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JOULIA

Electrification of industrial processes using induction and microwaves technologies

D4.4
Report on stakeholder needs

White Research

30/09/2025

Funded by the European Union

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Project Information

ACRONYM	**JOULIA**
TITLE	Electrification of industrial processes using induction and microwaves technologies
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START DATE OF THE PROJECT	01/12/2024
DURATION OF THE PROJECT	December 2024 – November 2028
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TOPIC	HORIZON-CL5-2024-D4-01-03
WEBSITE	www.jouliaproject.eu
COORDINATOR	CIRCE – Technology Center
PROJECT OVERVIEW	The JOULIA project is focused on **transforming energy-intensive industries by replacing traditional fossil fuel-based heating methods with advanced electric technologies**. These industries rely on **high-heat processes**, which are critical for manufacturing products like **rubber, ceramics, and plastics**. By focusing on specific, high-heat applications, JOULIA seeks to **showcase the potential of electrification to decarbonise operations, enhance efficiency, and drive sustainable industrial transformation.**

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Version	Date	Main modifications	Organisation
0.1	03/06/2025	First draft of the Table of Content	WR
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0.4	23/09/2025	Second consolidated version after peer review	WR
0.5	27/09/2025	Final Quality Review by the project coordinator	CIRCE
1.0	30/09/2025	Final Version for Submission	WR, CIRCE

DISCLAIMER OF WARRANTIES:

"The methodology for the Report on Stakeholder Needs of the JOULIA project (Grant Agreement number: **101192555**) leverages the extensive expertise, tools, and templates developed internally by White Research SRL. It incorporates European Commission guidelines and established best practices from relevant literature. This methodology builds on knowledge and approaches refined through White Research's involvement in previous projects, such as ROBIN (GA: **101060504**). These elements have been tailored to meet the specific needs of JOULIA while ensuring compliance with EU recommendations and the conditions outlined in the Grant Agreement. This report outlines the adapted methodology as it was further developed and implemented within the JOULIA project."

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Abbreviations

DSO	Distribution System Operator
EII	Energy-Intensive Industry
EMF	Electromagnetic Fields
EU	European Union
GHG	Greenhouse Gas Emissions
IEA	International Energy Agency
PI	Process Industry
PPE	Personal Protective Equipment
PV	Photovoltaic
R&D	Research & Development
ROI	Return on Investment
SME	Small and medium-sized enterprise
TSO	Transmission System Operator

Table 1: Abbreviations

Executive Summary

This document is the deliverable "**D4.4 - Report on stakeholders needs**" of the JOULIA project (Electrification of industrial processes using induction and microwave technologies) and focuses on **identifying the key challenges, needs, and perceptions of stakeholders who are central to the adoption and deployment of advanced induction and microwave heating technologies**. The study draws on **12 semi-structured interviews** across three main stakeholder groups: manufacturing industries, operators, and energy suppliers. These interviews, combined with a **literature research**, revealed valuable insights into both the barriers hindering widespread adoption and the opportunities that could accelerate deployment.

Several cross-cutting themes emerged from the analysis:

- **Technological and operational barriers**: Although stakeholders recognise the precision and energy efficiency of induction and microwave systems, limitations persist in integration, adaptability to complex geometries, and system reliability. Many SMEs also face technological risk aversion due to limited R&D resources and experience.
- **Infrastructural constraints**: Grid congestion, outdated infrastructure, and long permitting timelines were cited as major bottlenecks. Supply chain vulnerabilities, such as long lead times for key components, further complicate the deployment of these technologies.
- **Economic challenges**: High upfront costs and uncertain Return On Investment (ROI) remain significant barriers, particularly in the absence of stable, supportive policy frameworks. Electricity price volatility and unbalanced taxation policies were also highlighted as economic disincentives compared to fossil fuel alternatives.
- **Policy and regulatory misalignment**: Stakeholders called attention to fragmented and outdated regulations that fail to accommodate emerging technologies like induction and microwave heating. The need for clearer, long-term incentives and harmonised standards was widely agreed upon.
- **Workforce and organisational readiness**: There is a marked gap in skills and training related to electrified systems, particularly among operators and SMEs. Organisational inertia, coupled with a lack of internal champions, further slows down innovation.

The report concludes with **actionable recommendations**, including the development of scalable and modular technologies, investment in targeted training programmes, and policy reforms aimed at levelling the playing field between electricity and fossil fuels. It also emphasises the importance of coordination between industry, energy suppliers, and regulators to ensure infrastructure readiness, workforce upskilling, and market confidence. Findings of this report, will inform the development of targeted reskilling and upskilling modules (T14.5–T16.5), support the identification of health and safety requirements (T4.3), and shape tailored communication strategies (WP14–16) under the JOULIA Project.

1. Introduction: Industrial electrification state-of-play

The industrial sector remains one of the most energy-intensive segments of the global economy, responsible for over one-third of global energy demand and a significant share of greenhouse gas (GHG) emissions. **Its heavy reliance on fossil fuel-based heating systems underscores the urgent need for a transition to cleaner, more sustainable alternatives.**

In this context, the JOULIA project aims to electrify industrial heating processes through the development, demonstration, and replication of induction and microwave technologies. These advanced systems promise to provide contactless, precise, and efficient heating suitable for a wide range of temperature-dependent industrial operations. **The project's goals are not only technological but also societal and environmental**, reducing emissions, improving energy efficiency, and fostering sustainable industrial innovation across Europe.

1.1 Industrial electrification state-of-play

The **industrial sector plays a pivotal role in global energy consumption**, accounting for 37% of total energy demand and half of global heat demand[1,2]. With 70% of this energy sourced from fossil fuels and only 30% of the energy demand coming from electricity, the sector is responsible for over **40% of energy-related CO_2 emissions**[3]. In EU, the industrial sector is one of the largest energy consumers, responsible for 25% of total energy consumption. As indicated in **Figure 1**, electricity accounts for 33%, while the industrial share in **greenhouse gas emissions is 59%**, highlighting the sector's heavy reliance on fossil fuels[4,5].

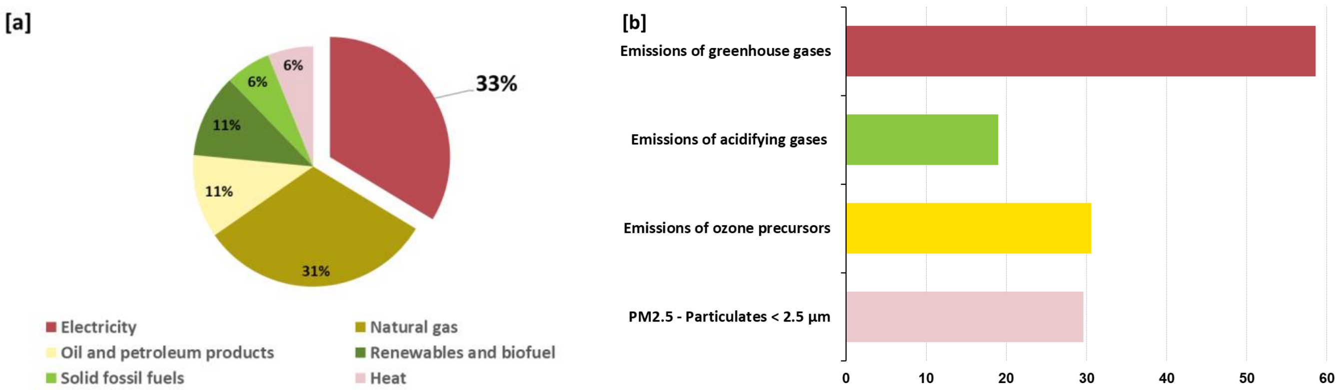

Figure 1: [a] Final energy consumption in the industry sector by energy product (Source: Eurostat (nrg_bal_s), 2022). [b] Air emissions as a % share in all NACE production activities (Source: Eurostat (env_ac_ainah_r2), 2022).

