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National Hydrogen Workforce Studies and Just Transition: A Comparative Framework and Typology Across 13 Countries

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Abstract

Context: National hydrogen strategies are increasingly accompanied by workforce and skills studies intended to anticipate labour-market implications of an emerging hydrogen economy. Yet these studies differ markedly in how deeply they analyse skill needs, how far they specify implementable measures, and whether they integrate social justice beyond rhetorical references. This article addresses the resulting fragmentation by developing a comparative framework that positions hydrogen workforce planning at the intersection of vocational education and training (VET), labour-market governance, and just transition.

Approach: The study employs a conceptual review design combined with structured qualitative content analysis of a purposive sample of national hydrogen workforce/skills studies (29 studies from 13 countries). A deductive coding scheme operationalises four analytical dimensions: Skills Analysis Depth (SA), Skills Implementation Depth (SI), Just Transition Analysis Depth (JTA), and Just Transition Implementation Depth (JTI). Each dimension is assessed on a four-point rating scale from 0 (absent) to 3 (fully quantified and road-mapped). Dimension profiles are then aggregated through decision rules into a typology that emphasises configurational patterns.

Findings: The analysis yields five ideal-typical stages of workforce planning configuration. Stage 0 (Workforce Analysts) provide diagnostic scoping without implementation. Stage 1

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(Strategic Workforce Framers) integrates workforce and justice primarily at the level of strategic discourse, with limited operationalisation. Stage 2 (Skills-Centric Planners) provides comparatively developed skills forecasting and training pathways, but keeps justice largely marginal. Stage 3 (Just Transition Integrators) links skills and justice considerations – often through territorial development and restructuring – yet remains uneven in the institutionalisation of justice measures. Stage 4 (Integrated Transition Governance Architects) combines advanced skills planning with operational just-transition instruments, including costed programmes, defined governance arrangements, and monitoring systems. The typology does not assess policy effectiveness or transition outcomes. Rather, it captures the degree of institutional specification and governance integration in national workforce planning. Higher stages therefore indicate more explicit and operationalised planning architectures, not superior social, economic, or environmental results.

Conclusion: The proposed four-dimension framework and typology offer a tool for comparing national hydrogen workforce studies and clarifying how planning logics shift from technocratic forecasting to transition governance. Substantively, the findings reposition VET from a delivery system for technical skills to a mediating governance actor whose contribution to hydrogen transitions depends on coordination with labour-market regulation, regional development, and social protection. The key message is that socially sustainable hydrogen transitions require workforce strategies that institutionalise justice, not merely acknowledge it.

Keywords: Workforce Studies, Workforce Planning, Skills Gap, Just Transition, Green Hydrogen, TVET

1 Introduction

Clean hydrogen is increasingly framed as a complementary decarbonisation option for sectors in which direct electrification is technically difficult or economically costly, notably high-temperature industrial processes and long-distance heavy-duty transport, and – under specific conditions – certain power-sector applications (e.g., flexibility provision, co-firing, or hydrogen-based generation) (Albrecht et al., 2020; Yang et al., 2022; Oshiro & Fujimori, 2024). Hydrogen has therefore moved from a largely technological niche discourse to the centre of strategic policy agendas. A screening of hydrogen strategies in 56 countries (representing over 90% of global GDP) already documented rapidly emerging national strategies and policy activity by 2020 (Albrecht et al., 2020), and by June 2021 at least 35 countries had published national hydrogen strategies or roadmaps (World Energy Council, 2021). This ongoing expansion of strategy-making is illustrated by the timeline of hydrogen strategies and roadmaps (Figure 1).

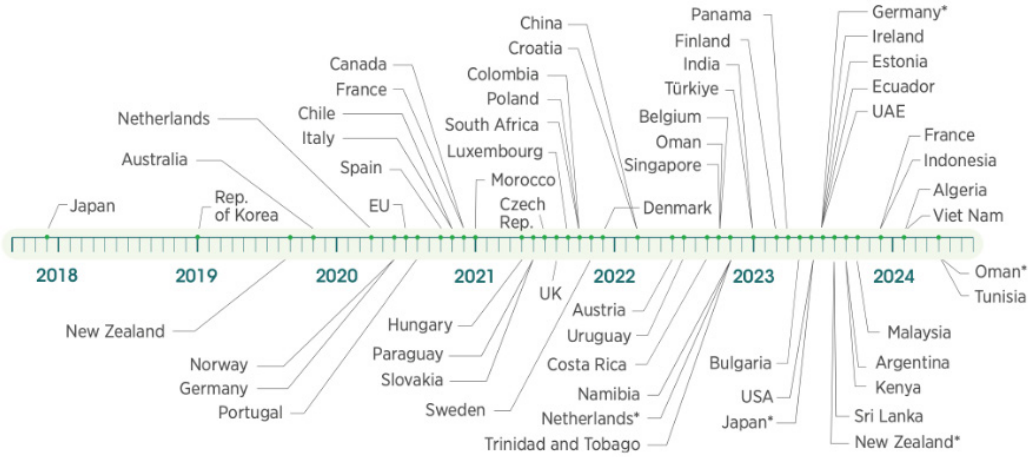

Figure 1: Timeline of Hydrogen Strategies and Roadmaps (International Renewable Energy Agency [IRENA], 2024b, p. 13)

Despite this policy momentum, workforce development and skills formation are often weakly institutionalised in hydrogen policy narratives. For example, in an IRENA membership survey on perceived barriers to developing hydrogen policies and strategies, the most prominent barriers include high costs of low-carbon hydrogen production, lack of dedicated infrastructure, climate concerns regarding current fossil-based hydrogen production, technology limits, and lack of access to capital and investment incentives – while skills and workforce constraints are not highlighted as barriers (IRENA, 2022, p. 32). Similarly, a proposed monitoring framework for the global hydrogen economy is structured across eight thematic fields (e.g., policy and regulation, research and innovation, industry and value creation, climate and energy, governance and social development), without defining workforce and skills development as a distinct monitoring dimension (Quitzow et al., 2022). In a cross-country review of international hydrogen strategies, acceptance and training issues are described as being addressed only by few countries – typically those with more advanced strategies – and the measures discussed include knowledge management and public communication as well as professional training for technical and rescue forces (Albrecht et al., 2020, p. 31). Explicit references to systematic workforce-training programmes remain sporadic; for example, the California case lists the establishment of workforce-training programmes as a single measure in Annex B (Albrecht et al., 2020, p. 146).

More recent strategy guidance increasingly recognises socio-economic considerations, including job creation and the reskilling of workers from fossil-fuel sectors, and emphasises the need to ensure that vulnerable groups are not left behind (IRENA, 2024b, p. 49). Nevertheless, the extent to which national transition pathways translate such concerns into concrete workforce planning remains uneven and difficult to compare across

countries. Complementing this strategy-screening perspective, an analysis of global hydrogen roadmaps combined with stakeholder interviews in the United States identifies workforce development as a salient barrier to creating a hydrogen market, alongside financing, infrastructure, and policy-related constraints (Iacob et al., 2025). In response, a growing number of national hydrogen workforce studies have been published to estimate labour and skill demands, map occupational change, and formulate training recommendations (McHenry et al., 2024). Yet these studies vary markedly in scope and orientation. Some prioritise quantitative forecasting of labour demand, while others foreground institutional capacity, reskilling pathways, and justice-related concerns such as regional equity, worker protection, and inclusive governance.

This divergence reflects a broader conceptual tension. Workforce planning is often treated as a technical question of skills supply and demand, whereas socio-technical transition research and just transition scholarship emphasise that hydrogen transitions reconfigure institutions, infrastructures, labour markets and governance arrangements. As a result, the explanatory power of workforce studies depends not only on how skill needs are analysed, but also on the extent to which justice and implementation features are specified and operationalised.

This article addresses that gap by developing a comparative framework for assessing national hydrogen workforce studies along four analytical dimensions: skills analysis (SA), skills implementation (SI), just transition analysis (JTA), and just transition implementation (JTI). The research questions are:

1. What characteristics do national workforce studies exhibit with regard to skills analysis depth, skills implementation depth, just transition analysis depth and just transition implementation depth?

2. What transnational similarities and differences can be identified across the analysed national hydrogen workforce studies?

3. What transnational patterns can be identified across these studies, and what do they imply for positioning workforce policy within broader hydrogen transition governance?

The contribution is both methodological, through the development of a replicable coding and scoring approach, and substantive, through the identification of patterns in how workforce development and just transition considerations are (or are not) embedded in national hydrogen transition pathways.

2 Hydrogen Transitions, Workforce Planning and VET

This section frames hydrogen deployment as a socio-technical transition and uses this lens to link infrastructure build-out and industrial restructuring to occupational change and training needs. It then shows why workforce planning must move beyond technocratic demand forecasting towards governance questions – including the positioning of VET and the relevance of just transition concerns.

2.1 Hydrogen as a Socio-Technical Transition

The hydrogen economy has evolved from a largely technological vision into a central component of climate and industrial policy (Bockris, 2013; International Renewable Energy Agency [IRENA], 2024b). In contemporary strategies, hydrogen is positioned less as a niche industrial input and increasingly as an energy carrier within "Power-to-X" configurations, i.e., as a coupling technology linking renewable electricity generation with industrial feedstocks, fuels, and storage functions (Plankenbühler et al., 2021). Parallel to these policy and strategy debates, a large technical review literature discusses hydrogen production pathways and end-use technologies (Dingenen & Verbruggen, 2021; Jamal et al., 2023; Olabi et al., 2023). Hydrogen is also frequently positioned as a potentially significant contributor to net-zero pathways toward 2050 (Pathak et al., 2023), and survey-based evidence indicates that hydrogen is among mitigation options referenced in countries' NDCs (IRENA, 2024a). Reviews underline that green hydrogen deployment is conditioned by resource requirements, technological maturity, and regulatory frameworks (Rey et al., 2023), and provide broader technological and geopolitical overviews of hydrogen development (Lebrouhi et al., 2022). Within the European policy context, strategy documents and policy aspirations have been synthesised in a comprehensive review of the European Strategy for Hydrogen (Vivanco-Martín & Iranzo, 2023). For international hydrogen trade, ports are highlighted as key nodes; a review of ports' readiness considers infrastructure, risk management, public acceptance, regulations and standards, and education and training (Chen et al., 2023). In particular, hydrogen is often framed as a key option to address decarbonisation bottlenecks in hard-to-abate sectors such as heavy industry and long-distance transport (Yang et al., 2022; IRENA, 2022). Policy debates also concern the role of different hydrogen production pathways within national transition trajectories. For example, a policy analysis of Germany discusses "blue hydrogen" as a potential enabler in the scaling of hydrogen infrastructures and markets (Dickel, 2020). In the power sector, the role of hydrogen co-firing is debated; scenario modelling suggests that co-firing may have limited impact on extending fossil-based power generation under low-emissions pathways (Oshiro & Fujimori, 2024).

Conceptualising hydrogen as an energy carrier highlights that hydrogen transitions are not reducible to isolated technological substitutions. Rather, they constitute socio-technical transformations that reconfigure infrastructures, industries, labour markets, governance arrangements, and social practices (Geels, 2002; Wang & Lo, 2021). This socio-technical perspective is also reflected in critical systematic reviews of industrial decarbonisation via hydrogen, which examine technical, economic, social, and political factors shaping hydrogen adoption (Griffiths et al., 2021). This broader understanding aligns with just transition scholarship, which explicitly links energy transitions to systemic changes in infrastructure, social organisation, and community trajectories (Wang & Lo, 2021). Sustainability-oriented analyses of green hydrogen production and export raise additional concerns about climate justice and local environmental risks (e.g., land and freshwater availability), emphasising the relevance of community engagement and governance standards (Cremonese et al., 2023). Demand-side analyses also point to distributional risks in residential hydrogen transitions, including potential impacts on vulnerable consumers if demand-side conditions are not considered (Sandri et al., 2021). Qualitative synthesis further points to implementation challenges and justice-relevant community impacts in industrial decarbonisation contexts (Sovacool et al., 2024). Complementing these perspectives, an integrative review synthesises socio-economic aspects of hydrogen energy, illustrating the breadth of non-technical considerations relevant to hydrogen transitions (Sharma et al., 2023).

