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RESEARCH ARTICLE

Mapping hydrogen-related employment patterns: A multi-sectoral analysis of recruitment data in three Scandinavian countries

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Abstract

This paper examines how emerging employment patterns reflect the early-stage structuring of the hydrogen economy in Sweden, Norway, and Denmark. Drawing on socio-technical systems theory and cluster analysis, we analyze 3,055 hydrogen-related job postings collected between August 2023 and September 2024. By applying unsupervised machine learning to categorize region–sector–job role combinations, we identify six distinct employment clusters, and four additional clusters focused specifically on engineering roles. Our findings show that hydrogen-related recruitment activity builds on existing industrial capabilities, regional specializations, and institutional frameworks. Norway's recruitment patterns align with its offshore energy and engineering sectors; Denmark exhibits a capital-concentrated, research-driven configuration; and Sweden's activity is centered on incumbent utilities integrating hydrogen into energy infrastructure. Engineering roles dominate across countries, yet the distribution of technical competencies and actor types varies significantly. This study contributes methodologically to sustainability transitions research by demonstrating how recruitment data can serve as early indicators of evolving socio-technical configurations. We show how cluster analysis can trace emerging employment structures and capture the spatial, sectoral, and competence dimensions of technological change. These insights contribute to the empirical study of sustainability transitions by revealing how national industrial structures, actor configurations, and sectoral linkages shape early labor market dynamics in the hydrogen economy.

Author summary

As countries pursue greener economies, hydrogen is expected to play a key role in decarbonizing energy, transport, and industry. But it remains unclear how this transition affects employment—where new jobs emerge, what skills are in demand, and which organizations are involved. In this study, we analyzed over

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3,000 job advertisements in Sweden, Norway, and Denmark to examine how hydrogen-related employment is beginning to take shape. The results show that most new jobs are concentrated in regions with strong existing industries and focus on engineering, project development, and research. National patterns differ: Norway builds on offshore energy and engineering firms, Sweden's recruitment is led by utility companies, and Denmark emphasizes research and technology development in the capital region. Our findings show that job data can offer early insights into how new technologies become embedded in existing industrial and regional systems—and provide valuable input for workforce planning in sustainability transitions.

1 Introduction

The global transition towards a net-zero society creates both opportunities and challenges for most economies as they strive to reduce greenhouse gas emissions. The creation of new "green" jobs has often been considered a crucial argument for increasing public acceptance and the perceived justice of transitions, especially in contexts where transitions may lead to a decline in established industries, such as fossil fuel production [1]. It has been estimated that globally, the creation of new renewable energy related jobs likely exceeds the lost jobs in fossil energy [2,3]. However, green industrial development is inherently uneven, as regions and sectors differ in terms of their preconditions for green industrial development [4]. Indeed, novel green jobs may be created in different locations than where jobs are lost – for example, in manufacturing regions instead of natural resource extraction regions – and the content and skill requirements of these jobs often shift towards more non-routine tasks [2].

In this context, job creation is not merely an economic side effect of sustainability transitions [5], but can serve as a valuable indicator of how regional industrial structures emerge around new technology [6]. As new value chains take shape, they bring new constellations of actors, new competence requirements, and new spatial patterns of industrial development. Sustainability transitions thus do not only reshape technological systems, but also the underlying socio-economic structures, including the geographies of employment and livelihoods, competence networks, and multi-sectoral linkages. It is, therefore, not surprising that economic goals are often integrated in policymaking related to sustainability transitions [7,8].

Despite this, the sustainability transitions literature has only begun to systematically examine how transitions influence new employment patterns—and how recruitment and employment trends, in turn, may interact with transition processes. To date, much of the existing literature has concentrated on focal technologies and single-sector transitions, paying less attention to technologies that cut across sectors and reconfigure entire value chains. For example, novel technologies such as hydrogen have the potential to create economic opportunities across energy, transport, and heavy industry, making hydrogen a technology of strategic multi-sectoral importance

[9]. Adopting a multi-sectoral perspective can therefore offer deeper insights into the scale and nature of employment shifts resulting from sustainability transitions [10].

Literature adopting a multi-system perspective on transitions has recently elaborated on how multi-sectoral interactions may affect, for example, system innovation processes [11], complementarities [12], material availability [13] and incumbent strategies [14] in sustainable innovations and transitions [15]. However, this literature has so far given limited attention to analyzing the multi-sectoral features of job creation and has paid little attention to the geography of multi-sectoral patterns. In particular, few studies have examined new employment patterns where technologies span multiple sectors and regional contexts. In short, there is a need for more knowledge on how sustainability transitions influence labor markets across regions and sectors—and how labor markets themselves contribute to shaping transition pathways [16,17].

Second, sustainability transitions literature has methodologically focused on qualitative process studies, often historical case studies [18]. While helpful in gaining in-depth insights into transition processes, the focus on qualitative case studies may create an overemphasis on context sensitivity, thereby diminishing attention to more global patterns of transitions [6]. Meanwhile, reaching qualitative in-depth reconstructions of transition processes in complex system settings may not be feasible due to the sheer scope of research. There is thus a need to expand the methodological toolbox of sustainability transition studies to fit the analysis of increasingly complex transition phenomena, such as multi-sectoral interactions.

In this paper, we contribute to addressing these research gaps through a quantitative analysis of job creation associated with the emerging "hydrogen economy" in three Scandinavian countries: Sweden, Norway, and Denmark. We focus on how emerging hydrogen-related employment patterns reflect broader changes in socio-technical configurations—understood here as alignments of actors, technologies, and institutions—across sectors and regions [6]. To this end, we pose two empirically grounded research questions aimed at identifying early hydrogen-related employment patterns across sectors and regions, and how these vary by job roles, actor types, and geography. The questions are the following:

1. How can job advertisements be used to identify emerging patterns of hydrogen-related employment across sectors and regions?
2. How do these patterns vary by actors involved, job roles, and geographical distribution?

In the paper, we propose that one can empirically trace aspects of emerging socio-technical configurations by analyzing how sectors and job roles cluster across different geographical contexts. By focusing on job creation within the hydrogen economy, we demonstrate how it creates specific employment patterns.

The method we propose is a quantitative approach that integrates employment data, including information on location, job roles and recruiting organizations, with an unsupervised machine learning model to identify patterns and relationships in large datasets. Unsupervised machine learning is a method originally developed in computer science. It is increasingly being applied in the social sciences for tasks such as topic modelling and pattern recognition without predefined categories. It is effective in working with a variety of variables, both categorical and numerical [19]. This method has been utilized for analyzing public media [20], political debates [21], customer energy behavior [22] and particularly patents [23,24]. By using this method, we can identify detailed patterns related to job creation, capturing sectoral differences and regional specializations among various actors, job types, and geographical contexts that might otherwise remain concealed in traditional case study-based qualitative analyses. While the approach provides valuable insights into early-stage labor market patterns, our data reflects only a short, one-year time frame and does not capture longitudinal change. The analysis should therefore be interpreted as a snapshot of emerging structures rather than evidence of fully formed labor market dynamics.

This paper is structured as follows. Section 2 reviews the literature on job creation in sustainability transitions and introduces our analytical framework, focusing on how employment data can inform the study of emerging socio-technical configurations. Section 3 outlines the research design, including the rationale for selecting the three Scandinavian countries, the data collection process and the use of unsupervised machine learning. Section 4 presents the empirical findings, based on a clustering analysis of hydrogen-related job advertisements across regions, sectors, and job roles—first for all jobs and then specifically for engineering jobs. Section 5 discusses the implications of the findings for understanding national and regional variation in hydrogen-related employment patterns, reflects on the methodological contribution of using job advertisement data and clustering techniques, and considers how labor market data can reveal early signals of broader socio-technical change. Section 6 concludes by summarizing the empirical insights gained from analyzing recruitment data, highlighting its relevance for understanding early-stage socio-technical transitions, and outlining directions for future research and policy application.

2 Multi-sectoral job patterns

When new technologies emerge, value chains and their interactions change, leading to economic restructuring, which may give rise to conflicts and tensions, but also to new economic and employment opportunities. Such restructuring reflects not only economic shifts but the emergence of new socio-technical configurations, where technologies, institutions, and actors co-evolve. Following Heiberg et al. [6], we conceptualize socio-technical configurations as alignments of actors, technologies, and institutions that stabilize practices in organizational fields. In this study, we extend this understanding by using employment patterns as a snapshot of such an alignment process.

