Labor market formation in the hydrogen economy: A cross-country comparison between sectoral and regional recruitment patterns in Denmark, Norway and Sweden

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Highlights

- Maps labor market formation in the Nordic hydrogen economy using job postings
- Identifies six distinct labor market clusters across sectors and regions
- Engineering jobs dominate but vary significantly across national contexts
- Combines machine learning and socio-technical theory in labor market analysis

Keywords: Hydrogen; Labor; Transition; Cluster Analysis; Competences; Multi-Systems; Recruitment

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Data Availability

All data used in this study are publically available at: https://uujzwk-hans-hellsmark.shinyapps.io/NordicH2ubs/#reqruitment

Competing interests

The authors declare no competing interests

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Abstract

The emergence of the hydrogen economy is expected to play a central role in industrial decarbonization, yet little is known about how hydrogen transitions shape labor markets across sectors and regions. This paper examines the formation of hydrogen-related labor markets in Sweden, Norway, and Denmark, using job postings as a proxy for recruitment activity. Drawing on socio-technical systems theory and cluster analysis, we identify emerging configurations of actors, competences, and regional specializations. Data was collected from national job portals between August 2023 and September 2024 and analyzed using unsupervised machine learning. Six labor market clusters were identified, showing distinct combinations of recruiting organizations, sectoral focus, and geographical distribution. Engineering jobs—comprising over 40% of the dataset—were also examined in a separate cluster analysis, revealing variation in recruitment needs across technical disciplines and national contexts.

Findings suggest that labor market formation is deeply shaped by prior industrial specializations and policy frameworks. Norway's labor market reflects its offshore energy legacy, dominated by consulting and engineering firms. Denmark shows a capital-concentrated, research-driven pattern, while Sweden's job creation is led by large incumbents, particularly in energy utilities. The study demonstrates how labor market data can serve as an empirical window into early-stage socio-technical configurations in sustainability transitions. It highlights the potential of combining digital trace data and machine learning to understand regional, sectoral, and competence dynamics in emerging green economies. This approach advances the study of sectoral labor dynamics in energy transitions and offers tools for informing cross-sectoral policy and workforce planning.

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. Creation of new “green” jobs has often been considered an important argument to increase public acceptance and justness of transitions, especially in contexts where transitions may lead to decline in established industries, such as in 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, but a critical indicator of how socio-technical configurations evolve around emerging technologies. 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 cross-sectoral linkages. It is, therefore, not surprising that economic and environmental goals are often integrated in policymaking related to sustainability transitions (5,6).

Despite this, the sustainability transitions literature has only begun to systematically examine how sustainability transitions drive the formation of new labor markets — and how labor market dynamics, in turn, shape transition processes themselves. First, much of the existing literature has focused 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 cross-sectoral importance (7). A multi-sectoral view may therefore be useful in better understanding the breadth and depth of changes in employment that sustainability transitions may have (8).

Literature adopting a multi-system dynamics perspective on transitions has recently elaborated on how cross-sectoral interactions may affect, for example, the system innovation processes (9), complementarities (10), material availability (11) and incumbent strategies (12) in sustainable innovations and transitions (13). However, this literature has yet had little dedicated attention to analyzing the multi-sectoral features of job creation in sustainability transitions. Moreover, prior literature has paid little attention to the geography of multi-system dynamics. In particular, little attention has been paid to 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 market formation across regions and sectors — and how labor markets themselves contribute to shaping transition pathways (14,15). Such insights are important for policymakers seeking a better understanding of the economic effects of transitions on society.

Second, sustainability transitions literature has methodologically focused on qualitative process studies, often historical case studies (16). While helpful in gaining in-depth insights on transition processes, the focus on qualitative case studies may create an overemphasis on context-sensitivity, diminishing the attention to more global patterns of transitions (17). Meanwhile, reaching qualitative in-depth reconstructions of transition processes in complex multi-systems settings may not be feasible due to the sheer scope of research. There is thus a need to extend the methodological toolbox of sustainability transition studies to fit the analysis of ever more complex transition phenomena, such as-systemic interactions.

In this paper, we address these research gaps through a quantitative analysis of job creation along hydrogen value chains in three Scandinavian countries: Sweden, Norway, and Denmark. In the paper, we pose two practical but important research questions for understanding the relationship between transitions and value chain formation and their effects on economies. The questions are the following:

1. *How can we measure the influence of emerging technologies, such as hydrogen, on the broader socio-technical configurations across different geographical contexts and sectors?*
2. *How do these configurations vary depending on the type of actors involved, the type of jobs created and their geographical distribution?*

In the paper we propose that one can measure impacts on socio-technical configurations by examining how various job types and sectors are combined in different geographical contexts. By focusing on job creation within the hydrogen economy, we illustrate how it creates specific employment patterns across diverse regions and sectors.

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. 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 (18). This method has been utilized for analyzing public media (19), political debates (20), customer energy behavior (21) and particularly patents (22,23). 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.

This paper is structured as follows. Section 2 reviews the literature on job creation in sustainability transitions and introduces our analytical framework, combining socio-technical systems theory with cluster analysis. Section 3 outlines the research design, including our data collection method and the rationale for selecting the three Scandinavian countries. Section 4 presents the empirical findings, based on a clustering analysis of job creation patterns across regions, sectors, and job roles—first for all jobs and then specifically for engineering jobs. Section 5 discusses the implications of these findings for understanding national and regional variations in hydrogen labor market formation, and reflects on the broader role of labor market data in analyzing socio-technical configurations. Section 6 concludes with policy and research implications.

