

Politecnico di Torino

Water Conservancy and Hydropower Technology Landscape: Patent Scenario

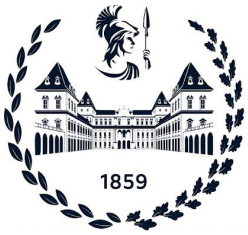
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Abstract

The global hydropower sector is undergoing a structural transition driven by the imperative of grid decarbonization and climate resilience. Traditional baseload generation is increasingly supplemented by utility-scale energy storage and cyber-physical asset modernization. This thesis conducts a comprehensive patent landscape analysis to map the technological trajectories and competitive dynamics of the global water conservancy and hydropower industry. Based on a validated dataset of 26,158 simple patent families with priority dates between 2000 and 2024, the research evaluates spatial distributions, International and Cooperative Patent Classifications (IPC/CPC), and corporate assignee portfolios.

The empirical results indicate that the sector has entered a secondary innovation cycle. While heavy civil engineering has reached technological maturity, current research and development (R&D) is densely concentrated in Pumped Storage Hydropower (PSH) integration and electromechanical flexibility. Furthermore, the competitive landscape reveals a distinct strategic bifurcation among leading innovators. Chinese State-Owned Enterprises (SOEs) demonstrate a quantitative dominance aligned with domestic capacity targets, concentrating their intellectual property in greenfield infrastructure and reversible pump-turbines. Conversely, Western Original Equipment Manufacturers (OEMs) operate in saturated markets, prioritizing a brownfield modernization strategy focused on digital twins, predictive maintenance algorithms, and advanced control architectures. Despite the presence of these multinational leaders, the market remains highly fragmented, with a persistent "long tail" of regional entities holding over 84% of the patent volume.

The study concludes that maintaining a competitive advantage in the modern hydropower sector requires a transition from hardware manufacturing scale to digital lifecycle services. Strategic recommendations are provided for capacity-driven entities to invest in core digital layers and for software-oriented firms to accelerate industrial servitization, alongside macro-level policy directives for standardizing data interoperability across aging grids.

Keywords: Hydropower Technology, Patent Landscape Analysis, Pumped Storage Hydropower (PSH), Digital Servitization, Technology Strategy.

Sommario

Il settore idroelettrico globale sta attraversando una transizione strutturale guidata dall'imperativo della decarbonizzazione della rete e della resilienza climatica. La tradizionale generazione di carico di base è sempre più integrata dall'accumulo di energia su scala di rete e dalla modernizzazione cyber-fisica degli asset. Questa tesi conduce un'analisi completa del panorama brevettuale (patent landscape analysis) per mappare le traiettorie tecnologiche e le dinamiche competitive dell'industria globale dell'energia idroelettrica e della conservazione delle acque. Basandosi su un set di dati

validato di 26.158 famiglie di brevetti semplici con date di priorità comprese tra il 2000 e il 2024, la ricerca valuta le distribuzioni spaziali, le classificazioni internazionali e cooperative dei brevetti (IPC/CPC) e i portafogli dei titolari (assignees) aziendali.

I risultati empirici indicano che il settore è entrato in un ciclo di innovazione secondario. Mentre l'ingegneria civile pesante ha raggiunto la maturità tecnologica, l'attuale ricerca e sviluppo (R&S) è fortemente concentrata sull'integrazione del pompaggio idroelettrico (PSH) e sulla flessibilità elettromeccanica. Inoltre, il panorama competitivo rivela una netta biforcazione strategica tra i principali innovatori. Le imprese statali cinesi (SOE) dimostrano una dominanza quantitativa allineata agli obiettivi di capacità nazionale, concentrando la loro proprietà intellettuale nelle infrastrutture greenfield e nelle turbine a pompa reversibili. Al contrario, i produttori di apparecchiature originali occidentali (OEM) operano in mercati saturi, privilegiando una strategia di modernizzazione brownfield incentrata su gemelli digitali, algoritmi di manutenzione predittiva e architetture di controllo avanzate. Nonostante la presenza di questi leader multinazionali, il mercato rimane altamente frammentato, con una persistente "coda lunga" di entità regionali che detiene oltre l'84% del volume dei brevetti.

Lo studio conclude che il mantenimento del vantaggio competitivo nel moderno settore idroelettrico richiede una transizione dai volumi di produzione hardware ai servizi digitali per l'intero ciclo di vita. Vengono fornite raccomandazioni strategiche affinché le entità guidate dalla capacità investano nei livelli digitali di base e le aziende orientate al software accelerino la servitizzazione industriale, unitamente a direttive politiche a livello macro per la standardizzazione dell'interoperabilità dei dati nelle reti obsolete.

Parole Chiave: Tecnologia Idroelettrica, Analisi del Panorama Brevettuale, Pompaggio Idroelettrico (PSH), Servitizzazione Digitale, Strategia Tecnologica.

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1 Introduction to the Technology – Reference Context

1.1 Background

The global landscape of water conservancy and hydropower is driven by two major global challenges: the increasing vulnerability of global water resources and the pressing need for a global energy transition. Driven by population growth, rapid urbanization, and economic development, the global demand for freshwater has been consistently increasing by approximately 1 % annually since the 1980s (UNESCO, 2024). Consequently, water scarcity has emerged as a major global threat. Recent assessments indicate that roughly half of the global population currently experiences severe water scarcity for at least one month per year, while 2.2 billion people remain without access to safely managed drinking water (UNESCO, 2024).

Simultaneously, the accelerating impacts of climate change are intensifying the global water cycle, leading to a marked increase in the frequency and severity of extreme hydrological events. Between 2002 and 2021, floods and droughts collectively affected over 3 billion people and triggered over USD 1 trillion in global economic losses (UNESCO, 2024). These significant human and economic impacts highlight the necessity for resilient water conservancy infrastructure—such as advanced flood control systems, modern irrigation networks, and robust reservoirs—to mitigate climate-induced disruptions and ensure social stability (UNESCO, 2024; International Hydropower Association, 2024a).

Parallel to the water crisis is the global mandate to decarbonize the energy sector. In this context, hydropower continues to serve as a foundational component of the renewable energy transition. Hydropower remains the largest single source of renewable electricity globally, accounting for approximately 14 % of total global electricity generation (International Energy Agency, 2024). Beyond base-load energy generation, modern water infrastructure provides a crucial dual function: it is estimated that the water storage capacity of the hydropower industry prevents over USD 130 billion in annual GDP losses globally from drought incidents alone (International Hydropower Association, 2024a). Therefore, the continuous development of water conservancy and hydropower technologies is essential to global sustainable development and climate resilience.

1.2 Global Economic Relevance and Market Dynamics

To accurately interpret the patenting trends of technology innovators (assignees), it is critical to evaluate the macroeconomic environment driving their R&D investments. The long-term commercial viability of hydropower is rooted in its highly competitive Levelized Cost of Electricity (LCOE) and long asset life. As of 2024, the global hydropower market size was valued at approximately USD 257.1 billion, and it is projected to reach USD 280.2 billion by 2030, growing at a Compound Annual Growth Rate (CAGR) of 1.5 % (Grand View Research, 2024).

In 2024, global hydropower installed capacity reached approximately 1443 GW

(Enel Green Power, 2024). Hydropower generation rebounded strongly by 10 % to reach 4578 TWh in 2024, following drought-affected lows in 2023 (International Hydropower Association, 2025). To double hydropower capacity by 2050 and achieve global climate goals, a cumulative investment of approximately USD 3.7 trillion is required, equating to about USD 130 billion annually (International Hydropower Association, 2024c).

1.2.1 A Decade of Global Capacity Additions

The past decade of global hydropower capacity additions illustrates a highly cyclical market influenced by mega-project completion cycles, supply chain disruptions, and climate anomalies. To present this macroeconomic trajectory, Figure 1 synthesizes historical capacity data and near-term projections primarily derived from the International Hydropower Association's (IHA) annual World Hydropower Outlook reports. As illustrated in the chart, the market experienced a historic low in 2023 (dropping to 13.5 GW) due to severe drought constraints. However, the graph indicates a significant recovery in 2024 (reaching 24.6 GW) driven by renewed global investments in energy storage, with an upward projection for 2025.

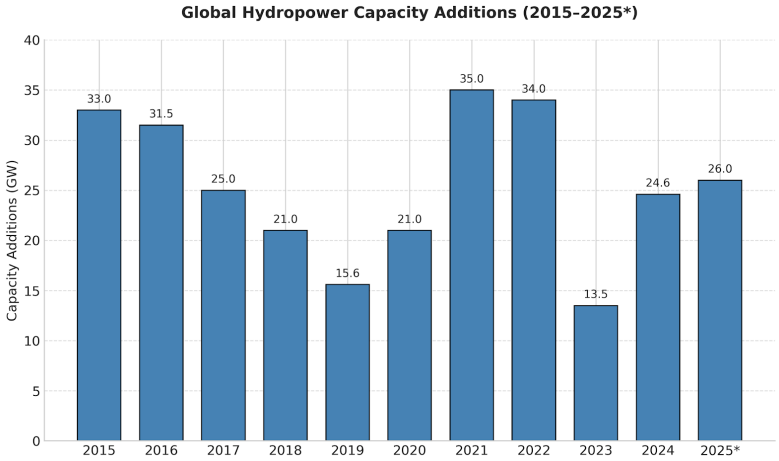


Figure 1: Global hydropower capacity additions (2015–2024)

1.2.2 The Capital Shift Toward Pumped Storage Hydropower (PSH)

A critical insight for future technological forecasting is the rapid capital shift toward Pumped Storage Hydropower (PSH). PSH currently provides over 90 % of all stored energy in the world (International Hydropower Association, 2024c). In 2024, 8.4 GW of PSH was commissioned, raising the total global PSH capacity to 189 GW, which represents a 5 % year-on-year increase (International Hydropower Association, 2025).

A key indicator of this economic shift is the current global development pipeline: out of the 1075 GW of planned hydropower development globally, an estimated 600 GW is dedicated to PSH, surpassing the 475 GW pipeline for conventional hydropower (International Hydropower Association, 2025). This macroeconomic reality justifies a strong focus on energy storage and variable-speed turbine technologies in the subsequent patent landscape analysis.

1.3 Regional Market Focus: Europe and China

For a comprehensive Management Engineering perspective, it is crucial to analyze the specific dynamics of the European and Italian markets, where the primary focus is on asset optimization and flexibility rather than greenfield mega-projects.

