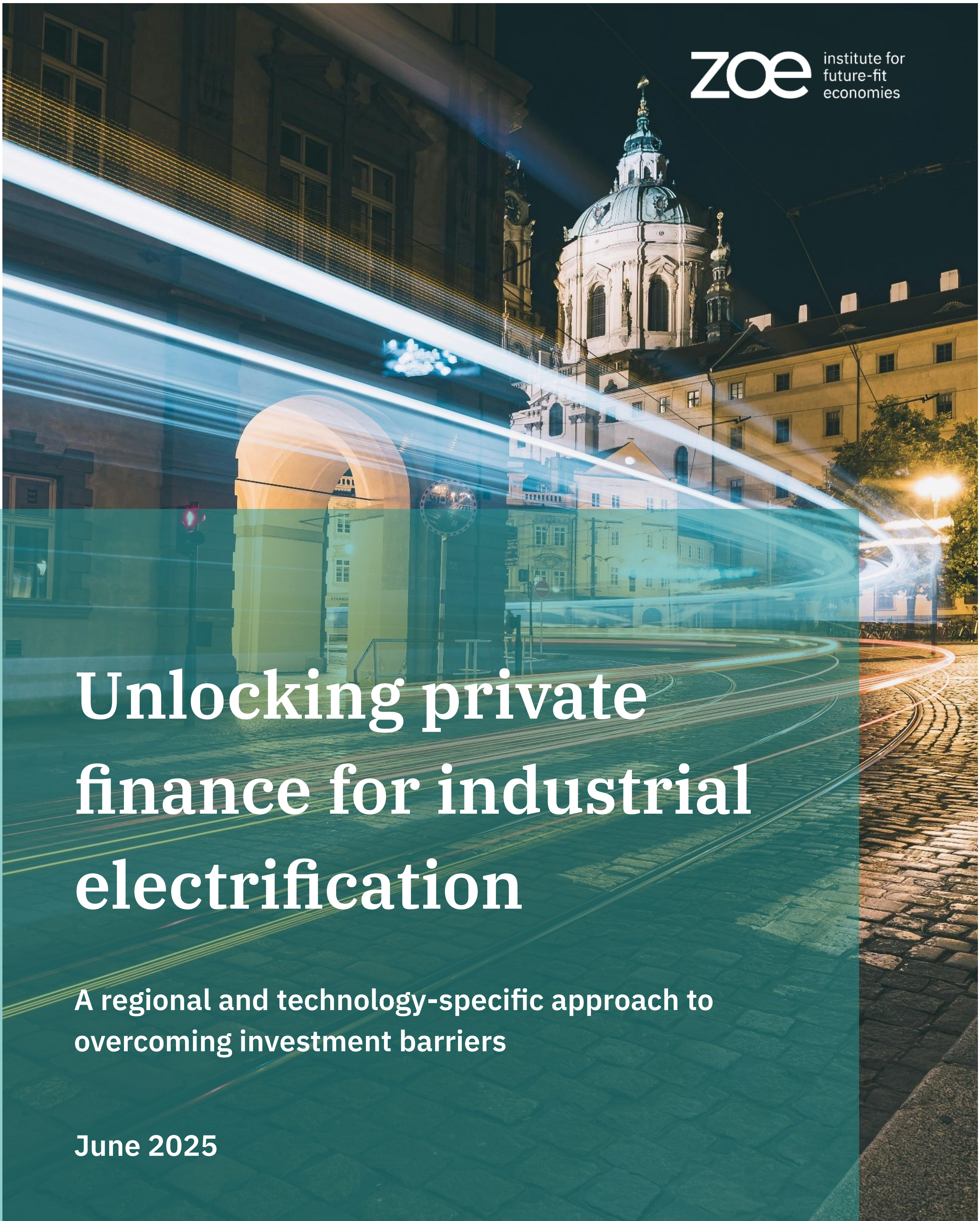

# Unlocking private finance for industrial electrification

**A regional and technology-specific approach to overcoming investment barriers**

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ZOE Institute for Future-fit Economies

# Imprint

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**Transparency**
The financial support of our funders is greatly appreciated and makes this work possible.

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# Table of contents

# Executive Summary

**Industrial electrification is essential to achieving the EU's climate objectives and to securing long-term industrial competitiveness. Yet current investment flows remain misaligned with this goal.** Fossil-based activities continue to attract substantial funding, while electrification technologies face underinvestment, particularly in regions with weaker investment conditions. Mobilising and redirecting private finance for industrial electrification at scale is critical and requires a nuanced understanding of the regional and technological barriers that shape investment decisions.

**This report provides decision makers across policy, finance, and industry with a practical framework to identify and address these barriers.** Using a clustering methodology, it categorises EU regions into five distinct regional profiles based on financial, technical, and institutional conditions that affect their industrial electrification readiness.

**Table 1**: Regional cluster profiles: characteristics and barrier levels for industrial electrification

| Number | Barrier Level | Countries | Description |
|---|---|---|---|
| Cluster 1 | Very Low Barriers | FI, PT, SE *(+ parts of ES, IE)* | Strong renewable energy (RE) potential, low operational costs, and largely decarbonised grids – making near-term, market-driven electrification feasible. |
| Cluster 2 | Low Barriers | AT, DE, DK, IE, NL | Combines excellent access to capital with mature industrial bases but faces high electricity costs and limited RE supply. |
| Cluster 3 | Moderate Barriers | BE, BG, ES, FR, LT | Middle-of-the-road regions with moderate investment conditions, characterised by favourable operational costs, average RE potential and electrification progress, but constrained by limited fiscal headroom. |
| Cluster 4 | High Barriers | EE, EL, HU, IT, SI, BG, HR *(+ parts of LT)* | These regions are challenged by high operating costs, weak financing conditions, and low grid decarbonisation. While industrial electrification rates and RE potential are high, this likely reflects legacy infrastructure rather than recent progress. |
| Cluster 5 | Very High Barriers | CZ, LV, PL, RO, SK | Most severe barriers, including limited access to finance, fossil-dependent grids, and low levels of industrial electrification. |

**To support differentiated policy responses, ZOE Institute's Private Finance Toolbox provides a structured approach to link investment barriers to suitable policy tools**. This report systematically links region- and technology-specific barriers to Toolbox categories, allowing for the identification of potential policy tools. These include:

- Measures to reduce capital and operational expenditure
- Initiatives addressing workforce challenges such as skills shortages and knowledge gaps
- Interventions promoting technological acceptance among decision makers

**Importantly, this is not a one-size-fits-all roadmap but a starting point. Decision makers are encouraged to integrate these insights with additional region- and technology-specific knowledge**. Engaging stakeholders through co-creative processes is essential to foster an inclusive, iterative approach that assesses feasibility and impact in the development of an optimal policy mix.

**By adopting this systemic, differentiated, and participatory approach, decision makers can unlock the full potential of industrial electrification across the EU** – accelerating the transition toward a more sustainable and future-fit industrial landscape.

# 1. Introduction

**The European Union (EU) is committed to become climate-neutral by 2050 – a target made legally binding through the European Climate Law. Achieving this goal will require a fundamental transformation of the EU's industrial sector.** The urgency of this transition is reflected in the current policy agenda: the Clean Industrial Deal with, for example, its Electrification Action Plan and Grid Package underscores the central role of electrification in achieving deep decarbonisation. Yet, progress remains uneven and the pace of investment in key sectors is not fast enough to meet 2030 and 2050 climate targets. Industry, as one of the highest energy consumers in the EU, accounts for a quarter of final energy consumption (Eurostat 2024a). Industrial decarbonisation is therefore essential for a successful climate-led transformation. Reducing industrial emissions, particularly from heat processes, will be critical for achieving near-term climate objectives while also supporting long-term competitiveness (Energy Independence Council, 2024).

**Electrification offers one of the most technically mature and economically efficient pathways for decarbonising industrial heat**. Clean technologies such as industrial heat pumps are already commercially available and can significantly reduce emissions in sectors like food, paper, and chemicals. Their technological readiness positions them as a cornerstone of short-term climate action and long-term competitiveness. However, deployment across the EU remains limited. The full potential of these technologies will not be realised without stronger policy signals, improved investment conditions, and strategic coordination across regions (Draghi Report, 2024; Fraunhofer ISI, 2024).