A central structural precondition of the emerging hydrogen economy is the large-scale availability of renewable electricity. The project materials therefore situate hydrogen within the expansion of renewable electricity capacity and generation and connect these developments to labour-market dynamics by referring to international assessments of renewable-energy employment and job measurement approaches (International Renewable Energy Agency, & International Labour Organization, 2021, 2024; Ferroukhi et al., 2020). National labour-market analyses similarly underline that the expansion of renewable energy and energy infrastructure is associated with changing occupational demand and recruitment pressures (Büchel et al., 2025). Analytically, this underlines that hydrogen transitions operate at the intersection of energy-system scaling, industrial restructuring, and workforce development rather than within a narrowly defined technology domain. This framing resonates with calls to analyse skills formation and VET in climate-changing worlds through a political-economy-ecology lens (Lotz-Sisitka et al., 2024).

At the level of national transition pathways, hydrogen strategies differ with respect to their intended role in domestic decarbonisation, industrial policy, and export-oriented development. For Brazil, for example, qualitative research highlights both the perceived investment potential and the relevance of regulatory, political, and infrastructure barri-

ers that require coordinated public–private action (Garlet et al., 2024). Complementing country-focused analyses, an expert survey covering multiple national contexts reports that experts anticipate a significant role for hydrogen while also highlighting perceived drivers, barriers, and policy conditions (Yap & McLellan, 2024).

From a labour-market perspective, such systemic change implies structural transformation: new occupations emerge, existing occupations are reconfigured, and certain activities decline. The project framing anticipates these dynamics by linking the expansion of a hydrogen economy to the growing need for a skilled workforce and by treating workforce planning as an integral part of hydrogen policy design. Once hydrogen is conceptualised as a socio-technical transition, the workforce question extends beyond quantitative issues of labour demand toward questions of institutional coordination, governance capacity, and social inclusion. This linkage is operationalised in the project's just transition framework through criteria such as labour impacts, reskilling, job quality, distributional justice, regional equity, inclusive governance, socio-technical adaptation, and public perception (García-García et al., 2020; Wang & Lo, 2021). Treating hydrogen as a socio-technical transition thus provides the conceptual rationale for assessing national workforce studies not only in terms of the analytical sophistication of their skills forecasting but also in terms of the extent to which they integrate governance and justice considerations into implementable transition pathways.

2.2 Workforce Planning Beyond Technical Forecasting

A large share of existing hydrogen workforce studies approach the topic primarily through the lens of labour supply and demand matching. Their analytical core typically consists of occupational mapping, quantitative projections of labour demand, and the identification of skill gaps along segments of the hydrogen value chain such as production, storage, transport, and end-use applications. This technocratic orientation reflects established traditions in manpower planning and sectoral workforce forecasting, where the main objective is to ensure that training systems produce the right number of workers with the right technical competences at the right time (McHenry et al., 2024).

From this perspective, workforce development is framed as a functional support system for industrial expansion. Education and training institutions, particularly VET providers, are positioned as adaptive suppliers of human capital responding to signals from industry and technology development (e.g. Green Skills for Hydrogen Project, 2023). Policy recommendations therefore focus on curriculum updates, the introduction of new qualifications, expansion of training capacity, and closer alignment between industry and education providers. While such measures are indispensable for building a hydrogen workforce, they implicitly

treat the transition as a largely technical and economic process and risk under-specifying governance and distributional challenges that shape who benefits from the transition.

Empirical studies illustrate how a provision-oriented view of workforce development plays out in specific occupational domains and training contexts. In an Australian study of plumber gasfitters, upskilling is analysed as a prerequisite for converting, installing, and maintaining hydrogen-based domestic appliances, and the study examines training-related intentions using the Theory of Planned Behavior (Sandri et al., 2024). A complementary Australian case study focuses on "skilling the green hydrogen economy" at the sectoral level (Beasy et al., 2023). More broadly, labour-market evidence based on online job postings suggests that low-carbon jobs can exhibit higher skill requirements – especially technical skills – while patterns of wage premia and geographic overlap with other jobs may change over time (Saussay et al., 2022). Together, these perspectives underline that training expansion and curriculum development need to be considered alongside incentives, mobility constraints, and the social distribution of transition opportunities.

Recent VET scholarship on green industrial transitions highlights that key concepts such as "green jobs" and "green skills" are often ill-defined and that VET greening is shaped by tensions between high-tech paradigms and inclusive approaches; it also points to the importance of sustainable work-based learning and the co-creation of skill formation for a just green transition (Thunqvist et al., 2023). Meta-reflective landscape reviews further suggest that many sustainability responses within VET remain reformist 'bolt-ons' rather than systemically transformative (Ramsarup et al., 2024). At the micro level, pedagogical approaches such as project- and collaborative learning modules can be used to introduce eco-friendly practices and circular-economy principles in VET (Nikoloudakis & Rangoussi, 2024). At the meso level, cross-border VET exchange partnerships illustrate how VET institutions can contribute to regional skills ecosystems by connecting training pathways, labour-market perspectives, and learning approaches across jurisdictions (Ramsarup et al., 2023, Wilde et al., 2025). And from a socio-technical transition research highlights that large-scale transformations are not only about technological substitution but also about the reconfiguration of institutions, power relations, and social structures (Geels, 2002). From this angle, workforce planning cannot be reduced to forecasting exercises; it becomes part of a broader governance challenge. Decisions about where hydrogen infrastructure is built, which industries are prioritised, and how public support is allocated have distributional consequences. They affect regions differently, reshape employment structures, and create both opportunities and risks for specific occupational groups.

The concept of a just transition makes these distributional and institutional dimensions explicit. It shifts attention from aggregate employment effects to questions of fairness, inclusion, and procedural justice (Wang & Lo, 2021). In this framework, workforce planning is not only about anticipating skill needs but also about managing social risks associated with structural change. This includes supporting workers in declining sectors, preventing new

forms of labour market segmentation, and ensuring that emerging green jobs provide decent working conditions (García-García et al., 2020).

Recent work on green hydrogen transitions underscores that these governance dimensions are politically contested and shaped by competing development strategies. For South Africa, policy debates around hydrogen are described as a struggle between contrasting projects, ranging from export-oriented strategies to justice-centred pathways (Kalt et al., 2023). For workforce planning, this implies that skill strategies are not politically neutral: they can reinforce or challenge distributional outcomes depending on which transition pathway is prioritised.

Complementing this, analyses of de-risking highlight that investment mobilisation and risk-sharing instruments are increasingly central to how hydrogen pathways are pursued. A policy perspective on Chile and South Africa argues that de-risking is frequently framed as necessary to overcome investment uncertainties, while also warning that certain financing arrangements may impose fiscal burdens and induce dependencies (Scholvin et al., 2025). A related critical political-economy account discusses how derisking schemes can structurally weaken states' capacity to discipline private capital in ways that support green industrialisation (Gabor & Sylla, 2023). For workforce planning, these arguments point to an additional layer of governance: the design of financing and risk-sharing arrangements can shape which value-chain segments are prioritised and, consequently, which training and reskilling demands become institutionally anchored.

Moreover, transition trajectories are actively stabilised through the coordination of expectations and the gradual increase of binding policy instruments. For Namibia and South Africa, a governance approach to "future-making" conceptualises hydrogen development as a process in which actors coordinate expectations across scales and employ instruments of increasing bindingness, even where industrial path creation remains uncertain (Klagge et al., 2025). This highlights that workforce planning maturity is closely linked to when and how training, reskilling, and social safeguards become embedded in binding governance arrangements.

Consequently, workforce planning beyond technical forecasting entails at least four additional layers. First, it requires a distributional perspective that considers who gains access to new employment opportunities and who bears adjustment costs (Wang & Lo, 2021; García-García et al., 2020). Second, it involves institutional coordination across policy domains, linking education and training policy with labour-market regulation, regional development, and social protection systems (Wang & Lo, 2021). Third, it calls for participatory governance mechanisms that involve social partners, local communities, and civil society in shaping transition pathways (García-García et al., 2020; Kalt et al., 2023). Fourth, it requires attention to the investment and expectation-governance layer through which hydrogen futures become materially and institutionally stabilised (Scholvin et al., 2025; Gabor & Sylla, 2023; Klagge et al., 2025).

Within this broader perspective, VET systems assume a more complex role. They are not only delivery institutions for technical skills but also mediating actors that can facilitate occupational mobility, support reskilling of displaced workers, and contribute to regional economic adaptation. This perspective also implies looking beyond predominantly formal spaces of learning and work, given the prominence of vocational learning outside formal provision (McGrath & Russon, 2023). Whether and how VET institutions are embedded in such governance arrangements becomes a key indicator of the institutional specification of workforce planning approaches.

For this reason, the analytical framework used in this study does not treat skills forecasting as sufficient. Instead, it distinguishes between analytical depth and implementation depth in both skills and just transition dimensions. This allows the analysis to capture whether national or nationally relevant workforce studies remain within a technocratic paradigm or move toward integrated transition governance where workforce development, social justice, and institutional design are explicitly connected.

3 Conceptual Framework

Building on this framing, this section develops the comparative framework used in the review. It combines two distinctions – skills versus justice and analysis versus implementation – into four operational dimensions (SA, SI, JTA, JTI) that guide the subsequent coding, scoring, and typology construction.

3.1 Conceptual Review as Knowledge Structuring in Hydrogen Workforce

Research on hydrogen workforce development is an emerging and highly heterogeneous field. It brings together strands from energy transition studies, labour market analysis, skills forecasting, vocational education and training (VET), and just transition scholarship. In such contexts, where empirical studies, policy reports, and strategic documents coexist without a stable shared framework, conceptual clarification becomes a necessary step in knowledge development. Conceptual review approaches are designed for this purpose: rather than aggregating statistical findings, they identify key constructs, analytical distinctions, and relationships that structure a field (Jaakkola, 2020). To support this mapping of patterns across documents, the analysis also draws on the logic of systematic theme identification as described by Braun & Clarke (2021).

In the context of hydrogen workforce planning, two conceptual tensions stand out. The first concerns the scope of workforce planning itself: is it primarily a technical exercise in labour demand forecasting and skills matching, or part of a broader governance process that shapes how socio-technical transitions unfold? The second concerns the relationship bet-

ween analysis and action: to what extent do workforce studies move beyond diagnosis toward operational, institutionalised measures?

Conceptual review as a method allows these tensions to be made explicit and analytically productive. Instead of treating national hydrogen workforce studies as directly comparable datasets, this study treats them as policy knowledge artefacts that express particular understandings of how workforce development relates to energy transitions. The goal is not to assess the empirical accuracy of forecasts but to analyse how problems are framed, which dimensions are emphasised, and how far planning extends into implementation.

This approach is particularly relevant in socio-technical transition contexts. Transition research has shown that large-scale transformations involve interactions between technologies, markets, institutions, and social practices (Geels, 2002). Workforce planning, when situated within this perspective, cannot be reduced to quantitative modelling. It becomes part of the institutional architecture through which transitions are governed. Conceptual review therefore provides a bridge between transition theory and workforce policy analysis by translating broad theoretical insights into operational analytical dimensions.