Socio-technical reconfigurations are multi-sectoral in nature, as generic solutions (such as green hydrogen) may be taken up in different sectors, and their diffusion and broader adoption lead to repercussions in other sectors, and vice versa [10]. While the existing literature has made important headway in conceptualizing and understanding the complexities and interdependencies introduced by multi-sectoral transitions, it has paid limited attention to how these patterns vary regionally and across different configurations of actors and competencies, particularly in relation to employment outcomes [10]. Hence, employment patterns have not been adequately explored as a systemic indicator of how socio-technical systems evolve across spatial and sectoral dimensions. In this section, we review the literature on these topics before exploring how multi-sectoral and regional patterns of job creation can be conceptualized as part of evolving socio-technical configurations. Unlike previous work, which primarily identifies configurations through discourses and institutional analysis [6], we focus on labor market outcomes as early indicators of such evolving alignments.

2.1 Competencies and job creation

Sustainability transitions have both direct and indirect impacts on employment [25]. These impacts can be divided into 1) job losses or "offshoring", 2) the creation of new "green" jobs, and 3) the transformation–or "greening"–of existing jobs.

In terms of job losses, the existing literature has particularly explored the effect of phasing out fossil fuels on employment, and the associated questions of justice in sustainability transitions. This literature tends to highlight the distribution of societal benefits and damages related to transitions [16]. Such controversies related to potential job losses have been linked to the so-called "environment vs. jobs" narrative, where sustainability-related actions have been framed in political debates as detrimental to people's livelihoods. These concerns are particularly relevant in regions where many jobs are linked to fossil energy supply [26,27].

The creation of new green jobs in sustainability transitions is linked to the narrative of green growth where novel green innovations may lead to creation of green industries and thus new economic opportunities and job creation around sustainable innovations [28]. An example is the European offshore wind industry, which has created multiple types of jobs throughout its value chain, including in turbine, turbine foundation, and cable manufacturing, and in various installation and maintenance-related segments, especially in Denmark, Germany, the United Kingdom, and the Netherlands [29]. These patterns reflect more than market growth: they represent regional socio-technical clusters where competencies, infrastructures, and policy frameworks have aligned to support emerging green industries.

New job creation depends not only on developing new skills but also on redeploying existing competencies from adjacent sectors. For example, manufacturing large-scale electrolyzers may require new expertise, but foundational competencies in electrochemistry and machinery are often available in fossil-based industries [30]. This competence shift illustrates how industrial relatedness facilitates the evolution of new socio-technical configurations through labor market transitions [16]. Moreover, green jobs often differ qualitatively from conventional roles—they tend to demand higher levels of formal education and creative problem-solving [31,32]. Crucially, their emergence is geographically uneven, often concentrated in regions with strong knowledge bases, innovation capacity, and institutional support for sustainability transitions [32].

In addition, sustainability transitions often lead to the transformation—or "greening"—of existing jobs across a wide range of sectors. For example, the electrification of transport requires that producers, users, and technicians adapt to new technologies such as battery-electric vehicles, prompting changes in production processes, service routines, and required competencies. These adjustments extend beyond individual skills to the systemic reorientation of industrial capabilities. In Norway, for instance, workers from the offshore oil and gas sector have transitioned into the offshore wind industry. This has enabled the latter to leverage existing technological know-how and infrastructure. However, it has also introduced dependencies and risks carried over from the fossil sector, including exposure to volatile market dynamics [33,34].

Such competence reallocation reflects the multi-sectoral dynamics of sustainability transitions, where industries do not evolve in isolation but interact through shared labor markets, technological linkages, and supply chains. A study from Norway found that actors across multiple sectors anticipate a growing need for transversal skills—particularly in sustainability, digitalization, and circular economy—underscoring the cross-cutting nature of competence development in transition contexts [35].

These examples illustrate how job transformation is not merely an outcome but part of broader socio-technical reconfigurations that take shape across regional and sectoral contexts. In the following section, we examine conceptual tools that allow us to analyze these interconnections systematically.

2.2 A multi-sectoral framework of studying job creation

The transition to a hydrogen-based economy is a complex process involving multi-sectoral interactions across time and space, necessitating the mobilization of human resources and the emergence of new employment patterns. This paper adopts an analytical framework that combines socio-technical systems theory with cluster analysis methodologies to study the early-stage employment outcomes of this multifaceted transition.

Our framework builds centrally on the work of Andersson et al. [36], who developed a "*morphology-based*" approach to analyzing the outcomes of directionality in socio-technical transitions. They depart from the fact that socio-technical systems evolve through processes of technological, institutional, and market development, which together shape the direction of transitions. More importantly, they emphasize that understanding transitions requires not only studying these processes but also mapping the concrete outcomes that result from them, including the spatial, sectoral, and competence-related socio-technical configurations that emerge in different contexts. This directs attention not only to the processes of change but also to their concrete manifestations in employment structures, which we interpret as early-stage socio-technical configurations.

Andersson et al. [36] provide a structured approach to characterizing the outcomes of actors, competencies, and infrastructures that materialize as new configurations take shape. By focusing on these directional outcomes, they demonstrate how transitions lead to the emergence of new socio-technical configurations, including clusters of activity that link specific sectors, technological skills and competencies, and regional conditions. This approach is highly relevant to understanding the hydrogen economy, which is unfolding through distinct sectoral, spatial, and competence-related pathways in Sweden, Norway, and Denmark.

The importance of regional industrial structure in enabling or constraining the emergence of new clusters is further highlighted by Boschma and Frenken [37,38], who argue that regions diversify into new industries related to their existing industrial base through a process of regional branching. This evolutionary perspective highlights that relatedness in, for example, technological knowledge enables firms to enter new industries by redeploying their existing competencies and skills to new uses [39]. This means that existing regional clusters with specific competencies are likely to diversify to technologically related industries, creating a regional pattern for new industry development [40]. This is especially relevant for understanding how the hydrogen economy builds on existing regional specializations. It also shows that clusters form and evolve over time, underscoring the significance of knowledge spillovers and actor networks in shaping innovation dynamics within and across regions [41,42]. This work provides a useful theoretical basis for understanding the co-evolution of hydrogen technologies, competence needs, and spatially anchored clusters, aligning with our focus on identifying hydrogen-related employment clusters in the three Scandinavian countries.

Previous scholarship highlights the importance of multi-sectoral interactions and actor constellations in shaping hydrogen transitions. Heiberg, Truffer, and Binz [6] introduce socio-technical configuration analysis (STCA) to capture how technologies, institutions, and markets co-evolve across sectors, shaping regional conditions. Löhr and Chlebna [43] emphasize the role of 'system entanglers'—actors who connect technological development across energy, transport, and industry—while Ohlendorf, Löhr, and Markard [44] demonstrate how discursive struggles influence which sectors and regions ultimately benefit from hydrogen-related employment. Drawing on the morphology-based perspective and the broader literature on socio-technical transitions and regional industrial development, we work with three interrelated dimensions that shape the early formation of hydrogen-related employment clusters.

Sectors. The hydrogen economy encompasses multiple sectors, including steel, energy, transport, and chemicals. Each sector contributes uniquely to hydrogen-related employment and technological advancement. For example, the steel industry sector in Sweden has pioneered the adoption of hydrogen technologies for fossil-free production [45,46], while Norway's energy sector emphasizes hydrogen as a clean export commodity [47]. Understanding these sector-specific roles is crucial for identifying the drivers of economic growth and emerging employment patterns within the hydrogen economy. Sectoral transitions, particularly in energy and transport, often require systemic coordination and long-term planning to align infrastructure investments, regulatory frameworks, and workforce development [48].

Competence and Skills. The transition to a hydrogen-based economy demands a diverse set of competencies and skills. Prior research indicates the emergence of both direct and indirect hydrogen-related employment opportunities, with a significant portion requiring advanced expertise in engineering, research, and technology development [49]. However, the hydrogen transition is also expected to create demand for a wide range of complementary skills in areas such as supply chain management, infrastructure planning, regulatory compliance, environmental monitoring, artificial intelligence and other digital skills [50–52]. This demand spans multiple educational levels, from vocational training programs to advanced academic degrees [32].

The emergence of these competence needs is closely linked to the interplay between regional industrial specializations, sectoral innovation processes, and national policy frameworks. As discussed by Santoalha et al. [53], regional capacities for green diversification depend not only on technological relatedness but also on the availability of skills that enable knowledge recombination across sectors. This reinforces the importance of understanding how skills and competence profiles vary across different hydrogen-related employment clusters, and how regional educational systems and industrial training programs can support the emergence of hydrogen-related expertise.