**A systemic understanding of investment barriers is essential.** Mobilising and redirecting private capital for industrial electrification requires more than isolated policy adjustments. It demands a systemic and holistic approach that identifies and addresses the full spectrum of investment barriers. These range from financial profitability concerns, such as high upfront costs, to real-economy implementation constraints, like skills shortages and deeper-rooted barriers, including power asymmetries and technological acceptance. Understanding and tackling this layered structure of investment barriers is critical to designing effective policy interventions that unlock private investment at scale. ▷▷ **see chapter 2**

**Regional and technological contexts matter. Investment barriers must also be understood in their regional and technological context.** Differences in barriers across regions include factors such as financing conditions, electricity prices, renewable energy potential, and grid decarbonisation readiness. Likewise, technologies such as industrial heat pumps face specific investment barriers such as capital expenditure, operational costs and technology acceptance. This report applies this dual lens to the investment challenge by analysing region- and technology-specific investment barriers. Taking industrial heat pumps as a representative case of electrification technologies, it maps region-specific investment barriers across the EU and identifies five regional profiles. These profiles provide a foundation for the design of more targeted and effective public policy responses. ▷▷ **see chapter 3**

**This complexity requires targeted policy intervention. One-size-fits-all approaches are unlikely to be effective**. A tailored approach, aligned with both regional disparities and technology-specific needs, is essential to unlock the full potential of industrial electrification.

**To support effective policy design, the report applies ZOE Institute's Private Finance Toolbox.** The Toolbox provides a structured approach to overcoming investment barriers at three levels: explicit, semi-explicit, and implicit. It assembles a wide range of policy tools to address specific investment barriers. It reveals that no single measure can address the full spectrum of investment barriers. Instead, a differentiated mix of policy intervention is needed. ▷▷ **see chapter 4**

**Some illustrative policy options include** *(non-exhaustive list)*:

- Public guarantees and green investment funds can help overcome high capital costs.
- Contracts for Difference and OpEx tax benefits can improve project bankability in regions with high energy prices.
- Feed-in tariffs and forward procurement can address supply chain or material input challenges.
- Fast-track permitting, grid access reforms, and one-stop-shops can reduce administrative inefficiencies.
- Training incentives and awareness platforms can help overcome skills shortages and resistance to change.
- Other or complementary tools may be required to match the unique combination of barriers in each case.

**This shows that enabling industrial electrification is not only a question of access to capital but also of addressing financial profitability concerns, real-economy implementation constraints and deeper-rooted barriers.**

# 2. Why the EU needs a technology- and region-specific approach

**Achieving industrial decarbonisation consistent with EU climate objectives will require the mobilisation and redirection of private investment toward industrial electrification.** Current estimates indicate that annual additional investments across all sectors must reach €477 billion by 2030 to meet EU climate targets (European Central Bank, 2025; I4CE, 2025). Although buildings and transport face the largest investment gaps to achieve this, the industrial sector stands out as a particularly strategic and cost-effective area for private investments. Industrial decarbonisation delivers high greenhouse gas (GHG) abatement per euro invested, especially through established technologies such as resistance heating, induction systems, and heat pumps (Institut Rousseau, 2024; Fraunhofer ISI, 2024). The technical potential is significant, with studies estimating that up to 90% of industrial process heat could be electrified using these mature technologies (Frauenhofer ISI, 2024; Waliszewska, 2024). Mobilising investment in industrial electrification therefore presents a major opportunity to accelerate decarbonisation, particularly in industrial heating processes (Rosenow et al., 2024).

**Mobilising and redirecting private capital for industrial electrification at the scale and urgency needed requires an understanding of both surface-level and deeper-rooted barriers to private investment.** Research and discussions with key stakeholders on industrial decarbonisation challenges highlight the urgent need for private finance to complement public investments (Energy Independence Council, 2024; European Central Bank, 2025). While limited access to capital remains a central concern, industries also face a range of financial profitability concerns such as high electricity prices and substantial capital expenditure requirements (Rosenow et al., 2024; Fraunhofer ISI, 2024). However, investment barriers extend beyond financial issues. Real-economy implementation constraints, such as labour shortages and a lack of specialised knowledge in supply chains, can delay or deter the adoption of electrification technologies in complex industrial settings. In addition, deeper-rooted barriers such as a low acceptance of new technologies and limited openness to change among investors, business leaders and political decision makers can further hinder investment (Energy Independence Council, 2024).

These combined challenges contribute to the continued reliance on fossil fuels for industrial heat processes in the EU, which remain heavily dependent on gas, coal, and oil despite the increasing availability of cleaner alternatives (Rosenow et al., 2024). This underscores the importance of identifying and addressing investment barriers through targeted public policy and establishing an enabling environment to unlocking private investment (Waliszewska, 2024).

**Investment barriers are context-specific and vary across EU regions. While many regions face high financing costs, this is not the case everywhere.** Other critical conditions such as fiscal capacity, cost of capital and renewable energy potential also differ significantly between regions. For example, Germany benefits from some of the lowest costs of capital for renewables globally, with a weighted average cost of capital as low as 1 to 2% for wind and solar, well below the EU average (International Renewable Energy Agency, 2023). These variations result in diverse starting points for industrial electrification and create unequal levels of readiness across the EU. These disparities can and should be addressed through a coordinated European approach that ensures all regions have the support needed to participate in the green transition (Bertram et al., 2024).

**Beyond regional disparities, different industrial sectors and technologies face distinct barriers that require tailored approaches.** Research indicates that up to 90% of the EU's remaining industrial energy demand could be met through direct electrification using existing technologies (Waliszewska, 2024). Only a limited number of energy-intensive sectors such as steel, metals, and chemicals cannot be fully electrified and should therefore be addressed separately in policy design. Several substitute technologies stand out due to their high technological readiness level (Energy Independence Council, 2024; Fraunhofer ISI, 2024). Large heat pumps, electric and electrode boilers, and deep geothermal energy offer promising, ready-to-use alternatives to natural gas across a wide range of industries (Energy Independence Council, 2024; European Commission JRC, 2023). These electrification technologies differ in their energy efficiency, cost structure, and suitability for specific industrial processes (Rosenow et al., 2024). As a result, they face different types of investment barriers. For instance, deep geothermal and large heat pumps are primarily constrained by high upfront investment and conversion costs, while electric and electrode boilers are more affected by high operational expenses (Energy Independence Council, 2024). This reinforces the need to assess each technology individually when designing investment strategies and public policy.

Embedded in a holistic and systemic approach to mobilising private finance for industrial electrification, **public policy must enable private investment and respond to regional realities and technological-specific constraints.** To understand how public policy can effectively accelerate industrial electrification, this report takes an approach centred on **two analytical dimensions**:

1. while most of the investment in industrial electrification must come from the private sector, public policy plays a critical role in creating the right investment conditions.
2. effective policy solutions must address both the diversity of regional contexts and the distinct investment barriers that different technologies face.

**The next parts** apply this lens to a specific case, examining how investment barriers manifest across European regions for a selected technology – industrial heat pumps.

**Industrial heat pumps offer a strategic, scalable, and immediately deployable solution for decarbonising low- to medium-temperature industrial processes such as food, paper, and chemicals.** Global estimates indicate that these systems could supply about 30% of total industrial heat demand up to 400°C by 2050, with half of this potential already achievable by 2030 (International Energy Agency, 2022). In Europe, heat requirements below 200°C account for 37% of total industrial demand and can already be met with existing heat-pump technologies, particularly in the food and beverage and pulp and paper sectors (European Commission, 2025; Jesper et al., 2021; Wolf et al., 2012). The EU currently holds a competitive edge in heat-pump innovation, supported by a high concentration of high-value patents and established industrial capabilities (European Commission JRC, 2023; Energy Independence Council, 2024). Although high-temperature industries such as steel and cement often dominate the public debate, heat pumps present a market-ready pathway to electrify a large share of industrial heat demand (Adamo et al., 2025).

However, deployment across Europe remains uneven due to several region-specific factors such as electricity prices, renewable energy potential, grid decarbonisation readiness, and international energy competitiveness (Rosenow et al., 2024; Energy Independence Council, 2024). Given their commercial maturity, and the diversity of regional deployment challenges, industrial heat pumps offer a strong case for applying a region- and technology-specific lens to the analysis of investment barriers. The remainder of this paper applies this dual lens to the deployment of industrial heat pumps as a case to illustrate how a region- and technology-specific approach to analysing investment barriers can help identify where public policy interventions are most needed and which could be considered.

# 3. Investment barriers to heat pump deployment in five regional clusters

**To understand where and why investment in industrial heat pumps is falling short, this chapter brings together an overview of investment barriers with a regional mapping of their occurrence.** This dual perspective clarifies which constraints are most significant in different parts of the EU and provides a basis for more targeted policy responses. It combines qualitative insights from desk-based research and expert interviews with a data-driven approach. Drawing on literature and stakeholder input, a detailed set of investment barriers was identified. These barriers were used to inform the selection of indicators, based on which regional clusters were identified. The clusters capture key contextual challenges, such as financing conditions, electricity prices, renewable energy potential, and grid decarbonisation readiness, faced by different regions.

## 3.1. Selection and categorisation of investment barriers

**Based on an extensive review of key publications and expert interviews, a comprehensive set of investment barriers to industrial electrification was identified.** The high electricity-to-gas price ratio stands out as the most consistently mentioned obstacle, followed by high upfront capital costs, supply chain skill shortages, retrofitting and grid connection expenses, and short payback period expectations. Notably, the review also points to deeper-rooted issues, with limited technological acceptance emerging as a particularly persistent challenge. Taken together, the findings show that while many barriers are financial in nature, others relate to real-world implementation challenges and more deeply rooted issues (Figure 1).