1.3.1 Europe's Focus on Flexibility and Modernization

European hydropower is a key component of the continent's renewable transition. As of 2024, Europe's total installed hydropower capacity stood at 263 GW, including 56 GW of pumped storage (International Hydropower Association, 2024b). Benefiting from above-average precipitation, European hydropower generation rebounded to a decade-high of 680 TWh in 2024 (International Hydropower Association, 2024b). Europe's strategy has shifted from capacity expansion to asset modernization: the market is primarily driven by the need for long-duration energy storage to counter the volatility of intermittent wind and solar. This is evidenced by a large European PSH project pipeline of 52.9 GW currently in development (International Hydropower Association, 2024b).

1.3.2 China's Hydropower Expansion and 14th Five-Year Plan Targets

Hydropower is essential to China's energy security and remains a key component of its zero-emissions power system. As the world's largest hydropower producer, China's total installed hydropower capacity reached 436 GW by the end of 2024 (National Energy Administration (NEA), 2025). During 2024, the country experienced substantial growth, adding 13.78 GW of new hydropower capacity (National Energy Administration (NEA), 2025). To accommodate the rapid expansion of intermittent renewables, there has been an elevated focus on pumped hydro storage (PSH) for grid firming, which reached 58.7 GW of installed capacity by the end of 2024 (China Electricity Council, 2025). This significant expansion allowed renewable sources to surpass 50% of China's total installed power capacity, marking a notable milestone in its energy transition (National Energy Administration (NEA), 2025). Looking forward to 2025 and beyond, China's 14th Five-Year Plan (2021–2025) for Renewable Energy sets ambitious targets, aiming for renewable electricity generation to reach 3,300 TWh by 2025 (National Development and Reform Commission (NDRC), 2022). To manage the large-scale integration of solar and wind power required to meet these targets, China is actively accelerating its storage infrastructure and mega-projects, including planned hydropower development on the lower reaches of the Yarlung Tsangpo river (State Council of the People's Republic of China, 2021). This creates favorable conditions for technological innovations and patenting activities in large-scale hydro engineering and grid integration.

1.4 Hydropower Technology Taxonomy

Translating these economic and technological trends into standardized search parameters is essential for constructing robust patent database queries (e.g., on platforms like Lens.org or Espacenet). The hydropower technology landscape can be categorized to define the relevant search parameters.

1.4.1 Core Technical Branches

First, *conventional and Run-of-River (RoR) hydropower* refers to facilities that utilize natural river flow or dam-regulated discharge to drive turbines without substantial pumping functions (U.S. Bureau of Reclamation, 2024). Second, *Pumped Storage Hydropower (PSH)* provides a distinct storage-oriented architecture in which water is transferred between upper and lower reservoirs, thereby functioning as a strategic "water battery" for balancing grid variability (Federal Energy Regulatory Commission, 2024). Finally, at the equipment level, the dominant conversion technologies are *reaction turbines* (notably Francis and Kaplan) and *impulse turbines* (primarily Pelton), which together constitute the technical core of mainstream hydropower generation systems (U.S. Bureau of Reclamation, 2024).

1.4.2 Emerging Innovation Frontiers

In parallel with these core branches, current innovation frontiers are increasingly defined by *digitalization and Digital Twin (DT) integration*, where IoT sensing, large-scale data analytics, and machine-learning-based models are combined to build virtual representations of physical assets for predictive maintenance and real-time optimization (Pacific Northwest National Laboratory, 2024). Moreover, an ecologically oriented trajectory is reflected in *environmentally-enhanced turbine design*, especially "fish-friendly" configurations using blunt blade geometries and strict hydraulic constraints (for example, a minimum pressure threshold of 10 psia) to reduce biological stress during downstream fish passage (Pacific Northwest National Laboratory and Tethys, 2024). In summary, the global hydropower sector is experiencing a structural shift. Driven by the dual imperatives of the global energy transition and climate resilience, the industry is shifting capital toward Pumped Storage Hydropower (PSH) and modernizing existing assets through digitalization and ecological enhancements. However, while market reports and macroeconomic policies outline these broad trajectories, understanding the empirical pace of innovation requires a more granular approach. To quantitatively track these technological shifts and identify the key organizations driving the state-of-the-art, it is necessary to translate these engineering concepts into measurable data. The following chapter will detail the methodology employed to achieve this, outlining how patent data is utilized as a technological indicator and how the taxonomy defined above is operationalized into structured search queries.

2 Method

2.1 Rationale for Patent Landscape Analysis

While macroeconomic indicators and market reports highlight the substantial capital investments required for the global energy transition, understanding the empirical trajectory of technological innovation requires a more granular approach. As the hydropower industry shifts from traditional heavy civil engineering toward smart grid integration, digital twins, and ecologically sustainable turbine designs, tracking the outputs of research and development (R&D) is important. In this context, patent documents serve as reliable and comprehensive sources of technological intelligence.

Statistical analyses based on patent data are highly utilized by researchers, investors, and policymakers because patents serve as quantitative indicators of phenomena that are otherwise difficult to measure, including innovation trends, knowledge spillovers, and the evolution of technological spaces (Abbas et al., 2014). Among various approaches to exploring industry opportunities, discovering technology opportunities from patent data is widely recognized as one of the most effective and frequently used methods (Yoon et al., 2020).

By conducting a comprehensive patent landscape analysis in the field of water conservancy and hydropower, this thesis aims to achieve four interconnected objectives. First, it seeks to map *technological trajectories* by identifying how innovation is reoriented toward contemporary constraints, including the expansion of Pumped Storage Hydropower (PSH), the digitalization of aging assets, and the emergence of fish-friendly turbine concepts. Furthermore, it aims to identify *key innovators* by revealing the leading assignees—from multinational corporations to universities and research institutions—and by clarifying the degree of competitive concentration in the sector. Additionally, the study tracks *geographical distribution patterns* to evaluate which countries and regions are leading R&D efforts, thereby reflecting the effectiveness of national policy frameworks, subsidies, and industrial capabilities. Finally, it evaluates *patent quality* beyond raw filing counts by incorporating forward-citation analysis to assess the technological influence and strategic significance of major patent portfolios.

Analyzing the patent landscape reveals the relationship between macroeconomic energy targets and micro-level technological realities. It offers insights into how the hydropower sector is developing technologies to support the future net-zero energy system.

2.2 Patents as a Data Source

To empirically analyze the technological evolution, geographical distribution, and key innovators within the hydropower sector, this study utilizes patent data as the primary source of technological intelligence. Patents are widely recognized as objective indicators of research and development (R&D) output and technological innovation. According to the guidelines provided by the World Intellectual Property Organization (WIPO) and the Organisation for Economic Co-operation and Development (OECD), patent documents contain structured and detailed technical information that is often unavailable in other scientific or commercial literature, making them a valuable resource for technology forecasting (Trippe, 2015; Organisation for Economic Co-operation and Development (OECD), 2009).

In accordance with established patent landscape methodologies, this analysis focuses on extracting and interpreting four core patent fields and structural metrics. First, *classification codes (IPC/CPC)* are used to reduce the incompleteness and semantic noise that often arise from keyword-only retrieval, especially when heteronyms, sector-specific jargon, or legal drafting strategies expand or obscure technical meaning; in this regard, the International Patent Classification (IPC) and Cooperative Patent Classification (CPC) provide a standardized, language-independent hierarchy that improves recall and interpretability (World Intellectual Property Organization, 2024b).

Furthermore, *assignee data* is analyzed to identify legally recognized owners of inventions and, by extension, to map dominant innovators, concentration levels (e.g., top 5, 10, or 20 entities), and competitive structures across the industry (Trippe, 2015). Additionally, *forward citations* are incorporated because filing volume alone cannot fully represent technological impact; citation frequency from subsequent patents is widely treated as a proxy for quality, influence, and knowledge spillover, with highly cited patents often representing foundational innovations (Trajtenberg, 1990; Harhoff et al., 2003). Finally, the analysis is consolidated at the *Simple Patent Family* level to prevent jurisdictional double-counting and ensure that each underlying invention is represented once in the empirical dataset.

2.3 Classification Mapping and Keywords for Patent Queries

Translating the economic and engineering realities into structured search parameters is essential for constructing reliable patent database queries (e.g., on platforms like Lens.org or Espacenet). To ensure high precision and recall in the upcoming patent landscape analysis, the search strategy combines text-based keywords with specific International Patent Classification (IPC) and Cooperative Patent Classification (CPC) codes. **Core IPC/CPC Classifications:**

- `F03B`: Machines or engines for liquids. This is the primary domain for hydro turbines (e.g., `F03B 1/00` for impulse turbines like Pelton, `F03B 3/00` for reaction turbines like Kaplan/Francis) (World Intellectual Property Organization, 2024a).
- `F03B 13/06`: Stations or aggregates of water-storage type (Specifically designates Pumped Storage Hydropower).
- `Y02E 10/20`: Hydro energy. A relevant cross-sectional tag applied to patents contributing to climate change mitigation through hydropower (United States Patent and Trademark Office, 2024).

Keywords Formulation: Based on the literature review, the following primary keyword sets will be structured using Boolean logic for title, abstract, and claims (TAC) searches:

- *Macro Domain:* Hydropower, Hydroelectric, hydro energy, water power.
- *Hardware/Typologies:* Turbine, Pumped Storage, Francis, Kaplan, Pelton, runner, penstock, wicket gate.
- *Innovation Niches:* Digital twin, predictive maintenance, smart monitoring, fish-friendly, safe fish passage.

2.4 Building Search Queries

The extraction of the patent dataset was conducted using **Lens.org**, an open-access and comprehensive database that aggregates patent data from major global

intellectual property offices. The structured search tool and the query text editor in Lens.org were utilized to combine text fields—specifically Title, Abstract, and Claims (TAC)—with IPC and CPC classification codes (Lens.org, 2024).