Geographical Space. Regional disparities in natural resources, infrastructure, industrial bases, and institutional capacities significantly influence the development of the hydrogen economy. Denmark's extensive wind energy resources position it as a leader in hydrogen production technologies [54], whereas Sweden's industrial northern regions are emerging as hubs for hydrogen-based steel manufacturing [46]. In Norway, the availability of natural gas resources and carbon capture and storage expertise contributes to the exploration of blue hydrogen projects, further highlighting how regional resource endowments shape technology pathways [47]. Geographical variation is not only shaped by resource availability but also by the presence of related industries, innovation ecosystems, and regional policy frameworks [55]. Regions with existing competencies in renewable energy technologies, heavy industry, or advanced materials science are better positioned to integrate hydrogen technologies into their industrial landscapes, illustrating how technological relatedness influences the spatial evolution of socio-technical configurations [37]. The capacity of regions to attract investment and talent also varies significantly, influenced by local institutional frameworks, knowledge networks, and collaboration platforms that support innovation and technology deployment [4]. By examining these geographical variations, we can better understand how location-specific factors contribute to the formation and success of hydrogen-related employment clusters.

3 Research design and case description

In this study, we collected data on new job creation to analyze and compare the emerging structure of the hydrogen economy across three Scandinavian countries. Drawing on the morphology-based framework described in Section 2, we apply cluster analysis to empirically identify and characterize patterns of hydrogen-related employment across sectors, regions, and job roles. This approach allows us to detect distinct employment clusters that underpin the early development of the hydrogen economy in Sweden, Norway, and Denmark

3.1 Case motivation and description

The three Scandinavian countries in this study—Sweden, Norway, and Denmark—were selected based on the principle of "most similar systems" [56]. Holding cultural, economic, and institutional factors relatively constant facilitates the identification of differences in recruitment patterns that are not explained by broader contextual variation. However, the industrial structures of the countries differ: Norway has strong offshore oil and gas and maritime sectors, Sweden has major manufacturing, steel and iron, and forestry sectors, while Denmark has large agriculture, renewable energy and pharmaceutical sectors. These pre-existing industrial structures provide different starting points to developing the hydrogen economy, making the three countries well-suited for examining differing emerging employment patterns in comparable institutional contexts.

Table 1 provides an overview of the number of hydrogen-related jobs, the number of recruiting organizations, the size of the labor market, GDP, and GDP per capita. The number of new jobs and the number of recruiting organizations varies substantially between the countries. Sweden reports significantly fewer hydrogen-related jobs than Denmark and Norway, where the most active regions individually account for more new jobs than the total observed in Sweden. The distribution of recruiting organizations also differs: in Norway and Sweden, three to four organizations account for over half of all postings, whereas job creation in Denmark is more evenly distributed across organizations. Regarding macroeconomic factors, the countries display broadly similar characteristics. Sweden has the largest labor market, Denmark has a slightly lower GDP, and Norway has a significantly higher GDP per capita—nearly twice that of Sweden.

While our dataset does not distinguish between different production methods of hydrogen in each job advertisement, national strategies in all three countries overwhelmingly emphasize the development of green hydrogen—that is, hydrogen produced through electrolysis powered by renewable energy such as wind, hydro, or solar. This is consistent with broader decarbonization goals and aligns with ongoing projects, including Denmark's wind-powered power-to-X (PtX)

Table 1. New jobs created in Sweden, Norway and Denmark from August 2023 until September 2024 and key country statistics for year 2023.

Country	New Jobs		Organizations		Country Statistics		
	Nr.	%	Nr.	%	Labor (mil.)	GDP (b$)	GDP/Cap. (k$)
SE	452	15	81	24	5.8	593	56
DK	862	28	121	35	3.2	404	68
NO	1,741	57	141	41	3.0	486	88
Total	3055	100	343	100	12	1483	212

Source: Own data, OECD [57] and World Bank [58].

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initiatives, Sweden's integration into electricity systems, and Norway's pilot-scale green hydrogen investments alongside blue hydrogen in some industrial projects.

3.2 Operationalization and data collection

Drawing on the conceptual distinctions developed in Section 2, we operationalize three dimensions—sector, job role (as a proxy for competencies and skills), and geographical space—as empirical indicators of the actor–competence–location alignments that underpin emerging socio-technical configurations. In practice, this means classifying each job posting by the recruiting organization's sector, the advertised job role, and the location of the position. These categorizations then serve as input for the cluster analysis, allowing us to detect recurring employment patterns that can be interpreted as outcomes of changes in socio-technical configurations at an early stage.

To analyze job creation in the hydrogen economy across the three Scandinavian countries, data was systematically collected from major recruitment websites: Platsbanken (Sweden), Finn.no (Norway), and Jobindex (Denmark). Job postings were collected weekly from August 20, 2023, to September 30, 2024, using a custom-built web scraper.

Using job postings as a proxy for job creation, his study enables a granular sector- and region-specific analysis of how recruitment patterns reflect technological shifts. Despite its relevance, this type of recruitment data has been largely overlooked in sustainability transition studies. This approach also facilitates comparisons across countries, helping to identify structural differences in how the hydrogen economy develops in different contexts. Job postings reflect near-term recruitment needs and hiring intentions, offering early signals of where and how hydrogen-related employment is beginning to take shape. While they do not capture all forms of employment, such as internal transfers or informal hiring, they serve as a valuable proxy for identifying early-stage recruitment patterns and emerging employment structures.

To ensure relevance, only job postings containing at least one of the following keywords were included: "hydrogen," "brintgas," "vätgas," or "power-to-x." This filtering method helped isolate positions directly related to hydrogen. What it captures are emerging value chains, projects, and industrial activities specifically and directly related to the production and use of hydrogen. It is important to note that this does not include system-wide and complementary technologies, such as fuel cells, unless hydrogen is specifically mentioned.

Following the initial data collection, a manual review process was conducted to remove any job postings unrelated to hydrogen, ensuring a high-quality dataset focused exclusively on hydrogen-related employment opportunities. Due to the differing structures of the websites, consistent categories had to be manually established, including a title that describes the type of job sought, the recruiting organization, a job description, the scrape date, and the workplace location. The names of the organizations and their locations were standardized. The job postings initially included detailed location information, often down to the street level. While this provided high granularity, it made it difficult to generalize findings or identify broader patterns. To improve consistency in cross-country comparisons, we ultimately aggregated location data to the regional level. In our analysis, regions typically refer to administrative divisions that encompass multiple municipalities (e.g., counties or similar units).

To analyze which types of organizations are creating jobs in the hydrogen economy, each recruiting organization was categorized into sectors through a bottom-up process, starting with specific labels and aggregating them into broader categories. A minimum threshold of 10 job postings per sector was applied to ensure analytical relevance and reduce noise from sparse categories, following common practice in exploratory quantitative research [19]. The resulting sector categories and their respective job counts are presented in Table 2. Similarly, job roles were categorized based on the titles listed in the advertisements, resulting in 17 distinct roles (Table 3), whose frequencies and proportions were compared across the three countries. Given the dominance of engineering jobs, we further subdivided this category into specific disciplines. While 27 types of engineering roles were identified, 15 of the least frequent were consolidated into an "Other" group, resulting in 13 engineering subcategories used in the final analysis (Table 4).

Table 2. Sectors used to categorize the organizations found in the dataset.

Sector	Description	Number of jobs
Energy technology manufacturer	Manufacturing components, modules or products used in other energy industries.	715
Consulting	Consulting agencies operating and providing knowledge and services within a variety of subjects and industry.	682
Energy utility	Produces and supplies energy.	509
Research & Education	Conducts research or provides education (e.g., universities, institutes).	287
Hydrogen technology manufacturer	Makes components for hydrogen production, storage, distribution, or use.	215
Other manufacturing	Manufactures components not classified as energy or hydrogen tech.	186
Fossil fuel & refinery	Extracts or refines fossil fuels like oil and gas.	124
Chemicals	Produces or processes chemical substances used in fuels or manufacturing.	98
Government & Public sector	Publicly funded bodies such as municipalities and regional authorities.	79
Legal & Economics	Operates in law, finance, or insurance (e.g., law firms, banks)	70
Metals & Mining	Extracts or processes metals and mineral materia.	59
Transport	Manufactures vehicles or provides transportation services.	16
Other	Does not fit any of the above categories.	15
Total	–	3,055

Source: Own compilation.

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These categorizations of job ads into sector, job role, and geography provide the empirical input for the cluster analysis in Section 4, which identifies recurring patterns in hydrogen-related recruitment.