[1] IEA (2025) *Industry*. Available at: https://www.iea.org/energy-system/industry (Accessed: 2 July 2025).
[2] Zhang, X., Li, Y., Chen, Q. (2022) 'Innovative approaches in thermal engineering', *Frontiers in Thermal Engineering*, 8, 940072. Available at: https://www.frontiersin.org/journals/thermal-engineering/articles/10.3389/fther.2022.940072/full (Accessed: 2 July 2025).
[3] Smith, J., Johnson, L., & Lee, M. (2020) 'Industrial energy consumption trends', *Environmental Research Letters*, 15(8). Available at: https://iopscience.iop.org/article/10.1088/1748-9326/abbd02 (Accessed: 2 July 2025).
[4] Eurostat (2024) *Final energy consumption in industry - detailed statistics*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics (Accessed: 2 July 2025).
[5] Eurostat (2025) *Industrial emission statistics*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Industrial_emission_statistics#:~:text=In%202022%2C%20the%20industrial%20share,acidifying%20emissions%20by%20production%20activities (Accessed: 2 July 2025).

These figures underline the **urgent need to decarbonise industrial heat**, a critical but complex task due to the **diversity of industrial processes, varying temperature requirements, and material constraints**[3].

Electrification, when powered by renewable energy, represents a key strategy for reducing emissions as it is considered, where feasible, to be the most **energy and cost-efficient** way to replace fossil fuel consumption all while **reinforcing industry competitiveness**[6]. Studies estimate that up to **92% of industrial process heat could be electrified** using technologies such as electric boilers, arc furnaces, industrial heat pumps, induction heating, plasma torches, and thermal storage. Despite this high potential, adoption remains low, **process heat electrification currently accounts for only 4%** due to **financial, technological, organisational, regulatory, and infrastructure**-related barriers[6,7]:

- **Financial and economic barriers** arise from the high relative cost of electricity compared to fossil fuels, significant capital investments for new equipment, and long payback periods. In competitive global markets, these cost pressures are particularly challenging.
- **Technological barriers** relate to the readiness and integration of electrification solutions, particularly for processes requiring high operating temperatures or reducing environments. Limited commercial availability, integration complexity, and perceived operational risks delay adoption.
- **Organisational barriers** are linked to risk aversion, short-term investment horizons, and shortages in personnel with the necessary skills to design, install, and operate electrified systems.
- **Regulatory and policy barriers** stem from uncertainty around access to hydrogen and CCUS networks, as well as emerging markets for low-carbon products, limiting confidence in future returns on electrification investments.
- **Infrastructure barriers** include constraints in grid capacity, long lead times for additional electricity network access, and regional supply limitations, all of which hinder the ability to switch at scale.

As **scepticism persists among industry players**[8], successfully transitioning to low-carbon energy systems demands not only advancements in renewable energy infrastructure and electrification technologies, but also a **deep understanding of the diverse needs and perspectives of key stakeholders**[9].

Emerging electrified heating technologies, such as induction and microwave heating, offer precise, energy-efficient, and emissions-free solutions for industrial processes, supporting the decarbonisation of key sectors[10]. That said, challenges still remain regarding their broader implementation. These issues, along with the differing perceptions and needs of key stakeholders, are further explored in Chapter 3: Key challenges, perceptions, and needs across stakeholder groups.

[6] Eurelectric (2025) *Unlocking the untapped potential of industrial electrification*. Available at: https://www.eurelectric.org/in-detail/unlocking-the-untapped-potential-of-industrial-electrification/ (Accessed: 2 July 2025).
[7] Department for Energy Security and Net Zero (2024) Electrification call for evidence: Formal summary of responses. Available at: https://assets.publishing.service.gov.uk/media/66e013650f4ba0621b086702/electrification-call for evidence formal summary of responses.pdf (Accessed: 2 July 2025).
[8] Smith, J., Johnson, L., & Lee, M. (2020) 'Industrial energy consumption trends', *Environmental Research Letters*, 15(8). Available at: https://iopscience.iop.org/article/10.1088/1748-9326/abbd02 (Accessed: 2 July 2025).
[9] Otto, S., Oberthür, S., Tönjes, A., Peterson, L., Hilton, F. et al. (2023) Sectoral Analysis of Energy Intensive Industries (Deliverable 4.3a). NDC ASPECTS Project, Horizon 2020. Available at: https://ndc-aspects.eu/sites/default/files/2023-10/D4.3a%20Sectoral%20Analysis%20of%20EIIs.pdf (Accessed: 2 July 2025).
[10] Boele, G. (2023) 'ESG Economist – Heating technologies to reduce emissions', ABN AMRO, 24 November. Available at: https://www.abnamro.com/research/en/our-research/esg-economist-heating-technologies-to-reduce-emissions (Accessed: 2 July 2025)

1.2 Contribution from partners

Table 2: Contribution table

Partner	Contribution
15. White Research	Task leader. Deliverable writing
5. K-FLEX	Assigned reviewer. Deliverable review
1. CIRCE	Project Coordinator. Deliverable quality review

1.3 Relation to other project activity

Table 3: Relation to other project activities

Task	Relation to other project activities
T4.4 - Mapping challenges, perceptions and needs of stakeholders on the adoption of induction and microwaves heating technologies	The results will provide key insights for the development of targeted reskilling and upskilling modules (T14.5 – T16.5), on the identification of health and safety requirements (T4.3) as well on the elaboration of targeted communication strategies (WP14-16).

2. Objectives and methodological approach

The objective of **Deliverable D4.4, *Report on Stakeholder Needs*** is to provide an in-depth understanding of the challenges and expectations of stakeholders who are directly or indirectly involved in the transition toward electrified heating systems. **These stakeholders include manufacturing industries (particularly in rubber, plastics, food, and ceramics), equipment operators, and energy suppliers.** Their insights are crucial to ensuring that technological solutions are not only technically sound but also practically implementable and economically viable.

The research underpinning this report was conducted using a mixed-methods approach. **Desk research and a literature review were complemented by 12 semi-structured interviews**, enabling a multidimensional analysis of the current state of industrial electrification. Interview participants were drawn from across Europe and represented a broad spectrum of organisational roles, from technical directors and R&D leads to operations managers and energy planners.

This report serves to frame the relevance of stakeholder input to the wider goals of the JOULIA project. The adoption of electrified heating technologies cannot be isolated from the ecosystem in which they operate, grid infrastructure, market incentives, regulatory environments, and the human factor all play critical roles. **By systematically mapping the perceptions, barriers, and needs of these stakeholders, this deliverable provides actionable insights to support the design, implementation, and scaling of JOULIA's technologies.** Specifically, the findings will inform the development of targeted reskilling and upskilling modules (T14.5 – T16.5), the identification of health and safety requirements (T4.3) as well the elaboration of targeted communication strategies (WP14-16).

2.1 Methodology and Approach

WR began research activities with a focus on identifying the barriers, enablers, and perceptions of key stakeholder groups regarding electrification in industrial settings. A state-of-the-art review was undertaken as it is the established approach for consolidating recent literature and relevant published material, enabling the analysis of emerging trends, stakeholder attitudes, and technological developments in the field[11].

This research sought to explore the current landscape of industrial electrification, assess the challenges hindering its advancement, and highlight the opportunities and drivers that support its broader implementation.

To deepen the understanding of stakeholder perspectives on industrial electrification, **12 semi-structured interviews** were conducted across selected stakeholder groups, specifically from **manufacturing industries, energy suppliers, and system operators**. These interviews aimed to complement the literature review by providing nuanced, ground-level insights into the perceptions, needs, and barriers or enablers surrounding industrial electrification, with a focus on the adoption of advanced electrified heating technologies such as induction and microwave heating. The interviews also helped to translate international findings within diverse industrial contexts, revealing context-specific opportunities and constraints. **They served as a vital tool to identify knowledge gaps, validate**

[11] Reis, T. (2016). Real World Research. Available at: https://www.academia.edu/86033008/Real_World_Research?auto=download (Accessed 2 Jul. 2025).

assumptions, and uncover dynamics within industrial and energy ecosystems that are often overlooked in existing literature.

2.2 Selection of the interviewing method and development of the interview guide

Insights from the literature review informed the development of a **unified interview questionnaire**. Interviews were conducted in a semi-structured, virtual format, allowing interviewers the flexibility to adapt the sequence of questions and explore emerging topics through follow-up probes. This flexible structure supported a more natural flow of conversation and enabled the capture of deeper insights. Additional written interviews were also conducted as more relevant stakeholders were identified during the process. While the questionnaire items were grounded in literature findings, they served as guiding themes rather than a rigid script, ensuring that discussions remained open and respondent-driven. Since the objective was to generate new insights from the interviewees' perspectives, rather than to test predefined theoretical constructs, the semi-structured format was deemed most appropriate[12].