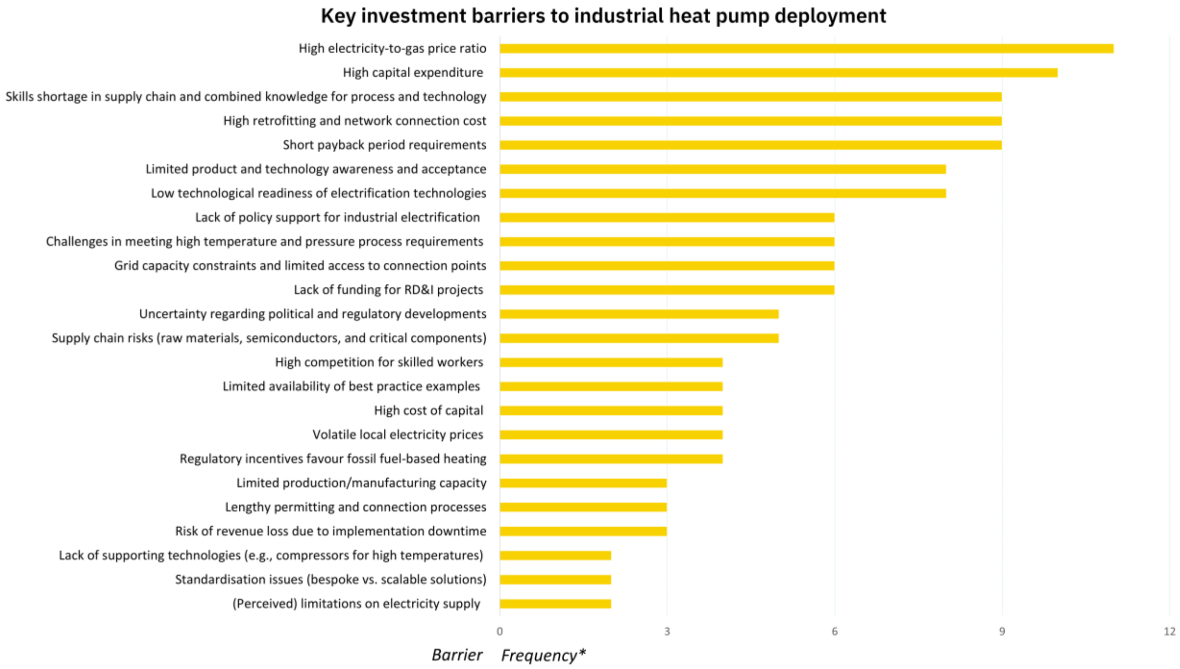


**Figure 1:** Key investment barriers to industrial heat pump deployment
** Frequency refers to the number of key reports which mention this specific barrier.*

**Electricity remains significantly more expensive than natural gas for industrial users in the EU, primarily due to higher taxes and policy-related costs, limiting the economic case for the deployment of industrial heat pumps.** Electricity prices for industrial users in the EU vary widely. According to data from 2024, the average was €0.19 per kWh, but prices in Cyprus and Ireland were over three times higher than in Finland and Sweden (Eurostat, 2024b). In contrast, natural gas remains considerably cheaper on average, though with notable variation. The price gap between electricity and gas is especially pronounced in countries with high gas subsidies or low import costs. A range of factors contributes to the variation in energy prices across the EU. These include geopolitical tensions, supply and demand conditions, the national energy mix, import diversification, network costs, severe weather events and different levels of excise duties and taxation (Eurostat, 2024b). A key reason for higher electricity prices is the heavier tax burden on electricity compared to fossil gas. In Italy, for example, non-recoverable taxes and levies made up nearly one quarter of the final electricity price (27.0%) for industrial users in the second half of 2024, compared to just over one tenth (13.3%) for natural gas (Eurostat, 2024b). Overall, these disparities often stem from legacy tax structures that were not designed with decarbonisation in mind. In practice, they can discourage fuel switching and weaken the economic case for industrial electrification (Rosenow et al., 2022).

While some experts argue that the rising cost impact of the EU Emissions Trading System (ETS) will eventually improve the business case for clean technologies, this effect is expected to materialise mostly after 2040 as carbon prices increase gradually (Wolf et al., 2024). For now, electricity prices for industrial users in the EU remain significantly higher than natural gas prices, and this price gap continues to limit the financial incentive for companies to transition to cleaner, electricity-based industrial processes (Bruegel, 2024).

**High upfront investment costs required for industrial heat pumps pose a key barrier to industrial electrification, driven by infrastructure challenges as well as elevated capital and retrofitting costs.** The capital expenditure for these technologies is high for several reasons, including the cost of advanced equipment built from high-tech components that are expensive to manufacture and scale (Frauenhofer ISI, 2024; Rosenow et al., 2024; European Heat Pump Association, 2024). In addition, most industrial sites are currently optimised for fossil fuel use and retrofitting them often requires significant structural redesign of heating processes. This is especially true in sectors where heating systems are integrated into complex production lines (Rosenow et al., 2024; Frauenhofer ISI, 2024). Experts also point out that retrofitting is frequently delayed until existing systems, such as gas boilers, reach the end of their life cycle. In addition to these challenges, many sites require costly infrastructure upgrades, including new grid connections, substations and internal wiring to handle increased electricity demand (Waliszewska, 2024; Agora Energiewende & Frauenhofer IEG, 2023).

**Industrial inertia and a lack of openness for change from investors and business leaders remain major barriers, reflected in the limited awareness and acceptance of new products and technologies.** Many firms continue to rely on long-standing practices and show a strong preference for familiar technologies, even when cleaner alternatives are available. This resistance to change slows the adoption of electrification (Energy Independence Council, 2024). These entrenched habits are further reinforced by organisational structures and decision-making processes that prioritise operational stability over innovation, particularly in energy-intensive sectors with limited capacity for change (Waliszewska, 2024). In several regions, this is compounded by a lack of visibility and knowledge about available electrification technologies. Industrial heat users, and even energy advisors, often lack awareness of viable solutions and the business case for switching (Rosenow et al., 2024). As a result, clean electrification technologies must compete with fossil-based systems that are well understood, widely available and supported by mature supply chains.

**Skills shortages and fragmented knowledge within the industrial supply chain pose a significant real-world implementation barrier.** The lack of skilled workers and qualified system integrators is widely acknowledged as a short-term obstacle to scaling industrial electrification (European Commission JRC, 2024). This challenge is not only quantitative, relating to the number of available workers, but also qualitative. There is a clear gap in integrated expertise across engineering disciplines, particularly in combining knowledge of thermal processes with the design and deployment of electrical systems (Jesper et al., 2021; Schlosser et al., 2020). The distinction between the quantity and type of skills is essential, as both dimensions are critical to the successful implementation of electrification technologies (Thiel et al., 2021). This is considered a short- to medium-term barrier as there is potential for the workforce to adapt. For example, gas boiler installers could gradually transition to heat pumps as market demand increases, and training pathways evolve to reflect changing technology needs (Czako, 2022). Addressing these gaps through targeted skills development programmes and industry-academic collaboration will be key to accelerating electrification in the industrial sector (Rosenow et al., 2024).

**Overall, the diversity of investment barriers and the fact that their significance vary across regions** requires not only a technology- but also a region-specific understanding, which the next section of the report explores in detail.

## 3.2. Mapping regional investment barriers

**Investment barriers to industrial electrification vary significantly across EU regions. Differences exist in characteristics like fiscal capacity, financing conditions, electricity prices, renewable energy potential, and industrial activity.** As a result, uniform policy approaches are unlikely to be effective. Instead, mobilising private investment requires solutions that respond to region-specific barriers. Designing such interventions first demands a clear understanding of where and how these barriers manifest. To support this, the following section presents a methodology that uses quantitative indicators to develop barrier profiles for Nomenclature of Territorial Units for Statistics (NUTS)-2 regions[1], enabling cross-regional comparison and clustering into shared investment typologies. This forms the basis for differentiated evidence-based policy support that aligns with regional conditions.

### Methodology

First, the quantitative indicators in Table 2 were selected to represent the most cited investment barriers (Figure 1).