2. Multi-system dynamics and new job creation

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 opportunities and job creation. Such transformations are multi-sectoral in nature, as generic solutions (such as zero-carbon hydrogen) may be taken up in different sectors, and their diffusion and broader adoption leads to repercussions in other sectors, and vice versa (24). While the existing literature has made important headway in conceptualizing and understanding the complexities and interdependencies introduced by multi-sectoral transitions, it has yet elaborated little on regional differences and directions that multi-sectoral transitions may have, especially in terms of employment (24). In the meantime, the literature on employment in sustainability transitions has until now had little attention on how job creation around novel technologies divides into different sectors. In this section we review the literature on these topics before exploring how the multi-sectoral and regional patterns of job creation in transitions can be conceptualized and analyzed.

2.1 Competences and job creation

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

In terms of the loss of jobs, the existing literature has particularly explored the effect of fossil fuel phase-out on jobs, and the consequent justness of sustainability transition. This literature tends to highlight the distribution of societal benefits and damages related to transitions (14). Such controversies related to potential loss of jobs have been linked to the so-called "environment vs. jobs" narrative, where sustainability-related action has been framed in political debate 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 kinds 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, United Kingdom and the Netherlands (29). It has been noted that new job creation is dependent on the development of workforce with new competences, but also workforce adapting old competences to new uses (14). This means that while new jobs in green industries may require new specific skills (e.g., manufacturing of large-scale and cost-efficient electrolysers), the fundamental competences needed (e.g., electrochemistry, machinery) can often be found in other related industries, including in fossil energy industries (30). However, the green jobs can nevertheless qualitatively differ from non-green jobs, e.g. in terms of requiring higher levels of creative problem-solving skills and higher formal education (31,32). Moreover, green jobs have been found to be geographically concentrated in regions with high levels of knowledge regarding green technologies (32).

In addition, existing jobs in various industries may change due to sustainability transitions. For example, electrification of transport requires that the producers, users and technicians of vehicles need to learn how to produce, operate and maintain battery-electric vehicles. In a study in Norway, it was found that actors across the country's economy expect that sustainability transitions lead to a generic need of developing competences in especially sustainability, circular economy and digitalization (33). In addition, jobs and competences in existing industries may be reoriented and transferred to develop new green industries. For example, in Norway, workforce in offshore oil and gas industry has been transferred to work on the development of offshore wind farms and technologies. This has provided the emerging offshore wind industry with a high-level of related technological competences but has also subjected the Norwegian offshore wind industry to the turbulent market conditions in the oil and gas market (34,35).

The regional and sectoral distribution of the loss of jobs, creation of jobs, and transformation (greening) of jobs are of importance to the justice and acceptance of transitions. In the following section we explore perspectives to conceptualize and analyze such topics.

2.2 A multi-dimensional approach 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 formation of new labor markets. This paper adopts an analytical framework that combines socio-technical systems theory with cluster analysis methodologies to study the outcome 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, including the spatial, sectoral, and competence-related configurations that emerge in different contexts.

Andersson et al. (36) provide a structured approach to characterizing these outcomes of actors, competences, and infrastructures that materialize as transitions unfold. 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 competences, and regional conditions. This approach is highly relevant to understanding the hydrogen economy, which is unfolding through distinct sectoral, spatial, and competence-related pathways across Sweden, Norway, and Denmark.

Building upon this morphology-based framework, we apply cluster analysis to empirically identify and characterize the socio-technical clusters emerging within the hydrogen economy. Cluster analysis allows for identifying geographically and sectoral distinct groupings—"clusters"—that consist of interconnected actors, competences, and infrastructures. These clusters represent localized innovation and economic activities, facilitating the diffusion of hydrogen technologies and the associated labor market transformation.

The application of cluster analysis in studying socio-technical transitions has been demonstrated in various contexts. For instance, Hirt et al. (37) analyzed the uneven diffusion of photovoltaic technologies in Switzerland by identifying regional clusters of innovation and adoption. Similarly, Santoalha et al. (38) examined how digital skills and relatedness influence green diversification across European regions, highlighting the role of regional clusters in fostering sustainable economic development. These studies underscore the utility of cluster analysis in unveiling the spatial and sectoral patterns that characterize technological transitions.

The importance of regional industrial structure in enabling or constraining the emergence of new clusters is further highlighted by Boschma and Frenken (39,40), who argues 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 allowing to redeploy their existing competences and skills to new uses (41). This means that existing regional clusters with specific competences are likely to diversify to technologically related industries, creating a regional pattern for new industry development (42). 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 (43,44). This work provides a useful theoretical basis for understanding the co-evolution of hydrogen technologies, competencies, and spatially anchored clusters, aligning with our focus on identifying distinct hydrogen-related clusters in the Nordic countries.

Recent scholarship highlights the importance of multi-sectoral interactions and actor constellations in shaping hydrogen transitions. Heiberg, Truffer, and Binz (17) introduce socio-technical configuration analysis (STCA) to capture how technologies, institutions, and markets co-evolve across sectors, shaping regional conditions for hydrogen adoption. Löhr and Chlebna (45) emphasize the role of 'system entanglers'—actors who connect technological development across energy, transport, and industry—while Ohlendorf, Löhr, and Markard (46) demonstrate how discursive struggles influence which sectors and regions ultimately benefit from hydrogen-related job creation. 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 formation and evolution of clusters within the hydrogen economy.

Sectoral Dynamics. The hydrogen economy encompasses multiple industries, including steel, energy, transport, and chemicals. Each sector contributes uniquely to job creation and technological advancement. For example, the steel industry in Sweden has pioneered the adoption of hydrogen technologies for fossil-free production (47,48), while Norway's energy sector emphasizes hydrogen as a clean export commodity (49). Understanding these sector-specific roles is crucial for identifying the drivers of economic growth and employment 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 (50).