WR developed an **interview questionnaire accompanied by a dedicated consent form**, along with three tailored interview guides designed for different stakeholder groups. The interview questionnaire consisted of an introductory note and three core parts:

- **Introduction**: The interviewee was informed about the JOULIA project, the concept and the overall purpose of the interview.
- **Opening (warm-up) and background information**: The interviewee was asked some opening questions related to their background, familiarity and previous experience with industrial electrification as well as a series of background information, such as nationality and professional expertise.
- **Main part (core questions)**: The interviewee was asked about the industrial electrification state-of-play, including the key drivers and barriers to the adoption of electrified heating technologies, such as induction and microwave heating. The discussion also explored perceptions of the current policy and regulatory environment, potential improvements or incentives to support electrification, and the skills needed, along with existing gaps, for the effective implementation and management of electrified systems in industrial settings.
- **Closing (clean-up)**: The interviewee was asked to follow-up with any additional information or thoughts they would like to provide (e.g., short- and long- term roadmap towards industrial electrification).

The full versions of the consent form and interview questionnaire are provided in **Annex A**.

2.3 Types of interviewees and interview process

A total of 12 interviews were conducted using an ***aggregated sample*** drawn from the selected stakeholder groups presented in **Table 2** below. These groups included representatives from manufacturing industries, energy suppliers, and system operators, ensuring a diverse and relevant range of perspectives. Each interview lasted approximately 30 to 40 minutes, including the introductory and

[12] Bryman, A. (2012) Social Research Methods. Oxford: Oxford University Press. Available at: https://www.scirp.org/reference/referencespapers?referenceid=2407183 (Accessed: 2 July 2025)

closing sections. The interviews were carried out by White Research, who also handled all aspects of data collection and confidentiality. Upon completion, participants were thanked for their time and informed about the forthcoming development of this deliverable. All personal data and interview notes were securely stored by WR in accordance with the project's Data Management Plan.

Table 4: Overview of the selected stakeholder groups and sample composition

Stakeholder group	Description	Type of interviewees
Manufacturing Industries	• **Process and Energy Intensive Industries** with a focus on the rubber, plastic, ceramic and food sector	• Production Managers • Operation Managers • Process Engineers • Sustainability Officers • R&D Managers
Operators	• **Operators** that handle, monitor and adjust heating and control systems	• Equipment Operators • Maintenance Engineers • Technical Supervisors • Process Technicians • Quality Assurance Engineers
Energy suppliers	• A wider group, including **Energy Providers, Renewable Energy Companies and Grid System Operators**	• Energy Sales Managers • Key Account Managers • Energy Transition Specialists • Technical Advisors

WR also reached out to JOULIA's synergy projects to identify potential interviewees, as a joint activity under our ongoing collaboration aimed at multiplying and maximising impact.

2.4 Approach followed for the analysis

Once all individual interview reports were collected and consolidated into a single database by WR, a **qualitative analysis** process was undertaken to distil meaningful insights from the raw data. A thematic analysis approach was applied, which is commonly defined as a method for identifying, analysing, and reporting patterns or themes within qualitative data[13]. This method allowed for the systematic reorganisation of interview content into structured themes that reveal deeper meaning and context.

Thematic analysis was chosen for its flexibility and suitability in handling complex, open-ended responses. In this case, interview notes from the 12 semi-structured interviews were first categorised into organising themes based on the interview questions. These were then further refined into more granular basic themes, informed by insights from the literature review. Higher-level themes, such as barriers, drivers, opportunities, and needs, provided an overarching structure to the analysis.

Although pre-existing categories posed certain constraints for theory-building, the thematic framework allowed sufficient inductive flexibility to ensure that stakeholder perspectives were faithfully captured. To coherently present the findings, a thematic matrix was used. This matrix method provides a systematic way to organise and compare data across themes and stakeholder groups, enabling

[13] Braun, V. & Clarke, V. (2006) 'Using thematic analysis in psychology', Qualitative Research in Psychology, 3(2), pp. 77–101. DOI: 10.1191/1478088706qp063oa (Accessed: 2 July 2025)

meaningful comparisons. Supporting quotations were extracted from the interview notes to substantiate key points and add depth to the analysis.

Table 5: Extract example of the thematic matrix used for the analysis

High-level theme	Organising theme	Basic theme	Example quote	Stakeholder tags
Barriers	Technological limitations	Lack of adequate infrastructure	***"...the grid needs upgrades, right now it can't support full electrification"***	Manufacturing industries, Energy suppliers
	Financial constraints	High upfront cost of electrified systems	***"...up-front costs are too high, especially for smaller companies"***	Manufacturing industries
Drivers	Sustainability targets	Emission targets and climate regulation	***"... we need to cut emissions, and electrification helps us meet those targets"***	Manufacturing industries, Energy suppliers
Skills and capacity	Workforce adaptation	Lack of in-house expertise	***"...we need training or specialised hirings in domains such as energy efficiency and advanced control"***	Manufacturing industries, Operators

3. Key challenges, perceptions and needs across stakeholder groups

This section brings together findings from **desk research, literature review, and interview insights** to highlight key challenges, perceptions, and needs across (i) manufacturing industries, (ii) operators, and (iii) energy suppliers. Combining these sources allowed for a **well-rounded view** of the electrification landscape from both technical and practical standpoints.

The analysis was structured around six critical and interconnected dimensions: **technological**, **infrastructural**, **economic**, **policy and regulatory**, **organisational**, and **skills and human capital**. This multidimensional lens ensured a comprehensive understanding of the drivers and barriers influencing electrification efforts, capturing not only **system-level readiness and capability gaps, but also the evolving needs** within the workforce and regulatory environment.

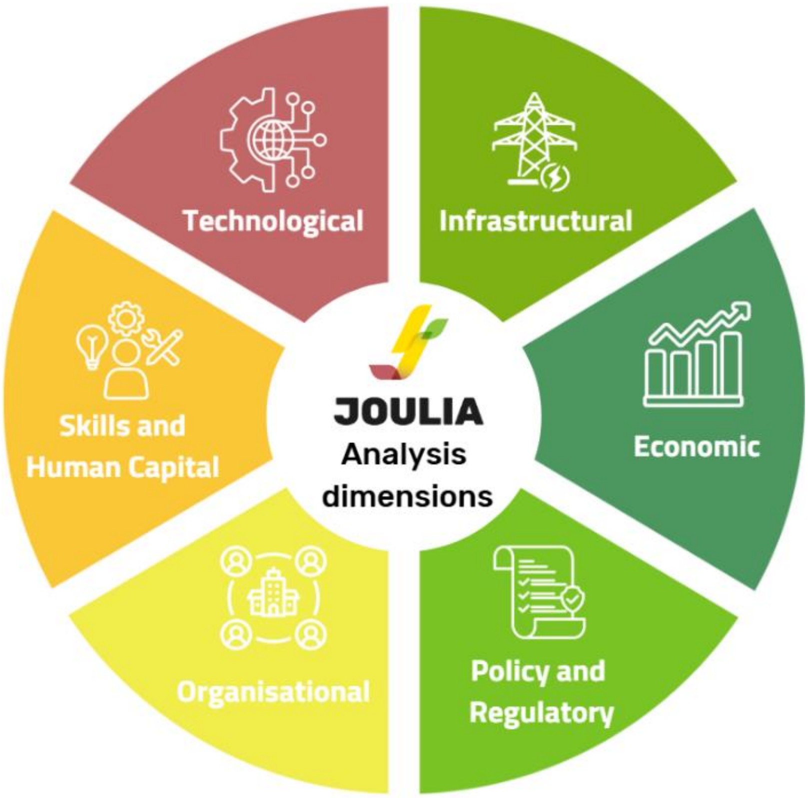

Figure 2: JOULIA analysis and findings dimensions

3.1 Manufacturing Industries

The following subsection explores all the different factors, based on the aforementioned dimensions, that shape electrification adoption, outlining both opportunities and barriers **as perceived by manufacturing industries**.