**Table 2:** Indicators reflecting investment barriers for industrial electrification across regions

| Indicator | Description | Investment Barriers (Chapter 3.1) |
|---|---|---|
| **OpEx Ratio** | Ratio of electricity to gas prices incl. taxes; reflects real-world switching costs and tax impacts. | - High electricity-to-gas price ratio<br>- Regulatory incentives favour fossil fuel-based heating |
| **Weighted Average Cost of Capital (WACC)** | Return on equity and cost of debt; proxy for investment conditions. | - High capital expenditure<br>- High cost of capital |
| **S1 Fiscal Sustainability Indicator** | Medium-term fiscal adjustment budget adjustment needed; higher values indicate limited fiscal space for public co-financing. | - Lack of policy support for industrial electrification<br>- Lack of funding for RD&I projects |
| **OpEx Competition Ratio** | Ratio of industrial electricity prices to U.S. baseline; high values indicate weaker global competitiveness. | - High electricity-to-gas price ratio |
| **Composite Small-Only Enterprise Index[2]** | Share of micro- and small firms in electrification-critical sectors; reflects structural implementation risk. | - Lack of policy support for industrial electrification<br>- Lack of funding for RD&I projects; Limited production/manufacturing capacity |
| **Renewable Electricity Potential** | Renewable output potential per capita; higher values indicate stronger structural basis for electrification. | - High electricity-to-gas price ratio (*relevant in the long-term*) |
| **Share of Electricity Consumption from Renewables** | Share of electricity already from renewables; signals current grid readiness for clean electrification. | - *Meta- level barrier (not captured in chapter 3.1): only with decarbonised grid can electrification contribute to decarbonisation* |
| **Industry Electrification Rate** | Proportion of industrial energy already electrified; indicates maturity and lower technical barriers. | - Limited product and technology awareness and acceptance<br>- Limited availability of best practice examples |

[1] For statistical purposes, the EU uses the NUTS classification (Nomenclature of Territorial Units for Statistics), which divides each country into three levels: NUTS 1 (major socio-economic regions), NUTS 2 (basic regions used for regional policy), and NUTS 3 (small regions used for more detailed diagnoses).

[2] This indicator serves as a proxy for companies' ability to identify and access relevant public support schemes, based on the assumption that smaller firms typically have fewer administrative resources to navigate such processes.

The indicators were chosen based on conceptual fit, data availability at the NUTS-2 level, and their ability to distinguish regional variation in electrification readiness. Data for these indicators was collected for all 235 NUTS-2 regions (see Appendix for more detail).

Measuring these proxies for investment barriers in all NUTS-2 regions enables a granular understanding of regional investment barriers. Given that many regions face similar patterns of challenges, regions can be grouped into clusters. The rationale behind this is to break down the 235 regions into a small number of clusters while ensuring that the regions within any given cluster are similar to each other in terms of investment barriers. To assess and rank the relative investment difficulty of regions, the Composite Investment Barrier Index (CIBI) was developed. It aggregates the core indicators above into a single score, where higher values reflect greater structural and financial barriers to electrification. This enables both intra-cluster comparison and relative ranking across the EU. The resulting clusters capture meaningful differences in electrification readiness and investment barriers, allowing for systematic benchmarking and targeted intervention[3].

## Regional clustering analysis results

The clustering analysis reveals five distinct groups of EU regions with varying levels of readiness for industrial electrification (see Figure 2 and Table 3).

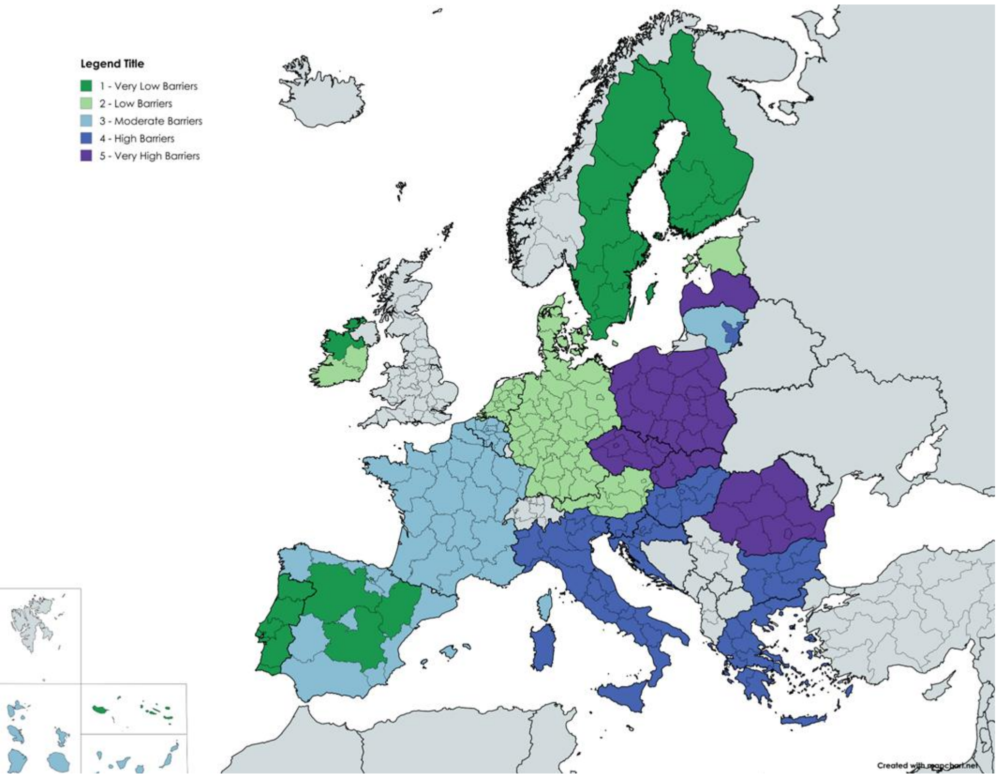


**Figure 2**: Regional clustering of investment barriers for industrial electrification

[3] While the dataset and clustering model provide a strong basis for comparing regional investment barriers, several limitations should be noted (see Appendix). Most indicators were only available at national level, reducing the granularity of intra-country variation. Temporal inconsistencies, equal weighting of variables, and the omission of governance capacity also affect interpretive depth. These constraints do not undermine the overall typology but should inform how results are applied in practice and guide future data improvements.

**Table 3**: Regional cluster profiles: characteristics and barrier levels for industrial electrification *(same as Table 1)*

| Number | Barrier Level | Countries | Description |
|---|---|---|---|
| Cluster 1 | Very Low Barriers | FI, PT, SE *(+ parts of ES, IE)* | Strong renewable energy potential (RE), low operational costs, and largely decarbonised grids - making near-term, market-driven electrification feasible. |
| Cluster 2 | Low Barriers | AT, DE, DK, IE, NL | Combines excellent access to capital with mature industrial bases but faces high electricity costs and limited renewable supply. |
| Cluster 3 | Moderate Barriers | BE, BG, ES, FR, LT | Middle-of-the-road regions with moderate investment conditions, characterised by favourable operational costs, average renewable potential and electrification progress, but constrained by limited fiscal headroom. |
| Cluster 4 | High Barriers | EE, EL, HU, IT, SI, BG, HR *(+ parts of LT)* | These regions are challenged by high operating costs, weak financing conditions, and low grid decarbonisation. While industrial electrification rates and renewable potential are high, this likely reflects legacy infrastructure rather than recent progress. |
| Cluster 5 | Very High Barriers | CZ, LV, PL, RO, SK | Most severe conditions, including limited access to finance, fossil-dependent grids, and low levels of industrial electrification. |

## Cluster 1: Electrification-ready (Very Low Barriers)

**Including regions in Finland, Portugal, Sweden, as well as parts of Spain and Ireland**

Cluster 1 comprises regions with the most favourable conditions for industrial electrification in Europe. These regions have the lowest operational electrification costs (OpEx ratio incl. taxes: 0.92, Rank 1/5) and the highest renewable electricity potential per capita (57.58 MWh, Rank 1/5). The grid is already largely decarbonised (60.16% renewables, Rank 1/5), allowing firms to electrify without major emissions penalties. Financing conditions are strong (WACC: 5.38%, Rank 2/5), and fiscal space is the best in the EU (S1: -0.21, Rank 1/5). Overall, cluster 1 regions show the lowest overall Composite Investment Barrier Index (CIBI) score of 0.36, making them strong candidates for low-intervention, market-led electrification (see Figure 2, Table 3, 4).

## Cluster 2: Capital-ready, energy-constrained (Low Barriers)

**Including regions in Austria, Germany, Denmark, Ireland and the Netherlands**

Cluster 2 regions offer excellent financing conditions, with the lowest WACC in the EU at 4.95% (Rank 1/5). Fiscal capacity is relatively strong (S1: 1.36, Rank 2/5) and grid decarbonisation is underway (46.98% renewable share, Rank 2/5). However, these advantages are offset by the highest electricity cost burden for firms (OpEx ratio incl. taxes: 3.31, Rank 5/5) and the lowest renewable electricity potential (19.86 MWh per capita, Rank 5/5), indicating a structural energy supply constraint. Overall, industrial electrification is less advanced than in most other clusters (31.15%, Rank 4/5). The CIBI score of 0.55 (Rank 2/5) suggests these regions can scale-up electrification if energy price distortions and infrastructure gaps are addressed (see Figure 2, Table 3, 4).