Competence and Skills. The transition to a hydrogen-based economy demands a diverse set of skills and competences. Prior research indicates the emergence of both direct and indirect employment opportunities, with a significant portion requiring advanced expertise in engineering, research, and technology development (51). 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, ai and digital skills (52–54). 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. (38), 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 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 (55), whereas Sweden's industrial northern regions are emerging as hubs for hydrogen-based steel manufacturing (48). In Norway, the availability of natural gas resources and maritime expertise contributes to the development of blue hydrogen projects, further highlighting how regional resource endowments shape technology pathways (49). Geographical variation is not only shaped by resource availability but also by the presence of related industries, innovation ecosystems, and regional policy frameworks (56). 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 systems (39). 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 clusters within the hydrogen sector.

By applying cluster analysis to these three dimensions, we identify and characterize the socio-technical clusters that underpin the hydrogen economy in Sweden, Norway, and Denmark. This methodological approach enables us to map the interconnections between sectors, skills and competences, and regions, revealing patterns of job creation and technological deployment. Furthermore, it facilitates a comparative analysis of national strategies, elucidating how different policy frameworks and industrial contexts influence the development of the hydrogen economy across the Nordic countries.

3. Research design and case description

In this study, data on the creation of new jobs was collected in order to analyze, compare and contrast outcomes in different dimensions of the hydrogen economy in three of the Nordic countries. The methods used for the collection of data and the analysis will be presented in the first part of this section, followed by a description of the cases included in the study.

3.1 Data collection and descriptive analysis

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

Using job postings as a proxy for job creation allows us to capture the structure of emerging labor markets within the hydrogen economy. Despite its relevance, this type of recruitment data has been largely overlooked in sustainability transition studies. By leveraging job postings, this study enables a granular sector- and region-specific analysis of how labor markets form in response to technological shifts. This approach also facilitates comparisons across countries, helping to identify structural differences in how the hydrogen economy develops in different contexts.

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 the hydrogen sector. 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 sites 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 (18). The resulting sector categories and their respective job counts are presented in Table 1. Similarly, job roles were categorized based on the titles listed in the advertisements, resulting in 17 distinct roles (Table 2), 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 3).

Table 1: 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.

Table 2: 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 professors, 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.

Table 3: 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.

3.2 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" (57). Holding cultural, economic, and institutional factors relatively constant facilitates the identification of differences in recruitment patterns that are not explained by broader contextual variation.

Table 4 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 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. With regard to 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 and Denmark.

Table 4: 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 (58) and World Bank (59).

Across all three countries, job creation is primarily concentrated in three sectors: energy technology manufacturing, consulting, and energy utilities. Fewer postings are observed in the transport sector and in other categories. There are also differences at the country level. In Sweden and Denmark, a relatively large share of jobs is found within research, while hydrogen technology manufacturers constitute a major recruiting sector in Denmark.

3.2 Cluster analysis

To identify patterns in hydrogen-related job creation, we conducted an unsupervised cluster analysis on the collected job posting data. This method allowed us to explore how jobs, sectors, and regions are interrelated in the emerging hydrogen economy, revealing clusters that reflect sectoral specialization, regional labor market dynamics, and variations in job demand.

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, given their geographical proximity and shared labor market.

To determine the optimal number of clusters, we employed silhouette scoring and examined within-cluster squared distances. 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 provide the foundation for the qualitative assessment of labor market formation 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 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.

4. Cluster analysis

This section presents the results of the cluster analysis used to identify emerging patterns in hydrogen-related job creation across sectors and regions. The analysis is based on unsupervised machine learning applied to recruitment data from Denmark, Norway, and Sweden. We first examine the full dataset to uncover general labor market clusters, followed by a more focused analysis of engineering jobs, which make up the largest job category.

4.1 Regions, sectors and job roles

The clustering of region–sector combinations revealed six distinct patterns of job creation. Four of these show clear sectoral and geographical profiles, while the remaining two are more diffuse. The spatial distribution of the clusters is shown in Figure 2.

Cluster 1, Offshore and Energy Engineering (Norwegian south-western Coast), consists of 552 jobs from energy technology manufacturers and consulting agencies located in the southwestern coast regions of Rogaland and Vestland. This cluster was among the first to emerge in the analysis, also when considering a smaller number of clusters. It suggests significant activity along the Norwegian coast, primarily around Stavanger and Bergen. Engineers represent the most sought-after skill set within the cluster, accounting for over 50% of all jobs. The second and third most in-demand roles are project managers, technicians, and maintenance staff. The high demand for project managers and technicians, alongside the large number of engineers, may indicate that these regions have advanced further in project implementation. Although many organizations contribute to this cluster, three organizations stand out, collectively accounting for over 80% of the jobs: Akkodis, a consulting agency offering services across a wide range of engineering fields; Aibel, which focuses on offshore infrastructure for the energy industry; and Aker Solutions, involved in offshore development for both oil and gas, as well as renewable energy installations. While other projects exist within the regions, only one pertains to blue hydrogen, whereas the others focus on green hydrogen.

Cluster 2, Industrial Engineering and Consulting (Oslo area), consists of 475 jobs involving energy technology manufacturers and consulting agencies, similarly to those in Cluster 1, although this time they are specifically located in Oslo and Akershus. This cluster emerged early in the analysis and demonstrated a significant demand for engineers; more than 60% of the jobs within this cluster are engineering jobs. In addition to engineers, there is also a demand for managers within this cluster. The recruitment of both engineers and managers may be attributed to the growth of organizations as they assume important roles in the hydrogen economy. The recruiting organizations with the most substantial presence within this cluster, accounting for over 75% of the jobs, are Akkodis, Aker Solutions, and Aibel. Although these organizations are not involved in any projects in Oslo or Akershus, Aker Solutions is participating in a nearby project in Lysekil, Sweden. There, they are collaborating with Preem and others to work on carbon capture from hydrogen production sourced from natural gas at one of Preem's sites in the region. This cluster further highlights the significance of the energy technology and consulting sectors in Norway.