The development of the search query was an iterative process, requiring continuous experimentation and validation to balance recall (retrieving all relevant patents) and precision (excluding irrelevant noise). Based on the technological taxonomy defined in Chapter 1, three distinct search queries were constructed:

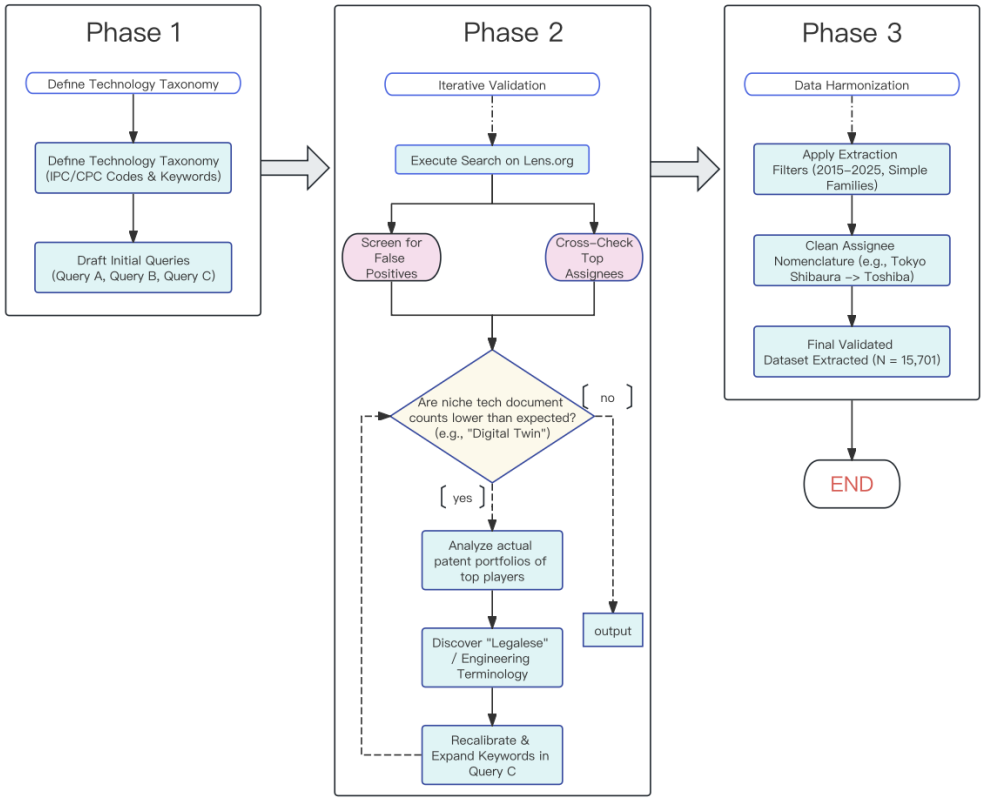


Figure 2: Iterative Workflow of Patent Data Extraction and Harmonization

2.4.1 Query A: Core Hydropower Landscape

The first query was designed to capture the overall technological baseline of the hydropower sector. To restrict the search exclusively to relevant domains, the query mandates the presence of the core classification codes (e.g., `F03B` for liquid engines/turbines or `Y02E 10/20` for hydro energy climate mitigation technologies). These codes were then intersected with core keywords representing primary hydropower technologies and structural components. The structured query used is as follows:

```
(class_ipcr.symbol:F03B* OR class_cpc.symbol:"Y02E 10/20") AND
(title:(hydropower OR hydroelectric OR "hydro energy" OR "water
↪  power" OR
turbine* OR Francis OR Kaplan OR Pelton OR runner* OR penstock OR
"wicket gate") OR abstract:(hydropower OR hydroelectric OR "hydro
↪  energy" OR
"water power" OR turbine* OR Francis OR Kaplan OR Pelton OR
↪  runner* OR
penstock OR "wicket gate"))
```

2.4.2 Query B: Pumped Storage Hydropower (PSH) Focus

Given the significant economic relevance and rapid capital shift toward grid stabilization technologies highlighted in Chapter 1, a dedicated query was constructed for Pumped Storage Hydropower. This query utilizes the specific IPC subgroup `F03B 13/06` (Stations or aggregates of water-storage type) and broadens the scope by including exact keyword matches across titles, abstracts, and claims:

```
class_ipc.symbol:"F03B 13/06" OR (title:("pumped storage" OR
↪  "pumped hydro") OR
abstract:("pumped storage" OR "pumped hydro") OR
claim:("pumped storage" OR "pumped hydro"))
```

2.4.3 Query C: Emerging Technologies and Innovation Areas

To map the digitalization and ecological enhancement of the hydropower sector, a third query targeted emerging innovation areas. It restricts the technological boundary using the core IPC/CPC codes to ensure relevance, but intersects them with advanced digitalization and ecological keywords (e.g., digital twins, machine learning, fish passage):

```
(class_ipcr.symbol:F03B* OR class_cpc.symbol:"Y02E 10/20") AND
(title:("digital twin*" OR "predictive maintenance" OR "condition
↪  monitoring" OR
"fault diagnosis" OR "machine learning" OR "neural network*" OR
↪  sensor* OR
"fish passage" OR ecolog*) OR abstract:("digital twin*" OR
"predictive maintenance" OR "condition monitoring" OR "fault
↪  diagnosis" OR
"machine learning" OR "neural network*" OR sensor* OR "fish
↪  passage" OR ecolog*))
```

2.5 Validation of Search Queries

The development of the search queries was an iterative process, requiring continuous experimentation and validation to balance recall and precision, a core requirement in patent landscape analysis (Abbas et al., 2014). To ensure the validity of the retrieved

data, the results were systematically reviewed. An initial screening was performed by scrolling through the retrieved patents online to detect false positives, ensuring that root terms did not inadvertently capture unrelated technologies, such as hydrogen fuel cells or general hydraulic machinery.

This validation was an iterative refinement process, as recommended by international patent search guidelines (Trippe, 2015). For instance, initial keyword searches for emerging digital technologies (Query C) yielded lower-than-expected document counts. By manually examining the actual patent portfolios of leading innovators like GE Renewable Energy, it was discovered that patent attorneys frequently utilize broader engineering terminology—such as 'condition monitoring' or 'fault diagnosis'—rather than commercial terminology like 'digital twin'. Consequently, the keywords in the final queries were expanded and recalibrated to capture these linguistic variations and legalese commonly encountered in patent literature (Trippe, 2015). Furthermore, an assignee-based verification was conducted. The retrieval of key industry leaders at the top of the assignee list—such as China Yangtze Power, Voith, State Grid, and GE Renewable Energy—confirmed the reliability of the chosen search parameters.

2.6 Data Cleaning and Harmonization

Raw patent datasets are inherently noisy, particularly concerning applicant names, due to corporate mergers, subsidiaries, localized spelling variations, and clerical errors during the initial filing process (Abbas et al., 2014; Yoon et al., 2020). To ensure the reliability of the innovator profiling (assignee analysis) in Chapter 3, a rigorous data cleaning and harmonization protocol was implemented prior to the final data extraction.

Following established methodological guidelines for patent landscape reporting (Trippe, 2015), special attention was dedicated to resolving the spelling variations of the same corporate entities. Manual grouping and consolidation were performed on the raw export from Lens.org. For example, legacy corporate registrations such as "Tokyo Shibaura Electric" were identified and merged into the contemporary parent entity, "Toshiba." Similarly, various abbreviations and branch registrations, such as "Gen Electric," were consolidated under the single corporate entity, "GE Renewable Energy."

Finally, after resolving assignee nomenclature, applying the earliest priority date filter (2000-01-01 to 2025-01-01), and consolidating all records by Simple Families to systematically eliminate double-counting, the core dataset (Query A) yielded a consolidated dataset of **26,158 patent records**. This clean, validated dataset, along with the respective subsets extracted via Queries B and C, provides a reliable empirical basis for the spatial, temporal, and competitive mapping presented in the following chapter. The final configuration of the search queries, their specific objectives, and the resulting dataset sizes after the harmonization process are summarized in Table 1.

Table 1: Overview of Patent Search Queries and Retrieved Results (2000–2025)

Search Focus	**Query Syntax (Lens.org)**	**Primary Objective**	**Simple Families**
A. Core Landscape	`(class_ipcr.symbol:F03B* OR class_cpc.symbol:"Y02E 10/20") AND (title:(hydropower OR hydroelectric OR "hydro energy" OR "water power" OR turbine* OR Francis OR Kaplan OR Pelton OR runner* OR penstock OR "wicket gate") OR abstract:(...))`	To capture the macro-level hydropower industry and general turbine technologies.	26,158
B. Pumped Storage	`class_ipcr.symbol:"F03B 13/06" OR (title:("pumped storage" OR "pumped hydro") OR abstract:("pumped storage" OR "pumped hydro") OR claim:("pumped storage" OR "pumped hydro"))`	To empirically track the substantial capital shift toward energy storage solutions.	4,913
C. Emerging Tech	`(class_ipcr.symbol:F03B* OR class_cpc.symbol:"Y02E 10/20") AND (title:("digital twin*" OR "predictive maintenance" OR "condition monitoring" OR "fault diagnosis" OR "machine learning" OR "neural network*" OR sensor* OR "fish passage" OR ecolog*) OR abstract:(...))`	To identify niche advancements in digitalization and eco-friendly turbine designs.	2,895

Note: Data extracted on March 20, 2026. All results are filtered by publication year (2015-2025) and consolidated by Simple Families to prevent double-counting.

3 Analysis and Results

Based on the methodological framework defined by WIPO and the OECD (Trippe, 2015; Organisation for Economic Co-operation and Development (OECD), 2009), this chapter presents the empirical findings from the patent landscape analysis. The analysis is built upon the core dataset of 26,158 validated simple patent families, supplemented by targeted sub-queries. The objective is to examine how the macroeconomic energy targets and market drivers discussed in Chapter 1 translate into specific technological developments and R&D investments.

To provide a structured and comprehensive evaluation, the results are organized into six main areas: (1) temporal trends based on earliest priority date, (2) geographical distribution of R&D, (3) innovator profiling and market concentration, (4) technological taxonomy across IPC and CPC classifications, (5) a targeted case study on Pumped Storage Hydropower, and (6) a subsequent case study on asset digitalization and predictive maintenance.

Before proceeding with the detailed analyses, the time frame of the dataset must be defined. An initial retrieval (Query A) was performed without any temporal limit to observe the long-term trend of hydropower patenting. This unrestricted search returned 33,934 simple patent families.

Figure 3 displays this historical trajectory from 1950 onwards. The data shows that prior to the year 2000, patenting activities in the hydropower sector were relatively stagnant and characterized by low annual filing volumes. The majority of these early patents involved basic mechanical improvements. However, starting from 2000, the industry began a clear and continuous expansion, reflecting the modernization of the sector.

Therefore, to focus on recent years and catch the newest developments in the field, we exclude the initial years where patent activity was trivial. By restricting the dataset to the earliest priority years between 2000 and 2024, the total number of records is refined to 26,158. This subset serves as the empirical basis for the remainder of the chapter.