## Cluster 3: Mixed readiness (Moderate barriers)

**Including regions in Belgium, Bulgaria, Spain, France, and Lithuania**

Cluster 3 represents 'middle-of-the-road' regions across all key metrics. OpEx ratios are favourable (2.37, Rank 2/5), renewable electricity potential is average (28.77 MWh/capita, Rank 3/5), and financing conditions are neither highly favourable nor restrictive (WACC: 5.50%, Rank 3/5). Electrification progress is underway (33.72%, Rank 2/5), but the biggest constraint in these regions is limited fiscal headroom, with the highest S1 value in the EU (4.46, Rank 5/5). The CIBI score of 0.55 (Rank 3/5) indicates moderate barriers (see Figure 2, Table 3, 4).

## Cluster 4: Low electrification readiness (High Barriers)

**Including regions in Estonia, Italy, Greece, Hungary, Croatia, Slovenia, and Bulgaria and parts of Lithuania**

Regions in cluster 4 face systemic constraints across multiple dimensions. Despite promising renewable potential (32.79 MWh/capita, Rank 2/5), electrification efforts are hampered by high operational cost burden (OpEx ratio: 3.04, Rank 4/5), weak financing conditions (WACC: 7.14%, Rank 4/5), and low-decarbonised grids (29.77%, Rank 4/5). Interestingly, industry electrification is the highest among all clusters (37.39%, Rank 1/5), but this may reflect legacy infrastructure rather than proactive transition measures. Fiscal capacity is middling (S1: 2.15, Rank 3/5). The CIBI score of 0.62 (Rank 4/5) highlights the need for comprehensive support (see Figure 2, Table 3, 4).

## Cluster 5: Lowest electrification readiness (Very High Barriers)

**Including regions in Poland, Romania, Czechia, Slovakia, and Latvia**

Cluster 5 represents the regions facing the most severe investment barriers to electrification. These areas suffer from the worst financing conditions (WACC: 7.77%, Rank 5/5), the least decarbonised grids (23.05% renewable share, Rank 5/5), and the lowest industrial electrification rates (27.95%, Rank 5/5). Renewable electricity potential is limited (21.28 MWh/capita, Rank 4/5) and fiscal conditions limit governments' ability to support industry (S1: 4.00, Rank 4/5). Operational costs are moderate (OpEx: 2.84, Rank 3/5). With a CIBI score of 0.70 (Rank 5/5), these areas require multi-dimensional policy support (see Figure 2, Table 3, 4).

Given the variation in electrification readiness across regional clusters, policy approaches to mobilising private finance for heat pump deployment must reflect these differing conditions. While regions within the same cluster tend to share similar characteristics, each cluster requires a distinct set of interventions. Using the clustering analysis as a foundation, targeted policy measures can be tailored to address the specific investment barriers of each profile to enable more effective and scalable mobilisation of private capital for industrial electrification.

**Table 4**: Comparative overview of key indicators across five European regional clusters

| Indicator | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 |
|---|---|---|---|---|---|
| S1 Indicator (budget adjustment needed in % of GDP) | -0.21% (-2.82) | 1.36% (-1.24) | 4.46% (+1.85) | 2.15% (-0.45) | 4.00% (+1.39) |
| **Rank** | 1 | 2 | 5 | 3 | 4 |
| WACC (return on equity and cost of debt in %) | 5.38% (-0.70) | 4.95% (-1.13) | 5.50% (-0.58) | 7.14% (+1.07) | 7.77% (+1.69) |
| **Rank** | 2 | 1 | 3 | 4 | 5 |
| Renewable Electricity Potential (in MWh/capita) | 57.58 (+29.27) | 19.86 (-8.45) | 28.77 (+0.46) | 32.79 (+4.48) | 21.28 (-7.03) |
| **Rank** | 1 | 5 | 3 | 2 | 4 |
| Share of Electricity Consumption from Renewables (%) | 60.16% (+23.9) | 46.98% (+10.73) | 30.91% (-5.34) | 29.77% (-6.49) | 23.05% (-13.21) |
| **Rank** | 1 | 2 | 3 | 4 | 5 |
| Industry Electrification Rate (%) | 32.89% (+0.05) | 31.15% (-1.69) | 33.72% (+0.88) | 37.39% (+4.55) | 27.95% (-4.90) |
| **Rank** | 3 | 4 | 2 | 1 | 5 |
| Composite Small-Only Enterprise Index (%) | 92.16% (+1.86) | 87.07% (-3.23) | 88.80% (-1.50) | 92.96% (+2.66) | 93.48% (+3.18) |
| **Rank** | 3 | 1 | 2 | 4 | 5 |
| OpEx Ratio (electricity-to-gas price ratio incl. taxes) | 0.92 (-1.82) | 3.31 (+0.56) | 2.37 (-0.38) | 3.04 (+0.30) | 2.84 (+0.09) |
| **Rank** | 1 | 5 | 2 | 4 | 3 |
| OpEx Competition Ratio (electricity prices over US benchmark) | 0.40 (-0.80) | 1.45 (+0.25) | 1.03 (-0.16) | 1.33 (+0.13) | 1.24 (+0.04) |
| **Rank** | 1 | 5 | 2 | 4 | 3 |
| Total Investment Barrier Index (CIBI) | 0.36 (-0.21) | 0.55 (-0.03) | 0.55 (-0.02) | 0.62 (+0.04) | 0.70 (+0.12) |
| **Rank** | 1 | 2 | 3 | 4 | 5 |

# 4. A policy toolbox to address investment barriers

**One-size-fits-all solutions fall short of addressing the region- and technology-specific nature of investment barriers. More targeted public policy approaches are necessary.** This section presents an overview of relevant policy tools based on ZOE Institute's Private Finance Toolbox. These tools should serve as a starting point and should be further developed through co-creative and inclusive processes between policymakers and different relevant stakeholders. To illustrate the use of the Toolbox, the next section takes regional clusters 4 (High Barriers) and 5 (Very High Barriers) as examples of where tailored public support is particularly important and contrasts them with cluster 1 (Very Low Barriers) where conditions are already favourable.

These three clusters were selected as examples of the five clusters from the previous section to reflect the full spectrum of electrification readiness and investment barriers across the EU. Cluster 1 includes frontrunner regions in Northern and Southwestern Europe with low operational costs, strong renewable potential, and favourable financing conditions. These regions require minimal policy intervention and serve as examples of successful industrial electrification under enabling conditions. In contrast, clusters 4 and 5 represent regions in Southern and Central-Eastern Europe, as well as the Baltic region, that face high to very high barriers. These include fossil-reliant grids that limit the decarbonisation potential of industrial electrification, weak financing conditions, an SME-dominated industrial structure. Comparing these clusters highlights the need for diverse policy mixes to address region-specific barriers and support industrial electrification more effectively across the EU.

To identify effective solutions for the varying regional needs, the **following section** presents the **Private Finance Toolbox** as a framework which links specific investment barriers to corresponding policy tools. It also provides an overview of policies designed to overcome the most prevalent barriers.[4]

## 4.1. Introducing the Private Finance Toolbox framework

The Private Finance Toolbox enables users to identify tailored policy responses by **linking specific investment barriers to appropriate public policy tools**. It is based on the principle that a systemic and holistic understanding of investment barriers is essential to designing effective and targeted interventions (Figure 3).

**The Toolbox conceptualises three levels of systemic change:**

1. **Explicit Level of Change:** Tangible investment barriers, such as capital expenditure, operational costs, human resources and technology.
2. **Semi-Explicit Level of Change:** Power dynamics and institutional challenges such as imbalances in decision-making authority, stakeholder representation and access to information.
3. **Implicit Level of Change:** Deeply ingrained mental models and beliefs that shape decision-making, including fundamental preferences, openness to change and risk preferences.

**Figure 3**: Toolbox methodology: Three levels of change

[4] While targeted policy support is needed to overcome regional investment barriers to industrial electrification, this support should be embedded in a broader strategic approach that considers where electrification is most viable and beneficial in the long term. Public support - whether financial, regulatory, or infrastructural - should be guided by a holistic assessment of regional strengths, including renewable energy availability, grid capacity, industrial structure, and workforce readiness. Bertram et al. (2024) have elaborated how such a strategic approach can be designed.

This framework enables a precise alignment of investment barriers with targeted policy tools to effectively mobilise private investment. (For a full overview of the comprehensive set of investment barriers associated with each level, please refer to the Toolbox methodology.)

The Toolbox provides a broad range of policy instruments across key policy areas such as public (co-)funding, financial and non-financial regulation, monetary policy, information and coordination measures, labour market and education. Some policy tools are designed to incentivise green investment, while others aim to disincentivise harmful or fossil-based activities.

Each policy card in the Toolbox includes key details such as policy status, affected entities, and the immediate fiscal effect. For the specific context of industrial electrification, an additional filter allows users to identify sector-specific policy tools.