Cluster 3, Energy Utilities (Capital Cities), consists of 258 jobs including energy utility organizations located around Oslo and Copenhagen. Over half of all jobs created by energy utility organizations can be found within this cluster. Thus, we observe a high concentration of hydrogen jobs created within the energy utility sector around the capitals of Norway and Denmark. The primary roles sought in this cluster are in engineering, finance and business development, management, and IT. The most prominent players are two utility companies focusing on renewables: Ørsted and European Energy in Copenhagen, along with Statkraft, a state-owned utility company also focused on renewable production, in Oslo. This recruitment may also be part of new developments in renewable hydrogen production in the regions. For example, Ørsted is currently involved in two projects aimed at producing hydrogen for transportation from renewable energy sources, such as offshore wind. Additionally, we find one actor with only one reported job in Akershus: Akershus Energi, which is part of a project focusing on hydrogen production from electrolysis and biogas for transport.

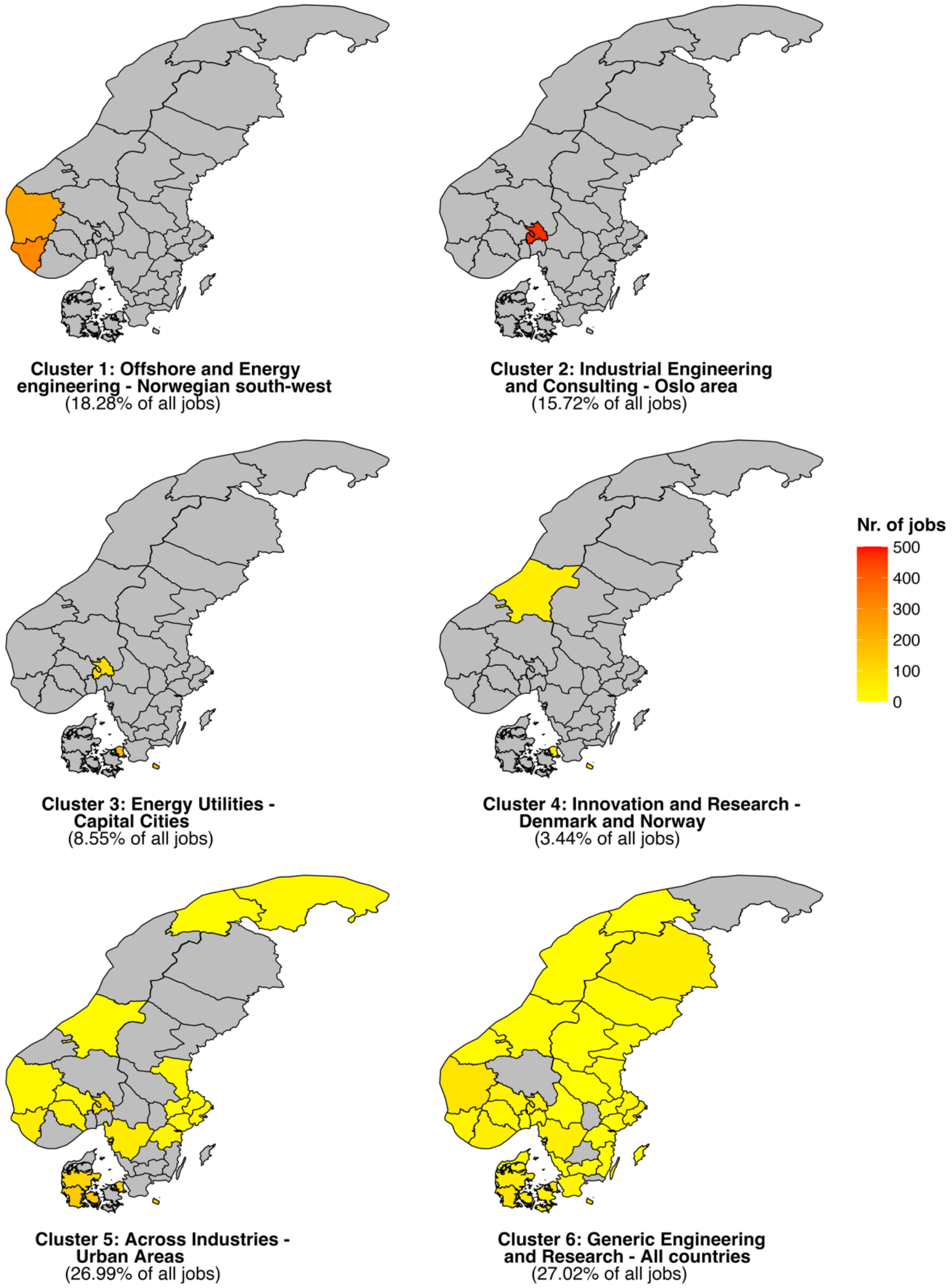

Figure 2: Geographical distribution of identified clusters, showing the name of each cluster and the total number of jobs associated with it. Note that multiple clusters can be present in the same geographical regions, as clusters are defined by combinations of sectoral characteristics, actor types, and job profiles, rather than by geographic boundaries alone. The color gradient indicates job concentration, with yellow representing areas with fewer jobs and red indicating areas with higher concentrations of jobs.

Cluster 4, Innovation and Research (Denmark and Norway), consists of 104 jobs primarily from universities in Trøndelag and around Copenhagen. Although most jobs in this sector are created by universities, such as the Technical University of Denmark (DTU) and the Norwegian University of Science and Technology (NTNU), other types of organizations are also present, including research institutes like SINTEF. Unsurprisingly, researchers and PhDs are the most sought-after qualifications within this cluster, accounting for more than three-quarters of the jobs. This cluster exhibits the highest concentration of jobs related to hydrogen research, with over a third of all research and PhD positions, as well as more than a third of all jobs created by research organizations. This high concentration may suggest that universities and institutes like NTNU and DTU are leading the way in investing in new hydrogen research.