Furthermore, the just transition literature adds an explicitly normative and institutional layer to this analytical task. Related VET-focused syntheses emphasise that skills agendas for green and just transitions require moving beyond narrow technical supply logics and engaging questions of work, livelihoods, and equity (Langthaler et al., 2021). It highlights that transitions are not only about system efficiency or emissions reduction but also about fairness, participation, and the distribution of risks and opportunities (Wang & Lo, 2021). Workforce planning becomes a key site where these justice concerns are either integrated or sidelined. A conceptual review framework is well suited to capture these variations because it focuses on how justice is defined, operationalised, and linked to skills policies in different national contexts.

Methodologically, this means that the study does not seek to rank countries according to performance, but to identify patterns of institutional specification based on how skills and justice dimensions are conceptualised and operationalised. The conceptual framework thus functions as a heuristic tool: it structures comparison, makes implicit assumptions visible, and enables cumulative discussion across cases without assuming uniform data or methods.

By clarifying the underlying constructs of skills analysis, skills implementation, just transition analysis, and just transition implementation, the conceptual review approach contributes to theory building in VET and transition studies. It shifts attention from isolated policy measures toward the coherence of planning logics and governance arrangements. In doing so, it provides a structured basis for analysing how VET systems are positioned within broader socio-technical transitions and how workforce planning can move from technical adjustment toward integrated transition governance.

3.2 Two Analytical Axes: From Skills Forecasting to Transition Governance

To move workforce research beyond a narrow focus on technical forecasting, this study structures its conceptual framework along two intersecting analytical axes. These axes make explicit the underlying assumptions about what workforce planning is meant to achieve and how it relates to broader socio-technical change. Together, they provide a bridge between skills research, transition theory, and just transition scholarship.

The first axis distinguishes between skills-oriented and justice-oriented perspectives. Traditional workforce planning approaches are primarily skills-oriented: they concentrate on identifying labour demand, defining qualification requirements, and aligning training systems with industrial needs. This orientation is rooted in human capital and manpower planning traditions, where the central concern is efficient labour market matching. In the context of hydrogen transitions, such approaches typically focus on technical competences in areas such as engineering, safety, maintenance, and system integration (Energy Skills Queensland, 2019; McHenry et al., 2024).

However, socio-technical transition research suggests that transformations of this scale are not only technological and economic but also institutional and social (Geels, 2002). They reshape regional economies, alter employment structures, and redistribute risks and opportunities across social groups. The justice-oriented perspective therefore extends workforce planning to include distributional and procedural questions: Who benefits from new employment opportunities? Which regions or sectors face adjustment pressures? How are affected workers and communities involved in decision-making processes? The just transition literature frames these issues in terms of fairness, inclusion, and participation, emphasising that socially sustainable transitions require deliberate institutional design (Wang & Lo, 2021; García-García et al., 2020).

The second axis distinguishes between analysis and implementation. Many workforce studies provide extensive analytical work, including labour market modelling, scenario analysis, and skills gap assessments. While such analyses are essential for evidence-informed policy, they do not automatically translate into action. Implementation involves the design of concrete measures, allocation of resources, assignment of institutional responsibilities, and the creation of monitoring and evaluation mechanisms. Distinguishing between analysis and implementation therefore allows the framework to capture whether workforce planning remains at the level of diagnosis or becomes embedded in governance structures.

Combining these two axes yields a matrix with four quadrants: skills analysis, skills implementation, just transition analysis, and just transition implementation. This structure makes it possible to identify different planning logics. A study may be strong in skills analysis but weak in justice implementation, indicating a technocratic orientation. Another may integrate justice concerns analytically but lack concrete measures, reflecting discursi-

ve commitment without institutionalisation. Only when both skills and justice dimensions move from analysis to implementation does workforce planning become part of a broader architecture of transition governance.

This two-axis model thus operationalises the shift from workforce planning as a technical support function toward workforce planning as an integral component of socio-technical transformation. It allows VET and workforce policies to be analysed not only in terms of their responsiveness to technological change but also in terms of their role in shaping fair and inclusive transition pathways. By making these distinctions explicit, the framework provides a structured basis for comparing national hydrogen workforce studies and for discussing how VET systems are positioned within wider transition governance arrangements.

3.3 From Analytical Distinction to Operational Dimensions

The conceptual distinctions introduced in the previous sections become analytically useful only when they are translated into operational dimensions that can be applied to empirical material. To move workforce planning beyond a narrow focus on technical forecasting, this study therefore develops a set of analytical dimensions that capture how national hydrogen workforce studies conceptualise and institutionalise the relationship between skills development and just transition.

The first step in this operationalisation is to recognise that workforce planning unfolds simultaneously in the realms of knowledge production and policy implementation. Many studies devote considerable effort to analysing labour demand, occupational change, and training needs, but differ substantially in the extent to which these analyses are linked to concrete policy instruments. Distinguishing between analytical depth and implementation depth allows the framework to capture this variation and to avoid conflating discursive recognition with institutional commitment.

At the same time, workforce planning in socio-technical transitions cannot be understood solely in terms of skills. As transition research has demonstrated, large-scale transformations are shaped by interactions between technologies, institutions, markets, and social practices (Geels, 2002). Workforce planning is therefore embedded in broader governance processes that influence how benefits and burdens are distributed. The just transition literature highlights that issues such as employment security, regional disparities, participation, and social protection are central to the legitimacy and sustainability of transition pathways (Wang & Lo, 2021; García-García et al., 2020). These insights motivate the inclusion of justice-related dimensions alongside skills-related ones. Crossing the distinction between analysis and implementation with the distinction between skills and justice yields four analytical dimensions.

Skills analysis refers to the extent and sophistication of assessments of current and future skill requirements. It includes occupational mapping, scenario modelling, identification of qualification pathways, and consideration of cross-cutting competences. High depth in this dimension indicates that workforce studies engage seriously with how technological and industrial change reshape work, an issue central to socio-technical transition theory (Geels, 2002).

Skills implementation captures the degree to which identified skill needs are translated into concrete measures. This includes the design of training programmes, allocation of funding, definition of institutional responsibilities, and mechanisms for monitoring and evaluation. When implementation depth is high, skills planning becomes embedded in governance structures rather than remaining a strategic recommendation.

Just transition analysis assesses whether workforce studies explicitly address the social and distributional implications of hydrogen transitions. This includes examining potential job losses and gains, regional imbalances, risks of labour market exclusion, and the quality of emerging employment. Such analysis reflects the recognition that transitions are socially differentiated processes that require attention to equity and vulnerability (Wang & Lo, 2021).

Just transition implementation, finally, evaluates the extent to which justice considerations are translated into operational policy instruments. This may involve targeted reskilling programmes for workers in declining sectors, regional development measures, structured social dialogue, or links to social protection systems. High depth in this dimension indicates that justice is institutionalised rather than treated as a rhetorical commitment (García-García et al., 2020).

Together, these four dimensions form an analytical matrix that makes it possible to position national or nationally relevant workforce studies along a continuum from technocratic skills planning to integrated transition governance. Importantly, the framework does not assume that all dimensions develop in parallel. A study may be advanced in skills analysis but weak in justice implementation, or vice versa. By capturing such asymmetries, the framework provides a nuanced tool for analysing how VET systems and workforce policies are embedded in broader socio-technical transformations and how far they contribute to socially inclusive transition pathways.

4 Methodology

This section specifies the research design used to analyse national hydrogen workforce studies as policy knowledge artefacts. It details document selection, deductive coding, the 0–3 rating rubrics, and the rule-based aggregation of dimension profiles into the typology.

4.1 Research Design

This study applies a structured qualitative research design to analyse how national hydrogen workforce studies conceptualise and operationalise workforce development in the context of socio-technical transition. Rather than treating these studies as neutral repositories of labour market data, they are understood as policy-oriented knowledge artefacts that reflect particular problem framings, institutional assumptions, and governance logics. The analytical focus therefore lies not on evaluating the accuracy of forecasts but on examining how workforce planning is constructed as a policy domain and how it is positioned in relation to skills systems and just transition.

The selection of documents follows a purposive logic aimed at capturing the diversity of existing approaches rather than achieving statistical representativeness. Document identification combined a keyword-based search (using the search string below) with a criterion-based screening procedure. The search string focuses on hydrogen and workforce/skills terminology; retrieved documents were then assessed against the inclusion and exclusion criteria (Scope, Evidence Base, Authority, Connectivity) to ensure that the final corpus is empirically grounded, institutionally credible, and connected to an established research or stakeholder landscape.

The selection was guided by the availability of explicit skills analyses. Methodologically, we proceeded in three consecutive stages. First, we conducted an exploratory, narrative search combined with backward and forward snowballing. Starting from key publications already known in the field, we screened reference lists and citation networks in order to identify additional national reports and policy documents that might not be indexed in conventional academic databases. This step allowed us to map the landscape of skills-related analyses in the hydrogen domain and to identify relevant country cases. Second, we implemented a systematic search using the predefined search string in the curated databases Scopus and Web of Science. In addition, Google Scholar was consulted to capture grey literature (Haddaway et al., 2015). The search string is formulated as follows:

> *(workforce OR skill* OR competenc* OR qualification*) AND ("hydrogen econom*" OR "hydrogen industr*") AND (demand OR requirement* OR "labour market" OR "labor market" OR need OR analysis OR "foresight stud*" OR gap)*

This protocol-driven search strategy was intended to ensure transparency and reproducibility. However, it became evident that formal database searches alone were insufficient to identify nationally commissioned reports and strategy papers, many of which are not consistently indexed. "In systematic reviews of complex and heterogeneous evidence (such as those undertaken for management and policymaking questions) formal protocol-driven search strategies may fail to identify important evidence. Informal approaches such as browsing, "asking around," and being alert to serendipitous discovery can substantially increa-

se the yield and efficiency of search efforts" (Greenhalgh & Peacock, 2005). Therefore, as a third step, we conducted a targeted free-text search. This included country-specific queries and the incorporation of contextual knowledge about relevant national cases (e.g., Australia, Brazil, Namibia, South Africa), complemented by further iterative snowballing. This staged approach ensured both systematic coverage and contextual sensitivity in identifying skills analyses across countries.

Inclusion criteria
To be selected as a national study, the findings had to fulfil the following criteria:

- Scope: Cover the national skills landscape.
- Evidence Base: Be based on empirical data (either primary or secondary).
- Authority: Be published in peer reviewed journal article indexed in Scopus/WoS (e.g., Australia: Beasy et al., 2023) or issued by national ministry/agency, intergovernmental organisation, or a formally mandated sector body (e.g., India: South Asia Regional Energy Partnership [Chaturvedi et al., 2024 / SAREP], 2024).
- Connectivity: Demonstrate a clear nexus to the broader research landscape, meaning the study is not isolated but part of a cumulative body of knowledge or an established stakeholder network.[1]

Exclusion criteria
Studies were excluded if they met any of the following criteria:

- Isolated case studies: Research that lacked integration into larger investigations, framework programs, or established stakeholder networks.
- Snapshot or short-term analyses: Studies providing only a singular, point-in-time perspective without contributing to a longitudinal or evolutionary understanding of the field.
- Lack of empirical documentation: Contributions that did not result in accessible, evidence-based reports or failed to provide verifiable country-specific data.

1 The search revealed three distinct types of national skills studies: (a) those embedded in large-scale investigations resulting in a single central publication (e.g., India); (b) those part of a framework program yielding a suite of complementary reports (e.g., Germany); and (c) long-term efforts by overlapping stakeholders (partly with regional perspectives) who, while connected through their findings, operated without a formal, self-contained program (e.g. Australia).