3.3 Cluster analysis

We apply cluster analysis to examine how emerging hydrogen-related employment patterns can be understood as early signals of evolving socio-technical configurations—operationalized through the empirical dimensions of sector, job role (as a proxy for competencies and skills), and geographical space.

This method enables us to uncover latent structures in the dataset and trace how jobs are distributed across sectors and regions in the Scandinavian hydrogen economy. Cluster analysis offers a scalable approach to detecting patterns that are difficult to capture through qualitative methods alone, providing empirical insights into the spatial and sectoral dimensions of early-stage recruitment activity. This approach aligns with previous applications of cluster analysis in transition studies. For example, Hirt et al. [59] used regional clustering to trace photovoltaic diffusion in Switzerland, while Santoalha et al. [53] linked digital skills and industrial relatedness to green diversification across Europe. These studies demonstrate the value of cluster analysis in identifying regional innovation dynamics and employment patterns in sustainability transitions.

We tested three clustering methods: hierarchical clustering, density-based clustering (DBSCAN), and centroid-based clustering (K-means). K-means, combined with a Euclidean distance function, was selected for its ability to generate the most distinct and interpretable groupings. Each data point in our analysis represented a unique combination of region and sector (e.g., "Rogaland–Consulting"), and was defined by the number of job postings across 17 job role categories. To simplify and improve interpretability, Oslo and Akershus were merged into a single region, motivated by their geographical proximity and shared labor market.

Table 3. Job roles used to categorize the job postings found in the dataset.

Job roles	Description	Number of jobs
Engineering	All jobs related to different engineering roles (Table 3).	1,304
Management other	Management roles not focused on specific projects, such as CEOs, operations managers, and department heads.	261
Technician & Maintenance	Focused on production, repair, and operational support, including technicians, mechanics, electricians, and welders.	242
Project management	Project planning and management.	186
Finance & Business development	Jobs within finance, accounting, economics as well as business development or analysis.	158
IT & Data science	Includes jobs working with software, data management, IT and data analysis.	126
PhD	Doctoral students.	122
Researcher	All jobs within research, except doctoral student, such as profes-sors, research assistants and other scientists.	92
Sales & Customer service	Jobs related to sales, product marketing or services as well as offering support of different kinds to customers.	92
Procurement & Logistics	Jobs related to procurement, logistics and supply chains.	92
Administration	Administrative or clerical work and secretaries.	67
Quality assurance	Inspection, controlling or assuring quality of products or services.	58
Law	Including lawyers and legal advisors.	39
Environmental	Sustainability or environmental expert and generalists positions.	31
HR	Human resources and recruitment.	31
Public administration	Administration within public sector.	20
Other	Includes all jobs which do not fall within any of the other 16 categories.	134
Total	–	3,055

Source: Own compilation.

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To determine the optimal number of clusters, we employed silhouette scoring and examined within-cluster squared distances [19]. These methods, widely used to assess clustering quality, indicated that the best results were likely to fall within 3–7 clusters. To ensure stability and reproducibility, the K-means algorithm was run 1,000 times for each candidate solution, and we used the Adjusted Rand Index (ARI), as recommended by Monti et al. [60], to evaluate consistency between runs. Following the cluster stability assessment frameworks outlined by Hennig [61] and Lange et al. [62], we found that the most robust configuration was a six-cluster solution, with an ARI of 0.98.

Among the six resulting clusters, two stood out for their strong internal coherence and thematic clarity: Cluster 1, Offshore and Energy Engineering (Norwegian south-western coast), and Cluster 2, Industrial Engineering and Consulting (Oslo area). Two other well-defined clusters were Cluster 3, Energy Utilities (Capital Cities), and Cluster 4, Innovation and Research (Denmark and Norway). The remaining two—Cluster 5, Across Industries (Urban Areas), and Cluster 6, Generic Engineering and Research (All Countries)—were more diffuse but still offered insights into broader recruitment trends. These six clusters serve as the basis for interpreting how hydrogen-related job creation varies across sectors and regions, as discussed in Section 4.

Because engineering jobs made up about one-third of all job postings, we conducted a separate cluster analysis specifically for these positions. We constructed a 13-dimensional matrix based on engineering role subcategories, following the same procedure described above. The silhouette scores and ARI again guided cluster selection, and the four-cluster

Table 4. Describes the different engineering roles used to categorize the engineering jobs found in the dataset.

Engineering roles	Description	Number of jobs
Electrical	Focus on power systems, electronics, and grid infrastructure.	328
Mechanical	Works with machines, equipment, and industrial systems.	311
Generic	Unspecified or broadly defined engineering roles.	162
Chemical	Specializes in industrial chemical processes and systems.	148
Risk & Safety	Focuses on risk assessment and safety compliance.	80
Automation	Develops automated systems for industrial applications.	79
Civil	Designs and manages infrastructure and construction projects.	44
Energy	Works in energy systems without further specialization.	38
IT/Software	Specializes in software, computing, and IT systems.	33
Marine	Designs and develops marine technologies and systems.	22
Materials	Focuses on materials science and applications in production.	15
Environmental	Works on environmental impact and sustainability assessments.	13
Other	Roles not fitting other categories, with low frequency.	31
Total	–	1,304

Source: Own compilation.

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solution achieved a perfect ARI of 1.0 and silhouette scores above 0.5 for most combinations, indicating high internal consistency.

This engineering-focused analysis revealed four clusters: (1) Offshore and Energy Technology (Norwegian south-western coast), (2) Energy Technology (Oslo & Rogaland), (3) Energy Infrastructure and Systems (Sweden), and (4) Technical Expertise (Across Sectors and Regions). The first two were similar in terms of recruiting sectors, job roles, and lead organizations—particularly engineering and consulting firms with ties to offshore or industrial energy. The third cluster, dominated by Swedish utility companies, reflected a distinct pattern of engineering recruitment focused on infrastructure and energy systems. The fourth was more dispersed and included engineering jobs across many sectors and regions. As with the general dataset, these engineering clusters should be interpreted as early signals of recruitment patterns, not as evidence of fully developed or stable employment structures.

4 Empirical findings

This section presents the results from two complementary cluster analyses designed to identify emerging patterns in hydrogen-related employment. The first captures broad regional, sectoral, and occupational configurations across all job postings, while the second focuses specifically on engineering roles—the most prevalent category in the dataset. Together, these analyses provide empirical insight into early-stage recruitment patterns and help trace the socio-technical configurations emerging in Denmark, Norway, and Sweden. Building on these results, Section 4.3 synthesizes key findings across clusters to compare how actor types, sectoral focus, and regional specialization shape national trajectories in the Scandinavian hydrogen economy.

4.1 Regions, Sectors and Job Roles

The cluster analysis of region–sector combinations revealed six distinct patterns of hydrogen-related job creation across Sweden, Norway, and Denmark. Four clusters exhibit clear sectoral and geographical profiles, while the remaining two are more diffuse and cross-cutting. These clusters reflect early-stage socio-technical configurations—combinations of regions, sectors, and job roles—that are forming around hydrogen technologies. Fig 1 illustrates the spatial distribution of these clusters, with intensity indicating areas of higher recruitment activity.

Cluster 1, Offshore and Energy Engineering (Norwegian south-western Coast), consists of 552 jobs from energy technology manufacturers and consulting agencies, located primarily in the southwestern coastal regions of Rogaland and Vestland. This cluster emerged early in the analysis and remained stable across different clustering configurations, indicating a strong and consistent pattern of recruitment activity. The jobs are concentrated around the industrial hubs of Stavanger and Bergen, which are key centers of offshore and energy-related expertise in Norway.

Engineers are the most sought-after job role, accounting for over 50% of the postings, followed by project managers, technicians, and maintenance staff. This combination of roles may reflect a regional focus on both planning and technical execution, consistent with ongoing or upcoming industrial hydrogen projects. Although several organizations contribute to this cluster, three companies dominate, collectively accounting for over 80% of the job postings: Akkodis, a consulting agency offering services across a wide range of engineering fields; Aibel, which specializes in offshore infrastructure for the energy industry; and Aker Solutions, involved in the engineering and development of oil and gas and renewable energy installations.

While multiple hydrogen-related initiatives are active in these regions, only one was identified as specifically connected to blue hydrogen, whereas the majority appear to focus on green hydrogen production. This suggests that coastal Norway is developing into a regionally anchored hydrogen cluster with strong links to existing offshore and energy engineering capabilities.