Cluster 5, Across Industries (Urban Areas), consisting of 802 jobs, slightly more distributed than above clusters but still focused on urban areas. The jobs within the cluster are spread across 18 regions and 8 sectors while still comprising 16 different competencies. The most important sectors for this cluster are energy utility and hydrogen technology manufacturer, each accounting for more than 20% of the jobs within the cluster, while sectors accounting for at least 10% of the jobs in the cluster are chemicals, energy technology manufacturing as well as fossil fuels & refinery. Also, engineering jobs are more sought after in this cluster than other competencies, accounting for more than 40% of the jobs. This further exemplifies the importance of engineers in the hydrogen economy. Although this cluster contains a wide spread of organizations, a few account for a larger share of the jobs. The largest is Vattenfall, accounting for 15% of the jobs in the cluster, followed by Topsoe, Nel, and Green Hydrogen Systems, each accounting for more than 5% of the jobs. This cluster demonstrates a high demand for hydrogen-related jobs within the manufacturing and utility industries across Sweden, Norway and Denmark.

Cluster 6, Generic Engineering and Research (All countries), consist of 847 jobs spread across 37 regions, 13 sectors and 17 competences. This cluster did not provide as interpretable patterns as other clusters did. Although some more activity can be found within certain regions, there are only a few regions that account for more than 5 % of the jobs within the cluster. However, we can see that more than 20 % of the jobs within this cluster are within the research sector, while more than 25% are engineering jobs. The higher demand for engineers is a pattern found across the dataset, being the most sought-after competence, accounting for more than 40% of all jobs in the dataset.

The similarities between Cluster 1, Offshore and Energy Engineering (Norwegian south-western Coast), and 2, Industrial Engineering and Consulting (Oslo area), are apparent, consisting of the same sectors with very similar sought-for competences and recruiting organizations. The differences lie in their geographical positioning and a slight difference with regards to which competences that are sought for. While both clusters primarily recruit engineers, in Oslo and Akershus there is also a high demand for general managers, while in Rogaland and Vestland there is a specific demand for project managers, technicians and maintenance staff. This difference indicates that while a lot of development related to hydrogen is taking place both on the coast and around Oslo, the deployment and operation of projects are more present on the coast.

Two other clusters presenting clear similarities are Cluster 5, Across Industries (Urban Areas), and Cluster 6, Generic Engineering and Research (All countries). These are the clusters with the least interpretability and seem to rather be two clusters consisting of jobs and sectors which were not many enough to form their own cluster. Both consists of a wide array of regions, sectors and competences. What sets them apart is that Cluster 5 was slightly more niched than Cluster 6. In Cluster 5, we only find sectors related to manufacturing, refining and utility with a concentration towards energy related industries such as fossil fuels, hydrogen and renewable technologies. However, neither of these clusters can tell us much about specific patterns in certain sectors or regions, although they still contribute to general patterns found throughout the dataset.

The high demand for engineers is evident, being the most sought-after competence within every cluster except for Cluster 3, Energy Utilities (Capital Cities). This demand could signal the current state in which the hydrogen economy is in. Projects may be in a planning phase, or on a small industrial level which not yet have resulted in a high demand for more menial industrial labour. While we find 1282 engineering jobs related to hydrogen, we only find 237 jobs within technician & maintenance, indicating that there are yet few actual hydrogen facilities in place. The fact that engineers can be found to be central in most regions and sectors could also indicate that this competence is needed throughout the entire value chain and perhaps also through all steps in the development of the hydrogen economy.

From the clusters, it is clear that the organizations leading the hydrogen economy in Scandinavia consist of energy technology companies and consulting agencies in Norway. Clusters 1, Offshore and Energy Engineering (Norwegian south-western Coast), and 2, Industrial Engineering and Consulting (Oslo area), which represent energy engineering on the Norwegian south-western coast and in the Oslo area, account for about a third of all jobs, concentrated in Oslo, Akershus, Rogaland, and Vestland. It appears that during the fall/winter of 2023 and spring/summer of 2024, this is where most of the socio-economic development occurred regarding job creation.

Meanwhile, we also observe distinct activity in research and utility in both Norway and Denmark, particularly in Cluster 4, Innovation and Research (Denmark and Norway), and Cluster 3, Energy Utilities (Capital Cities). In these clusters, Hovedstaden stands out as the region with the highest number of jobs being created. This indicates that Denmark shows a particularly focused activity around the capital city. In contrast, Norway has five regions with distinct recruitment patterns. Swedish regions, on the other hand, do not experience the same level of job creation, and the patterns in Sweden are not as pronounced as those in Norway and Denmark. The jobs in Sweden are more evenly distributed and not as numerous. However, it can be noted that there is increased activity within energy utility in Sweden, partly evidenced by the many jobs created by Vattenfall in the country. However, while we observe certain recruitment patterns, it is important to note that second largest and largest clusters, namely Cluster 5, Across Industries (Urban Areas), and Cluster 6, Generic Engineering and Research (All countries), lack the distinct features present in the other clusters. This suggests that although some patterns can be identified across many jobs—about half of the dataset—there is a fairly even distribution across sectors, regions, and competencies without a clear, interpretable pattern.

4.2 Focusing on engineering jobs

Since there were significantly more engineering jobs than other types, and because engineering jobs vary widely in their fields, a clustering analysis was conducted specifically for engineering jobs. This analysis revealed new patterns that were not present in the general clustering analysis. The number of clusters was set to four, which identified one distinct cluster, two quite similar clusters, and one mixed cluster. The clusters and their geographical concentrations can be found in Figure 3.