– Purely theoretical or methodological papers: Articles focusing exclusively on conceptual frameworks or search strategies without an empirical application to specific country contexts.

– Disconnected grey literature: Reports produced by stakeholders acting in isolation, whose findings showed no nexus or cumulative relevance to the broader body of research or the findings of other established actors.

Analysis and synthesis

Purpose of the review is to examine interlinked concepts within the identified hydrogen workforce study (skills analysis depth, skills implementation depth, just transition analysis depth and just transition implementation depth) "in order to clarify their characteristics, thereby achieving a better understanding of the meaning of [those] concept[s]" (Coughlan & Cronin, 2017, p. 158). Methodologically, the research design combines a conceptual review approach with structured qualitative content analysis. Conceptual review is used to clarify key constructs and analytical distinctions across heterogeneous policy and research documents and to connect the analysis to broader debates in transition and VET research (Braun & Clarke, 2021; Jaakkola, 2020). The full-text coding follows a deductive category system and is conducted as qualitative content analysis in the sense of systematic, rule-guided and transparent category application (Kuckartz, 2014; Schreier, 2012). The four main categories correspond to the analytical dimensions, and each category is specified by five sub-dimensions that serve as coding guides (Appendix A). In contrast to a fully inductive thematic analysis, the coding is therefore primarily framework-driven, while interpretive judgement is retained for handling ambiguous passages conservatively.

The unit of analysis is the national hydrogen workforce study as a whole. Each document is treated as a coherent expression of how workforce challenges are defined, which policy domains are considered relevant, and how responsibilities are distributed across institutions. This holistic perspective is necessary because workforce planning in socio-technical transitions typically spans multiple sectors and governance levels, linking industrial strategy, education policy, labour-market regulation, and social protection. The analytical procedure involves a three-step process.

– First, each selected document is coded according to the four analytical dimensions defined in the conceptual framework: skills analysis depth, skills implementation depth, just transition analysis depth, and just transition implementation depth. Within each dimension, attention is paid to how problems are framed, which actors are addressed, and whether measures are described in general terms or specified in operational detail.

– Second, the coded evidence is synthesised to assign each study a score profile across the four dimensions (SA, SI, JTA, JTI) using the rating scale and dimension-specific rubrics described in Section 4.4.

– Third, the resulting score profiles are aggregated using explicit decision rules to assign each study to one of the five typology types presented in the findings section (see Section 4.5 and Table 3).

This design does not aim to produce generalisable quantitative measures but to enable structured comparison and theory-informed interpretation. By combining qualitative content analysis with a conceptual framework grounded in transition and just transition scholarship, the study seeks to make explicit how workforce planning in hydrogen transitions moves along a continuum from technocratic skills forecasting toward integrated transition governance.

4.2 Document Sample

The empirical basis of this study consists of national hydrogen workforce or skills studies that explicitly address labour market, workforce, or skills implications of hydrogen or closely related Power-to-X strategies. Documents were selected through purposive sampling to capture variation in geographical context, institutional setting, and planning approach. Selection was guided by the inclusion and exclusion criteria specified above (Scope, Evidence Base, Authority, Connectivity), ensuring that the final sample is empirically grounded, institutionally credible, and connected to an established research or stakeholder landscape.

The resulting sample comprises national workforce studies that differ in scope, institutional authorship, and level of policy authority, ranging from strategy-linked workforce assessments to agency-led skills reports. The aim of the sample is not statistical representativeness but analytical diversity suitable for typology construction.

The final sample comprises 29 national hydrogen workforce or skills studies. Documents were selected purposively to capture variation in geographical context, institutional setting, and planning approach. For transparency, the dimension scores and typology assignment for each study are summarised in Table 3 (Section 5).

4.3 Sub-Dimensions and Coding Procedure

The four main dimensions of the analytical framework (Skills Analysis – SA; Skills Implementation – SI; Just Transition Analysis – JTA; Just Transition Implementation – JTI) constitute the overarching structure of the analysis. Each dimension is specified through a set of sub-dimensions that serve as coding guides for the structured qualitative content analysis.

These sub-dimensions translate abstract constructs (e.g., "skills analysis" or "just transition implementation") into observable textual features in workforce studies. Their purpose is not to introduce additional rating categories; rather, they are used to make the assignment of the 0–3 scores more transparent, reduce arbitrariness, and increase replicability by anchoring each score in a consistent set of indicators across documents.

The sub-dimensions are derived deductively from the conceptual framework and the literature on socio-technical transitions and just transition. Transition research highlights that systemic change affects multiple levels of economic and social organisation – including occupations, regions, institutions, and governance arrangements – and therefore implies that workforce planning cannot be reduced to occupational forecasting alone (Geels, 2002). Just transition scholarship adds a focus on labour impacts, distributional justice, participation, and institutional safeguards (Wang & Lo, 2021; García-García et al., 2020). These theoretical strands inform the selection of sub-dimensions across both the skills and the justice dimensions.

Skills Analysis (SA). The sub-dimensions capture whether workforce studies (a) provide structured assessments of labour demand; (b) examine the supply side of education and training systems; (c) quantify skill gaps and/or employ scenarios or modelling; (d) specify identifiable qualification pathways; and (e) consider cross-cutting competences such as digital, safety, or systems competences. Together, these indicators distinguish between general statements about "skills needs" and evidence-based, structured diagnoses of workforce requirements.

Skills Implementation (SI). The implementation-focused sub-dimensions examine whether skills-related recommendations are translated into operational measures. Coding therefore assesses whether (a) concrete training measures are proposed; (b) resources and timelines are specified; (c) institutional responsibilities are assigned; (d) monitoring and evaluation mechanisms are included; and (e) risks or implementation challenges are addressed. Collectively, these aspects indicate the degree to which skills planning is institutionalised within governance structures and differentiate rhetorical commitment from implementable measures.

Just Transition Analysis (JTA). The justice analysis sub-dimensions are designed to capture whether workforce studies move beyond aggregate job numbers and address the social differentiation of hydrogen transitions. Sub-dimensions assess whether studies analyse (a) labour impacts (including job creation and displacement, reskilling needs, and – where discussed – job quality); (b) distributional justice and regional equity (who benefits and who bears adjustment costs across regions and social groups); (c) stakeholder participation and inclusive governance (including roles of unions, communities, social dialogue and participation arrangements); (d) socio-technical system links (connections between workforce dynamics and broader infrastructure development, industrial restructuring, and socio-technical readiness differences); and (e) public perception and acceptance (legitimacy, transparency, outreach, and communication measures).

To strengthen the conceptual clarity and operational consistency of these justice-related sub-dimensions, the coding of JTA is explicitly aligned with a synthetic Just Transition framework developed from Wang and Lo (2021) and García-García et al. (2020). This framework organises just transition concerns into five criteria: (1) labour impacts, reskilling, and job quality; (2) distributional justice and regional equity; (3) inclusive governance, policy consistency, and community engagement; (4) socio-technical adaptation and multi-dimensional integration; and (5) public perception, stakeholder support, and transparency. In the present study, these five criteria are used as interpretive prompts to identify and extract relevant evidence for the JTA dimension, thereby ensuring that the coding captures both distributive and procedural aspects of justice and their linkage to socio-technical change.

Accordingly, during coding, these five criteria are used as interpretive prompts for identifying text passages and empirical claims that evidence (or the absence of) justice analysis. We examined, for example, whether documents explicitly address job displacement and reskilling pathways and/or job quality; whether they anticipate uneven regional burdens and specify equity concerns; whether governance arrangements include structured participation or social dialogue; whether workforce issues are embedded in a broader socio-technical transition narrative (rather than treated as an isolated labour-market problem); and whether acceptance is addressed through public engagement, outreach, and transparency measures relevant to trust and legitimacy.

Just Transition Implementation (JTI). The implementation sub-dimensions assess whether justice considerations are translated into operational policy instruments and governance arrangements rather than remaining at the level of principles. In line with just transition scholarship emphasising the gap between discursive commitment and institutional implementation (Wang & Lo, 2021; García-García et al., 2020), and with the International Labour Organization's guidance on policy coherence, social dialogue, and monitoring and evaluation in just transition processes (International Labour Organization [ILO], 2015), coding focuses on five implementation features: (a) action specification (clearly defined justice instruments and target groups); (b) resources and timelines (budgets/funding sources and phased schedules); (c) governance and accountability (assigned responsibilities and formalised participation/oversight structures); (d) monitoring and evaluation, including feedback and – where specified – grievance or remediation channels; and (e) risk management and contingency planning (identification of key social/political implementation risks and fallback options). High implementation depth is coded when studies specify these elements in an integrated manner, including governance and monitoring arrangements that enable adaptation over time.

Table 1. Dimensions and Sub-Dimensions Guiding Coding

Dimension	Sub-dimensions guiding coding
Skills analysis	Skills demand assessment; Skills supply & training provision; Quantified skills gap & forecasting; Qualification pathways & certification standards; Cross-cutting & future-proof competences
Skills implementation	Action specification; Resources & timeline; Governance & responsibility; Monitoring, evaluation & feedback; Risk management & contingency planning
Just transition analysis	Labour impacts, reskilling & job quality; Distributional justice & regional equity; Inclusive governance, policy coherence & community engagement; Socio-technical adaptation & system integration; Public perception, stakeholder support & transparency
Just transition implementation	Action specification; Resources & timeline; Governance & accountability; Monitoring, evaluation & grievance; Risk management & contingency planning

In practice, coding proceeds through a structured full-text reading of each workforce study. Evidence relevant to each sub-dimension is identified and documented, but the sub-dimensions are not scored separately. Instead, they serve as qualitative anchors for assigning the overall score (0–3) for each main dimension, consistent with the rating scale introduced in Section 4.4. This approach preserves analytical flexibility while ensuring that scores are grounded in multiple observable features rather than in isolated statements. Where evidence remains ambiguous, the lower score is assigned to maintain conservative coding.

To enhance reliability of coding and scoring, both authors independently applied the coding guide and the 0–3 rating scale to all documents. The resulting score profiles were then compared; deviations were discussed and resolved through consensus, yielding a single agreed score per dimension for each study. Where the evidence in a document remained ambiguous, the lower score was retained to maintain conservative coding. We did not report a formal inter-rater reliability coefficient because the ratings are ordinal and rubric-guided, rely on interpretive judgement across heterogeneous policy documents, and the small sample size limits the interpretive value and stability of conventional reliability statistics. Given the ordinal rubric-based scoring and small N, we prioritised structured consensus over statistical reliability coefficients. The quality assurance therefore rests on double coding and structured reconciliation.

By combining theoretically derived sub-dimensions with a structured coding procedure, the methodological approach balances conceptual coherence with empirical sensitivity. This enables the analysis to capture both the technical components of workforce planning and the extent to which justice considerations are embedded as operational governance features within hydrogen transition pathways, and it supports a robust comparison of how VET-related workforce planning is positioned within broader transition governance frameworks.

4.4 Rating Framework and Operationalisation

To translate the conceptual framework into a comparative analytical tool, this study employs a structured rating framework that captures the degree of analytical and implementation depth across the four dimensions of workforce planning. The purpose of this framework is not to quantify policy performance but to create a transparent and replicable procedure for assessing how far national hydrogen workforce studies move beyond technical forecasting toward integrated transition governance.

The rating framework is based on a four-point ordinal scale ranging from 0 to 3. This scale distinguishes between the absence of discussion, general recognition, partial operationalisation, and fully developed, institutionalised measures. The same scale is applied to both analytical and implementation dimensions in order to maintain comparability and to emphasise that analytical sophistication and policy implementation are conceptually distinct. Dimension-specific rubrics for Skills (SA, SI) and Just Transition (JTA, JTI) are provided in Appendix B (Tables B1–B2).