3.1.1 Technological dimension

Technological limitations and integration challenges

Electrification technologies are widely recognised in the literature as pivotal for decarbonising manufacturing, particularly in Process and Energy Intensive Industries (PIs and EIIs)[14]. These technologies improve energy efficiency, reduce emissions, and contribute to broader sustainability goals. **Induction and microwave heating, in particular, are valued for delivering rapid, localised heat with high precision and minimal energy waste.**

Studies indicate that induction heating can achieve 30–50% energy savings compared to conventional fossil-fuel-based methods, due to direct material heating and reduced thermal losses. It also enables 50–70% faster heating times, greater precision and control, and reduced maintenance through remote diagnostic capabilities[15]. Microwave technologies offer selective volumetric heating, enabling shorter processing times, lower energy use, and the elimination of combustion-related emissions. Together, these technologies contribute meaningfully to lowering the carbon footprint of PIs[16].

However, **the literature also identifies several technological and implementation challenges**. Induction systems depend on costly components, such as power electronics and cooling systems, and are limited by the inductor's low adaptability and lack of interchangeability, which hinders their use in heating complex geometries and reduces flexibility in multi-product environments. Microwave systems face scaling limitations, non-uniform heating, and integration difficulties. Retrofitting them into existing production lines, such as in ceramics or food drying, can be problematic due to material compatibility and production scale mismatches[17,18].

Insights from expert interviews strongly echoed the findings from the literature, adding practical context to the benefits and challenges of electrification technologies. One innovation director remarked, ***"..Induction is not just about heating; it's about precision, speed, and energy savings. It helps us hit our sustainability targets while improving our bottom line,"*** highlighting how the technology simultaneously advances environmental and economic goals. Another expert underscored the complexity of implementing microwave systems: ***"..You can't just plug in a microwave system. You have to rethink the whole process layout and design around it. That takes investment and trust in the technology."*** These reflections underscore the systemic nature of adopting advanced thermal technologies, where integration often requires not only new equipment but also reconfigured processes and operational mindsets.

[14] Department for Energy Security and Net Zero (2024) Electrification call for evidence: Formal summary of responses. Available at: https://assets.publishing.service.gov.uk/media/66e013650f4ba0621b086702/electrification-call for evidence formal summary of responses.pdf (Accessed: 2 July 2025)
[15] ESC Induction (2025) Why manufacturers are switching to induction heating. Available at: https://www.escinduction.com/why-manufacturers-are-switching-to-induction-heating (Accessed: 2 July 2025)
[16] International Energy Agency (2022) Industry – Topics. Available at: https://www.iea.org/energy-system/industry (Accessed: 2 July 2025)
[17] Verougstraete, B. et al. (2025) 'Advancements and challenges in electric heating for enhanced temperature swing adsorption processes', *Separation and Purification Technology*, 353, 128522. Available at: https://www.sciencedirect.com/science/article/pii/S1383586624022615 (Accessed: 2 July 2025)
[18] El-Mashad, H. M. et al. (2017) 'Application of induction heating in food processing and cooking', *Food Engineering Reviews*, 9(2), pp. 82–90. DOI: 10.1007/s12393-016-9156-0 (Accessed: 2 July 2025).

Challenges around adoption were especially evident among small and medium-sized enterprises (SMEs), which typically face resource constraints, limited technical capacity, and greater aversion to technological risk. A process engineer emphasised this point, stating, ***"..We need smarter, more flexible systems. It's not one-size-fits-all, especially in ceramics and polymers."*** This highlights a critical need for adaptable, modular solutions that can accommodate diverse product lines and materials without demanding complete process overhauls. Overall, the interviews reinforced the literature's view that while induction and microwave heating offer compelling advantages, their widespread deployment depends on overcoming integration barriers, and developing scalable, user-friendly technologies.

3.1.2 Infrastructural dimension

Infrastructure limitations

The literature identifies **grid capacity and infrastructure as critical barriers to industrial electrification**. Global power networks have struggled to keep pace with the rapid deployment of renewables and the surge in grid connection requests, revealing a **widening gap between decarbonisation ambitions and infrastructure readiness**[19]. Technically, these challenges stem from **ageing grid components, limited transmission and distribution capacity, and legacy systems designed for centralised fossil-based generation**. Such systems are often ill-suited to handle decentralised, variable renewable energy sources, leading to grid congestion, voltage instability, and frequency fluctuations, especially during periods of high demand or intermittent supply. While emerging technologies such as battery storage and smart energy management offer a partial solution, the absence of scalable and flexible grid infrastructure remains a major bottleneck for electrifying EIIs[20].

Interview findings validated these concerns. Several participants cited limited access to reliable renewable electricity and inadequate grid support as key constraints. A technical director from a green ammonia initiative explained, ***"..We installed our own solar arrays to bypass grid constraints. It's not just about going green, it's about being independent and controlling costs."*** Another site manager at a steel processing plant remarked, ***"..We invested in battery storage to stabilise our energy use, but without a grid that can flex with our load and generation, it only takes us so far."***

Supply chain challenges

Compounding these challenges are **severe supply chain disruptions**. Procurement times for critical components, such as power transformers and high-voltage cables, have doubled since 2019, with lead times reaching up to four years for transformers and over five years for direct current cables. **Rising costs and long delays are placing additional strain on project timelines and budgets**. Although manufacturers are expanding capacity, efforts are slowed by **uncertainties around long-term demand**

[19] REN21 (2024) *Renewables 2024 Global Status Report – Energy Systems & Infrastructure (Module 4: Systems)*. REN21 Secretariat, Paris. Available at: https://www.ren21.net/wp-content/uploads/2019/05/gsr2024_SYSTEMS_module.pdf (Accessed: 2 July 2025)

[20] Wattstor (n.d.) Overcome grid constraints. Available at: https://wattstor.com/insight/grid-constraints/#:~:text=Capacity%20constraints%20occur%20when%20the,and%20lower%2Dvoltage%20distribution%20networks.&text=Congestion%20in%20lines%20due%20to%20high%20demand%20or%20inadequate%20infrastructure (Accessed: 2 July 2025)

and skilled labour shortages. These issues come at a pivotal moment, with more than 1,600 GW of advanced-stage solar and wind projects currently awaiting grid connection[21,22,23,24].

3.1.3 Economic dimension

High up-front investment challenges

Despite the compelling efficiency and decarbonisation potential of electrified heating technologies, the literature highlights **high upfront investment as a major economic barrier**. The cost of critical components, such as induction coils, power electronics, and control systems, can be prohibitively expensive, particularly for SMEs[25]. Electrified technologies often involve **long payback periods, and expected financial returns can be uncertain**, especially in sectors operating with tight margins.

Interviewees agreed with desk research findings, frequently citing cost as the primary hurdle to adoption. As a sustainability lead from a flooring manufacturer noted, ***"..The cost is the number one concern. Even when the ROI is promising, it's hard to push investment."*** On the other hand, some stressed that once this initial barrier is overcome, technologies like **microwave and induction heating can extend equipment life spans and improve process efficiency** helping to offset upfront costs over time.

To bridge the gap between potential and investment hesitancy, several interviewees underscored the importance of **real-world demonstrations**. Pilot projects that showcase the technical and economic viability of electrified heating systems were seen as critical for facilitating transition decisions and building confidence among firms. One process engineer highlighted, ***"..We need to see it working, on-site, in real conditions, before leadership can agree to make this kind of transition."***

Electricity costs constraints

The literature highlights **electricity price volatility as a key barrier to industrial electrification**. For energy-intensive sectors, where energy makes up a significant share of operational costs, unpredictable electricity prices introduce financial risk and complicate long-term planning. This uncertainty can discourage firms from transitioning away from fossil fuels, even when the technical feasibility of electrified heating is well established.

Interviewees strongly reinforced these concerns. Many pointed to the **high and fluctuating cost of electricity relative to natural gas as the single greatest obstacle to adoption**. As one energy manager at a metal processing firm explained, ***"..It's hard to justify switching when electricity prices are unpredictable, the risk is still too big."*** Concerns about international competitiveness, especially in sectors exposed to global markets, were also frequently raised. Without stable and affordable electricity, firms are reluctant to invest in electrified heating technologies that could compromise their cost position.