Cluster 2, Industrial Engineering and Consulting (Oslo area), consists of 475 jobs from energy technology manufacturers and consulting agencies, primarily located in Oslo and the surrounding Akershus region. This cluster also emerged early in the analysis and remained stable across different clustering configurations, indicating a robust pattern of recruitment activity. While not a major site for hydrogen production, the Oslo region plays a central role in engineering services and corporate operations.

Engineering roles make up more than 60% of all postings, followed by various management positions. The prominence of these roles suggests a regional specialization in design, planning, and project coordination functions within the hydrogen economy.

The cluster is dominated by three organizations—Akkodis, Aker Solutions, and Aibel—which together account for over 75% of all postings. These firms maintain offices or recruit in Oslo region but conduct hydrogen-related activities elsewhere. For example, Aker Solutions is involved in a project in Lysekil, Sweden, developing carbon capture linked to hydrogen production from natural gas in partnership with Preem.

The cluster reflects the role of Oslo region as important administrative and engineering centers for hydrogen-related activities, hosting firms that support the development of hydrogen projects across the broader Scandinavian region.

Cluster 3, Energy Utilities (Capital Cities), consists of 258 jobs posted by energy utility companies located primarily in Oslo and Copenhagen. The cluster shows a clear spatial concentration of recruitment in national capitals, reflecting the central role of major utility firms in shaping hydrogen-related employment.

The most frequently advertised roles include engineers, followed by positions in finance and business development, management, and IT. This indicates a mix of technical and administrative functions associated with utility-led hydrogen initiatives.

The cluster is dominated by three large organizations: Ørsted and European Energy in Denmark, and Statkraft in Norway. These companies are all engaged in renewable energy production and have public or hybrid ownership structures. Some of the identified job postings are linked to ongoing hydrogen projects, such as Ørsted's initiatives to produce renewable hydrogen for transport using offshore wind.

A small number of postings also come from other actors, including Akershus Energi, which is participating in a project combining electrolysis and biogas for transport applications. Taken together, these patterns suggest that national utility

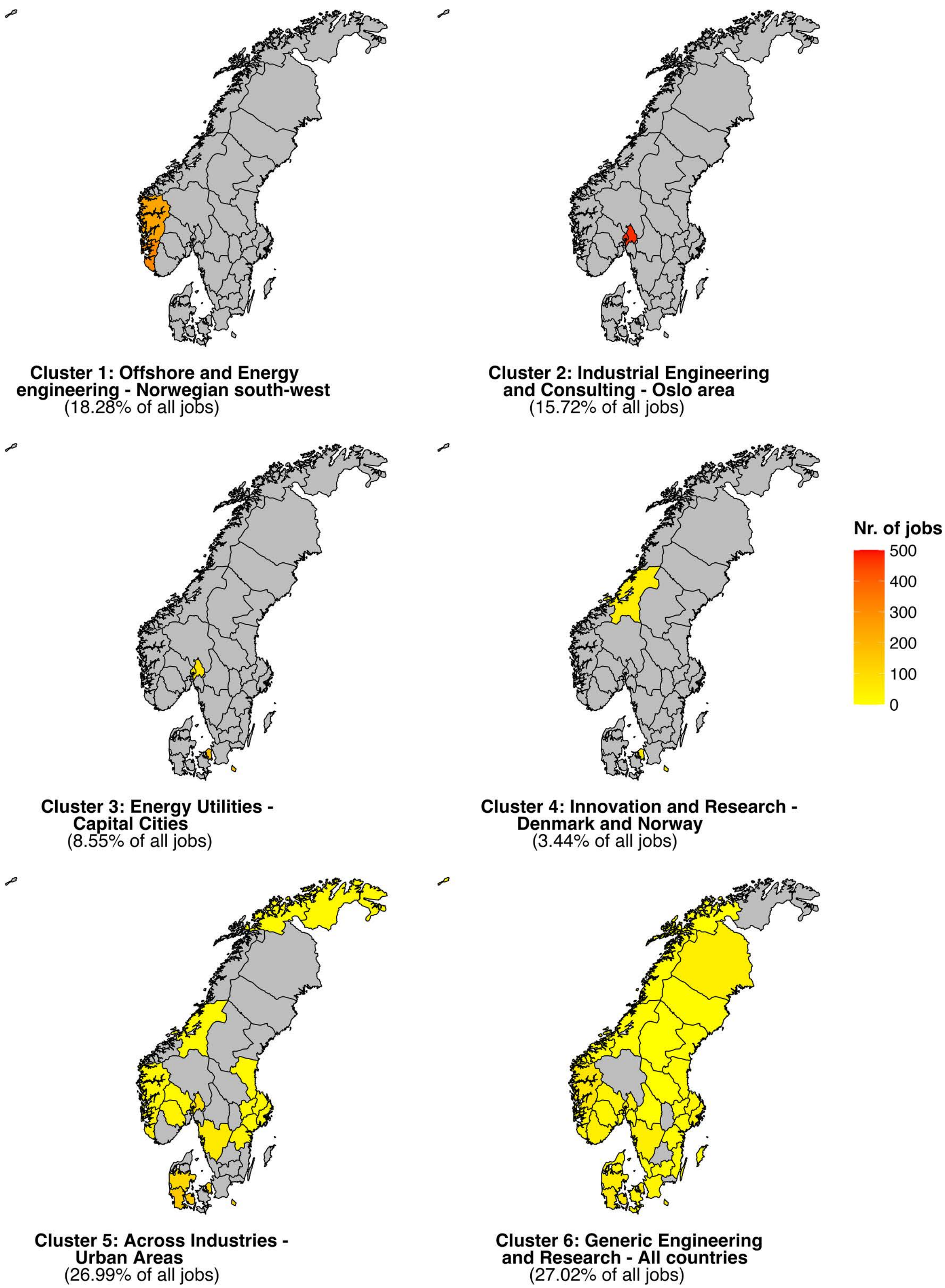

Fig 1. Geographical distribution of identified clusters (percentage of all jobs in brackets). Multiple clusters can overlap in the same regions, as clusters are defined by sectoral characteristics, actor types, and job profiles rather than by geographic boundaries. The color gradient indicates job concentration, with yellow representing fewer jobs and red higher concentrations. Basemap source: Natural Earth [63].

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firms are emerging as key actors in early-stage hydrogen recruitment, particularly in capital regions where project development and coordination functions are often concentrated.

Cluster 4, Innovation and Research (Denmark and Norway), consists of 104 jobs, primarily posted by universities and research institutes located in Trøndelag and the Copenhagen region. The cluster reflects a geographically concentrated pattern of hydrogen-related recruitment in the research and higher education sector.

The majority of postings are for researchers and PhD candidates, which together account for more than three-quarters of the jobs in this cluster. This indicates a strong focus on research and early-stage innovation within the hydrogen field.

Key recruiting organizations include the Technical University of Denmark (DTU), the Norwegian University of Science and Technology (NTNU), and research institute SINTEF. These research organizations are prominent actors in the Scandinavian hydrogen research landscape and appear to be expanding their activities in this area.

This cluster accounts for over one-third of all research and PhD positions identified in the dataset, as well as a comparable share of jobs created by research organizations. The data suggests that research-intensive institutions are playing a central role in shaping hydrogen-related competence development, particularly in regions with strong university infrastructures.

Cluster 5, Across Industries (Urban Areas), consists of 815 jobs distributed across 18 regions and 8 sectors, with a concentration in urban areas. While more geographically and sectorally dispersed than the preceding clusters, it still reveals recurring patterns of recruitment activity related to the hydrogen economy.

The dominant sectors are energy utilities and hydrogen technology manufacturers, each accounting for over 20% of the postings. Additional sectors with a notable presence include chemicals, energy technology manufacturing, and fossil fuels and refining—each representing at least 10% of the jobs in the cluster.

Engineering remains the most in-demand job role, accounting for more than 40% of all postings. This continues the pattern seen in other clusters, where technical competencies play a key role in hydrogen-related labor market formation.

Although a wide range of organizations is represented, a few major actors account for a substantial share of job creation. Vattenfall alone contributes 15% of the cluster's jobs, followed by Topsoe, Nel, and Green Hydrogen Systems, each with more than 5%.

Overall, this cluster illustrates a broad-based demand for hydrogen-related skills across multiple industrial sectors and countries, particularly in larger urban centers.

Cluster 6, Generic Engineering and Research (All countries), comprises 816 jobs distributed across 37 regions, 13 sectors, and 17 competence categories. The cluster emerged as a residual grouping, encompassing postings that did not fit more narrowly defined sectoral or regional profiles. As such, it lacks the geographical and thematic coherence seen in other clusters.