Table 2. Generic Rating Scale (0–3) used Across all Dimensions

Score	Analytical dimensions (skills or justice)	Implementation dimensions (skills or justice)
0	No discussion of the issue	No measures proposed
1	Generic or rhetorical statements without systematic analysis	Vague commitments without instruments, budgets, or timelines
2	Thematic plans with partial detail, including some structured evidence or modelling	Named measures with partial resources, timelines, or institutional responsibilities
3	Quantified, modelled, evidence-based assessment with clear conceptual framing	Fully costed and time-bound roadmap for key measures, with designated governance/oversight; monitoring and evaluation indicators (and, where applicable, feedback or grievance channels) and risk/contingency provisions.

Table 2 provides the generic 0–3 scaling logic for all four dimensions, while Appendix B specifies dimension-specific rubrics (Tables B1–B2) that translate this generic logic into observable anchors for Skills (SA/SI) and Just Transition (JTA/JTI). This division keeps the main text readable while allowing the operationalisation to be audited in detail. The scaling logic reflects a central concern in just transition research: the gap between discursive commitment and institutional implementation (Wang & Lo, 2021). By using the same scale for skills and justice dimensions, the framework avoids implicitly privileging technical aspects of workforce planning over social ones and enables the analysis to reveal asymmetries, such as cases where skills planning is highly developed analytically but justice considerations remain rhetorically framed.

Operationalisation proceeds through a guided reading of each workforce study. For analytical dimensions, attention is given to the presence of data, modelling, occupational ana-

lysis, or structured assessments of impacts. For implementation dimensions, coding focuses on whether measures are linked to identifiable institutions, funding streams, timelines, or monitoring mechanisms. Where evidence is ambiguous, the lower score is assigned in order to maintain conservative coding.

Importantly, the rating framework does not assume that higher scores automatically imply better policy outcomes. Instead, it captures the degree to which workforce planning is conceptually integrated and institutionally anchored. This approach aligns with socio-technical transition perspectives that emphasise the role of institutions and governance arrangements in shaping transformation pathways (Geels, 2002). It also resonates with just transition scholarship, which highlights the need to move from normative principles toward operational policy instruments (García-García et al., 2020).

By making coding criteria explicit and linking them to theoretically grounded dimensions, the rating framework provides a structured basis for cross-national comparison while preserving the qualitative and interpretive nature of the analysis.

4.5 Typology Construction and Interpretive Logic

The final step of the methodological approach consists of translating the dimension-specific ratings into an overarching typology of workforce planning configurations. The purpose of this typology is not to classify countries in a normative hierarchy, but to identify recurring patterns in how skills and justice dimensions are combined and institutionalised. In other words, the typology provides an interpretive device that links the analytical framework to broader questions of transition governance.

Typology construction follows a rule-based aggregation logic. Each national workforce study receives a profile based on its scores in the four dimensions: skills analysis depth, skills implementation depth, just transition analysis depth, and just transition implementation depth. Rather than calculating numerical averages, the typology focuses on configurations of strengths and weaknesses across these dimensions. This configurational perspective reflects insights from socio-technical transition theory, which emphasises that system change is shaped by interacting institutional elements rather than by linear progress along a single scale (Geels, 2002).

Based on the four dimension scores, a typology of workforce planning configurations is derived using explicit decision rules (see Table 3):

- Integrated Transition Governance Architects (Stage 4): SA ≥ 3 and SI ≥ 2, and just transition is fully integrated (JTA ≥ 3 and JTI ≥ 2).

– Just Transition Integrators (Stage 3): SA ≥ 1 and SI ≥ 1, while both justice dimensions reach thematic/action-plan depth (JTA ≥ 2 and JTI ≥ 2), without reaching Stage 4 thresholds.

– Skills-Centric Planners (Stage 2): Skills planning is developed (SA ≥ 2 and SI ≥ 1), while justice remains marginal (JTA ≤ 1 and JTI ≤ 1).

– Strategic Workforce Framers (Stage 1): Skills implementation is present (SA ≥ 1 and SI ≥ 1) and justice is treated at thematic depth (JTA ≥ 2), but justice implementation remains limited (JTI ≤ 1).

– Workforce Analysts (Stage 0): Analytical framing is present (SA ≥ 1 and JTA ≥ 1), while implementation is absent for both dimensions (SI = 0 and JTI = 0).

These cut-offs were calibrated against the observed distribution of score profiles to yield empirically populated and conceptually distinct configurations, while preserving the conceptual meaning of each dimension and the ordinal logic of the rating rubrics. The typology represents dominant governance logics rather than a linear progression. Higher stages indicate greater institutional specification of planning (i.e., more explicit analysis, instruments, responsibilities, and resourcing), not necessarily better transition outcomes.

The typology distinguishes five ideal-typical stages of workforce planning configuration. These stages represent dominant governance logics, and higher stages indicate greater institutional specification of planning (i.e., more explicit analysis, instruments, responsibilities, and resourcing), not necessarily better transition outcomes.

Stage 0 captures studies that provide diagnostic scoping of hydrogen workforce and just transition issues but remain implementation-silent in both domains.

Stage 1 reflects early or strategic phases of policy development. Workforce issues are acknowledged, but planning remains largely qualitative and unconnected to concrete institutional arrangements. This stage corresponds to discursive integration of workforce concerns into hydrogen strategies without operational follow-through.

Stage 2 represents a skills-centred, technocratic model of workforce planning. Here, skills analysis is often sophisticated, and measures for training provision may be partially specified. However, justice considerations are limited or treated as secondary. Workforce planning is framed primarily as a problem of supply alignment with emerging industries, consistent with a human capital perspective.

Stage 3 marks a shift toward more integrated approaches linking skills planning with justice-related transition measures in contexts of structural transformation. Nevertheless,

implementation remains uneven, with limited long-term institutionalisation or national coordination. This stage reflects an intermediate form of transition governance.

Stage 4 reflects the most integrative configuration in the typology. Workforce development is embedded in a comprehensive governance architecture that links industrial strategy, labour-market policy, regional development, and social protection. Justice considerations are not only analysed but translated into concrete instruments and institutional arrangements. In this configuration, workforce planning becomes a core component of transition governance rather than a supporting technical function.

The typology highlights how different institutional contexts shape the balance between skills and justice dimensions. By making these configurations visible, the typology supports comparative analysis and theory building in VET and transition research. It shows how workforce planning can evolve from a narrow focus on technical forecasting toward a broader role in shaping socially inclusive socio-technical transformations.

5 Findings: A Typology of National Hydrogen Workforce Studies

Applying the rule-based decision logic introduced in Section 4.5 to the coded dimension profiles results in five distinct stages of workforce planning configuration. These stages reflect different combinations of analytical depth and implementation depth across skills and just transition dimensions. Table 3 summarises the dimension scores and typology assignment for each study, using short IDs for traceability. Appendix C (Table C1) provides the corresponding extraction table with document-level metadata for transparency and traceability.

Table 3: Dimension scores and Typology

Study	Author	SA	SI	JTA	JTI	Stage
Australia	Energy Skills Queensland, 2019	2	2	1	0	2
Australia	Victorian Hydrogen Hub, 2022	2	2	0	0	2
Australia	Beasy et al., 2023	2	1	1	0	2
Brazil	GIZ & SENAI, 2023	2	2	0	0	2
Canada	Hufnagel-Smith, 2022	2	2	2	1	1
Chile	GIZ, 2020	3	0	2	0	0
Chile	GIZ, 2021	3	0	1	0	0
Chile	Asociación Chilena de Hidrógeno, 2023	3	1	2	1	1
Chile	Ministry of Energy (Chile), 2024	1	2	2	2	3
Chile	Bravo-Ortega et al., 2025	1	1	3	2	3
France	France Hydrogène, 2022	2	1	0	0	2
Germany	Zinke, 2022	2	1	0	0	2
Germany	Schur et al., 2023	3	1	0	0	2

Germany	Felkl, 2023	2	1	0	0	2
Germany	Hiller, 2023	2	1	0	0	2
Germany	Schad-Dankwart, 2023	2	1	0	0	2
Germany	Schneider, 2023	2	1	0	0	2
Germany	Ronsiek et al., 2024	3	1	0	0	2
India	Chaturvedi et al., 2024 (SAREP / USAID)	3	2	2	2	3
Jordan	MED-GEM Network, 2024	2	2	1	0	2
Namibia	GIZ, 2023	2	2	2	2	3
Namibia	GIZ, 2025	2	2	2	2	3
Netherlands	Leguijt et al., 2021	3	1	0	0	2
Netherlands	UN Global Compact Netherlands & Groene VermogenNL, 2024	2	2	2	2	3
Scotland	Weir et al., 2023	3	2	1	0	2
UK	The Energy Institute, 2023	2	2	1	0	2
UK	Hydrogen Skills Alliance, 2025	2	2	2	2	3
Uruguay	Ministerio de Trabajo y Seguridad Social (MTSS-DINAE), 2025	3	2	2	2	3
South Africa	Department of Higher Education and Training, 2024	2	2	1	1	2

Note. Stage 0 = Workforce Analysts; Stage 1 = Strategic Workforce Framers; Stage 2 = Skills-Centric Planners; Stage 3 = Just Transition Integrators; Stage 4 = Integrated Transition Governance Architects.

Workforce Analysts (Stage 0)

Stage 0 captures studies that provide analytical framing of workforce and justice dimensions but do not translate either domain into implementation measures. By definition, these documents meet at least minimal analytical thresholds for skills and justice (SA ≥ 1; JTA ≥ 1), while both implementation dimensions remain absent (SI = 0; JTI = 0). In this configuration, workforce planning operates primarily as diagnostic scoping: it clarifies possible labour-market implications, value-chain linkages, or distribution-relevant considerations, but without specifying training measures, responsible institutions, timelines, or instruments.

The dominant governance logic at this stage is discursive and analytical integration without institutionalisation. VET systems may be acknowledged as relevant, yet they are not positioned within an operational transition framework with defined responsibilities or resourcing. Importantly, Stage 0 does not imply low analytical sophistication; rather, it highlights a gap between diagnosis and actionable implementation design.

Examples include Chile's scenario-based labour-chain quantification studies (GIZ, 2020; GIZ, 2021), which score high on skills analysis (SA = 3) and include transition-relevant framing, but do not specify operational training measures (SI = 0) and do not translate justice considerations into implementable instruments (JTI = 0).

Strategic Workforce Framers (Stage 1)

Stage 1 studies go beyond purely diagnostic analysis by specifying at least some skills-related implementation actions (SI ≥ 1) and by treating justice at thematic depth (JTA ≥ 2), yet they

do not translate justice into action-plan depth (JTI ≤ 1). Accordingly, workforce planning functions primarily as strategic framing with partial operationalisation: skills measures may be proposed (e.g., curriculum updates, pathway concepts, coordination proposals), while justice is framed in terms of inclusion, affected groups, legitimacy or acceptance, but without a robust package of implementable instruments.

The dominant governance logic is discursive integration with selective operational follow-through. VET is recognised as an actor for delivery and adaptation, but the justice dimension remains largely non-instrumental: it is articulated as a policy objective and interpretive lens rather than embedded in institutional safeguards, social protection linkages, or formalised governance arrangements.

Examples include Canada's workforce assessment framework (Hufnagel-Smith, 2022), which links workforce development to inclusive growth and engagement with Indigenous communities (JTA = 2) and outlines structured actions for workforce development (SI = 2), but remains below action-plan depth in justice implementation (JTI = 1). A similar configuration is visible in Chile's industry-led human capital study (H2 Chile, 2023), which quantifies human-capital needs (SA = 3) and thematises distributional and community concerns (JTA = 2), while implementation proposals remain largely at the level of commitments and coordination (SI = 1; JTI = 1).