Cluster 1, Offshore and Energy Technology (Norwegian south-western Coast), comprises 215 jobs primarily located in Vestland, with some in Rogaland. These positions are filled by energy technology manufacturers in Rogaland, as well as by consulting agencies and energy technology firms in Vestland. This cluster indicates a high demand for electrical and mechanical engineers, each representing more than one-fifth of the jobs, followed by chemical and unspecified engineers, with each accounting for over 10% of the positions. Aibel has a strong presence in both regions, while Akkodis accounts for the majority of jobs in Vestland, with Aker Solutions ranking as the third largest recruiting entity in the area. This cluster highlights the significance of Akkodis, Aker Solutions, and Aibel in the Norwegian hydrogen-related job market, reinforcing Norway's strong industry linkages between energy technology, consulting, and offshore infrastructure development.

Cluster 2, Energy technology (Oslo & Rogaland), comprises 436 jobs primarily situated in Oslo and Akershus, with some positions also available in Rogaland. These roles are filled by energy technology manufacturers and consulting firms in the Oslo area, as well as consulting agencies in Rogaland. Most positions fall under electrical and mechanical engineering, each representing over a fifth of the total jobs. In and around Oslo, organizations like Akkodis, Aker Solutions, and Aibel primarily recruit for this cluster, while in Rogaland, Akkodis is the main recruiter for engineers. This cluster further highlights the significance of these three recruiting organizations in advancing the Norwegian hydrogen economy.

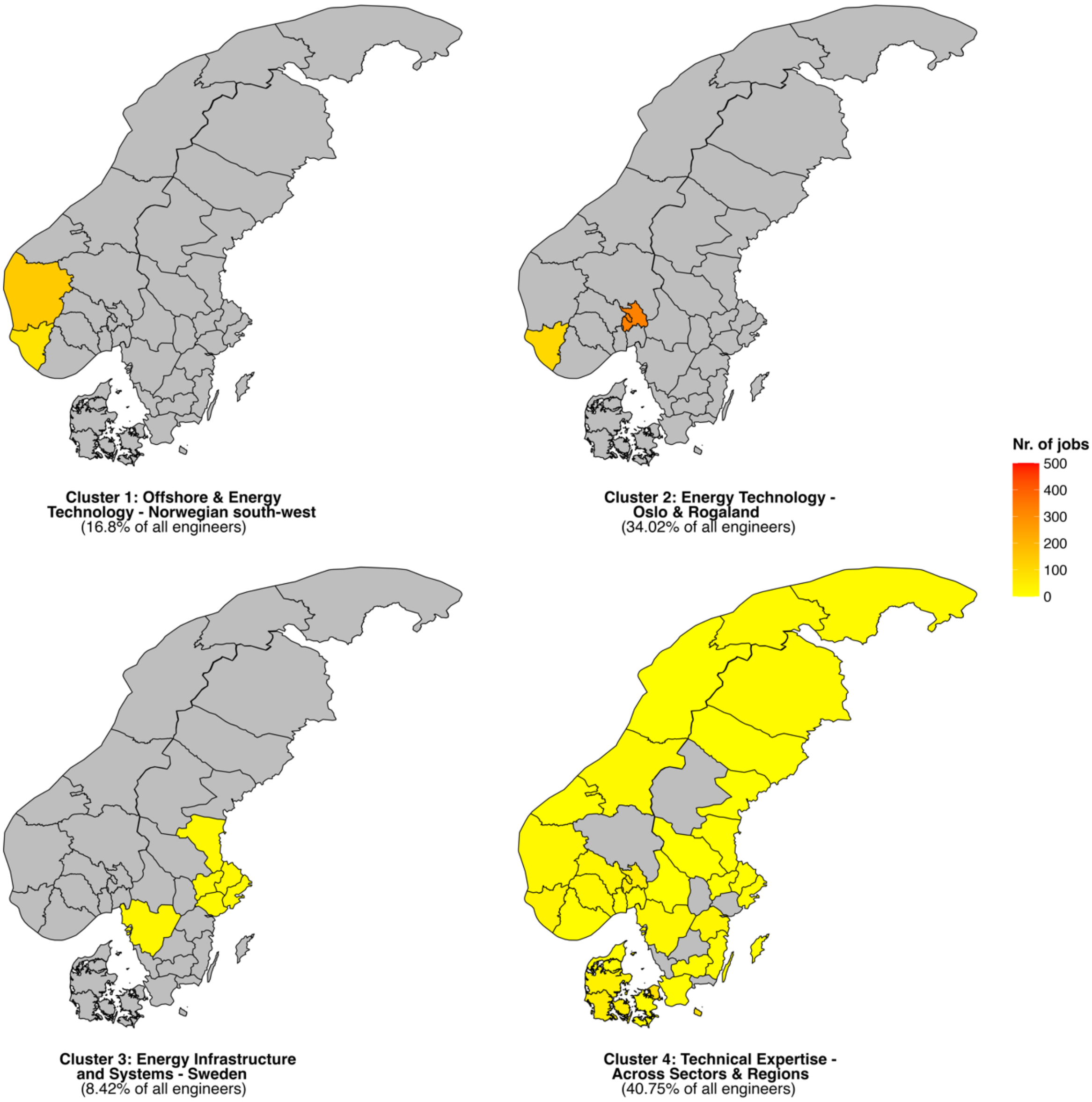

Figure 3: Geographical location of the engineering clusters, including name and total number of engineering jobs. Note that there is an overlap in regions, this is due to clusters being associated to cluster/sector combinations and not regions alone. The concentration of engineering jobs can be seen ranging from fewer jobs (yellow) to more jobs (red).

Cluster 3, Energy Infrastructure and Systems (Sweden), consists of 108 jobs that are exclusively recruited within Energy utility in Sweden. The five Swedish regions—Gävleborg, Stockholm, Södermanland, Uppsala, Västmanland, and Västra Götaland—show a similar pattern of engineer recruitment that differs from other regions and countries. These jobs are primarily in electrical engineering, making up more than a fifth, followed by civil engineering. All but one of the jobs in this cluster were recruited by Vattenfall. Thus, Vattenfall appears to be a major player in Sweden, leading the recruitment of engineers within the Swedish hydrogen economy. They are currently involved in two projects related to synthetic fuel production in Västra Götaland and Stockholm. Energy utilities and new types of fuels may represent the most critical part of the value chain in Sweden’s hydrogen economy. The concentration of electrical and civil engineers recruited by the utility company Vattenfall suggests that Sweden’s hydrogen economy is more focused on integrating hydrogen into existing power and utility networks.