Engineering and research are the most prominent job roles in this cluster, with engineers accounting for approximately 25% of postings and research-related roles representing over 20%. This reflects a broader trend across the dataset, where engineering consistently ranks as the most sought-after competence. The postings are scattered, with few regions contributing more than 5% of the cluster's total jobs, and no single sector dominating the cluster.

The diffuse nature of Cluster 6 limits the extent to which clear interpretations can be drawn. However, its size and diversity suggest that hydrogen-related recruitment is emerging across a wider array of locations, sectors, and organizational types, even if not yet forming distinct patterns.

4.2 Engineering jobs

Since there were significantly more engineering jobs than other types, and because engineering jobs vary widely in their fields, a separate clustering analysis was conducted focusing specifically on them. This analysis aimed to uncover patterns not visible in the general clustering analysis and to explore how engineering competencies are distributed across sectors and regions. The number of clusters was set to four, which identified one distinct cluster, two quite similar clusters, and one mixed cluster. The geographic distribution of these clusters can be found in Fig 2.

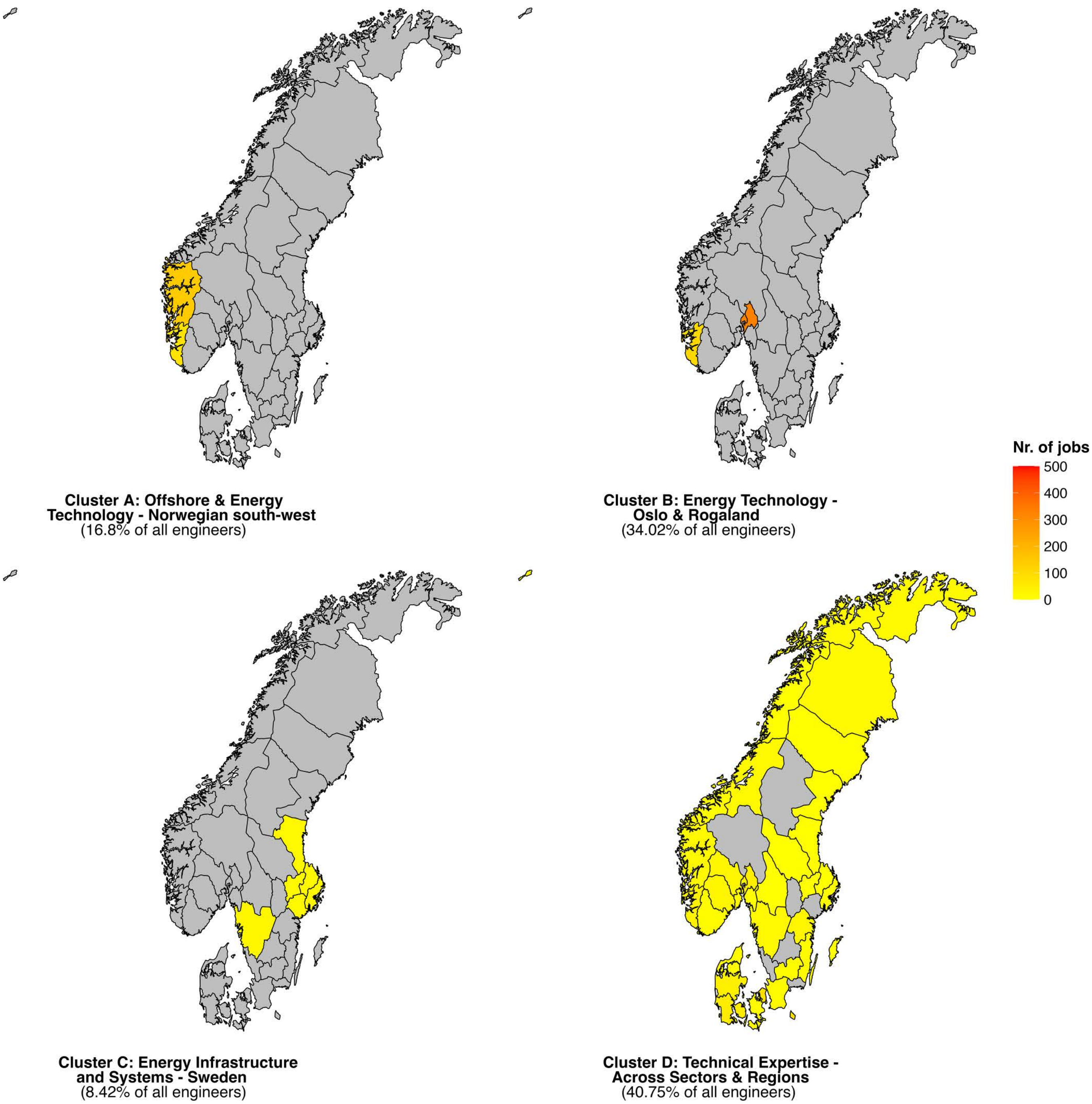

Fig 2. Geographical distribution of identified clusters (percentage of all jobs in brackets). Clusters are defined by sectoral and occupational characteristics rather than regions alone, so overlaps occur. The color gradient indicates engineering job concentration, from fewer jobs (yellow) to more jobs (red). Basemap source: Natural Earth [63].

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Cluster A, Offshore and Energy Technology (Norwegian south-western Coast), comprises 215 engineering jobs primarily located in Vestland, with a smaller share in Rogaland. The cluster is dominated by energy technology manufacturers and consulting firms, reflecting the strong petro-maritime industrial base of Norway's southwestern coast. Electrical and mechanical engineering roles are the most frequently recruited, each accounting for more than one-fifth of the postings, followed by chemical and general engineering positions.

The majority of jobs in this cluster are concentrated among three organizations: Akkodis, which accounts for most engineering roles in Vestland; Aibel, active in offshore infrastructure; and Aker Solutions, with a presence across both oil and gas and renewable energy projects. Together, these firms represent the core of the cluster's recruitment activity. The presence of all three in both regions illustrates the continued importance of offshore and energy-related engineering expertise in shaping hydrogen-related labor demand in coastal Norway.

Cluster B, Energy Technology (Oslo and Rogaland), comprises 436 engineering jobs concentrated in Oslo and Akershus, with additional activity in Rogaland. The cluster is shaped by recruitment from energy technology manufacturers and consulting agencies operating in both regions. Electrical and mechanical engineers make up the largest share of roles, each accounting for over one-fifth of the total postings.

Recruitment is led by three organizations—Akkodis, Aker Solutions, and Aibel—which together represent a substantial portion of job creation within the cluster. In Oslo region, these firms dominate the demand for engineering talent, while Akkodis also has a strong presence in Rogaland. The concentration of recruitment in the capital region alongside Rogaland points to a dual regional focus in Norway's hydrogen economy, combining industrial expertise with institutional and organizational capacity.

Cluster C, Energy Infrastructure and Systems (Sweden), consists of 108 engineering jobs recruited exclusively within the energy utility sector. These positions are distributed across six Swedish regions—Gävleborg, Stockholm, Södermanland, Uppsala, Västmanland, and Västra Götaland—where recruitment patterns show a clear emphasis on utility-driven hydrogen integration.

Electrical engineers account for the largest share of roles in this cluster, followed by civil engineers. The recruitment is almost entirely driven by a single organization: Vattenfall. With involvement in projects focused on synthetic fuel production in Västra Götaland and Stockholm, Vattenfall emerges as the dominant actor shaping Sweden's hydrogen-related engineering labor market.

The composition of this cluster suggests that Sweden's hydrogen development is closely linked to large-scale utilities and infrastructure systems. Rather than manufacturing or offshore activities, the emphasis appears to be on integrating hydrogen into existing energy networks and supporting the transition to new fuel technologies.

Cluster D, Technical Expertise (Across Sectors and Regions), comprises 522 engineering jobs distributed across 34 regions and 12 sectors, making it the most geographically and sectoral dispersed of the engineering clusters. While the distribution is broad, more than 10% of the jobs are located in the Copenhagen area, where Ørsted stands out as the leading recruiting organization.

Mechanical engineers represent the largest share of roles in this cluster, followed by chemical, electrical, and general engineering positions. The jobs are concentrated in energy technology manufacturing, hydrogen technology manufacturing, fossil fuels, energy utilities, consulting, and other manufacturing sectors.