Skills-Centric Planners (Stage 2)

Stage 2 studies represent a technocratic model of workforce planning. They combine comparatively developed skills planning (SA ≥ 2 and SI ≥ 1) with very limited justice integration (JTA ≤ 1; JTI ≤ 1). Skills-oriented recommendations often include structured occupational mapping, training pathway proposals, and – in some cases – labour-market modelling or scenario-based estimates. However, justice issues such as worker protection, regional disparities, social dialogue, or social-protection linkages remain marginal by design, or are only briefly acknowledged.

The dominant governance logic is supply-side adjustment in support of industrial expansion, consistent with a human-capital perspective: VET is positioned as a responsive training system that should align provision to emerging occupational needs, but not as a central governance actor for managing distributive conflicts or the social dimensions of structural change.

This configuration comprises primarily skills-focused gap analyses and roadmaps (e.g., Energy Skills Queensland, 2019; Victorian Hydrogen Hub, 2022; Leguijt et al., 2021; Ronsiek et al., 2024; The Energy Institute, 2023). Across these cases, implementation may reach action-plan depth in skills (SI ≥ 1), yet justice remains marginal (JTA/JTI ≤ 1).

Just Transition Integrators (Stage 3)

Stage 3 captures configurations in which both justice dimensions reach thematic/action-plan depth (JTA ≥ 2; JTI ≥ 2) alongside at least basic-to-developed skills planning (SA ≥ 1; SI ≥ 1). In these studies, justice is not only analysed but also translated into implementable elements – such as inclusion measures, stakeholder arrangements, place-based training infrastructures, targeted access instruments, or explicit benefit-sharing provisions – typically at action-plan depth rather than as fully costed, KPI-driven roadmaps.

Conceptually, this stage marks a shift toward more integrated transition governance: workforce planning is embedded in wider socio-technical change narratives (regional industrial restructuring, infrastructure build-out, local capacity constraints, legitimacy and acceptance), rather than treated as a stand-alone labour-market exercise. While the label highlights that such integration often has a place-based or territorial dimension, Stage 3 in the current corpus also includes national or programme-oriented plans that operationalise justice through concrete measures.

Empirically, this configuration is represented by studies such as India's skill gap assessment (Chaturvedi et al., 2024) and Uruguay's hydrogen employment and skills analysis (MTSS-DINAE, 2025), which combine structured skills planning with explicit inclusion and transition measures (JTA = 2; JTI = 2). Further examples include action plans and programme designs with justice-linked training measures and governance components (e.g., Ministerio de Energía, 2024 (Chile); GIZ, 2023/2025 (Namibia); UN Global Compact Network Netherlands, 2024; UK's Hydrogen Skills Alliance, 2025). Across these cases, implementation depth is substantive but typically not fully costed and not governed through comprehensive KPI-based monitoring systems across the entire policy package.

Integrated Transition Governance Architects (Stage 4)

Stage 4 describes the most institutionally specified configuration. It combines advanced skills planning (SA ≥ 3; SI ≥ 2) with high-depth just transition integration (JTA ≥ 3; JTI ≥ 2), meaning that both skills and justice measures are specified in implementable terms (instruments, responsibilities, and resourcing) and linked to governance and oversight arrangements. In such configurations, workforce development is embedded in a comprehensive governance architecture that links industrial strategy, labour-market policy, regional development, and social protection. Depending on implementation depth, Stage 4 packages may include monitoring systems and – where specified – grievance or remediation channels and contingency provisions.

In the present sample, no study meets the full Stage 4 thresholds. Stage 4 is therefore retained as an ideal-typical benchmark that clarifies what fully integrated, institutionally specified workforce planning would entail, rather than as an empirically populated category in the current corpus.

Concluding interpretive synthesis (across Stages 0–4)
Across configurations, the findings indicate that the decisive threshold for more institutionally specified planning is not skills-forecasting sophistication alone, but the extent to which justice considerations are translated into concrete instruments and governance arrangements (i.e., the shift from justice-as-framing to justice-as-implementation). The typology distinguishes dominant governance logics rather than a linear progression, and higher stages indicate greater institutional specification of planning (more explicit analysis, instruments, responsibilities, and resourcing), not necessarily better transition outcomes.

Although the typology defines ideal types, some documents still exhibit mixed features (e.g., strong skills implementation combined with limited justice implementation). In such cases, classification follows the explicit decision rules, prioritising the implementation thresholds that define each configuration. Stage 0 is analytically important in this regard, because it makes visible that even highly sophisticated analytical studies may remain implementation-silent, highlighting a recurring gap between diagnosis and actionable transition governance.

6 Discussion and Conclusion

6.1 Discussion

The typology developed in this study reveals a fundamental shift in how workforce planning is conceptualised within hydrogen transitions. Rather than representing a purely technical function aimed at aligning training provision with emerging industrial demand, workforce planning increasingly appears as a component of broader transition governance. This shift has important implications for research on vocational education and training (VET), which has traditionally focused on qualification systems, curricula, and institutional arrangements within education and training systems themselves.

From technocratic planning to transition governance
The findings demonstrate that analytical sophistication in skills forecasting alone does not define more advanced workforce planning. The decisive threshold lies in the institutional specification of justice measures and the embedding of workforce development in coordinated governance structures. In less specified configurations, workforce planning remains confined to labour supply considerations and sectoral skills alignment. In more specified configurations, it becomes embedded in multi-level governance architectures that link industrial strategy, labour-market policy, regional development, and social protection. Importantly, higher scores capture the degree of specification and institutional anchoring of planning, not the effectiveness or distributional outcomes of implementation.

This shift mirrors insights from socio-technical transition theory, which emphasises that large-scale transformations are shaped not only by technological innovation but by institutional coordination and governance design (Geels, 2002). Workforce planning, in this perspective, is not a peripheral support function but a key mechanism through which transitions are steered and stabilised.

Contribution to VET research: from provision to governance

For VET research, the typology suggests a conceptual reframing. Traditional VET scholarship often treats education and training systems primarily as providers of occupational competences. The present analysis shows that, in the context of systemic transitions, VET institutions also function as governance actors embedded in broader policy frameworks. Their role extends beyond curriculum adaptation toward participation in coordinated transition strategies that address social inclusion, regional restructuring, and labour-market risk management.

This perspective connects VET research more closely with transition studies and labour-market governance. It highlights that the positioning of VET systems within inter-ministerial coordination structures, regional development programmes, and social dialogue mechanisms is as important as their internal pedagogical or curricular reforms. In this sense, VET becomes a mediating institution between economic transformation and social cohesion.

Justice as an indicator of institutional specification

The analysis further shows that the operationalisation of justice considerations functions as a key indicator of institutional specification in workforce planning. While justice is often present rhetorically in strategic documents, only the more institutionally specified configurations translate these principles into concrete instruments such as targeted reskilling programmes, regional adjustment measures, or formalised stakeholder participation. This aligns with just transition scholarship stressing that fairness and inclusion depend on institutional arrangements rather than normative commitments alone (Wang & Lo, 2021; García-García et al., 2020).

For VET research, this means that questions of equity, access, and inclusion must be analysed not only within education systems but also in relation to how workforce policies are embedded in broader social and regional governance structures. VET's contribution to a just transition cannot be understood solely through participation rates or curriculum content; it also depends on how training opportunities are linked to social protection, regional development, and labour-market regulation.

Policy implications and future research

From a policy perspective, the findings underline the need to align skills planning with social and regional policy instruments. Workforce strategies that focus narrowly on technical skill supply risk reinforcing existing inequalities, for example by concentrating opportunities in

already advantaged regions or occupational groups. More mature approaches demonstrate how workforce planning can be integrated into coordinated governance frameworks that combine education policy, labour-market regulation, and social dialogue. This is particularly relevant because strategy-level diagnostics of hydrogen policy barriers have historically foregrounded costs and infrastructure while not highlighting skills constraints (IRENA, 2022). Although more recent strategy guidance explicitly calls for job creation, reskilling and the inclusion of vulnerable groups (IRENA, 2024b), workforce and skills development still tends to be weakly institutionalised in monitoring proposals (Quitzow et al., 2022).

Future research should examine how different governance configurations influence the effectiveness and social outcomes of workforce planning in hydrogen and other green transitions. Comparative studies could explore how institutional traditions in VET, labour-market regulation, and regional policy shape the trajectory from technocratic planning toward integrated transition governance. Such work would further strengthen the link between VET research and broader debates on socio-technical transformation.

Complementing macro-level typologies of national workforce planning, further research could connect planning logics to micro-level training implementation and occupational practice. Empirical studies already examine, for example, the upskilling of existing trades for hydrogen applications (Sandri et al., 2024) and hydrogen safety training for first responders using blended learning and virtual reality approaches (Tretsiakova-McNally et al., 2017). Linking such implementation-oriented evidence to national planning documents would help to clarify how workforce strategies translate into occupational readiness, safety-critical competence development, and socially inclusive transition outcomes.

The typology is analytical rather than evaluative. It does not rank countries according to policy performance or distributive outcomes. Instead, it identifies configurations of planning logics based on the degree to which skills and justice dimensions are translated into institutionalised governance arrangements. In this sense, higher stages represent greater institutional specification and coordination capacity, not normative superiority or empirical effectiveness of transition results.

6.2 Conclusions, Limitations and Further Research

This study set out to analyse how national or nationally relevant hydrogen workforce studies conceptualise and operationalise workforce development in the context of socio-technical transition. The results show that these studies differ systematically in their depth of analysis, their level of implementation detail, and – most importantly – the extent to which they integrate justice considerations into workforce planning.

The typology developed in this article demonstrates that the decisive distinction is not merely the sophistication of skills forecasting. While many studies provide increasingly de-

tailed projections of labour demand and training needs, only a subset embed these analyses within institutional frameworks that address distributional impacts, regional disparities, and social inclusion. The shift from less to more institutionally specified configurations is therefore marked less by improved technical modelling than by the institutionalisation of justice-oriented measures.

This finding reframes workforce planning from a predominantly technocratic exercise toward a component of transition governance. In higher-stage approaches, workforce development is integrated into coordinated policy architectures linking industrial strategy, labour-market regulation, regional development, and social protection. Workforce planning thus becomes a key mechanism through which hydrogen transitions are socially mediated and politically stabilised.

The study makes three main contributions to the literature: (1) The study advances VET research by introducing a distinction between analysis depth and implementation depth in workforce planning. This distinction helps clarify why highly detailed skills forecasts do not automatically translate into socially inclusive transition pathways. By conceptualising VET not only as a provider of qualifications but also as a governance actor embedded in multi-level policy frameworks, the study expands the theoretical lens through which VET's role in systemic transformation can be understood. (2) The article contributes to just transition research by operationalising justice considerations within the specific field of workforce policy. Rather than treating just transition as a general normative principle, the framework identifies concrete analytical and implementation dimensions through which justice is – or is not – embedded in workforce planning. This allows systematic differentiation between rhetorical commitment and institutionalised practice. (3) The study provides a methodological contribution through a transferable, dimension-based evaluation framework and a rule-based typology. The framework enables structured comparison of national workforce studies despite differences in data sources, institutional contexts, and policy traditions. It offers a tool that can be adapted for analysing workforce planning in other sectors undergoing decarbonisation.