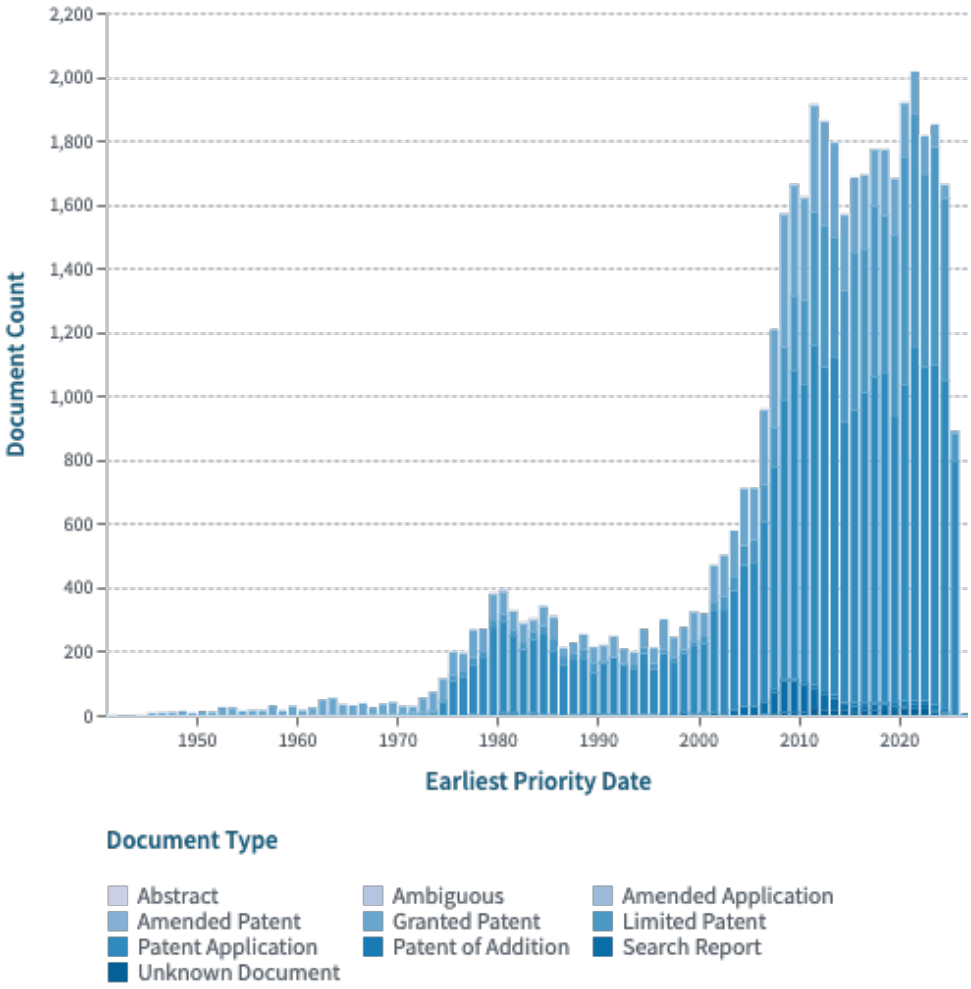


Figure 3: Query A Results Overview

3.1 Temporal Evolution of Hydropower Innovation (2000–2024)

3.1.1 Methodological Note on Time Frame Selection

In accordance with international standards for technology forecasting outlined by WIPO and the OECD (Trippe, 2015; Organisation for Economic Co-operation and Development (OECD), 2009), this temporal analysis prioritizes the Earliest Priority Date (or Application Date where priority is unavailable) rather than the publication year. While publication dates are subject to administrative and legal variations across jurisdictions, the priority date reflects the exact moment of "strategic intent" (Organisation for Economic Co-operation and Development (OECD), 2009)—the point at which an organization commits R&D resources.

Furthermore, an initial unrestricted search of the global patent landscape revealed that patenting activity in the hydropower sector was largely stagnant and trivial throughout the late 20th century. However, the turn of the millennium marked a structural transition. Therefore, to capture the complete modern evolutionary trajectory—from the dawn of the 21st century's renewable energy integration to the current era of digitalization—while excluding historical noise, this study strategically

restricts the dataset to patents with an Earliest Priority Date between 2000 and 2024.

3.1.2 Phase-wise Analysis of the Innovation Trajectory

Based on the distribution of the 26,158 patent families illustrated in Figure 4, the modern hydropower innovation landscape over the past two decades can be categorized into three distinct evolutionary phases:

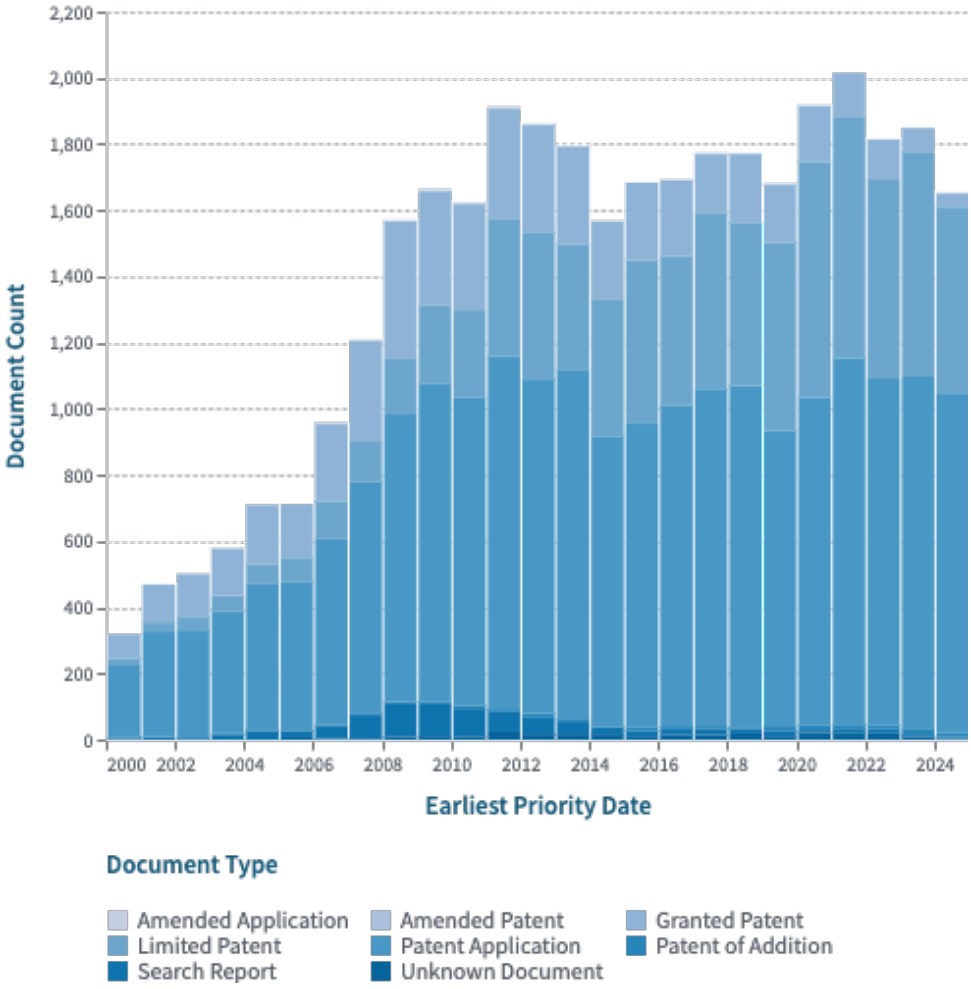


Figure 4: Query A Results Overview

Phase I: Initial Incubation (2000-2006). During this period, the industry exhibited stable but relatively low-volume patenting activity, with annual filings consistently remaining between the 300 and 700 document threshold. This phase represents a conventional era where hydropower was primarily viewed through the lens of large-scale, base-load civil engineering projects (International Hydropower Association, 2024c; U.S. Bureau of Reclamation, 2024). Technological innovation was largely incremental, focusing on foundational mechanical engineering within the IPC F03B classification, specifically traditional turbine efficiency and structural dam integrity (World Intellectual Property Organization, 2024a).

Phase II: First Expansion Wave (2007-2013). A decisive inflection point occurred

after 2007, where annual filings surged past 1,900 families by 2013. This period marks the transition of hydropower from a traditional utility to a critical component of the global energy transition. This surge is directly correlated with the global capacity additions observed during this decade (International Hydropower Association, 2024c). The growth was further catalyzed by the rapid expansion of renewable energy targets, triggering a wave of R&D in variable-speed turbines and large-scale Pumped Storage Hydropower (PSH) infrastructure to support grid firming and flexibility (Yang et al., 2024; Pérez-Díaz et al., 2015).

Phase III: Sustained Maturation and Digital Transition (2014-2022). The data reveals that hydropower innovation reached its historical peak in 2022, with total applications exceeding 2,000 families annually. This peak represents the convergence of two modernizing forces: the physical expansion of energy storage capacity and the digital transformation of existing fleets (Xu et al., 2023). As the average age of the global hydropower fleet—particularly in Europe—approaches 45 years, the industry has shifted its R&D focus from sheer capacity volume to operational value, prioritizing asset modernization and life-extension retrofitting over greenfield construction (Quaranta et al., 2021). This shift is empirically evidenced by the rising share of patents related to digital twin modeling, predictive maintenance algorithms, and advanced sensor integration (Sahu et al., 2021b; Tao et al., 2022).

3.1.3 The 18-Month Publication Lag and Data Interpretation

As illustrated in the temporal distribution in Figure 4, the data for the years 2023 and 2024 displays an apparent sharp decline in patenting activity. It is essential to clarify that this observation does not represent a genuine reduction in research and development output within the hydropower sector. Instead, this phenomenon is a structural artifact of the international patent system. Under the regulatory frameworks of the Patent Cooperation Treaty (PCT) and the majority of national jurisdictions, patent applications remain confidential for a standard period of 18 months following the earliest priority date before they are officially published (Trippe, 2015). Consequently, the datasets for these most recent priority years are inherently incomplete, as a significant volume of the technological filings made during this window has not yet entered the public domain (Organisation for Economic Co-operation and Development (OECD), 2009). This administrative lag is a standard constraint in patent bibliometrics and must be accounted for when interpreting the trajectory of the latest innovation cycle.