Cluster 4, Technical Expertise (Across Sectors and Regions), consisting of 522 jobs, shows no clear pattern. The jobs are scattered across 34 regions and 12 sectors, featuring a wide range of engineers. Although the jobs are distributed quite evenly, more than 10% of the engineering jobs in this cluster are located around Copenhagen, where Ørsted is the leading recruiter. The cluster primarily consists of mechanical engineering jobs, making up more than a fifth, followed by chemical and electrical engineering jobs, as well as general, unspecified engineering jobs. Most jobs are found in energy technology manufacturing, hydrogen technology manufacturing, the fossil fuel industry, energy utilities, consulting, and other manufacturing sectors. This highlights the demand for engineers in energy-related industries.

It is apparent that the Engineering Cluster 1, Offshore and Energy Technology (Norwegian south-western Coast), and the Engineering Cluster 2, Energy technology (Oslo & Rogaland), share clear similarities. We see the same actors creating most of the jobs, with similar types of engineers being recruited. What sets them apart is that Engineering Cluster 1 shows a higher demand for chemical and generic engineers than Engineering Cluster 2. The overlaps between these two engineering clusters and the clusters, including all jobs in Figure 2 are quite apparent.

A common pattern across the four engineering clusters is the primary demand for electrical and mechanical engineers, as well as chemical and general engineers. Given hydrogen's significant potential to stabilize variations in the energy system, the high demand for electrical engineers is not surprising. Similarly, the demand for mechanical and chemical engineers suggests the necessary competence for constructing various machines used to produce, process, or utilize hydrogen. Together, these four clusters indicate that engineering jobs in the hydrogen economy are largely driven by energy technology manufacturers, consulting agencies, and utilities, with Norway’s focus on offshore and industrial applications, Sweden’s concentration in utility-driven hydrogen integration, and Denmark showing a broad sectoral spread centered around its capital. While the demand for specific engineering jobs is quite similar across the Scandinavian countries, we find a notably greater need for electrical engineers within the energy utility sector in Sweden, indicating a stronger Swedish interest in connecting hydrogen functionalities to the power production industry. Combining the results from the two clustering analyses gives a broader picture of the technical system that is the growing hydrogen economy in Scandinavia. In Norway we find recruiting organizations within the field of consulting and energy technology are responsible for a large part of job creation. However, the importance of consulting agencies may reflect the phase of development in hydrogen economy and that it is within energy technology engineering in general that most of the development takes place at the moment. An interesting note is the connection that the Norwegian energy technology companies have to offshore industry, and the connection to oil and gas industry in particular. These connections are not found in Sweden or Denmark, indicating a difference in preceding technological knowledge and natural resources between the countries. The possibility to extend the use of domestic natural gas resources creates an incentive to explore gas reformation pathway in Norway, potentially creating a blue hydrogen direction in this country which is not as prominent in its neighboring countries. In the meantime, the advanced engineering competences in gas technologies originating from the Norwegian oil and gas industry are an advantage in any kind of hydrogen technologies, both green and blue. Such factors show that Norway's engagement in hydrogen innovation is driven and shaped by its historical strengths.

The clustering analysis of engineering jobs revealed information about recruitment in Sweden, which the general analysis did not capture. In Sweden, we see that it is primarily within Energy utility, specifically one actor (Vattenfall), that is leading the deployment of new hydrogen-related jobs. This indicates that less knowledge of manufacturing technologies may be diffused in Sweden, compared to its neighbors. Also, the weaker presence of jobs in Sweden could indicate a weaker formation of legitimacy for hydrogen technologies. In Denmark we see that many jobs are created covering a wide range of sectors and competencies, with a distinct interest in research and management. The central feature for Denmark is that we see most jobs created in the Copenhagen region. Although one could expect a lot happening in a capital region, it is interesting to note that within every cluster placed in Denmark there is an increased presence in and around Copenhagen, suggesting that the development in multiple sectors is taking place there. Overall, the market formation appears strongest in Norway and Denmark, with most jobs being created.

5. Discussion

This study set out to examine how the hydrogen economy is shaping labor markets in Sweden, Norway, and Denmark by addressing a) how can we measure the influence of emerging technologies, such as hydrogen, on broader socio-technical configurations across different geographical contexts and sectors; and b) how these configurations vary depending on the type of actors involved, the type of jobs created, and their geographical distribution.

By leveraging a clustering approach to analyze recruitment data, we identified distinct sectoral and regional patterns that illustrate the specific characteristics of the hydrogen-related labor markets across the three countries. The results suggest that hydrogen economy development results in highly specialized outcomes, shaped by sectoral specialization, existing industrial structures, and national policy frameworks. This reinforces the view that labor market formation is not simply a byproduct of technological innovation but a key dimension of how sustainability transitions unfold across regions, sectors, and actor networks (13,40). In other words, the spatial and sectoral emergence of job creation reflects and actively contributes to the directional dynamics of socio-technical transitions.

This is particularly relevant in our case, where our focus is on high-skilled jobs, in which the content and competence requirements are directly linked to the evolving technological trajectories and institutional contexts. The type of work being created—whether engineering, research, or project management jobs—provides important clues about which parts of the hydrogen value chain are emerging most prominently.