Although the cluster lacks a clear geographical or sectoral profile, it reflects a widespread demand for engineering expertise across multiple energy-related industries and value chains. This diffuse pattern suggests that hydrogen-related engineering roles are emerging in diverse organizational and regional contexts beyond the dominant clusters identified earlier.

4.3 Comparative insights across clusters

The results from the two clustering analyses—one based on all hydrogen-related job postings and one focused specifically on engineering roles—reveal both shared occupational patterns and distinct national and regional differences in hydrogen-related employment. This section integrates insights from both analyses to highlight how sectoral focus, actor types, and regional specialization shape the emerging hydrogen economy across the three Scandinavian countries.

Among the six clusters derived from the full dataset, two (Cluster 1: Offshore and Energy Engineering and Cluster 2: Industrial Engineering and Consulting) show strong structural parallels. Both are located in Norway and dominated by the same engineering and consulting firms—Akkodis, Aibel, and Aker Solutions. While Cluster 1 includes more project management and technical roles and is centered on the coastal regions of Rogaland and Vestland, Cluster 2, located around Oslo and Akershus, shows a greater emphasis on general management. These differences may reflect regional functional specializations within the broader Norwegian hydrogen economy.

Clusters 3 (Energy Utilities) and 4 (Innovation and Research) capture distinct actor constellations. Cluster 3 is centered around utility-led development in Oslo and Copenhagen, while Cluster 4 is dominated by university and research institute hiring in Trøndelag and Denmark's capital region. These clusters highlight the roles of infrastructure and R&D institutions in shaping national hydrogen strategies.

Clusters 5 and 6 are more dispersed. Cluster 5, with a stronger industrial focus, includes energy utilities, manufacturers, and refiners, while Cluster 6 features a broader mix of sectors and roles with weaker geographic or sectoral concentration. Both appear to reflect more generalized or early-stage recruitment across the hydrogen economy.

Engineering stands out as the dominant job category, accounting for over 40% of postings across the dataset. Electrical and mechanical engineers are most frequently recruited, followed by chemical and general engineering roles. This reflects the broad technical demands of the hydrogen economy, including system integration, infrastructure development, and technology design. In contrast, technician and maintenance roles are relatively few (8%), suggesting that large-scale deployment is still limited, and hiring remains concentrated in the planning and early implementation phases.

The separate clustering of engineering jobs adds further nuance by showing how technical competencies are distributed across countries, reinforcing the finding that hydrogen-related employment in Norway is closely tied to energy and offshore industries, Denmark's is centered around institutional actors in Copenhagen, and Sweden's is driven largely by utility firms focused on energy integration.

Across both cluster analyses, Norway stands out for its concentrated and industrially aligned hydrogen-related recruitment activity, with strong recruitment hubs in Stavanger, Bergen, and Oslo region. Denmark shows institutional coordination around utilities and research, primarily in the capital region. Sweden's recruitment is more fragmented and utility-led, centered on actors like Vattenfall but lacking the industrial cohesion seen in its neighbors. The importance of consulting agencies is also quite evident throughout the analysis. Consulting agencies make up a large portion of jobs in many of the clusters, which may indicate that specific expertise in hydrogen technologies is still limited and is being brought in from these agencies.

Together, the analyses show how national trajectories, existing competencies, and industrial legacies shape hydrogen-related employment. The engineering clusters, in particular, underscore how specific technical roles are distributed across countries and sectors—providing early insight into the socio-technical configurations of the Scandinavian hydrogen economy.

5 Discussion

This paper has shown how hydrogen-related job postings can provide early insights into emerging employment patterns and socio-technical configurations in Sweden, Norway, and Denmark. Using cluster analysis of recruitment data, we identified distinct sectoral and geographical patterns that reflect how the hydrogen economy is beginning to manifest across these countries. Job creation is unevenly distributed and shaped by national industrial structures, sectoral specialization, and policy priorities. And the nature of the jobs—whether in engineering, research, or project management—offers clues about which parts of the hydrogen value chain are gaining traction.

While the analysis is limited to a one-year snapshot, it captures an early-stage outcome of changes in socio-technical configurations that warrant further investigation. Building on these empirical patterns, the following section interprets national and sectoral variations to explore how institutional and industrial structures shape emerging hydrogen-related employment patterns.

5.1 National patterns and sectoral variations

The study highlights three key differences between the Scandinavian countries regarding how hydrogen-related jobs are emerging.

To begin with, Norway's job patterns suggest a strong alignment with its existing industrial base, particularly in offshore energy and engineering services. The dominance of consulting agencies and energy technology firms along the southwestern coast and in Oslo indicates that early hydrogen development is building on the established capabilities of the oil and gas, and hydropower sectors. For example, engineering competencies in gas processing technologies, developed to manage natural gas, can be redeployed to applications of zero-emission hydrogen production and use [35]. This illustrates how regional industrial specialization and multi-sectoral alignments within the broader socio-technical configuration—particularly the interplay between offshore energy, engineering services, and consulting—shape emerging patterns of hydrogen-related employment [29,34].

The strong role of engineering and consultancy agencies also suggests a concentrated alignment of actors within the national socio-technical configuration, where a few large consulting firms, engineering specialists, and energy producers interact across sectoral boundaries, providing services and expertise rather than specialized hydrogen technology providers. This also becomes evident when examining the engineering clusters. The first, centered around Oslo, reflects the capital region's role as a hub for energy consulting and technology firms that support the development of hydrogen projects across the country. Engineering consultancies dominate this cluster, emphasizing project design, feasibility assessments, and system integration work, which reinforces Oslo's position as a key node in Norway's hydrogen-related socio-technical configuration and a center of engineering expertise in energy applications in the Scandinavian regions. The second Norwegian engineering cluster is concentrated along the southwestern coast, particularly in Rogaland and Vestland, home to many firms with roots in the offshore oil and gas and maritime sectors. Here, the demand for mechanical, electrical, and process engineers reflects the ongoing adaptation of offshore engineering capabilities to hydrogen and related renewable energy technologies [34]. This spatial concentration exemplifies how regional industrial specialization and technological relatedness with existing industries influence emerging patterns of hydrogen-related employment.

In Denmark, hydrogen-related employment is shaped by a concentration of research, consulting, and technology development activities, particularly in and around Copenhagen. This reflects the national Power-to-X strategy, which emphasizes public investment in R&D, multi-sectoral collaboration, and Denmark's wind power advantage to scale hydrogen production [64]. The strategy aims to promote multi-sectoral pathways by integrating PtX into hard-to-electrify sectors and positioning Denmark as a global exporter of hydrogen technologies, supported by coordinated regulation and infrastructure planning. This orientation toward knowledge production is evident in emerging multi-sectoral socio-technical configurations, linking universities, research institutes, and consultancies in early-stage project development and feasibility assessments [65].

These patterns reflect Denmark's tradition of coordinated policy [66], now reinforced through recent adoption of mission-oriented strategies to support the green transition [65]. While Sweden's focus on grid integration reflects its growing wind power capacity, Denmark has long addressed these challenges by leveraging its extensive wind resources and incorporating PtX into its national energy strategy [54]. Unlike Norway and Sweden, Denmark lacks a clear cluster of engineering-intensive hydrogen manufacturing jobs. Still, its long-standing experience with grid balancing and renewable integration suggests a shared focus with Sweden on hydrogen system integration—driven in Denmark by coordinated public investment and planning, and in Sweden by incumbent utilities expanding their existing infrastructure.

Hydrogen-related recruitment activity in Sweden is distinctly shaped by a strong concentration of jobs within incumbent firms, particularly the state-owned utility Vattenfall. This suggests that Sweden's hydrogen economy is developing primarily through *intra-sectoral integration*—where hydrogen technologies are incorporated into the existing electricity and utility sector—rather than through the formation of broader multi-sectoral socio-technical configurations linking actors and competencies across multiple industries. This pattern reinforces the dominant role of incumbent utilities operating within a relatively stable sectoral boundary. Rather than fostering new inter-industry clusters or novel multi-sectoral actor constellations, Sweden's hydrogen employment appears tied to extending and optimizing current energy infrastructures. As a result, job creation is concentrated in roles that support integration into the electricity system, including electrical and civil engineers working on grid connectivity, planning of electrolysis plants, and site development. This also explains why the engineering cluster in Sweden centers on electrical engineering and energy utilities, with limited diversification into related sectors such as manufacturing, logistics, or consulting.