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[21] ACER (2024) Monitoring Electricity Infrastructure. Available at: https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER_2024_Monitoring_Electricity_Infrastructure.pdf (Accessed: 2 July 2025)

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[24] Evans, L. et al. (2012) '[Title]', Energy Policy. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0301421512003709 (Accessed: 2 July 2025)

[25] UIHM (n.d.) Advantages and disadvantages of induction heating technology. Available at: https://www.uihm.com/pdf/Induction-Technology/Advantages-and-disadvantages-of-induction-heating-technology5.pdf (Accessed: 2 July 2025)

3.1.4 Policy and Regulatory dimension

Policy landscape limitations

The literature points to a lack of coordinated and targeted policy support as a key barrier to the widespread adoption of electrified heating technologies in industry. While EU and national funding schemes exist to support industrial innovation and decarbonisation, these programmes often prioritise more established technologies, such as solar PV, wind, or hydrogen, over solutions like microwave or induction heating.

Interviewees consistently noted this mismatch, emphasising that **electrified heating technologies are frequently overlooked in current support mechanisms**. Several stressed that policy frameworks need to evolve to better reflect the specific needs of process industries, and to offer consistent, long-term incentives that reduce investment risk and support the commercialisation of emerging technologies. As a technical director from the ceramics industry remarked, ***"..Electrified heating is still seen as experimental in many circles. Proving the technology is essential before incentives kick in, we need industry to be more involved in shaping the regulatory and funding landscape."***

Taxation and regulatory constraints

One of the most cited issues, both by literature and interviewees, is the **taxation imbalance.** Electricity, whether renewable or not, is often taxed more heavily than fossil fuels, which undermines the financial incentives to switch to electrified heating. Additionally, current carbon pricing schemes remain too low to meaningfully influence industrial behaviour. Regulatory hurdles such as **lengthy permitting processes for grid upgrades and unclear technical standards** further slow progress. Interviewees cite that, in some regions, securing approval for transmission-level grid connections can take over a decade, far outlasting the installation timelines for renewable generation.

3.1.5 Organisational dimension

Mindset and leadership challenges

Organisational inertia remains a significant barrier to the electrification of industrial heating processes. As one R&D lead described, ***"..In this industry, the mindset is: if it works, don't fix it."*** This outlook is particularly persistent in mature sectors where legacy fossil-fuel systems continue to operate reliably, and change is often perceived as costly, disruptive, or risky.

Beyond technical hesitancy, **leadership commitment** plays a critical role. Firms with strong executive buy-in and a clear sustainability agenda were notably more advanced in planning or piloting electrification projects. In contrast, companies without senior-level engagement or clearly defined decarbonisation targets showed lower levels of readiness. Interviewees also emphasised the value of internal champions, individuals or teams who actively advocate for change, connect technical and strategic goals, and help navigate institutional resistance.

Skills and workforce challenges

Skilling and workforce capacity emerged as parallel challenges. While large firms with proactive skilling strategies are beginning to adapt, many organisations, particularly SMEs, struggle with limited access to personnel qualified to implement and manage complex, high-voltage heating systems. As one respondent from a mid-sized manufacturing firm noted, ***"..It's much harder for smaller companies. We can't afford to take people off the line for weeks of training, even if the technology is promising."***

In parallel, a recurring theme across interviews was the skills gap. ***"..You can't just hire any technician to run these systems"***, explained a sustainability director. ***"..You need specialists; people who understand energy efficiency, system integration, and control systems. That's why we're investing in training."*** Interviewees frequently highlighted topics such as energy efficiency, flexibility, energy storage, sustainability, energy management, and temperature control as critical areas of focus. They also noted that many companies are already addressing these through internal training programs, specialised hiring, or partnerships with universities to build the necessary expertise.

3.1.6 Needs to overcome barriers

Both the literature and interviewees highlight the urgent need for **tailored, scalable, and adaptable solutions** to enable the broader adoption of electrified industrial technologies. Unlocking the full decarbonisation potential of electrification requires overcoming existing technological limitations and providing firms with **targeted financial incentives, harmonised policy frameworks, and robust institutional support**.

Specifically, more **targeted, streamlined, and predictable policy frameworks** are essential. This includes rationalising energy taxation to create parity between electricity and fossil fuels, strengthening carbon pricing to more accurately reflect environmental costs, ensuring stable and transparent electricity markets, and broadening the eligibility criteria for funding to include a wider range of electrified heating technologies. These measures are key to lowering investment barriers, boosting confidence among manufacturing industries, and accelerating the transition to low-carbon industrial processes.

Coordinated action is also needed to address infrastructure and systemic constraints. **Transparent infrastructure planning, streamlined permitting processes, and improved procurement strategies** are all critical. Building **more resilient and diversified supply chains** will enhance infrastructure readiness and facilitate the deployment of electrified solutions at scale.

Organisational barriers also need to be tackled. Firms must demonstrate **stronger leadership commitment** to electrification, underpinned by a clear sustainability vision and a culture that embraces innovation and risk-taking. **Targeted training, knowledge-sharing initiatives, and participation in industry networks** can help organisations overcome internal inertia. Clear and consistent policy signals further empower businesses to move beyond hesitation and actively pursue electrification strategies.

Addressing workforce challenges is equally crucial. There is a clear need for **expanded, accessible training programs** tailored to the technical skills required for electrified heating technologies. Support for SMEs is particularly vital, financial incentives can facilitate workforce upskilling without interrupting operations. **Collaboration between industry, education providers, and policymakers** is essential to develop a pipeline of specialists capable of managing advanced energy systems. Promoting knowledge-sharing networks and disseminating best practices will help close the skills gap and support widespread technology adoption.

In summary, manufacturing industries generally view electrification as a critical opportunity for enhancing energy efficiency and achieving sustainability goals. However, they also recognise significant challenges, particularly around costs, infrastructure, and workforce readiness that must be addressed to make widespread adoption viable and economically attractive.

3.2 Operators

The following subsection explores all the different factors based on the aforementioned dimensions, that shape electrification adoption, outlining both opportunities and barriers **as perceived by operators**.

3.2.1 Technological dimension

Operating and monitoring challenges

Operators are central to the successful adoption of electrified heating technologies, acting as the key link between advanced systems and existing production processes. While these technologies are known for benefits such as **improved safety, greater process precision, and reduced emissions, they also introduce new operational complexities**. Induction heating demands continuous real-time feedback and system adjustments, which contrast with the more predictable behaviour of traditional gas burners. Similarly, microwave heating requires precise thermal management due to localised hot spots and high electric field strengths, increasing the need for advanced process monitoring[26,27,28].

Interviewees validated these points, highlighting how the complexity and reliability concerns of electrified systems slow adoption. A mid-sized plant operator captured this: ***"..The systems are complex, too complex for facilities used to running on gas burners. And if it fails, we can't afford downtime."*** Operators often face steep learning curves in understanding system dynamics, especially in environments with high electrical noise. Additionally, an R&D manager emphasised the critical nature of precise temperature and process control in microwave heating: ***"..Temperature and process control is critical. Even a slight deviation can result in a different product."*** These insights underscore the increased responsibility placed on operators and the elevated risk of process disruptions.

Safety challenges

Safety perceptions also differ significantly between technologies, with operators drawing clear distinctions between induction and microwave heating. **Induction heating is generally well accepted and seen as safer than open-flame methods**, primarily due to its precise, localised heating and the absence of combustion. Risks such as burns or electric shocks are viewed as manageable with standard precautions like **PPE, regular maintenance, and accessible emergency shut-offs**. Concerns around EMF exposure are minimal, with operators considering them low-risk when basic protocols are followed.