3.1.4 Growth Drivers in Specific Technologies

While the aggregate data demonstrates a sustained upward trajectory, a single aggregate view of the 26,158 patent families obscures the underlying structural shifts within the industry. An analysis of the specialized technological subsets indicates that the growth observed after 2014 was significantly influenced by advancements in Pumped Storage Hydropower (PSH). As national electrical grids required greater capacity to assimilate fluctuating power from solar and wind sources, the demand for utility-scale energy storage became a primary driver for innovation (Yang et al., 2024). This industrial response is closely aligned with macroeconomic policy mandates, such as the strategic targets outlined in China's 14th Five-Year Plan (National

Development and Reform Commission (NDRC), 2022).

Simultaneously, there has been a consistent increase in patenting activity related to digitalization. The growth in filings for digital twins and predictive maintenance technologies reflects a strategic transition in mature hydropower markets. Asset operators are increasingly investing in software-based solutions to monitor mechanical fatigue and extend the operational lifecycle of aging infrastructure. This trend is corroborated by technical evaluations from the U.S. Department of Energy and various industry case studies (Pacific Northwest National Laboratory, 2021, 2024).

3.1.5 Document Type and Legal Status Analysis

Beyond absolute volume, the stratification of document types in Figure 4 reveals a consistent proportion of granted patents corresponding to the priority years between 2010 and 2018. This grant ratio indicates a stable survival rate of hydropower innovations during substantive patent examination, providing empirical support for the technical validity of the research and development investments made during the expansion phases. Furthermore, the accumulation of active, granted patents within this period creates a patent thicket (Trippe, 2015), effectively raising technological barriers for new market entrants.

3.1.6 Technology Life Cycle and S-Curve Analysis

Evaluating this temporal landscape through the Technology Life Cycle (TLC) framework provides further analytical clarity. While the traditional civil engineering aspects of hydropower entered a maturity phase in the late 20th century, the patent growth observed after 2007 provides empirical evidence of a "Double S-Curve" phenomenon.

This renewed upward trajectory represents the emergence of a secondary S-Curve, driven primarily by cross-disciplinary innovation. As traditional mechanical improvements approach thermodynamic limits, research and development efforts have shifted toward electromechanical flexibility and cyber-physical integration. Consequently, the temporal trajectory indicates that the modern hydropower sector is undergoing a renewed growth phase, with major organizations actively securing foundational patents for grid-scale energy storage applications.

3.2 Geographical Distribution of Patent Filings

The spatial distribution of patenting activities provides a macro-level overview of global hydropower innovation centers. By analyzing the jurisdictions where patent protection is actively sought, it is possible to observe the alignment between national infrastructure investments, regional energy transition strategies, and empirical technological outputs.

Based on the updated dataset of 26,158 simple patent families, the jurisdictional analysis reveals a highly concentrated distribution. As illustrated in Figure 5, patenting activity is primarily centered in East Asia, supplemented by specialized Western innovation clusters.



Figure 5: Word Cloud

3.2.1 Patent Activity in China

Figure 5 illustrates the quantitative lead of China within the global patent landscape, accounting for 16,757 families. Representing a substantial majority of the global total, this significant ratio compared to the second-place United States indicates a high geographical concentration of renewable energy intellectual property.

This high volume of patenting activity is supported by a state-led dual strategy. First, China continues to execute large-scale greenfield hydropower projects. As outlined in national development frameworks, projects such as those on the lower reaches of the Yarlung Tsangpo river require continuous proprietary innovations in high-head dams and high-capacity turbines (State Council of the People's Republic of China, 2021). Second, to meet national renewable targets and manage the intermittency of expanding solar and wind capacities (National Development and Reform Commission (NDRC), 2022), domestic research and development has prioritized advanced reversible pump-turbines utilized in Pumped Storage Hydropower (PSH) networks (Yang et al., 2024).

3.2.2 Patent Activity in North America

The United States, with 4,034 patent families, and Canada, with 1,113 families, represent the North American cluster. In contrast to the capacity-oriented model driven by new construction in East Asia, the North American technological trajectory is primarily characterized by the modernization of legacy assets.

Because the domestic market for large-scale greenfield dams is largely saturated, North American innovation is pivoting toward improving the operational flexibility

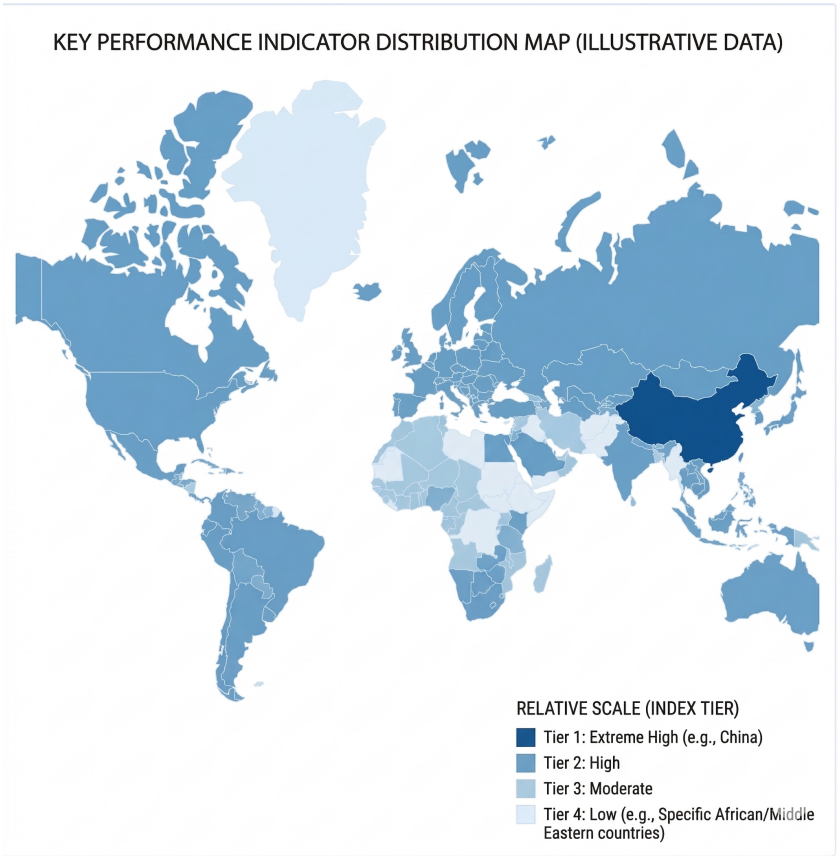


Figure 6: Global Hydropower Distribution Map

of the existing fleet. Cross-industry technological spillover is evident in this region, with research initiatives led by institutions such as the Pacific Northwest National Laboratory (PNNL) advancing patenting activities in predictive maintenance and digital twin modeling (Pacific Northwest National Laboratory, 2021). These software-centric innovations aim to optimize operational efficiency and grid resilience without necessitating new civil infrastructure.

3.2.3 Interpretation of WO and EP Filings

A rigorous methodological interpretation of the patent landscape requires addressing the significant presence of WO (WIPO) filings, totaling 3,000 families, and EP (European Patents) filings, totaling 1,754 families. According to established patent landscape guidelines, these filings represent international gateways that indicate high-value commercialization strategies rather than innovation confined to a single jurisdiction (Trippe, 2015). The high volume of WO applications suggests that a substantial portion of hydropower innovation is intended for global market protection and technology transfer.

The EP filings signify the collective research and development output of the European hydropower cluster. Recent assessments indicates that the European hydropower fleet is aging, with many plants requiring significant modernization and life-extension retrofits (Quaranta et al., 2021). Facing stringent regional ecological regulations and a saturated market for new large-scale dams, European innovators appear to prioritize high-value niches. This strategic focus is reflected in the patenting of

technologies related to ecological mitigation and digital retrofitting, allowing these organizations to maintain a competitive advantage in asset optimization services.

3.2.4 Comparison of Major Jurisdictions (CN, US, EU)

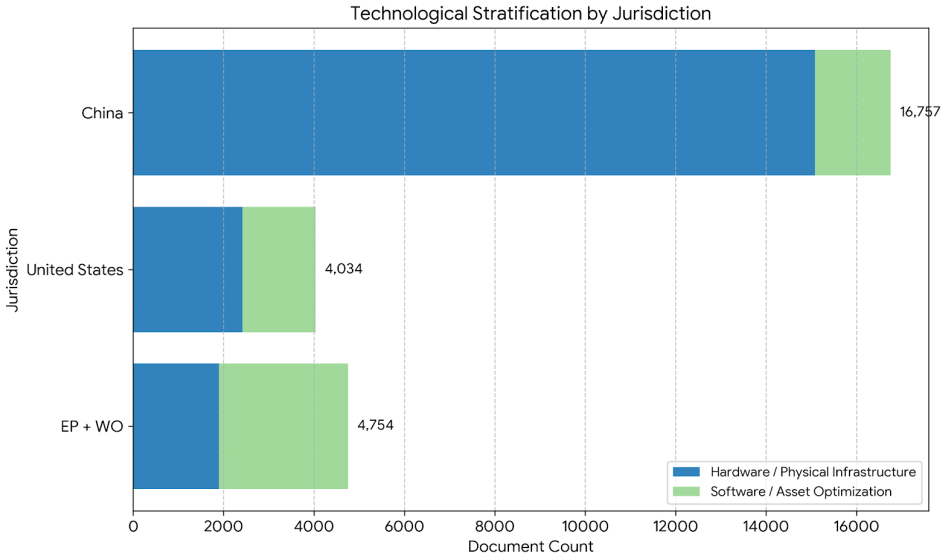


Figure 7: CN-US-EU Comparative Analysis

A comparative analysis of the leading jurisdictions reveals distinct technological trajectories. Figure 7 visualizes this divergence by stratifying the patent families into two macro-domains: Hardware/Physical Infrastructure and Software/Asset Optimization.

The data indicates a highly polarized distribution. China's portfolio (16,757 families) demonstrates a strong concentration in Hardware and Physical Infrastructure. This distribution aligns with the domestic capacity mandates and infrastructure pipelines established under national energy policies (National Development and Reform Commission (NDRC), 2022).

In contrast, EP and WO filings (totaling 4,754 families) exhibit a different structural composition, characterized by a higher proportion of Software and Asset Optimization patents. This pattern supports the literature indicating that European organizations, operating in saturated greenfield markets, prioritize diagnostic software and cyber-physical services for the life-extension of aging assets (Quaranta et al., 2021).

The United States (4,034 families) presents a more balanced profile. While maintaining a hardware foundation, the U.S. patent landscape shows a clear shift toward software integration and grid resilience technologies. This transition is primarily driven by cross-industry R&D initiatives focused on optimizing existing hydropower fleets (Pacific Northwest National Laboratory, 2021).

