverse water-gas shift reaction. In a first instance, the synthesis of the nanoparticles with optimal induction heating performance, first developed in INDUCT, will be upscaled to kg scale and surface modifications will be made for integration in the different use cases.

5 Contributions to objectives of the program

The INDUCT project has made significant contributions to the TSE Industry Program under MMIP7 – CO₂-free industrial energy management. By focusing on electrified and resource-efficient processing of laminated glass, INDUCT directly supports the transition towards fossil-free, flexible, and circular industrial energy systems. Aligned with the MMIP7 principles of reduce, re-use and replace, INDUCT developed an innovative process that replaces conventional energy-intensive lamination and recycling methods with selective inductive heating of nanoparticle-enhanced interlayers. This approach significantly reduces overall energy demand by heating only the functional layer instead of the full glass system, while enabling electrification of the process using renewable electricity.

The project further contributes to circular industry objectives by enabling recovery and reuse of intact glass sheets, avoiding downcycling and reducing the need for primary raw materials. Through integration of material development, process validation and system design, INDUCT demonstrated the technical feasibility of inductive (de)lamination and developed a TRL5 concept for industrial implementation, supporting scale-up towards real-world deployment.

In addition, the techno-economic assessment showed that the INDUCT concept can deliver both economic and environmental benefits, with an estimated 25% cost reduction compared to conventional laminated glass production, while lowering CO₂ emissions and supporting circular value chains.

Through its integrated approach to electrification, energy efficiency and circular material use, INDUCT contributes to the broader MMIP7 objectives by demonstrating how innovative process technologies can enable a CO₂-free industrial energy system. The project results provide a strong foundation for further development, industrial demonstration, and alignment with Dutch climate and circular economy targets.

6 Dissemination

The INDUCT project results were presented at *Projecten op het Podium* in Utrecht. In addition, the final INDUCT demonstrators will be displayed at the *Rethinking Materials Trade Fair* in London.

Dissemination on the project includes the following:

- › On research paper in preparation: Structure–Property Correlations of Iron@Iron Oxide Nanoparticles Synthesized by Hot-Injection (not yet published; targeting submission to ACS Nano).
- › Manuscript in preparation: One-Step and Solvent-Free Synthesis of Functionalized Fe/FeO_x Core-Shell Nanoparticles (Materials Advances, revised version in preparation).
- › Manuscript in preparation: Size-dependent induction heating properties of octahedron-shaped Fe₃O₄ nanoparticles near the multi-domain limit for (de)bonding on demand applications (Intended submission to Journal of Materials Chemistry A).
- › One poster presentation: One-Step and Solvent-Free Synthesis of Functionalized Fe/FeO_x Core-Shell Nanoparticles (NWO CHAINS, 2025).

A patent application has been filed based on the key results of the INDUCT project (application number P140720EP00).

7 Signatures

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