In contrast, **microwave heating continues to face significant hesitation.** Operators often associate it with harmful radiation, despite strong safety evidence and protective shielding. The discomfort is heightened by a lack of familiarity and unease with working in close proximity to the equipment. Many operators expressed that safety measures are poorly communicated, reinforcing uncertainty and resistance. As one process lead noted, ***"..There's no evidence of harmful microwave effects, but operators still see it as radiation, especially being so close. Skill levels are low, they're wary of new technologies, and we really need someone dedicated to safety to drive trust and adoption."*** This

[26] Verougstraete, B. et al. (2025) 'Advancements and challenges in electric heating for enhanced temperature swing adsorption processes', *Separation and Purification Technology*, 353, 128522. Available at: https://www.sciencedirect.com/science/article/pii/S1383586624022615 (Accessed: 2 July 2025)
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[28] Jones, D.A., et al. (2002) 'Microwave heating applications in environmental engineering—a review', Resources, Conservation and Recycling, 34(2), pp. 75–90. DOI: 10.1016/S0921-3449(01)00088-X. Available at: https://www.sciencedirect.com/science/article/pii/S092134490100088X (Accessed: 2 July 2025)

underscores the **need for dedicated safety roles, clear protocols, and hands-on engagement to build operator confidence in emerging systems.**

3.2.2 Infrastructural dimension

Operators rarely cite broader infrastructure issues like grid capacity or renewable integration; those concerns typically fall to technical and engineering or managerial departments. Nevertheless, they do experience indirect effects, such as disrupted workflows, **highlighting the need for more seamless infrastructural integration.**

3.2.3 Economic dimension

Economic considerations, such as capital expenditure, electricity pricing, and return on investment, are generally beyond the remit of operators. These decisions are handled at the managerial or strategic level. Still, **operators are often aware of and affected by cost-driven decisions, such as delayed technology upgrades or restricted access to new equipment**. In some cases, resource limitations translate into understaffing or pressure to maintain productivity with outdated systems, subtly reinforcing resistance to technological change.

3.2.4 Policy and Regulatory dimension

Operators tend to have limited direct exposure to policy or regulatory frameworks governing electrification, carbon pricing, or funding eligibility. These elements are largely navigated by regulatory affairs teams or senior executives. Nonetheless, operators often experience downstream effects, such as the **adoption of unfamiliar systems driven by compliance needs, or procedural changes linked to new safety or emissions standards**. When not accompanied by adequate communication and training, such shifts can increase uncertainty and resistance at the operator level.

3.2.5 Skills & Human Capital dimension

From the operator perspective, the shift to electrified heating technologies introduces a notable adjustment in day-to-day responsibilities. Operators cited feeling underprepared to manage the increased complexity of systems like induction and microwave heating, which require greater technical fluency than traditional combustion-based equipment. As one operator cited, ***"..It's not just about operating a machine, you need to understand energy flows, feedback, and control settings in real time."*** These concerns directly validated what many manufacturing industry representatives also noted: that the successful adoption of electrified heating depends not only on system design but also on the skills and capacity building of those handling them. Both groups stressed the lack of accessible, hands-on training, especially in smaller firms, where formal upskilling is often limited. **Operators repeatedly emphasised the need for practical, application-based learning focused on energy efficiency, temperature control, and system integration**, echoing broader calls from firms to prioritise workforce development alongside technological innovation.

3.2.6 Needs to overcome barriers

To fully leverage the potential of electrified heating technologies, **operators require targeted support that addresses both technical and human-centric challenges.** This includes the development of tailored training programs that go beyond theoretical instruction, **offering hands-on, system-specific learning focused on real-time monitoring, control systems, and safe operation**. Addressing concerns around system complexity and reliability through transparent communication, operator-focused demonstrations, and clear standard operating procedures is also essential.

Safety remains a critical priority. Building trust in technologies like microwave and induction heating will require **proactive communication about health risks, alongside visible safety measures.** These include shielding, clear signage, emergency shut-off protocols, and personal protective equipment (PPE), all tailored to the specific characteristics of each technology. Several interviewees highlighted the value of designating on-site safety leads to help embed these practices and foster confidence among teams.

Ultimately, structured involvement of operators in the rollout of new systems, paired with strong training and robust safety protocols, will be essential to bridging the gap between innovation and day-to-day production practice.

3.3 Energy Suppliers

The following subsection explores all the different factors based on the aforementioned dimensions, that shape electrification adoption, outlining both opportunities and barriers **as perceived by energy suppliers**.

3.3.1 Technological and infrastructural dimension

The literature identifies **energy suppliers as critical enablers of industrial electrification**, tasked with managing rising energy demand, especially from high-load, high-precision processes like induction and microwave heating, while integrating variable renewable energy sources reliably and sustainably. **This transition places growing strain on both the digital and physical aspects of the grid infrastructure**. On the technological front, advanced grid management tools such as **dynamic line rating, smart meters, real-time telemetry, and automated dispatch systems** are increasingly necessary to maintain stability and optimise the balance between supply and demand. However, despite the rapid expansion of renewable generation, the deployment of these digitalisation technologies often lags behind, particularly in less developed regions. This digital gap restricts grid operators' ability to monitor and respond effectively to the complex, non-linear load profiles introduced by electrified industrial processes, which are characterised by sharp peaks, temporal clustering, and regional variability. To address these challenges, there is growing interest in modelling tools like **digital twins** that simulate grid behavior, improve resilience, and enable predictive maintenance.

Simultaneously, physical grid infrastructure presents significant bottlenecks. The literature points to the **lengthy timelines and high costs associated with upgrading substations and extending transmission lines** as major impediments to timely industrial electrification. In mature markets, **regulatory hurdles, fragmented planning processes, and local opposition to new infrastructure projects** cause considerable delays[29]. For instance, in Europe, it can take a decade or more to plan, permit, and construct high-voltage transmission lines, far longer than the development cycles for new renewable generation. These delays often stem not only from technical limitations but also from institutional inertia and capacity constraints within the energy sector.

Interviewees largely aligned with the literature in emphasising the operational pressures on energy suppliers to manage fluctuating industrial demand alongside intermittent renewable supply. A project manager at a regional utility summarised this challenge: ***“..Smart grids and demand flexibility aren’t optional anymore, they’re essential to keep the system stable as electrification ramps up.”*** Several participants stressed the importance of advanced digital control systems and real-time data to manage these evolving load patterns. A grid operations engineer noted, ***“..Without accurate, real-time visibility into industrial demand, we’re constantly reacting instead of planning.”***

Experts also highlighted the growing inadequacy of existing infrastructure and planning frameworks. While renewable generation is being deployed at pace, grid upgrades lag behind, often due to regulatory inertia and fragmented coordination. An energy consultant with experience in large-scale electrification projects explained, ***“..It can take years to upgrade a substation. That’s time industries, especially***

[29] IEA (2025) ‘Rising component prices and supply chain pressures are hindering the development of transmission grid infrastructure’, IEA News. Available at: https://www.iea.org/news/rising-component-prices-and-supply-chain-pressures-are-hindering-the-development-of-transmission-grid-infrastructure (Accessed: 2 July 2025)

smaller ones, don't have if they're serious about decarbonising." This view was echoed by a distribution system planner, who observed, ***"..There's still a disconnect between the pace of industrial electrification and what the grid can realistically deliver in terms of capacity and responsiveness."***

In discussing demand-side response mechanisms, several experts criticised the oversimplification of industrial loads within current schemes. ***"..Not all flexible loads are equal,"*** said a senior system analyst. ***"..Treating them as interchangeable ignores the local grid constraints and timing issues that enable effective demand response."*** Coordination gaps between TSOs and DSOs were also identified as a persistent bottleneck, particularly for smaller industrial actors who are rarely included in strategic planning. A policymaker close to regulatory design concluded: ***"..If we want industries to be part of the solution, we need to recognise the real operational and financial barriers they face, not just assume they'll respond to price signals."***

3.3.2 Economic dimension

Economic incentives remain a significant barrier to industrial electrification from the energy suppliers' perspective. High electricity costs, including taxes, network fees, and legacy levies originally designed for fossil fuel power systems, often make grid-based renewable electricity less competitive compared to fossil fuels, particularly for EIIs[30]. This misalignment discourages electrification uptake and encourages industrial users to seek alternatives like self-generation. For instance, widespread industrial self-generation using onsite renewables can reduce grid demand flexibility, complicating load balancing and grid management.

Energy suppliers interviewed validated these economic concerns, reflecting a shared awareness of the challenges posed by current pricing structures. One regional utility project manager stated, ***"..We see many industrial customers generating their own power from solar because the grid costs are simply too high."*** This trend toward self-generation aligns with observations from manufacturing industries, underscoring a broader industry response to economic pressures.