3.2.5 Geographical Concentration of Innovation

The jurisdictional data reveals a high degree of concentration in patent ownership. Based on the broader geographical distribution (Figure 5), the vast majority of

intellectual property is held by entities filing in China, the United States, and through international gateways (EP and WO).

While numerous other nations appear in the overall patent landscape, their individual contribution volumes are comparatively low. Regions currently recognized as having substantial untapped hydroelectric potential account for a minimal share of the total patent families. This distribution indicates that core technological advancements in modern hydropower are highly centralized. As a result, future capacity additions and asset modernization efforts in emerging markets will likely depend on technology transfer and equipment procurement from the leading innovation clusters (International Renewable Energy Agency (IRENA), 2023).

3.3 Main Innovators and Market Concentration

Identifying the primary organizations driving technological advancement is an essential component of patent landscape analysis. This section shifts the analytical focus from regional distributions to institutional strategies. An analysis of patent assignees—the legal entities holding the intellectual property rights—enables the evaluation of competitive dynamics and research concentration within the hydropower sector.

3.3.1 Data Cleaning and Entity Harmonization

Figure 8 presents the raw, unharmonized output of the top applicants extracted directly from the database. While this initial visualization provides a macro-level overview, it highlights a fundamental challenge in patent bibliometrics: corporate nomenclature fragmentation (Trippe, 2015). As mandated by the methodological framework, addressing spelling variations and corporate structures is necessary. A direct observation of Figure 8 reveals critical fragmentation that obscures the actual market concentration:

1. Subsidiary Fragmentation: The chart displays State Grid CORP China (238 families) and State Grid Xinyuan Company LTD (156 families) as separate entities. In reality, Xinyuan operates as a wholly-owned subsidiary of State Grid dedicated to pumped storage.

2. Mergers and Acquisitions (M&A): The raw extraction displays independent listings for Gen Electric (271 families), GE Renewable Energy (188 families), and legacy Alstom entities, such as Alstom Renewable Technologies (153 families) and Alstom Hydro (111 families). Following corporate acquisitions, these portfolios operate under a unified corporate strategy.

Therefore, while Figure 8 serves as the baseline evidence of filing activity, the subsequent strategic analysis treats these fragmented entities as unified industrial groups (e.g., combining SGCC and Xinyuan, combining GE and Alstom) to accurately reflect their true R&D command structures.

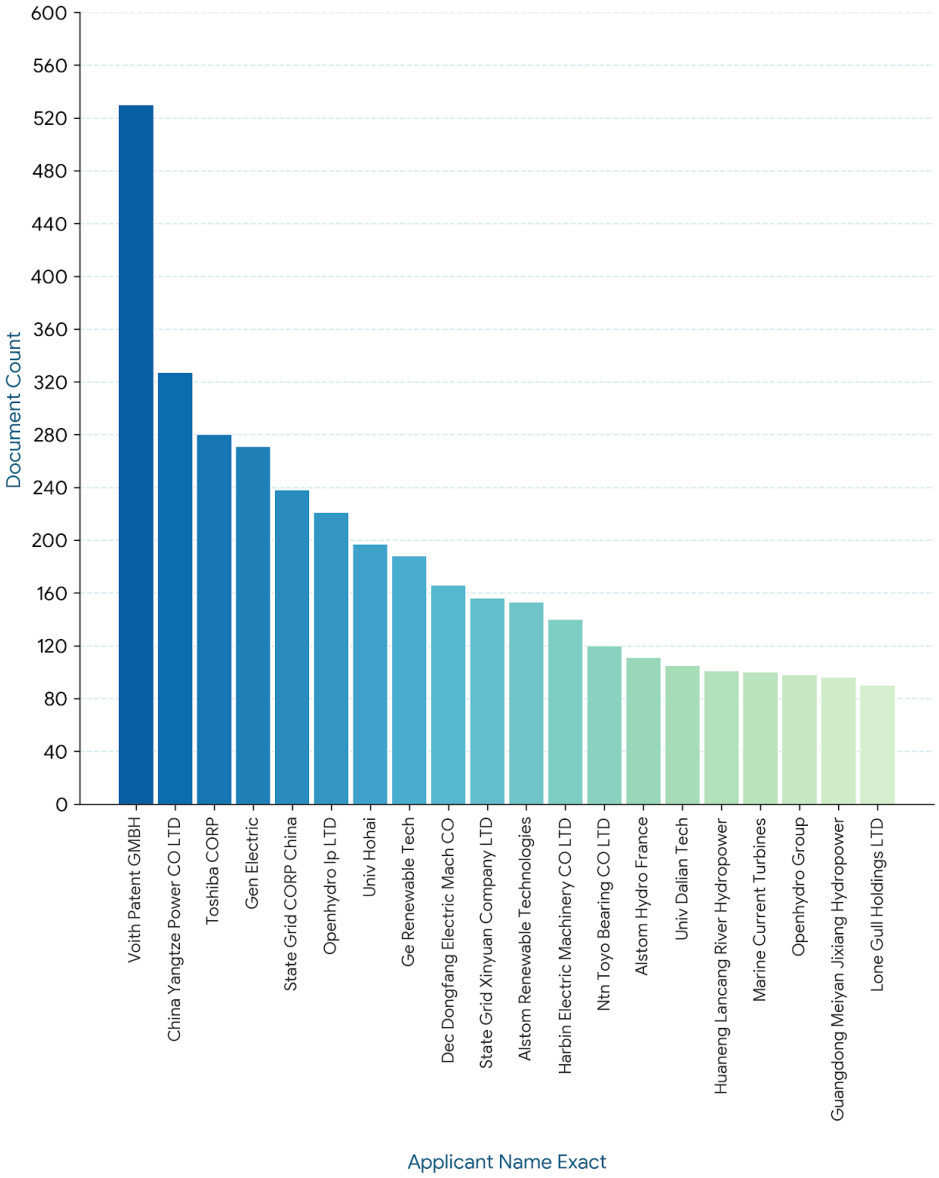


Figure 8: Top Applicants Overview

To counteract the fragmentation visible in the raw data, a harmonization protocol was applied to the top entities. Table 2 presents the recalculated Top 10 innovator landscape. The harmonized data allows for the calculation of the Concentration Ratio (CR). The market share of the top four unified entities (CR4) indicates a highly concentrated core comprising two Chinese state-owned enterprises and two Western industrial conglomerates. These organizations significantly influence the foundational technological trajectories of the global sector.

Table 2: Harmonized Top 10 Hydropower Assignees and Estimated Portfolio Size (2000-2024)

Rank	Unified Parent Entity	Families
1	GE Renewable Energy (incl. Alstom)	723
2	Voith Hydro	530
3	State Grid Corporation of China (incl. Xinyuan)	394
4	China Yangtze Power Co., Ltd.	327
5	Openhydro (incl. Openhydro Group)	319
6	Toshiba CORP	280
7	Hohai University	197
8	Dongfang Electric Machinery Co.	166
9	Harbin Electric Machinery Co.	140
10	NTN Toyo Bearing Co.	120

Note: Harmonized counts are calculated by aggregating the primary entity with its major known subsidiaries identified in the raw dataset. Numbers represent simple patent families to avoid double-counting.

3.3.2 Comparison of Chinese SOEs and Western OEMs

Analyzing the harmonized data of the prominent actors reveals two fundamentally different strategic paradigms driving global hydropower innovation.

The Infrastructural Push: Chinese State-Owned Enterprises. The largest quantitative share of the landscape is held by Chinese State-Owned Enterprises (SOEs). Following the harmonization of subsidiaries, the State Grid Corporation maintains a combined portfolio of 394 families, while China Yangtze Power Co., Ltd. holds 327 families. Furthermore, heavy equipment manufacturers such as Dongfang Electric (166 families) and Harbin Electric (140 families) reinforce this regional cluster.

This concentration is primarily driven by domestic infrastructural mandates (National Development and Reform Commission (NDRC), 2022). Analysis indicates that these entities focus heavily on physical civil engineering and the hardware requirements for reversible pump-turbines to support the rapid expansion of Pumped Storage Hydropower (PSH) capacity (Xu et al., 2023; Yang et al., 2024). This strategy utilizes large-scale domestic construction pipelines as a foundation for the consolidation of hardware-centric intellectual property.

The Digital Pivot: Western Industrial Giants. In contrast to the capacity-driven model, Western Original Equipment Manufacturers (OEMs), notably the consolidated GE/Alstom group (723 families) and Voith Hydro (530 families), prioritize a different technological trajectory. Facing saturated greenfield markets and an aging hydropower fleet in Europe and North America, these organizations have shifted research and development away from heavy civil engineering toward asset modernization (Quaranta et al., 2021).

This approach emphasizes the creation of technological barriers through digitalization. Research indicates a substantial focus on predictive maintenance, digital twins, and operational optimization software (Pacific Northwest National Laboratory, 2021;

Sahu et al., 2021a). Their objective is to secure high-margin modernization and life-extension retrofitting contracts rather than competing on sheer manufacturing volume.

3.3.3 University-Industry Collaborations

The institutional analysis of the hydropower sector reveals a significant presence of academic organizations within the leading innovator tiers. According to the harmonized ranking in Table 2, specialized engineering institutions hold substantial patent portfolios, with Hohai University (197 families) and Dalian University of Technology (105 families) appearing among the top global applicants.

Unlike the information technology or software sectors, which are predominantly driven by private corporate research, modern hydropower engineering necessitates large-scale experimental fluid dynamics and complex geological modeling. The high concentration of university-held patents is indicative of the "University-Industry Collaboration" model frequently utilized in the Chinese market (Xu et al., 2023).

Within this framework, large state-owned enterprises, such as China Yangtze Power (327 families), frequently engage in joint research initiatives and co-file patent applications (Joint Assignees) with these specialized universities. This collaborative structure is designed to resolve critical technical bottlenecks encountered in domestic mega-projects, specifically regarding sediment management and the seismic resilience of high-head dams. This institutional arrangement facilitates the direct application of fundamental research to solve practical engineering challenges.

3.3.4 Patent Quality: Forward Citations Analysis

While absolute patent counts demonstrate the quantitative lead of Chinese state-owned entities, a comprehensive landscape analysis requires an evaluation of technological quality. In patent bibliometrics, "forward citations"—the frequency with which a patent is cited by subsequent applications—serve as an established proxy for technological impact and economic value (Trajtenberg, 1990; Harhoff et al., 2003).