## 4.2. Matching toolbox barriers and region-specific constraints

This section applies the framework in a region-specific context. Table 5 presents the most significant investment barriers in the two regional clusters facing the highest overall challenges, regional clusters 4 (High Barriers) and 5 (Very High Barriers). The data indicators from the regional analysis provide an evidence base for identifying the relevant barriers. Where indicators point to elevated barriers, the logic of the Private Finance Toolbox is used to guide policy responses. In this case, key barriers include high capital expenditure (CapEx), high operating costs (OpEx), and material input risks, which can be directly linked to specific indicators from the regional analysis (see column Data indicators). The table shows that both cluster 4 and cluster 5 face high CapEx, driven by elevated weighted average costs of capital (WACC), as well as high OpEx resulting from an unfavourable electricity-to-gas price ratio. In addition, a low share of renewables in the electricity mix corresponds to the material input barrier, as defined in the Toolbox framework.

**Table 5:** Key investment barriers: Linking regional indicators to Toolbox framework

| Toolbox barrier | Data indicators | Prevalence in cluster 4 | Prevalence in cluster 5 | Prevalence in cluster 1 |
|---|---|---|---|---|
| **High capital expenditure (CapEx)** | WACC in % | High WACC make CapEx costly | High WACC make CapEx costly | Low WACC make CapEx favourable |
| | **Rank** | 4 | 5 | 2 |
| **High operational expenditure (OpEx)** | OpEx Ratio | High electricity-to-gas price ratio makes OpEx costly | High electricity-to-gas price ratio makes OpEx costly | Low electricity-to-gas price ratio makes OpEx favourable |
| | **Rank** | 4 | 4 | 1 |
| **High operational expenditure (OpEx)** | OpEx Competition Ratio | High OpEx Competition ratio makes OpEx comparatively costly | Medium OpEx competition ratio makes OpEx comparatively costly | Low OpEx competition ratio makes OpEx favourable |
| | **Rank** | 4 | 3 | 1 |
| **Material input** | Share of Electricity Consumption from Renewables (%) | Low RE share in the grid limits decarbonisation potential | Low RE share in the grid limits decarbonisation potential | High RE share ensures decarbonisation potential |
| | **Rank** | 4 | 4 | 1 |

In contrast, cluster 1 demonstrates strong electrification readiness, characterised by low capital and operating costs (CapEx and OpEx) and a high share of renewable energy in the electricity mix. It ranks as the highest-performing regions across the EU and serves as a reference case for low investment barriers. While the focus for cluster 1 lies in scaling and optimising existing policies to accelerate electrification, clusters 4 and 5 require more comprehensive public intervention to unlock their potential.

This comparison highlights the varying degrees of readiness for industrial electrification, the diversity of investment barriers in their intensity and regional variation and underscores the need for differentiated support strategies.

## 4.3. Policy tools to overcome investment barriers

Table 6 presents an overview of potential policy tools tailored to the investment barriers identified in regional clusters 1, 4, and 5. It also includes tools that address additional barriers frequently cited in the literature but not captured by the quantitative regional analysis. Therefore, the table covers not only CapEx, OpEx, and Material Input, but also the following barriers: *Human resources* (corresponding to skills shortages in supply chains and specialised knowledge), *Openness for change* (related to limited product and technology awareness and acceptance), and *Amortisation structure* (reflecting the barrier of short payback period requirements).

**Table 6:** Toolbox application: Exemplary instruments for addressing technology- and region-specific electrification barriers

| Toolbox barrier | Policy tools |
|---|---|
| ***Regional clusters 4 and 5 investment barriers (see chapter 3.2)*** | |
| **High capital expenditure (CapEx)** | • Counter-guarantee by Public Banks<br>• Default Green Investment and Pension Fund Allocations<br>• Phase out of Environmentally Harmful Subsidies<br>• Taxonomy of Environmentally Harmful Activity |
| **High operational expenditure (OpEx)** | • Contracts for Difference (CfD)<br>• Emissions Cap & Trading System (ETS)<br>• Energy Efficiency Obligation Schemes (EEOS)<br>• OpEx Tax Benefit |
| **Material input** | • Energy Policy Coordination<br>• Fast-track Approval Processes<br>• Feed-in Tariffs for Green Energy<br>• Forward Commitment Procurement |
| **Toolbox barrier** | **Policy tools** |
| ***Prevalent non-quantitative investment barriers from desk research (see chapter 3.1)*** | |
| **Human resources** | • Hiring Subsidies<br>• National Green Skills and Workforce Planning Strategy<br>• Sectorial Workforce Transition Agreement |
| **Openness for change** | • Coordinating Platforms<br>• Curricula for Green Education<br>• Information Sharing Platforms & Databases<br>• Showcasing Climate-friendly Peer Behaviour in Investment Decisions |
| **Amortisation structure** | • Accelerated Depreciation of Green Investments |

This overview illustrates that a broad range of policy tools is available to address key investment barriers to industrial electrification across regions. To reduce high capital needs, policy tools such as public guarantees and targeted green fund allocations can help lower investment risk and attract long-term finance. For regions facing high operational costs, tools like Contracts for Difference or OpEx-tax incentives can stabilise cash flows and strengthen the business case for technologies such as industrial heat pumps, particularly where energy prices remain elevated.

Skills shortages are addressed through workforce planning and training incentives, while resistance to change is countered by peer learning platforms and awareness tools. Finally, policy tools like accelerated depreciation help overcome investor reluctance tied to short payback expectations.

Overall, successfully accelerating industrial electrification requires more than improved access to capital. It also calls for a targeted policy mix that addresses financial profitability concerns, real-world implementation constraints, and deeper-rooted investment barriers. Selecting the most appropriate tools requires policymakers to understand the specific regional and technologic context and actively engage with stakeholders through a co-creative process to ensure tailored and effective solutions.

# 5. Conclusion

**Industrial electrification is essential to achieving the EU's climate and decarbonisation objectives, yet varying regional and technology-specific investment barriers pose ongoing challenges to progress.** This report equips stakeholders across industry, finance, and policy with a comprehensive framework to navigate this complexity and unlock private capital where it is most needed.

**A clustering methodology identifies five distinct regional profiles across the EU, each defined by a unique combination of financial, technical, and institutional barriers.** These profiles reflect a spectrum of readiness for industrial electrification, ranging from regions positioned to scale deployment, to those requiring more substantial public support. Recognising these differences is critical for designing targeted policy solutions tailored to regional contexts.

**To facilitate such targeted responses, ZOE Institute's Private Finance Toolbox offers a systematic framework that links investment barriers** – spanning financial profitability concerns, real-world implementation constraints, and deeper-rooted challenges – to corresponding policy tools.

**Matching region- and technology-specific barriers systematically with the Toolbox categories enables the identification of illustrative policy tools.** These include, for example, measures to reduce capital and operational expenditures, initiatives addressing workforce challenges such as skills shortages and knowledge gaps, and interventions promoting acceptance for electrification technologies. Applying this approach lays the foundation for the design of policy mixes aligned with each regional profile, thereby maximising the effectiveness and impact of public interventions.

**Importantly, this is not a one-size-fits-all roadmap but a starting point. Decision makers are encouraged to integrate these insights with additional regional and technology-specific knowledge**. Engaging stakeholders through co-creative processes is essential to foster an inclusive, iterative approach that assesses feasibility and impact in the development of an optimal policy mix.

In practice, this means:

- **Diagnosing** the unique investment conditions of each region using regional cluster analysis.
- **Applying** the Toolbox framework to tailor policy options to these specific conditions.
- **Collaborating** with investors, industry leaders, and civil society to co-create policy interventions rooted in regional realities.

**By adopting this systemic, differentiated, and participatory approach, decision makers can unlock the full potential of industrial electrification across the EU** – accelerating the transition toward a more sustainable and future-fit industrial landscape.

# Bibliography

Adamo, A., Martín, H., de la Hoz, J. & Rubio, J. (2025): 'A review of worldwide strategies for promoting high-temperature heat pumps', *Applied Sciences*, 15 (2), article 839.

Agora Energiewende & Fraunhofer IEG (2023): The roll-out of large-scale heat pumps in Germany. Strategies for the market ramp-up in district heating and industry.

Bertram, L., Hafele, J., Korinek, L., & Kiecker, S. (2024): A unified industrial strategy for the EU. Cologne: ZOE Institute for Future-Fit Economies.

Bruegel (2024): Energy prices and industrial competitiveness in Europe. Brussels: Bruegel.

Czako, V. (2022): Skills for the clean energy transition. European Commission: Petten, JRC129676.

Draghi, M. (2024): The future of European competitiveness: A competitiveness strategy for Europe. Report by Mario Draghi, Special Advisor to the President of the European Commission, submitted 9 September. European Commission.

Energy Independence Council (2024): Security-oriented Energy Policy – A financing strategy for Germany's independence from natural gas

European Central Bank (2025): Investing in Europe's green future. ECB Occasional Paper Series No. 367.

European Commission (2025): Clean Industrial Deal. COM(2025), Brussels, 26 February.