The prominence of Vattenfall and the relative absence of new market entrants underscore earlier research suggesting that Sweden's hydrogen developments are primarily driven by established players in the energy and steel sectors, with less participation from smaller or new firms compared to other countries [67]. This entrenched incumbent dominance highlights hydrogen's role primarily as an enabler for enhancing the electricity system's balance, flexibility, and the integration of renewable energy, rather than serving as the foundation for an independent hydrogen sector (especially compared to Denmark and Norway).

Spatially, Sweden's hydrogen engineering jobs are primarily confined to major urban centers on the west and east coasts of Sweden, where large utilities maintain their headquarters and operations, contrasting with Norway's distributed industrial and offshore clusters and Denmark's more diverse research hubs. This geographical concentration within Sweden could reflect the difficulties in recruiting high-skilled personnel to Northern Sweden, where a few of the large hydrogen projects are located. This pattern of an incumbent-driven, highly concentrated, and utility-focused labor market not only aligns with Sweden's traditional institutional framework but also poses questions about the flexibility and adaptability of the Swedish hydrogen sector to leverage emerging technological and market opportunities beyond the control of established energy systems.

While the patterns observed in each country reflect distinct national contexts, some tentative contrasts can be noted. Norway's cluster-based patterns reflect strong sectoral relatedness in offshore and energy engineering, while Denmark's innovation-led approach leverages public R&D investments and institutional coordination. In contrast, Sweden's incumbent-driven configuration emphasizes grid integration within established utilities. These patterns offer a provisional view of how hydrogen-related employment is emerging, reflecting early-stage patterns rather than fully consolidated industrial pathways. Taken together, these differences illustrate how multi-sectoral labor market configurations emerge unevenly depending on national context, actor types, and spatial-industrial preconditions.

The outcomes observed suggest that the hydrogen economy is expanding primarily in regions with strong existing industrial infrastructures. Rather than catalyzing labor market growth in peripheral or structurally disadvantaged regions, most new hydrogen-related jobs are found in or around already industrialized urban centers. This suggests that hydrogen job creation may indicate early signs of path transformation, where existing capabilities are being redirected or adapted for hydrogen-related activities, rather than signaling the emergence of entirely new regional economic structures.

These national and sectoral contrasts also resonate with the morphology-based approach to directionality proposed by Andersson et al. [36], which emphasizes that transitions can give rise to distinct socio-technical configurations differing in their spatial anchoring, sectoral composition, and competence base. Our cluster analysis provides an empirical counterpart to this conceptual framing: the Norwegian clusters illustrate a concentrated, sectoral related configuration anchored in offshore engineering hubs; Denmark shows a more distributed, research- and innovation-led configuration; and Sweden's pattern reflects an incumbent-dominated, utility-integrated configuration. Seen through this lens, the observed recruitment patterns represent early "directional outcomes" in the morphology of the Scandinavian hydrogen economy—configurations that could consolidate or shift as technologies mature and markets evolve.

5.2 Observing outcomes of changing socio-technical configurations

The findings demonstrate that outcomes of changing multi-sectoral socio-technical configurations can be empirically observed through recruitment data, where clusters of job creation reflect the interaction between sectoral specialization, regional competencies, and actor constellations. By applying cluster analysis to hydrogen-related job postings, we can reveal clear patterns multi-sector interaction, skill development, and the roles of different actors within the emerging hydrogen sector economy.

Cluster analysis offers a way to systematically capture these patterns, showing how technologies, actor constellations, and competencies align within specific regional and sectoral contexts. This provides a means to empirically observe the early-stage recruitment structures, including which types of actors lead the process, which competencies are mobilized, and how these processes vary across different institutional and industrial settings. While these findings are based on a one-year snapshot and do not track change over time, they can still serve as early signals of evolving socio-technical configurations. By identifying clusters of activity, we can also observe indications of how transitions may begin to take shape, such as through path creation—where new technological competencies emerge—and path transformation, where existing competencies are redeployed into new applications [36].

This study contributes methodologically to the sustainability transitions field by demonstrating how computational social science techniques—particularly machine learning in the form of unsupervised clustering of job advertisements—can be used to operationalize and observe socio-technical configurations. While previous research has primarily relied on qualitative approaches [18], this study shows how labor market data can be leveraged to generate comparative, empirical insights into the geography and structure of emerging green employment. This approach complements case-based research by offering a scalable and data-driven method to map how technologies—such as hydrogen—intersect with existing labor market structures across regions and sectors.

Over time, continued observation of labor market trends could help indicate if new clusters solidify, whether new groups form around emerging technologies, and how skills evolve in response to shifting technological and institutional contexts. However, such interpretations should remain tentative until supported by longitudinal data. We interpret these cluster patterns not as definitive causal mechanisms, but as an empirical snapshot of evolving socio-technical configurations [68,69]. When established actors branch into new industries by reallocating their skills, they might also withdraw if market conditions change, highlighting the tentative and context-dependent nature of these early employment shifts.

While this study offers valuable insights into emerging employment patterns in the hydrogen economy, several limitations must be acknowledged. Our dataset is based on job postings, which may underrepresent certain employment types, such as internally filled positions and informal hiring. Additionally, we do not focus on jobs requiring lower skill levels, which are an important aspect when new technologies are being scaled up. The data we collected also provides only a snapshot from one year. It would have been beneficial to compare over a longer time frame and include more countries; however, we were unable to find comparable datasets that would allow us to do so.

Furthermore, the hydrogen economy is still emerging, meaning that current job patterns may not be stable over time. Longitudinal studies are needed to confirm whether observed clusters persist, evolve, or dissolve. Many hydrogen-related jobs intersect with multiple sectors, including energy, transport, and chemicals, making it essential to conduct more detailed network analyses to understand sectoral spillover effects and cross-industry hiring dynamics. Moreover, while our study highlights differences between countries, it does not systematically analyze policy interventions or other contextual conditions that shape these variations. Future research should explore how government incentives, industrial policies, and regional strategies influence hydrogen-related employment patterns, illuminating the role of institutional frameworks in workforce development within the hydrogen economy. Additionally, future research could integrate survey data or firm-level employment statistics to complement these findings.

6 Conclusions

This paper has explored how recruitment data can reveal early patterns of hydrogen-related employment across Sweden, Norway, and Denmark. Using machine learning in the form of unsupervised clustering techniques, we identified recurring socio-technical configurations—comprising alignments of sector, job role, and location—that offer empirical insights into how the hydrogen economy is taking shape in different national and regional contexts.

The results show that hydrogen-related employment is not forming as a stand-alone sector but instead reflects how existing industrial structures are adapting and reallocating competencies in sustainability transitions. Norway's patterns are tightly coupled with its offshore energy and engineering base; Denmark's are shaped by coordinated institutional efforts and R&D investments; and Sweden's are dominated by incumbent utilities integrating hydrogen into energy systems. Engineering roles—especially in electrical and mechanical fields—are central across all countries, though their distribution and organizational anchoring vary.

Methodologically, the study contributes to transition research by demonstrating how job advertisements can be used to observe early-stage socio-technical configurations. Cluster analysis enables the detection of geographic and sectoral regularities in recruitment that may otherwise remain obscured in qualitative case studies. This approach offers a scalable tool for identifying tentative signals of emerging industrial activity, actor alignment, and competence mobilization.

At the same time, the findings must be interpreted with caution. The data represents a one-year snapshot and cannot track how employment patterns evolve over time. For example, research and engineering jobs may be overly represented in the current early phase of the "hydrogen economy" as most hydrogen projects are still in the planning phase, while technician and maintenance jobs in existing hydrogen facilities are still limited because of the same reason. Furthermore, job advertisements do not capture informal hiring, internal recruitment, or lower-skilled roles, which are likely to become more prominent as the hydrogen economy matures. Still, the observed clusters—particularly those in engineering—highlight how transitions may begin through the redirection of existing capabilities rather than the creation of entirely new economic structures.

Looking ahead, future research should integrate longitudinal data to examine whether the observed configurations consolidate, shift, or dissolve. Comparative studies across additional countries, as well as mixed-method analyses combining job data with policy analysis or firm-level interviews, would help contextualize recruitment patterns within broader institutional and industrial dynamics. For policymakers, tracking recruitment trends offers a practical lens for monitoring which parts of the hydrogen value chain are developing, where skill gaps may emerge, and how existing sectors are participating in the green transition. These insights can support targeted workforce development initiatives, inform green industrial policy, and guide the allocation of education and training resources.

By linking patterns of job creation to national transition strategies and regional industrial legacies, this paper contributes to a deeper understanding of how the early stages of socio-technical transitions become embedded in labor markets—and how recruitment data can offer early insights into these transformations.

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