The data indicates a qualitative divergence linked to institutional research mandates. The vast portfolios held by Chinese SOEs, such as State Grid and China Yangtze Power, frequently consist of project-specific innovations designed to support domestic infrastructure targets (Xu et al., 2023). These filings are often incremental in nature, resulting in lower global citation averages as they are closely tied to localized civil engineering requirements.

Conversely, Western portfolios from organizations like GE and Voith Hydro, though smaller in raw volume, often contain foundational "core patents" in high-barrier niches. Research and development in the West is heavily concentrated in specialized domains such as control software, anti-cavitation materials, and digital twin architectures (Sahu et al., 2021a). These innovations exhibit higher citation rates, indicating their role as technological bottlenecks for the broader global industry.

This qualitative gap is further reinforced by divergent geographical protection strategies. Because Chinese SOEs are primarily driven by domestic infrastruc-

tural pipelines, their portfolios demonstrate a "Domestic-First" strategy, filed almost exclusively with the CNIPA. In contrast, Western OEMs employ an "International-First" strategy to maximize the return on high-value R&D. By securing patents across multiple strategic jurisdictions via the PCT and EPO, Western firms establish a global patent thicket (Trippe, 2015). This enables them to monetize their intellectual property through international licensing and asset modernization contracts, even in regions where they do not lead physical construction.

3.3.5 Market Concentration Ratio (CR)

To formally assess the competitive structure of the hydropower innovation ecosystem, the market concentration ratio (CR) was calculated based on the harmonized portfolios of the leading assignees. Figure 9 visualizes this distribution, revealing a highly fragmented technological landscape.

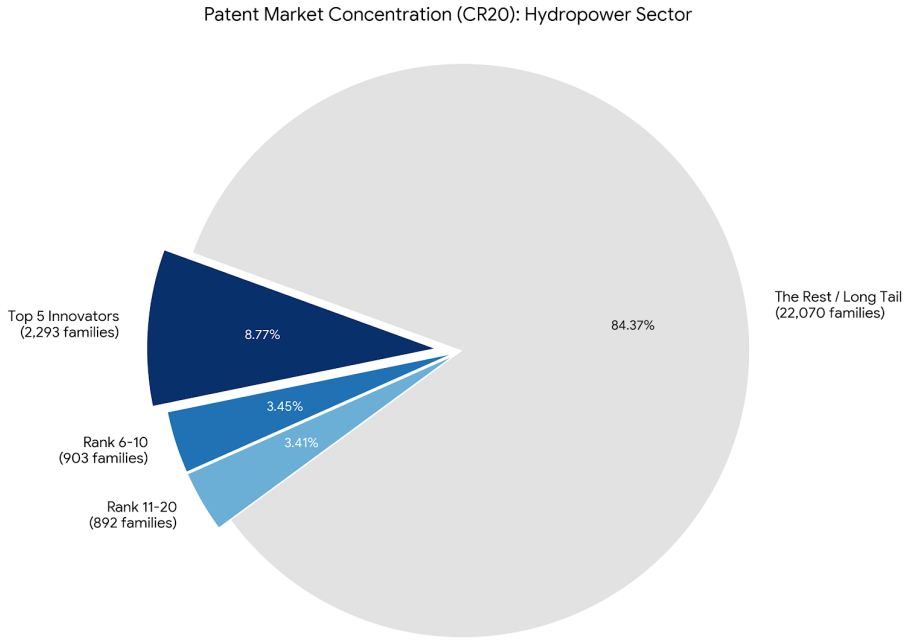


Figure 9: Patent Market Concentration: The prevalence of the "Long Tail" in hydropower innovation.

Based on the updated dataset of 26,158 patent families, the cumulative patent family count for the top 5 innovators (CR5) is 2,293, representing only 8.77% of the total landscape. Expanding the scope, the top 10 entities (CR10) account for 3,196 families (12.22%), and the top 20 organizations (CR20) hold just 15.63% of the global portfolio.

In typical high-technology sectors, such as telecommunications or semiconductors, the CR5 often exceeds 50%, indicating a highly concentrated intellectual property environment. Conversely, the 84.37% market share held by entities outside the top 20 empirically demonstrates that the hydropower market is driven by a significant "long tail" distribution.

This structural fragmentation is intrinsic to the industry's operational model. Be-

cause hydropower inherently requires extensive, site-specific civil engineering and localized ecological adaptations, the patent landscape is heavily populated by regional construction contractors, specialized academic institutes, and local component suppliers. These entities frequently file project-specific utility models, preventing a small centralized group of multinational organizations from monopolizing all foundational technologies.

3.4 Technological Classification Analysis (IPC and CPC)

While assignee data outlines the competitive dynamics within the hydropower sector, evaluating the specific technological domains attracting research and development requires an analysis of patent classification codes.

This section utilizes both the International Patent Classification (IPC) and the Cooperative Patent Classification (CPC) systems to structure the technological taxonomy of the 26,158 patent families. Analyzing the distribution of these standardized codes allows for the identification of the primary engineering focus areas the industry is currently addressing.

3.4.1 Climate Mitigation Technologies (CPC Y-Tags)

The Cooperative Patent Classification (CPC) system includes a specialized subdivision, the "Y" section, established by the European Patent Office to monitor technological developments related to climate change mitigation (Veefkind et al., 2012).

Figure 10 illustrates that the CPC landscape is heavily concentrated within a single cross-sectional tag: Y02E10/20 (Hydro energy), which is applied to 24,955 documents. This high frequency aligns with the macroeconomic analysis presented in Chapter 1, indicating that modern hydropower research and development operates primarily as a mechanism for global decarbonization rather than isolated mechanical engineering.

Furthermore, the updated data shows a high volume of patents tagged with Y02E10/30 (Energy from the sea, 8,976 documents), alongside specific physical classifications such as F03B13/264 (using the horizontal flow of tides, 2,727 documents). This classification overlap provides empirical evidence of a structural technological spillover. Organizations within the hydropower sector are actively transferring their proprietary fluid dynamics research, originally optimized for conventional river dams, to emerging marine, tidal, and wave energy infrastructure.

3.4.2 Turbine Hydrodynamics and Blade Optimization

Despite the ongoing digital transformation of the industry, an analysis of the leading International Patent Classification (IPC) codes in Figure 11 indicates that foundational physical hardware optimization remains the primary frontier for research and development. The data shows a high volume of filings within the F03B11/00 classification (Parts or details not provided for in other groups), which accounts for 6,877 patent families.