Several limitations must be acknowledged. The analysis is based on strategy and planning documents rather than on empirical data about implementation outcomes. As a result, the typology captures planned governance arrangements rather than actual policy effectiveness. Importantly, the typology should not be interpreted as an outcome evaluation. It does not measure whether hydrogen transitions generate more employment, greater equity, or faster decarbonisation. Instead, it assesses how workforce planning is conceptually framed and institutionally specified within national governance architectures. Higher stages reflect greater formalisation, operationalisation, and integration of skills and justice dimensions, but they do not imply more successful or socially preferable transition trajectories. In addition, the typology is heuristic and ideal-typical; individual countries may display internal variation ac-

ross regions or policy domains that is not fully reflected in national-level documents. Finally, the framework emphasises institutional design and may underrepresent informal practices or local initiatives that also shape transition dynamics.

The justice dimension in this study integrates labour impacts, regional equity, participatory governance, socio-technical integration, and public perception. While this reflects the multidimensional character of just transition scholarship, it also entails conceptual breadth. The framework deliberately adopts an expansive interpretation of justice as embedded in governance design; however, this aggregation may blur analytical distinctions between labour-market equity, democratic participation, and industrial coordination. Subsequent work could disaggregate these sub-dimensions more explicitly or test whether they cluster empirically into separable justice logics.

The empirical corpus combines different types of documents, including scenario-based modelling studies, government action plans, industry white papers, and research reports. Although inclusion criteria were applied systematically (Scope, Evidence Base, Authority, Connectivity), the documents differ in institutional mandate and policy proximity. As a result, the unit of comparison is "national hydrogen workforce studies" as governance artefacts rather than a uniform document genre. This heterogeneity may affect comparability, particularly between analytical modelling reports and strategy-linked implementation plans. Future research could apply the framework separately to distinct document types to test robustness.

The 0–3 rating scale provides structured rubrics to enhance transparency and replicability. Nevertheless, scoring remains interpretive, particularly when distinguishing between thematic depth and partial operationalisation. Although independent double coding and consensus reconciliation were applied, the absence of formal reliability coefficients and the reliance on holistic document-level judgement may limit replicability. Further research could test inter-rater stability across independent research teams or apply quantitative calibration techniques.

The typology identifies configurations of governance logic rather than a linear developmental trajectory. However, because higher stages correspond to greater institutional specification, there is a risk of implicit evolutionary interpretation. The present analysis does not establish temporal sequencing or causal progression between stages. Longitudinal research would be required to examine whether and under which institutional conditions countries shift from technocratic skills planning toward more integrated governance configurations.

Although the study repositions VET as a governance actor within socio-technical transitions, it does not systematically differentiate between national VET regime types (e.g., coordinated, liberal, or state-led systems) when interpreting typology placement. The interaction between workforce governance configurations and institutional VET traditions remains an open research question. Comparative institutional analysis could further clarify how established VET architectures condition the translation of hydrogen workforce planning into implementable justice-oriented governance.

The analysis operates at the national-document level. In practice, hydrogen transitions often unfold through regionally differentiated industrial clusters, pilot zones, or subnational governance arrangements. National-level documents may therefore underrepresent internal variation. Future research could apply the framework at subnational level or integrate regional case studies to capture intra-country heterogeneity.

The findings suggest several directions for future research. First, the analytical framework could be applied to other sectors of the green transition, such as renewable electricity, battery value chains, or low-carbon materials, to examine whether similar patterns of workforce planning configuration emerge. Second, longitudinal studies could explore how countries shift between configurations over time and which institutional factors facilitate more integrated approaches. Third, more detailed empirical research is needed on the role of VET institutions in more institutionally specified contexts. Case studies could investigate how VET providers participate in regional transition strategies, how reskilling programmes are implemented in practice, and how social dialogue mechanisms shape training provision. Finally, future work could connect planning typologies with outcome indicators such as employment trajectories, regional inclusion, or job quality in order to better understand the social effectiveness of different workforce planning models. By situating workforce planning at the intersection of VET, labour-market governance, and socio-technical transition, this study highlights the importance of institutional design for socially inclusive hydrogen pathways.

Ethics Statement

This paper fully complies with the principles and guidelines of the ethical statement for publications of the IJRVET. The conducted research did not include human participants. The authors report there are no competing interests to declare.

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Appendix

Appendix A. Coding guide

Tables A1–A4 provide the coding guide used for the structured qualitative content analysis. For each dimension, the five sub-dimensions are specified by their conceptual core and a set of inquiry questions that were used as interpretive prompts during full-text coding.

Table A1. Coding guide for Skills Analysis Depth (SA)

Sub-dimension	Level of analysis	Conceptual core	Inquiry questions (interpretive prompts)
Skills Demand Assessment	Occupation / task	Identify current and future job roles and task profiles along the hydrogen value chain.	Which occupations (ISCO/NOC codes) are required per H_2 segment? Are task analyses or competency statements provided? Are demand figures time-phased?
Skills Supply & Training Provision	Institution / provider	Map existing education and training programmes (VET, HE, CPD) that feed the value chain.	Which TVET schools, universities, private providers deliver relevant courses? What is current annual graduate output? Any dedicated H_2 training centres?
Quantified Skills Gap & Forecasting	Region / sector	Quantify mismatches between demand and supply and model future scenarios.	Is there a quantified gap (FTE deficit/surplus) by occupation and year? Are scenarios (technology, policy) modelled? Sensitivity analysis?
Qualification Pathways & Certification Standards	System / sector	Define new or adapted curricula, occupational standards and certification schemes.	Are new competency standards drafted? Stackable micro-credentials or RPL pathways? Alignment to EQF/NQF levels?
Cross-Cutting & Future-Proof Competences	Individual / cross-occupation	Address transversal skills (digitalisation, data analytics, H_2 safety culture, sustainability literacy) that cut across job families.	Does the study explicitly identify transversal digital and soft skills required for H_2 jobs? Are upskilling programmes for these competences proposed?

Table A2. Coding guide for Skills Implementation Depth (SI)

Sub-dimension	Level of analysis	Conceptual core	Inquiry questions (interpretive prompts)
Action Specification	Policy / programme	Concrete training and reskilling actions.	Are concrete actions named (what, who, when)? Are objectives and target groups explicit?
Resources & Timeline	Financial / scheduling	Assign budgets, funding sources and phased schedules.	Cost estimates per action? Funding sources identified? Deadlines or phased roll-out?
Governance & Responsibility	Institutional	Define lead agencies, roles, legal mandates and coordination bodies.	Who is responsible for each action? Inter-ministerial or PPP steering bodies? Regulatory or legal basis?
Monitoring, Evaluation & Feedback	M&E / data system	Establish KPI system, baselines, review cycles and adaptive learning.	Indicators, baselines and targets defined? Frequency of progress reports? Corrective-action mechanisms?
Risk Management & Contingency Planning	Risk / scenario	Plan for budget overruns, technology delays, social backlash and market volatility.	Are key risks identified (technical, financial, social)? Contingency funds or fallback options? Scenario-based stress tests?

Table A3. Coding guide for Just Transition Analysis Depth (JTA)

Sub-dimension	Level of analysis	Conceptual core	Inquiry questions (interpretive prompts)
Labour Impacts, Reskilling & Job Quality	Worker / occupation	Direct impacts on workers and occupational groups; human-capital policy.	Which jobs are at risk, created or transformed? What reskilling / up- and re-training plans exist (funding, capacity)? How are wages, H&S, diversity and inclusion safeguarded?
Distributional Justice & Regional Equity	Region / social stratum	Fair allocation of benefits and burdens across territories and social groups.	Which regions/communities gain or lose economically? How are vulnerable groups compensated or prioritised? Fit with climate-, energy- and environmental-justice principles?
Inclusive Governance, Policy Coherence & Community Engagement	Institutional / policy	Quality, transparency and consistency of decision-making structures.	Are affected stakeholders formally represented (unions, local government, Indigenous groups)? Is there vertical policy alignment (national–regional–local)? What dispute-resolution and accountability tools exist?
Socio-Technical Adaptation & System Integration	System / sector	Co-evolution of technology, infrastructure, standards and institutions for an equitable system transition.	How are technical pathways (H_2 production, grids, safety codes) aligned with social needs and skills supply? Are sector- or region-specific disparities addressed in the system design? Is there an iterative learning and feedback loop?
Public Perception, Stakeholder Support & Transparency	Society / public sphere	Build trust and societal licence to operate through information, dialogue and monitoring.	What outreach and education campaigns are in place? Are data and progress reports publicly accessible?

Table A4. Coding guide for Just Transition Implementation Depth (JTI)

Sub-dimension	Level of analysis	Conceptual core	Inquiry questions (interpretive prompts)
Action Specification	Policy / programme	Concrete justice instruments (e.g., wage insurance, regional funds, social-dialogue bodies).	Which specific just-transition instruments are proposed to protect affected workers or communities? Do the measures describe objectives, target groups and expected benefits?
Resources & Timeline	Financial / scheduling	Assigned budgets, funding sources and phased schedules for every just-transition instrument.	Is a dedicated budget or funding source identified for each justice measure, and is the amount fully costed? Does the study provide a clear timetable specifying start, milestone and completion years?
Governance & Accountability	Institutional / legal	Formal bodies, legal mandates and stakeholder representation overseeing just-transition measures.	Which institutions or multi-stakeholder boards will govern the justice instruments, and are their mandates legally defined? How are labour unions, local communities or Indigenous peoples formally included in decision-making and oversight?
Monitoring, Evaluation & Grievance	M&E / social audit	Equity KPIs, review cycles and channels for complaints or redress.	Does the study set measurable equity indicators and provide baseline and target values? Is there a formal grievance or appeals mechanism for affected stakeholders?
Risk Management & Contingency Planning	Risk / scenario	Plans for social-risk mitigation (e.g., mass layoffs, funding shortfalls, community backlash).	Which social or political risks have been identified, and how severe are they rated? Are contingency funds, alternative employment schemes or mediation protocols in place to manage these risks if they materialise?

Appendix B. Dimension-specific rating rubrics

Table B1. Skills rating rubric (Rating I)

Score	Skills Analysis Depth (SA)	Skills Implementation Depth (SI)
0 – None / Absent	Report contains no discussion of required hydrogen-related skills or occupations.	No action, budget, timeline or governance for training measures.
1 – Basic / Token	Generic statements (e.g., "new skills will be needed"); lists broad job families but no task detail or numbers.	Vision-level pledges ("develop reskilling programmes") without actors, cost or schedule.
2 – Thematic / Action Plan	Sector-specific role mapping; qualitative gap discussion; some link to existing courses. Limited or no quantification.	Specific training actions named or indicative budgets/timelines or lead agencies; pilot projects sketched.
3 – Quantified / Road-mapped	Full demand-vs-supply modelling; numeric gaps by occupation/region/year; draft curricula, competency standards, micro-credentials.	Costed, time-bound roadmap for all key skills actions; funding sources, KPIs, monitoring and risk plans in place.

Table B2. Just transition rating rubric (Rating II)

Score	Just Transition Analysis Depth (JTA)	Just Transition Implementation Depth (JTI)
0 – None / Absent	No mention of labour, equity, or justice issues in the transition.	No justice instruments, budgets, or governance proposed.
1 – Basic / Token	Justice buzz-words or high-level principles, but no specific groups, regions or data analysed.	Vague commitment ("support fairness") but no concrete instrument, cost, or timeline.
2 – Thematic / Action Plan	Dedicated section identifies affected groups/regions; qualitative governance or compensation ideas; may cite limited figures.	Named justice measures (fund, wage-top-up, etc.) with at least one of: budget or timeline or responsible body; still partial.
3 – Quantified / Road-mapped	Justice fully quantified (jobs or income impacts mapped, regional equity tables); legal or policy mechanisms described; equity KPIs defined.	All key JT instruments fully costed and scheduled; governance formalised (e.g., by law); monitoring, grievance and contingency funds specified.