5.1 National and sectoral variations

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

To begin with, the Norwegian industrial and offshore focus, with the dominance of consulting agencies and energy technology firms along the southwestern coast and in Oslo suggests that Norway's hydrogen economy is shaped by the existing industrial base, and especially its large energy industry, both oil and gas and hydropower. For example, engineering competences in gas processing technologies, developed to manage natural gas, can be redeployed to applications of zero-emission hydrogen production and use (33). This way, the incumbent capabilities and established supply chains shape the early labor market configuration (29,35). The strong role of engineering and consultancy agencies also suggest an early-stage project-based development process, where multiple firms provide specialized expertise rather than a small number of dominant technology providers. This also becomes evident when examining the engineering clusters that emerge. 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, reflecting the status of Oslo as a major hub of energy technology engineering competencies in Nordic countries. The second Norwegian engineering cluster is concentrated along the southwestern coast, particularly in Rogaland and Vestland, home to many firms with roots in offshore oil and gas. Here, the demand for mechanical, electrical, and process engineers reflects the ongoing adaptation of offshore engineering capabilities to hydrogen and related renewable energy technologies (35). This spatial concentration exemplifies how regional industrial specialization and technological relatedness with existing industries drive the formation of hydrogen labor markets.

Denmark's hydrogen labor market is strongly shaped by its innovation-driven economy, with job concentrations in research, consulting, and technology development, particularly in the Copenhagen region. This reflects the national Power-to-X strategy, which emphasizes public investment in R&D, cross-sectoral collaboration, and Denmark's wind power advantage to scale hydrogen production (63). The strategy aims to integrate PtX into hard-to-electrify sectors and position Denmark as a global exporter of hydrogen technologies, supported by coordinated regulation and infrastructure planning. The innovation system's orientation toward knowledge production is visible in the prominent role of universities, research institutes, and consultancies in early-stage project development and feasibility assessments (64). These patterns reflect a shift toward more goal-directed innovation governance in Denmark, building on its tradition of coordinated policy and recent adoption of mission-oriented strategies in the green transition (64,65). Notably, however, Denmark lacks a distinct cluster of engineering-intensive hydrogen manufacturing jobs, unlike Norway and Sweden, suggesting a narrower industrial base in the hydrogen value chain.

For Sweden, the hydrogen labor market is distinctly shaped by a strong concentration of jobs within incumbent firms, notably Vattenfall. This indicates that Sweden's hydrogen economy is predominantly developing through the integration of hydrogen technologies within the existing energy structures, rather than through the formation of new industry clusters or dedicated sectors. Such integration primarily involves the addition of hydrogen production and storage into established electricity systems, necessitating a high demand for electrical and civil engineers who focus on grid integration, electrolysis plant design, and site planning, which also explains the engineering cluster in Sweden being focused on electrical engineering and energy utilities.

The prominence of Vattenfall and the relative absence of new market entrants underscore earlier research suggesting that Sweden's hydrogen developments are mainly propelled by established players in the energy and steel sectors, with less participation from smaller or new firms compared to the other countries (66). 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 coast 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.

5.2 Measuring socio-technical configurations

The findings demonstrate that emerging socio-technical configurations can be empirically observed through labor market data, where clusters of job creation reflect the interaction between sectoral specialization, regional competencies, and actor constellations. By systematically implementing cluster analysis on hydrogen-related job postings, we can pinpoint clear patterns in industrial development, skill formation, and actor roles within the emerging hydrogen economy.

These spatial and sectoral patterns illustrate how new socio-technical configurations are shaped by interaction between pre-existing capabilities, new technological opportunities, and policy-driven incentives. The socioeconomic outcomes indicated by these findings suggest that the growth of the hydrogen economy primarily occurs where existing industrial structures are present. Rather than creating new jobs in more peripheral regions with previously fewer economic opportunities, most new jobs were found around already industrially important cities. This indicates that the creation of new hydrogen jobs serves as an opportunity to gradually replace existing jobs, possibly in oil and gas, rather than to create new jobs in new locations.

Cluster analysis offers a way to systematically capture these patterns, showing how technologies, actor constellations, and competences align within specific regional and sectoral contexts. This provides a means to empirically observe the early-stage formation of new value chains, including which types of actors lead the process, which competences are mobilized, and how these processes vary across different institutional and industrial settings. By identifying clusters of activity, we can also observe how transitions unfold through both path creation—where new technological competences emerge—and path transformation, where existing competences are redeployed into new applications (36).

Thus, job posting data offers a valuable complementary lens for examining socio-economic dynamics and in the future it could probably also be used to unfold socio-technical outcomes of sustainability transitions. While previous research on socio-technical transitions has primarily been qualitative (16), leveraging labor market data and cluster analysis enables a broader, empirical mapping of how transitions unfold across regions, sectors, and value chains. This approach helps trace how emerging technologies—such as hydrogen—become embedded within existing socio-technical systems or contribute to the formation of entirely new configurations (13,17). As transitions unfold, ongoing observation of labor market trends can indicate if new clusters solidify, whether new groups form around emerging technologies, and how skills evolve in response to shifting technological and institutional contexts. At the same time, when established actors branch out into new industries by reallocating their skills, they might also withdraw and return to their original sectors if market conditions shift.

While this study offers valuable insights into labor market formation 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 necessary to track how recruitment patterns evolve as the industry matures. 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 labor markets, 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

Overall, our findings reinforce the view that hydrogen labor markets are forming in distinct ways across regions and sectors, driven by national industrial legacies, sectoral priorities, and policy environments. Norway's energy industry focus, Sweden's utility-driven hydrogen adoption, and Denmark's research-driven approach illustrate the varied pathways through which hydrogen transitions unfold.

By combining quantitative cluster analysis with socio-technical transition perspectives, this study demonstrates how recruitment data can serve as an empirical window into labor market transformations in sustainability transitions. Future research should build on these findings by integrating longitudinal labor market data, firm-level hiring strategies, and policy analysis to provide a more comprehensive understanding of how hydrogen economies evolve over time.

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