European Commission, DG ECFIN (2024): Debt Sustainability Monitor. Institutional Paper 271. https://economyfinance.ec.europa.eu/document/download/e3a23fba14024cc9b5717473b5e7842a_en?filename=ip271_en.pdf

European Commission, Joint Research Centre (2024): Clean Energy Technology Observatory: Heat Pumps in the European Union – 2024 Status Report on Technology Development, Trends, Value Chains and Markets (JRC139377). Publications Office of the European Union.

European Heat Pump Association (EHPA) (2024): Financing heat pumps: Barriers and solutions.

European Parliament and Council (2021): Regulation (EU) No. 2021/1119 of 30 June 2021 on establishing the framework to achieve climate neutrality... Official Journal L 243, 1-17.

Eurostat (2024a): Final energy consumption in industry - detailed statistics, Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics

Eurostat (2024b): Electricity and natural gas prices: Second half of 2024. Luxembourg: Statistical Office of the European Union.

Eurostat (2025a): Electricity prices for nonhousehold consumers – biannual data (from 2007 onwards). Eurostat database, dataset NRG_PC_205. https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_205

Eurostat (2025b): Gas prices for nonhousehold consumers – biannual data (from 2007 onwards). Eurostat database, dataset NRG_PC_203. https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_203

Eurostat (2025c): Share of energy from renewable sources – electricity. Eurostat database. https://ec.europa.eu/eurostat/databrowser/product/page/NRG_IND_REN

Eurostat (2025d): Final energy consumption by fuel – industry. Eurostat database. https://ec.europa.eu/eurostat/databrowser/product/page/NRG_BAL_C

Eurostat (2025e): Structural business statistics overview. Eurostat database. https://ec.europa.eu/eurostat/databrowser/product/page/SBS_SC_OVW

Fraunhofer ISI (2024): Direct electrification of industrial process heat: An assessment of technologies, potentials and future prospects for the EU. Study on behalf of Agora Industry. Berlin: Agora Industry, 5 June.

Heun, M.K., de Oliveira, L.F.S. and Brockway, P.E. (2021): A physical supply-use model of global energy system transitions, *Energy Policy*, 155, 112327.

International Energy Agency (2022): The future of heat pumps. International Energy Agency.

Institut Rousseau (2024): Road to Net Zero: Bridging the Green Investment Gap. Paris: Institut Rousseau, February.

Institute for Climate Economics (2024): European Climate Investment Deficit Report. Paris: I4CE, February.

International Energy Agency (IEA) (2022): The Future of Heat Pumps. Paris: IEA.

International Renewable Energy Agency (IRENA) (2023): The cost of financing for renewable power. Report. Abu Dhabi: IRENA.

Jesper, M., Schlosser, F., Pag, F., Walmsley, T. G., Schmitt, B. & Vajen, K. (2021): Large-scale heat pumps: Uptake and performance modelling of market-available devices. Renewable and Sustainable Energy Reviews, 137.

Polzin, F., Egli, F., Steffen, B. and Schmidt, T.S. (2019): How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. Renewable and Sustainable Energy Reviews, 114, p.109309.

PRB (2024): Study on cost of capital – Methodology review and update. https://eusinglesky.transport.ec.europa.eu/document/download/31d201d9e48b4ad0aec3f66c7fe61d31_en?filename=240625_Cost%20of%20Capital%20Guidelines_published.pdf

Rosenow, J., Oxenaar, S. & Pusceddu, E. (2024): Some like it hot: Moving industrial electrification from potential to practice. Brussels: Regulatory Assistance Project, December.

Schlosser, F., Jesper, M., Vogelsang, J., Walmsley, T.G., Arpagaus, C. and Hesselbach, J. (2020): Large-scale heat pumps: Applications, performance, economic feasibility and industrial integration. Renewable and Sustainable Energy Reviews, 133, p.110219.

Thiel, G.P. and Stark, A.K. (2021): To decarbonize industry, we must decarbonize heat. Joule, 5(3), pp.531–550.

U.S. Energy Information Administration (EIA) (2025): Average retail price of electricity to ultimate customers by end-use sector. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

Waliszewska, A. (2024): An Electrification Action Plan to Secure EU Industry's Future. E3G briefing, October.

Wolf, S., Baccianti, C. & Schütze, F. (2024): Carbon pricing and industrial transformation: The long-term role of the EU ETS. Berlin: Ecologic Institute.

Wolf, S., Lambauer, J., Blesl, M., Fahl, U. & Voß, A. (2012): Industrial heat pumps in Germany: Potentials, technological development and market barriers. ECEEE Summer Study on Energy Efficiency in Industry.

# Appendix: Methodology

# K-means clustering analysis

### Purpose and scope

This analysis segments European regions (at the NUTS-2 level) to better understand shared barriers to industrial electrification. The objective is to support more geographically targeted policy interventions by identifying patterns in fiscal conditions, cost structures, and renewable readiness that affect electrification investment feasibility across regions.

### Clustering

To identify meaningful regional groupings, two clustering methods were explored: K-Means and K-Median. Both are unsupervised machine learning techniques that group regions with similar characteristics, but they differ in how they treat the underlying data. K-Means assigns regions to clusters by minimizing their distance from the group's average (centroid), making it suitable for normally distributed data. In contrast, K-Median relies on the median and Manhattan distance, which makes it more robust to skewed distributions and outliers—features often present in fiscal and energy-related variables. To enhance the reliability of the clustering results, both winsorized scaling (which caps extreme values without discarding data) and robust scaling (based on the median and interquartile range) were applied as preprocessing steps. These approaches helped stabilize the input data, reduce distortion, and improve cluster cohesion. While both clustering methods produced comparable results, K-Means combined with winsorized scaling ultimately provided the most balanced and interpretable segmentation. This combination offered strong statistical performance, better cross-country comparability, and clearer policy relevance. The final choice was supported by robustness checks, cluster validation metrics, and visual inspection using PCA projections.

### Indicators used

Eight indicators were selected to reflect the most relevant economic, institutional, and technical barriers. These include: the S1 fiscal sustainability indicator (capturing medium-term public finance constraints), the weighted average cost of capital (WACC), the OpEx electrification ratio (electricity-to-gas price ratio including taxes), and a benchmark comparison of industrial electricity prices to U.S. levels. Additionally, renewable generation potential per capita, the share of electricity from renewables, industrial electrification rate, and a composite index of small firms in key sectors were included. These variables jointly capture investment conditions, operational cost risks, institutional capacity, and implementation readiness.

A detailed overview of the indicators is below.

- **S1 Fiscal Sustainability Indicator**
  The S1 indicator captures the fiscal adjustment needed over the medium term (10–20 years) to ensure public debt sustainability. This fiscal effort is measured as the improvement in the structural primary balance (SPB) cumulated over the five years after the forecast and then sustained for a decade. The SPB is a country's budget balance before interest payments and corrected for circumstantial dynamics such as factors related to the business cycle, one-off or temporary measures. It reflects the capacity of regional or national governments to co-finance industrial policy, infrastructure, and incentive schemes. S1 was chosen over alternatives (S0 and S2) as it aligns best with the time horizon of industrial decarbonisation planning. High values signal constrained public budgets and limited ability to support the transition (European Commission, DG ECFIN, 2024).
- **Weighted Average Cost of Capital (WACC)**
  WACC combines the return on equity and cost of debt to represent the minimum return investors require to fund industrial projects. It offers a comprehensive picture of financing costs. Although Cost of Debt was considered, its perfect correlation with WACC ($r = 1.00$) made it redundant. WACC was retained as the more complete measure for this barrier (PRB, 2024).
- **OpEx Ratio**
  This indicator compares electricity and gas prices (including taxes) for energy-intensive industries, capturing the real-world cost of switching from fossil fuels to electricity. It includes tax-related price effects, making it

a direct proxy for financial barriers. A higher ratio indicates that electricity is significantly more expensive, implying lower feasibility without policy support (Eurostat, 2025a; Eurostat, 2025b).

- **OpEx Competition Ratio**
  This variable benchmarks regional electricity prices (incl. taxes) against the U.S. industrial baseline of €0.08/kWh. A higher ratio signals weaker international cost competitiveness, particularly in export-oriented sectors. Regions with high ratios may face structural disadvantages without targeted policy intervention (U.S. Energy Information Administration (EIA), 2025).
- **Renewable Electricity Potential**
  This metric reflects the theoretical maximum renewable output per capita. It serves as a proxy for structural readiness to supply clean electricity. Higher values suggest stronger regional capacity for local, low-carbon energy generation and lower dependency on external or fossil-based sources (Heun et al., 2021).
- **Share of Electricity Consumption from Renewables (%)**
  This indicator shows how much of a region's electricity consumption was already met by renewables in 2021. It provides a snapshot of grid cleanliness and informs whether electrification leads to actual emissions reductions. High shares indicate immediate potential for clean electrification; low shares imply a need for upstream decarbonisation (Eurostat, 2025c).
- **Industry Electrification Rate**
  This indicator measures the share of industrial energy use that is already electrified, excluding fossil feedstocks. It captures existing progress and remaining technical barriers. Higher electrification rates suggest fewer challenges ahead and reduced need for large-scale retrofitting (Eurostat, 2025d).
- **Composite Small-Only Enterprise Index**
  This index isolates the share of micro- and small enterprises (excluding medium firms) in energy intensive industries. These firms often lack credit access, technical expertise, and staff to manage energy transitions. The index shows high variation and non-redundant correlation with the Composite SME Index (r = 0.90), making it a precise proxy for firm-size-related structural barriers (Eurostat, 2025e).