Appendix C. Extraction table

Table 3 reports the final sample (n = 29) used for the dimension scoring and typology assignment. Based on the decision rules in Section 4.5, all studies could be assigned to one of the five typology stages. The corresponding extraction table (Table C1, below) provides more detailed descriptions of each document, including title, authoring body, actor type and primary data basis.

Table C1. Extraction table – Overview of analysed hydrogen workforce studies

Country / Region	Reference (in-text)	Study title	Lead authoring body	Actor type	Primary Data Basis
Australia	Energy Skills Queensland, 2019	Research Report: Skills Gap Analysis between the Hydrogen sector and the gas industry	Energy Skills Queensland	Industry association	DB; DS-M; I
Australia	Victorian Hydrogen Hub, 2022	Hydrogen Skills Roadmap: An analysis of the skills and training needs to support a future hydrogen economy	Victorian Hydrogen Hub (Swinburne University of Technology)	Research consortium	DS-M; S; I; VA
Australia	Beasy et al., 2023	Skilling the green hydrogen economy: A case study from Australia	Victorian Hydrogen Hub (Swinburne University of Technology); University of Tasmania	Research consortium	S; I
Brazil	GIZ & SENAI, 2023	Mercado de Hidrogênio Verde e Power to X: Demanda por Capacitações Profissionais	Projeto H2Brasil (SENAI; GIZ)	Multi-stakeholder partnership	DS-M, S; I; CL
Canada	Hufnagel-Smith, 2022	Assessing the workforce required to advance Canada's hydrogen economy	The Transition Accelerator	Research consortium	DS-P
Chile	GIZ, 2020	Cuantificación del encadenamiento industrial y laboral para el desarrollo del hidrógeno en Chile	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)	Public agency	DS-M, LM, DB

Chile	GIZ, 2021	Cuantificación del encadenamiento laboral para el desarrollo del hidrógeno en Chile bajo un escenario de exportación (Reporte final)	GIZ	Public agency	DS-M, LM
Chile	Asociación Chilena de Hidrógeno, 2023	Estudio H2 Chile: Capital humano de la industria del hidrógeno renovable: Desafíos actuales y futuros	Asociación Chilena de Hidrógeno (H2 Chile)	Industry association	DS-M; DB; CL
Chile	Ministerio de Energía, 2024	Plan de Acción Hidrógeno Verde 2023–2030	Ministerio de Energía (Chile)	Government ministry	DS-P, I
Chile	Bravo-Ortega et al., 2025	Estudio brechas de género en la industria del hidrógeno verde (Informe final)	Ministerio de Energía (Chile)	Government ministry	DS-M; S; I
France	France Hydrogène, 2022	Skills and professions of the hydrogen sector: Planning ahead to successfully develop an industry of strategic importance (White paper)	France Hydrogène	Industry association	DS-M; I
Germany	Zinke, 2022	Erzeugung, Speicherung und Transport von Wasserstoff	Federal Institute for Vocational Education and Training (BIBB)	Public agency	DS-M; I; FV
Germany	Felkl, 2023	Sektoranalyse: Chemie- und Raffinerieindustrie	BIBB	Public agency	DS-M; I; FV
Germany	Hiller, 2023	Sektoranalyse: Wärmeversorgung –	BIBB	Public agency	DS-M; I
Germany	Schad-Dankwart, 2023	Sektoranalyse: Stahlindustrie	BIBB	Public agency	DS-M; I; FV
Germany	Schneider, 2023	Sektoranalyse: Verkehrssektor	BIBB	Public agency	DS-M; I
Germany	Schur et al., 2023	Arbeitskräftebedarf und Arbeitskräfteangebot entlang der Wertschöpfungskette „Wasserstoff“: Abschlussbericht der ersten Projektphase	BIBB	Public agency	DS-M; LM; I
Germany	Ronsiek et al., 2024	Arbeitskräftebedarf und Arbeitskräfteangebot entlang der Wertschöpfungskette Wasserstoff: Szenario-v2.1	Institute for Employment and Research (IAB)	Public agency	DS-P; LM; I
India	Chaturvedi et al., 2024	Skill Gap Assessment Across Green Hydrogen Sector in India	South Asia Regional Energy Partnership (SAREP) (USAID); Skill Council for Green Jobs (SCGJ)	Multi-stakeholder partnership	DS-P; LM; I; CS; VA
Jordan	MED-GEM Network, 2024	Jordan skills gap analysis	MED-GEM Network	Multi-stakeholder partnership	DS-M; S; I
Namibia	GIZ, 2023	Enhancing Employability: Skills needs and gap analysis in Namibia's PtX sector and recommendations for a skills development programme	GIZ / International PtX Hub	Public agency	DS-M; I
Namibia	GIZ, 2025	TVET skills for renewable energy and green hydrogen in Namibia: Consolidated report (skills gaps across 11 occupational areas)	GIZ (ProTVET Project)	Public agency	DS-M; S; I; FV

Nether-lands	Leguijt et al., 2021	Jobs from investment in green hydrogen: Update and extension	CE Delft	Research consortium	DS-P; LM
Nether-lands	United Nations Global Compact Network Nether-lands & Groene VermogenNL, 2024	Building Bridges: Make Hydrogen Work – International Approach	UN Global Compact Network Netherlands; Groene Vermo-genNL	Multi-stakeholder partnership	DS-P; I
Scotland (UK)	Weir et al., 2023	Mapping the current and forecasted hydrogen skills landscape	ClimateXChange	Public agency	DS-M; LM; I
United Kingdom	The Energy Institute, 2023	Landscape review of skills needed for an emerging hydrogen based economy	The Energy Institute	Industry association	DS-M; S; I
United Kingdom	Hydrogen Skills Alliance, 2025	Empowering the Future: A Strategic Skills Plan for the UK Hydrogen Economy	Hydrogen Skills Alliance	Multi-stakeholder partnership	DS-P; S; I
Uruguay	Ministerio de Trabajo y Seguridad Social – Dirección Nacional de Empleo, 2025	Estudio prospectivo de mercado laboral en la cadena de hidrógeno verde y derivados en Uruguay: Impactos en empleo, perfiles ocupacionales y formación profesio-nal al 2024	Ministerio de Trabajo y Seguridad Social – Dirección Nacional de Empleo (MTSS-DINAE)	Government ministry	DS-P; LM
South Africa	Department of Higher Education and Training, 2024	Identification of skills needed for the hydrogen economy (Research report)	Department of Higher Education and Training	Government ministry	DS-M; I; CL

DB – Database mining, DS-M: Desk study as declared method, DS-P: Desk study as analytical practice, LM: Labour market modelling, S: Surveys, I: Interviews / consultations, CS: Case studies, VA: Vacany analysis / job advertisements, CL – Cluster / skills clustering analysis, FV – Field visits / site visits

Appendix C provides an overview of the hydrogen workforce studies included in the analytical corpus. The purpose of this table is to document the basic characteristics of each study. Each row represents one study. The columns capture the following attributes:

Country / Region: This column identifies the national context to which the study refers. It defines the comparative unit used in the subsequent typology and allows differences in institutional and policy environments to be traced.

Year: This indicates the publication year of the document. It situates the study within a particular phase of hydrogen strategy development and allows temporal differences in planning approaches to be considered.

Study title: A shortened version of the document title is provided for ease of reference. This enables clear identification of each study while keeping the table concise.

Lead authoring body: This column names the organisation primarily responsible for producing or commissioning the study. It documents the institutional origin of the analysis and provides insight into the authority and policy proximity of the document.

Actor type: Actor type classifies the lead authoring body into analytically defined categories that reflect different governance logics of knowledge production and policy influence. The

classification does not reproduce labels used in the documents themselves, but is applied consistently based on the institutional character of the organisation responsible for the study. The following categories are used:

- Government ministry: A national ministry or government department directly responsible for policy design and strategic decision-making.

- Public agency: A single organisation with a formal public or quasi-public mandate and a stable institutional identity, typically responsible for operational, regulatory, advisory, or implementation-related functions within a policy field.

- Research consortium: A collaboration of universities, research institutes, or consultancies primarily engaged in analytical, scientific, or advisory work rather than formal policy authority.

- Industry association: A sectoral industry body, employer organisation, or business-led platform representing the interests of firms or industry groups.

- Multi-stakeholder partnership: A formally structured collaboration between multiple organisations from different institutional spheres (e.g., government, industry, research, international organisations) that jointly produce a study or initiative without constituting a single institutional actor.

The distinction between public agency and multi-stakeholder partnership is institutional rather than functional. A public agency is one organisation with its own mandate and continuity, even if it works closely with other actors. A multi-stakeholder partnership, by contrast, is a joint arrangement in which several organisations act together without merging into a single institutional entity.

Primary data basis: This column identifies the empirical and analytical foundations on which each study relies. Multiple codes may be assigned where different data sources or analytical approaches are used.

- DB = Database mining / database-derived evidence: Use of an existing structured database as an empirical source (typically administrative or proprietary), which is mined/extracted to identify job roles and/or qualification, licensing and skills requirements (e.g., the SkillPASS database in the Australia 2019 report)

- DS-M = Desk study as declared method: The study explicitly identifies document review, literature review, policy analysis, or secondary data analysis as a formal methodological component. Desk-based analysis is described as a defined step in the research design.

- DS-P = Desk study as analytical practice: The study demonstrably relies on systematic and structured analysis of existing reports, policy documents, statistical sources, or prior research as a substantive analytical input, even if such desk-based work is not formally labelled as a method. Indicators include structured synthesis of secondary sources, comparative review of policies or programmes, or analytical use of existing statistical or market data beyond general contextual description.

- LM = Labour market modelling: Use of original quantitative employment projections, workforce forecasting, or scenario-based labour demand modelling developed within the study. LM is coded only when the study produces its own forward-looking numerical estimates or modelling results. Summarising, citing, or discussing employment projections produced by other sources does not qualify as labour market modelling and is instead captured under DS-M or DS-P where relevant. Descriptive presentation of existing labour statistics without modelling or projection also does not qualify as labour market modelling.

- S = Surveys: Structured questionnaires administered to employers, workers, training providers, or other stakeholders.

- I = Interviews / consultations: Semi-structured or structured interviews, expert consultations, focus groups, or stakeholder workshops used as a primary data source.

- CS = Case studies: In-depth examination of specific regions, projects, industries, or pilot initiatives to derive workforce or skills insights.

- VA = Vacancy analysis / job advertisements: Systematic analysis of job vacancy postings as an empirical source to identify demanded occupations, qualifications, skills, or task profiles. VA is coded only when the study itself conducts a structured analysis of vacancy data (e.g., collection, coding, text analysis, or frequency analysis of job ads). Mere reference to external vacancy data or existing vacancy studies does not qualify as VA.

- CL – Cluster / skills clustering analysis: Systematic clustering or structured classification of occupations, skills, or qualification requirements using an explicit analytical framework. CL is coded only when the study performs its own structured clustering or mapping logic beyond descriptive synthesis.

- FV – Field visits / site visits: On-site visits to companies or facilities (e.g., plant tours, site inspections, workplace observations) used as an empirical input to inform workforce or skills analysis. FV is coded when the study reports conducting site visits and explicitly uses insights from these visits in the analysis. If site visits are embedded within systematic case

studies, code CS; FV is used only when visits are described as a distinct method or as ad-hoc field input.

Multiple codes may be assigned where studies combine different data sources.

Reference: This column provides the in-text citation format used in the article (e.g., Author, Year). It ensures a direct link between the table and the reference list and allows readers to trace each document to its full bibliographic entry.