Interviewees highlighted that addressing these economic barriers requires coordinated policy reform. They advocated for dynamic pricing models that better reflect grid conditions and incentivise flexible consumption patterns, which would benefit both suppliers and industrial users. This consensus among energy suppliers and manufacturing industries indicates a critical need for aligned economic incentives to foster electrification and facilitate grid integration of renewables.

3.3.3 Policy and Regulatory dimension

The regulatory landscape governing industrial electrification and grid infrastructure remains fragmented and inconsistent, even in regions with ambitious renewable energy targets. Studies highlight a disconnect between national decarbonisation objectives for industry and energy infrastructure planning processes, leading to misaligned timelines and priorities. Regulatory approval procedures for grid upgrades or new connections often lag behind the pace of industrial development, creating bottlenecks.

[30] Eurelectric (2025) Unlocking the untapped potential of industrial electrification. Available at: https://www.eurelectric.org/in-detail/unlocking-the-untapped-potential-of-industrial-electrification/ (Accessed: 2 July 2025)

Additionally, funding streams for grid digitalisation and electrification technologies are typically siloed and poorly coordinated with industrial support programmes. The IEA emphasises that **governance frameworks for electricity grids generally lack the ambition and coordination** evident in renewable generation policies, limiting the speed of industrial electrification[31].

Energy suppliers and innovation leads consistently voiced concerns that regulatory incentives and policies are poorly aligned with industrial electrification needs. An innovation lead involved in grid flexibility noted, ***"..Policy incentives are often misaligned. We need a clearer link between funding, grid planning, and industry decarbonisation goals."*** This view resonates with industry representatives who have similarly flagged the need for integrated planning and streamlined permitting processes. Interviewees stressed that the lack of coherence between energy infrastructure regulations and industrial timelines hinders the efficient rollout of electrification technologies and grid upgrades.

3.3.4 Organisational and Skills and Human Capital dimension

Organisational readiness within energy suppliers is increasingly recognised as a critical enabler for industrial electrification, requiring flexibility not only in technology but also in internal structures and human capital. **The shift towards managing complex industrial loads demands that suppliers evolve from traditional commodity providers to integrated system operators, coordinating efforts across policy compliance, digital technology management, and customer engagement**. The IEA notes that many suppliers are forming partnerships with technology firms and academic institutions to build the multidisciplinary expertise necessary for this transition, fostering innovation and accelerating capability development.

Senior leaders emphasised that organisational flexibility is as vital as technical adaptability. A senior utility director explained, ***"..Flexibility isn't just technical, it's organisational. You need people who understand the whole system."*** To this end, utilities are building integrated teams that bridge grid operations, regulatory frameworks, and customer relations. Joint ventures and collaborations with external technology and research partners are key strategies to expand knowledge and operational capacity in response to new industrial electrification demands.

Simultaneously, the transition to flexible, digitalised energy grids requires a workforce equipped with advanced skills in areas like data science, software engineering, and power electronics, fields historically underrepresented within energy suppliers. To address this, many utilities have initiated reskilling programs and partnered with academic institutions to develop specialised curricula focusing on smart grid technologies and modern energy systems.

An energy director highlighted this workforce transformation, stating, ***"..We're working with third parties and forming specialised partnerships. This isn't just about hiring more engineers, it's about a fundamental shift in how we operate."*** Interviewees stressed the importance of building interdisciplinary teams and fostering continuous learning, warning that without substantial investment in human capital, technological and policy advances would have limited impact.

[31] IEA (2025) 'Rising component prices and supply chain pressures are hindering the development of transmission grid infrastructure', IEA News. Available at: https://www.iea.org/news/rising-component-prices-and-supply-chain-pressures-are-hindering-the-development-of-transmission-grid-infrastructure (Accessed: 2 July 2025)

3.3.5 Needs to Overcome Barriers

Overcoming the complex interplay of technological, infrastructural, regulatory, and organisational challenges in industrial electrification demands a multifaceted approach. **Accelerated deployment of smart grid technologies**, such as real-time monitoring, predictive analytics, and automated control, will be critical for managing the variable and growing demand from electrified industries. Additionally, **streamlining and integrating grid planning processes** can help reduce delays in infrastructure upgrades while maintaining regulatory compliance and public engagement. **Holistic coordination between TSOs and DSOs** is needed to enable effective grid management, while strengthened collaboration between energy suppliers and industrial consumers will facilitate demand response, load shifting, and the deployment of energy storage solutions. Advanced digital modelling tools, such as digital twins, can further support infrastructure resilience by enabling precise simulation, proactive maintenance, and long-term planning.

Economic and market-related barriers also require targeted interventions. **Electricity pricing structures must be reformed** to support grid-based renewable energy and industrial electrification. This includes implementing time-of-use tariffs that incentivise off-peak consumption, removing fossil fuel–favourable tax distortions, and providing financial incentives for industrial participation in flexible demand programs. Energy suppliers need clearer regulatory mandates to actively engage industrial users in demand response initiatives, fostering grid flexibility while supporting decarbonisation goals. Broader economic reforms must carefully balance affordability, grid reliability, and sustainability to enable a just and effective energy transition.

On the regulatory front, reforms must focus on **harmonising permitting procedures and aligning grid development with industrial decarbonisation timelines**. Improved coordination across funding, planning, and regulatory bodies is essential to remove bottlenecks and streamline investment in necessary infrastructure. Prioritising industrial loads in upgrade schedules and embedding electrification into national energy and climate strategies can fast-track industrial transitions.

Organisationally, energy suppliers must build **internal capabilities** that align innovation, regulation, and workforce development. Developing cross-functional teams skilled in grid operations, compliance, and digital technologies is key to navigating the complexities of modern energy systems. Investment in workforce reskilling and upskilling, particularly through partnerships with educational institutions and technology providers, will help ensure a talent pipeline capable of managing the shift to digital, flexible, and decarbonised grids. Alongside technical skills, change management efforts should focus on fostering a systems-thinking mindset, encouraging interdepartmental collaboration, and embedding a culture of continuous innovation and agility.

Energy suppliers view industrial electrification as both a strategic opportunity and a complex operational challenge. While it enables decarbonisation and new service models, it also places unprecedented strain on outdated infrastructure and requires rapid digitalisation and organisational transformation. Without coordinated policy reform and investment in grid capacity, suppliers risk being unable to meet the evolving demands of electrified industries.

The table below summarises the main **enablers, barriers, and needs** identified across the three key stakeholder groups.

Table 6: Enablers, barriers and needs across stakeholder groups

Category	Enablers	Barriers	Identified Needs
Technological	High thermal efficiency of induction and microwave systems Rapid, localised heat delivery	High capital cost of components (e.g., induction coils, microwave generators) Limited adaptability for complex geometries System integration challenges (e.g., temperature control, electromagnetic compatibility)	Development of modular and flexible systems suitable for diverse industrial contexts Scalable solutions with real-world validation Enhanced control system precision and optimisation
Infrastructural	Deployment of on-site renewable energy (e.g., solar PV) Early-stage energy storage demonstrations (e.g., thermal, IoT-enabled)	Grid congestion and insufficient capacity for industrial loads Lengthy permitting processes for grid upgrades Inconsistent renewable energy availability	Strategic grid reinforcement and forward-looking planning Cost-effective and scalable storage technologies Investment in smart grid infrastructure and digital monitoring
Economic	Availability of EU funding mechanisms Long-term operational savings through improved energy efficiency	Volatility of electricity prices High upfront investment and uncertain ROI Electricity taxation that undermines low-carbon business cases	Predictable financial incentives and long-term funding instruments Fiscal reforms favouring electrification over fossil fuels Targeted support for early-stage industrial scale-up
Policy & Regulation	Alignment with EU Green Deal and SDG targets Decarbonisation mandates driving corporate commitments	Fragmented regulatory landscape Disproportionate taxation on electricity vs fossil fuels	Simplified and streamlined regulatory procedures Harmonised EU-level standards and technical guidelines Broader policy incentives supporting emerging electrification technologies
Organisational	Commitment from leadership teams to sustainability agendas Existing reskilling efforts in large enterprises	Organisational resistance to change Risk aversion in legacy-heavy industrial sectors	Promotion of innovation-oriented culture within firms Internal champions to advocate for electrification initiatives Integration of electrification into long-term corporate strategy

Category	Enablers	Barriers	Identified Needs
Skills & Human Capital	Workforce development initiatives in energy efficiency and digital control Collaborations with academic institutions	Insufficient technical expertise on induction and microwave systems Limited awareness and interest among operators	Multi-level training programs Standardised educational curricula focused on industrial electrification Practical, hands-on learning formats tailored to industrial contexts

Conclusions

The findings of D4.4 underscore the complexity and interdependence of factors shaping the adoption of electrified heating systems in industry. While induction and microwave technologies offer clear advantages in energy efficiency, emissions reduction, and process precision, their successful deployment hinges on a confluence of technical readiness, supportive policy, infrastructure availability, and stakeholder buy-in.