### Data processing and scaling

To assess which regions face the most significant barriers to industrial electrification, we assembled a harmonised dataset covering all 235 NUTS-2 regions in the European Union. This geographic scale aligns with the level at which cohesion policy and energy investment instruments are typically deployed, allowing for policy-relevant granularity. All indicators identified - capturing fiscal capacity, financing conditions, electricity cost structures, renewable energy potential, grid decarbonisation, and enterprise structure -were compiled from harmonised, EU-wide data sources. Data were collected at regional level to reflect spatial variation in electrification readiness.

Before clustering, all variables were converted to numeric format and cleaned for missing or incomplete entries. Continuous variables were z-score standardised to ensure comparability across regions. Winsorisation was applied to cap extreme values at defined percentiles, particularly for indicators sensitive to population size (e.g. renewable potential per capita), in order to reduce the influence of outliers without discarding any observations.

As a robustness check, the dataset was also scaled using a robust method based on medians and interquartile ranges. Cluster assignments remained largely stable across both scaling approaches, confirming methodological consistency. A small number of regions -such as parts of Spain, Lithuania, and Ireland - shifted between clusters due to their proximity to classification thresholds. These edge cases were manually reviewed and reassigned based on contextual alignment with neighbouring regions in terms of economic structure and electrification readiness. This ensured analytical coherence while preserving statistical rigour. Visual diagnostics, including boxplots and principal component analysis (PCA) projections, confirmed that the preprocessing steps improved data symmetry and mitigated the effect of skewed distributions. The final dataset provides a harmonised investment barrier profile for each region and serves as the empirical foundation for the clustering analysis presented in Step 3.

### Determining the number of clusters

The optimal number of clusters (K) was identified through a combination of internal validation metrics and visual diagnostics to ensure both statistical robustness and policy relevance. Key metrics included the silhouette score (measuring internal cohesion), the Calinski-Harabasz index (comparing between- and within-cluster variance), the Davies-Bouldin index (penalizing overlapping clusters), and inertia (capturing within-cluster compactness). To complement these quantitative indicators, the Elbow Method was also used—a visual technique that plots inertia across different values of K. The "elbow point" in this curve indicates where adding more clusters begins to yield diminishing returns in clustering quality. In this case, the elbow appeared clearly around K = 5, reinforcing the results of the statistical metrics.

Overall, K = 5 emerged as the most balanced and interpretable configuration. It achieved a strong silhouette score of 0.439, maintained analytical clarity, and ensured meaningful cross-country representation, with each cluster comprising an average of 8.2 countries. This balance between technical performance and geographic diversity makes K = 5 particularly well-suited for informing EU-wide and cross-border electrification policy strategies.

### Comparing K-Means and K-Median

Both K-Means and K-Median clustering methods were tested at K = 5 to evaluate their suitability for regional segmentation. While K-Median produced slightly higher silhouette scores, indicating marginally tighter clusters, it also tended to group regions primarily within national boundaries. This reduced the diversity of each cluster and limited the ability to draw meaningful cross-country comparisons, which are critical for EU-level policy design. In contrast, K-Means produced clusters that were more geographically mixed, offering greater interpretability and policy relevance. Although PCA projections revealed that the data did not naturally form perfectly spherical clusters, conditions under which K-Means typically performs best, the marginal gain in robustness from K-Median did not justify the loss in cross-border insight. On balance, K-Means combined with winsorized scaling was selected for its superior ability to reflect structural commonalities across regions, rather than within isolated national contexts, making it better aligned with the goals of comparative and integrated policy analysis.

### Robustness checks and final choice

Robustness checks confirmed that the preprocessing steps, especially winsorization and robust scaling, significantly improved cluster quality. Variables such as fiscal indicators and energy costs showed persistent skew, but the adjusted data retained meaningful structure. While K-Median was better at handling residual outliers, it resulted in clusters that were less meaningful for EU-wide analysis due to national concentration. Based on these findings, K-Means with robust scaling was selected as the final method, offering a reliable, interpretable, and regionally balanced clustering solution.

### Sectoral sensitivity: ESDR data inclusion

To test the effect of including sector-specific enterprise structure data, a version of the clustering included ESDR indicators for small, medium, and large firms. This altered the clustering structure significantly, reassigning nearly 95% of regions. Although silhouette scores remained acceptable, several clusters became dominated by just one or two countries, reducing their usefulness for comparative policy work. The analysis concludes that ESDR indicators are better used for post-clustering profiling or after dimensionality reduction techniques such as PCA.

## Step-by-Step calculation process of the CIBI

### 1. Inversion of positively correlated indicators

Some indicators - like Renewable Potential, Share of Renewables, and Industry Electrification—are positive signals, meaning higher values imply fewer barriers. These are mathematically inverted to align their meaning with the rest of the indicators.

$$x'_{rj} = \begin{cases} -x_{rj}, & \text{if } j \in \mathcal{I}_{\text{inv}} \\ x_{rj}, & \text{otherwise} \end{cases}$$

Where:

- xrj is the original value of indicator j for region r
- x'rj is the adjusted value after inversion
- Iinv  includes:
    - Renewable Potential (MWh/capita)
    - Share of energy from renewables in electricity
    - Industry Electrification (%)

### 2. Normalization (Min-Max Scaling)

To ensure comparability across different units and ranges, all adjusted indicators are normalized to a scale from 0 to 1 using min-max scaling:

$$\tilde{x}_{rj} = \frac{x'_{rj} - \min(x'_{\cdot j})}{\max(x'_{\cdot j}) - \min(x'_{\cdot j})}$$

Where:

- x~rj is the normalized value for indicator j in region r
- The denominator ensures that the range of each indicator is preserved and standardized

### 3. Composite Score Calculation

Finally, the normalized scores for each region are averaged to generate the Composite Barrier Index:

$$CIBI_r = \frac{1}{n} \sum_{j=1}^{n} \tilde{x}_{rj}$$

Where:

- CIBIr  is the composite index score for region r
- n=8n, the total number of indicators

A higher CIBI score means that the region faces more severe or numerous barriers industry electrification. A lower score suggests a more favourable investment environment. This index helps policymakers quickly identify priority areas for reform, compare regions objectively, and track progress over time.

The methodology ensures that diverse factors affecting industry electrification investment are captured in a balanced, transparent, and interpretable way.

### Data limitations

While the dataset and clustering model provide a robust framework for comparing structural investment barriers to industrial electrification across European regions, several limitations should be acknowledged to ensure appropriate interpretation and application.

Most indicators—such as the Weighted Average Cost of Capital (WACC), OpEx ratios, fiscal sustainability (S1), SME structure, and industrial electrification rates—were only available at the national level. These values were uniformly assigned to all NUTS-2 regions within each country, limiting the ability to reflect intra-national variation in financing conditions, grid cost structures, or firm demographics. This limitation is particularly relevant for large or economically diverse member states, where regional disparities can be significant. For example, electricity price burdens in southern Italy or eastern Germany may differ substantially from national averages, but such distinctions are not captured in the analysis.

The dataset also integrates indicators from multiple years, primarily 2021–2023, and includes some forward-looking estimates (e.g. projected 2025 WACC). Although this approach reflects the most current data available, it introduces a degree of temporal inconsistency that may affect strict comparability across variables. Nevertheless, all indicators are broadly aligned with the present or near-term investment landscape.

In the clustering process, all indicators were z-score standardised and equally weighted to ensure methodological neutrality and prevent any single variable from dominating the results. However, this equal weighting does not reflect differences in the real-world policy significance of certain barriers. For instance, fiscal constraints may have a more immediate and constraining impact on industrial investment than variations in SME density.

Finally, the analysis does not account for governance quality, administrative capacity, or regional implementation readiness—factors which are not systematically available at the NUTS-2 level but may substantially influence electrification outcomes. These dimensions should be considered in future research or incorporated into follow-up diagnostics at the national or subnational level.

Despite these limitations, the clustering typology remains a useful tool for identifying structural patterns, informing policy prioritisation, and guiding the allocation of support instruments across the EU.

ZOE Institute for Future-Fit Economies is a non-profit and independent think & do tank. We are dedicated to research for a future-fit economy. At the interface of politics, science and civil society, we develop trend-setting impulses for the fundamental questions of economic development.


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