Across all three stakeholder groups, manufacturing industries, operators, and energy suppliers, there is a **strong consensus on the transformative potential of these technologies**. However, real-world adoption is significantly constrained by systemic barriers. These include high capital expenditures, electricity price volatility, fragmented policy frameworks, and insufficient grid capacity. Additionally, organisational inertia and limited access to specialised skills compound the challenge, especially for SMEs.

One of the most notable conclusions is the mismatch between innovation timelines and the institutional structures that govern energy, regulation, and workforce development. This disconnect risks stalling momentum unless proactively addressed.

To overcome these barriers, the report proposes several targeted actions:

- **Policy reform**: Align taxation and carbon pricing mechanisms to favour electrification. Simplify permitting for grid upgrades and support funding schemes that include emerging technologies like microwave and induction heating.
- **Infrastructure modernisation**: Accelerate grid reinforcement and digitalisation, including investments in smart meters, storage solutions, and demand-side flexibility mechanisms.
- **Workforce development**: Launch multi-tiered training programmes, particularly aimed at operators and SMEs, focusing on energy management, system integration, and process control.
- **Technology demonstration and validation**: Expand pilot projects and real-world demonstrations to provide proof-of-concept and reduce perceived investment risks.
- **Cross-sectoral coordination**: Foster collaborative frameworks that engage policymakers, energy providers, technology developers, and end users to ensure alignment of objectives and timelines.

In summary, the D4.4 report reinforces that **electrification is not solely a technical upgrade, it is a systemic transition that requires coordinated efforts across sectors, disciplines, and governance levels**. Findings from this report, will inform the development of targeted reskilling and upskilling modules (T14.5–T16.5), support the identification of health and safety requirements (T4.3), and shape tailored communication strategies (WP14–16).

By addressing the barriers and enabling conditions identified here, electrified technologies have the potential to support a significant shift in how industrial heat is generated and managed, advancing the EU's goals for climate neutrality and sustainable industry.

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Annex

ANNEX A

Informed consent form

INFORMED CONSENT FORM

Who we are:

On behalf of White Research SRL, we are contacting you in the framework of the JOULIA project, funded by the European Union under the Horizon Europe Programme for Research and Innovation. A detailed description of how JOULIA handles personal data is presented in the project's Privacy Policy that accompanies this Consent Form (see below).

Project: JOULIA – Electrification of industrial processes using induction and microwaves technologies (GA Number 101192555).

Partners involved:

#	Organisation name	Role	Address	Phone	E-mail
1	White Research SRL	Interview performance, data collection, storage and analysis	Avenue de la Toison d'Or, 67	+32 2 520 00 09	info@white-research.eu

Responsible persons:

#	Role	Name	E-mail
1	JOULIA Associate Project Manager	Stela Ntevetzaki	sntevetzaki@white-research.eu
2	JOULIA Associate Project Manager	Maria Kontogianni	m.kontogianni@white-research.eu

What do we need from you?

You have been invited to take part in this interview because you are part of one of the main target groups (manufacturing industries, operators, energy suppliers) of the JOULIA project.

You will be asked a series of questions related to (i) General information; (ii) Industrial electrification drivers; (iii) Industrial electrification barriers; (iv) Other aspects of industrial electrification (e.g., policy landscape, up-skilling and re-skilling needs).

This will ultimately help us better understand and shape the perceived barriers, opportunities, and incentives associated with the electrification of industrial processes. The interview is expected to last **no more than 30 – 35 minutes** and will be performed by White Research SRL, who will take written notes during the interview.

To effectively conduct this interview, we need to process some of your personal data (background information):

- Your professional info (organisation, job position, field of expertise).
- Your personal opinions on the subject matter.

Why do we need your data & what will we do with them?

We need your data to contact you in order to plan and carry out the aforementioned interview and to resolve any ambiguities, questions, and other issues that may arise after and as a result of the interview. We also need to keep your data in the written notes to keep track of the interview process. The project's deliverables that will be derived from the interview will not include your personal data or any other information that could identify you. Your personal data will remain on our written notes we will make during the interview.

We will mention only the stakeholder group you are part of (anonymously).

We will share your data with the other JOULIA project partners involved in this task and who will participate in the drafting of the relevant deliverables. We are also obliged to grant access to your data to:

- EU officials such as our Project Officer for purposes related to the project's evaluation;
- EU agencies and other authorities for project auditing purposes.

Your data will be stored internally by the JOULIA partnership throughout the duration of the project (November 2028). In particular, the data will be stored in a secured cloud environment of the project, where only project partners have access to.

We would also be very happy if you give us your consent to contact you in the future to ask you to participate in other project activities and also to inform you about the project's progress (e.g., by sending you a newsletter or similar messages).

How can you withdraw your consent?

You should know that you can withdraw your consent at any time by communicating either on the phone or by email with the responsible persons listed on the previous page. With regards to the informational messages and newsletters, you can always opt out by simply clicking the link "Unsubscribe" or something similar included at the end of all the relevant messages.

I hereby give my consent to the processing of my personal data needed for:

*(Please, tick the boxes below to confirm that you give us your consent for the respective subject. Any boxes left unticked mean that **you do not consent to the relevant subject**.)*

#	Consent Subject	Tick box

1	My participation in an interview that will be carried out by JOULIA to learn more about my experience and personal views on the enablers and barriers of electrification of industrial processes	
2	My participation in future activities of JOULIA	
3	Receiving newsletters regarding JOULIA activities	

____________________________ __________________ _____________________

Name of participant Date Signature

Interview Questionnaire | Est. Duration 30’

Part 1: Background information | Est. Duration 2’

1. **Could you please share your gender?**
2. **Could you please share your age?**
3. **Which of the following stakeholder groups do you associate with?**
   - ☐ Manufacturing Industries
   - ☐ Operators
   - ☐ Energy Suppliers

   What is your current role/ position within your organisation?
4. **What is the size of your organisation?**
5. **What geographical region does your work mainly focus on?**
6. **Do you hold expertise in a specific industrial sector?**
7. **Do you hold expertise in a specific process or electrification technology**?

Part 2: Industrial electrification drivers | Est. Duration 8’

1. **Are you aware of any factors driving the adoption of electrified heating technologies in industries?**
2. **In your opinion, what is the main driver of industrial electrification?**

Part 3: Industrial electrification barriers | Est. Duration 8’

3. **What are the key barriers to electrifying industrial processes?**
4. **In your opinion, what is the main barrier to industrial electrification?**
5. **What areas of improvement or innovation should be prioritised to overcome these barriers, and why?**

Part 4: Policy landscape | Est. Duration 4’

6. **Do you believe the policy/ regulatory support is sufficient when it comes to industrial electrification? Why or why not?**
7. **What policy and/ or (financial) incentives would you recommend for boosting industrial electrification?**

Part 5: Skilling and re-skilling | Est. Duration 4’

8. **What key skills are essential for effectively implementing and managing electrified systems?**

9. **How would you assess the current skill levels in relation to these requirements?**

Part 6: Final thoughts | Est. Duration 2’

At this point the interviewee is free to share his/her final thoughts, provide any comments or recommendations, and highlight anything important.

10. **Do you have any final thoughts or key takeaways you’d like to share?**

11. **What do you see as the next steps for electrifying industrial processes in the short term and what in the long-term?**