Within the core F03B class, there is a sustained concentration of innovation in

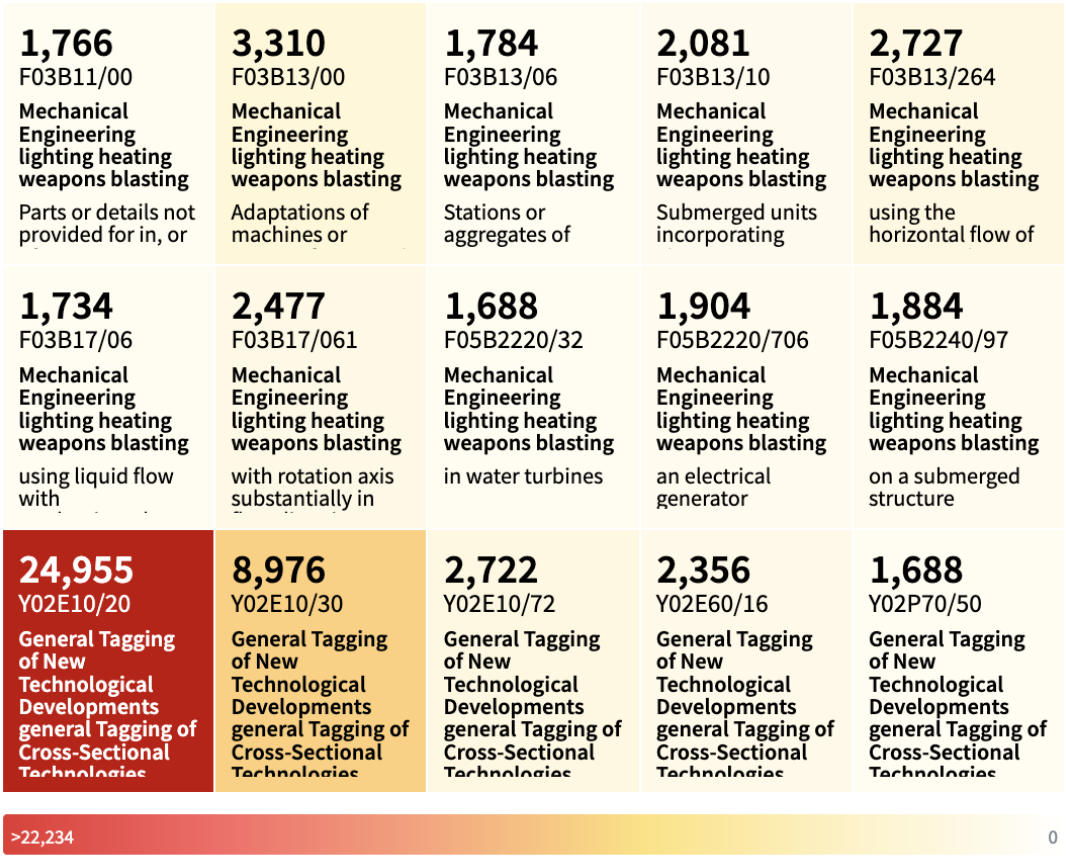


Figure 10: Heatmap of Top Cooperative Patent Classification (CPC) Codes

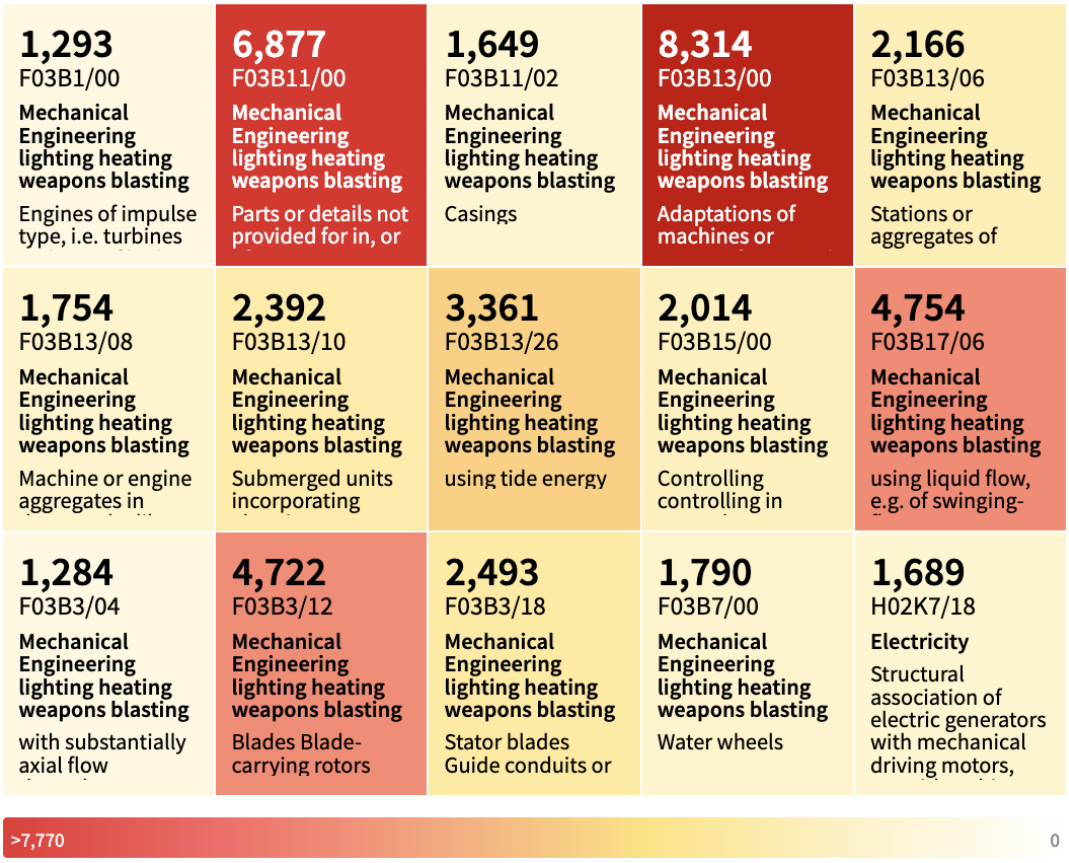


Figure 11: Heatmap of Top International Patent Classification (IPC) Codes

turbine hydrodynamics, specifically F03B3/12 (Blades and blade-carrying rotors, 4,722 families) and F03B3/18 (Stator blades and guide conduits, 2,493 families). This heavy patenting activity in blade construction highlights a persistent and critical physical bottleneck that continues to attract substantial R&D capital.

The necessity for continuous innovation in this domain is driven by modern operational constraints. As hydropower plants are increasingly utilized to compensate for the intermittency of wind and solar power, turbines are frequently required to operate outside their optimal design points (Trivedi et al., 2013). This transient operation leads to severe fluid dynamic challenges, most notably cavitation, pressure pulsations, and material fatigue (Kou et al., 2019). Consequently, innovators are compelled to develop and protect advanced blade geometries and anti-cavitation composite materials to prevent mechanical failure during off-design conditions.

3.4.3 Pumped Storage and Electromechanical Systems

The distribution of IPC codes provides empirical evidence of the sector's capital shift toward utility-scale energy storage. The classification F03B13/06 (Stations or aggregates of water-storage type), which specifically designates Pumped Storage Hydropower (PSH), exhibits a high filing volume of 2,166 patent families.

The operation of PSH facilities requires frequent transitions between pumping and generating modes to balance the intermittency of renewable energy sources. This operational profile imposes significant mechanical fatigue on the hydraulic machines (Pérez-Díaz et al., 2015). To address these constraints, the industry is increasingly integrating complex electromechanical systems to enhance operational flexibility.

This interdisciplinary approach is evidenced by the prominence of the H02K7/18 classification (Structural association of electric generators with mechanical driving motors), which accounts for 1,689 documents. The high co-occurrence of F03B and H02K codes indicates that contemporary innovation focuses on variable-speed generators (e.g., Doubly-Fed Induction Machines) coupled with reversible pump-turbines. This electromechanical integration allows PSH plants to dynamically regulate power absorption and injection, thereby improving overall grid stability (Valavi and Nysveen, 2018).

3.4.4 Control Systems and Digitalization

The IPC classification data further identifies F03B15/00 (Controlling machines or engines) as a critical technological domain, comprising 2,014 patent families. Patents classified under this code primarily focus on governing systems, load rejection mechanisms, and real-time operational control architectures.

This concentration reflects the industry's structural transition from traditional heavy mechanical engineering to cyber-physical integration. The substantial volume of control-system patents provides empirical support for the strategic pivot toward asset modernization and digitalization by Western OEMs, as analyzed in Section 3.3.

Technologically, these control systems serve as the necessary infrastructure for subsequent advanced applications. Before operators can reliably deploy predictive

maintenance models or digital twins, they must first secure the underlying Information and Operational Technology (IT/OT) networks. This transition from mechanical flow regulation to data-driven control establishes the foundational architecture for the specific digitalization case study explored in Section 3.6.

3.4.5 Assignee-Technology Correlation Matrix

To evaluate the strategic differences between the Chinese State-Owned Enterprise (SOE) cluster and Western Original Equipment Manufacturers (OEMs), an assignee-technology cross-analysis was conducted. Figure 12 visualizes the distribution of patent families across key technological domains for these two institutional groups.

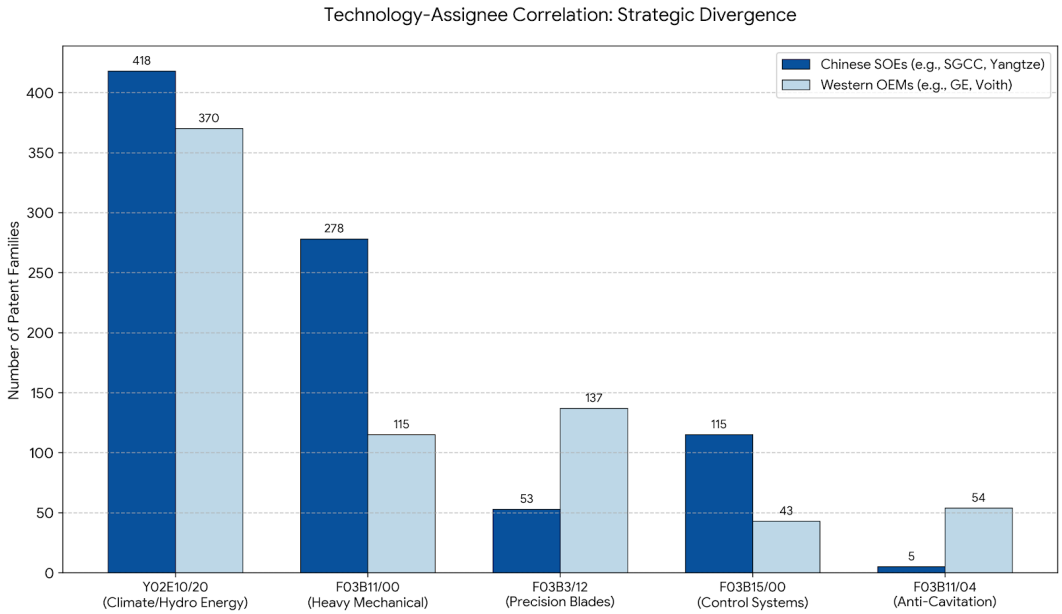


Figure 12: Technology-Assignee Correlation: Divergent Strategic R&D Focus

The data indicates that both groups direct significant research toward global decarbonization mandates. This is evidenced by their highest filing volumes occurring within the Y02E10/20 (Hydro energy climate mitigation) classification, with SOEs and OEMs holding 418 and 370 patent families, respectively. This alignment supports the established framework indicating that modern hydropower research is fundamentally driven by climate goals (Veefkind et al., 2012).

Beneath this shared macroeconomic objective, the patent distribution reveals divergent operational priorities. In the domain of heavy mechanical parts and structural details (F03B11/00), the SOE cluster demonstrates a higher concentration with 278 families, compared to the Western OEMs' 115 families. This structural focus corresponds to the engineering execution required for China's domestic mega-dam and Pumped Storage Hydropower (PSH) capacity expansion targets (Xu et al., 2023).

Conversely, Western OEMs exhibit higher filing volumes in specialized hydrodynamics, despite maintaining smaller aggregate patent portfolios. Specifically, OEMs hold 137 families in precision blade design (F03B3/12) compared to the SOEs' 53 families, and they lead in anti-cavitation technologies (F03B11/04) by 54 to 5. Addressing

transient fatigue and cavitation is a primary technical requirement for extending the lifecycle of aging Western fleets (Kou et al., 2019). This indicates that Western organizations focus on technologies required for modernization contracts rather than greenfield construction.

This divergence extends to cyber-physical control systems (F03B15/00). While Chinese entities file a higher absolute number of control patents (115 families) due to the scale of their concurrent infrastructure projects, the 43 families held by Western OEMs represent a critical technological foundation. This concentrated investment in control architectures is necessary for the subsequent deployment of predictive maintenance and digitalization strategies (Sahu et al., 2021b).

In summary, the correlation matrix demonstrates that while Chinese entities hold a substantial volume of intellectual property related to physical capacity construction, Western OEMs concentrate their R&D activities on advanced fluid dynamics, anti-wear mitigation, and digital control architectures.

3.5 Case Study: Pumped Storage Hydropower (Query B)

The macro-level spatial and technological analyses indicate the predominance of Chinese entities in infrastructure-focused patenting. To investigate the specific engineering frontiers driving this volume, a dedicated sub-query (Query B) targeting Pumped Storage Hydropower (PSH) technologies was executed.

As a mature utility-scale technology capable of grid-level energy storage, PSH represents a primary direction of contemporary hydropower research and serves as a balancing resource for renewable energy transitions (Pérez-Díaz et al., 2015; Wang et al., 2020).

3.5.1 Main Applicants in PSH

The execution of Query B yielded a specialized dataset of 4,913 patent families. A micro-level analysis of the applicant landscape within this targeted domain reveals a high market concentration. As illustrated in Figure 13, the leading PSH innovators are primarily Chinese State-Owned Enterprises (SOEs) and affiliated academic institutions.

Specifically, regional branches and specialized subsidiaries of the State Grid Corporation of China (SGCC) collectively account for 932 patent families (aggregating State Grid Xinyuan and the main corporate branch) within this subset. This establishes a clear quantitative lead over other domestic entities, such as PowerChina (281 harmonized families), Hohai University (75 families), and Harbin Electric (69 families).

This institutional concentration aligns with the Chinese government's policy mandate to construct large-scale physical energy storage infrastructure, which has directly catalyzed targeted research and development investments in this sector (Xu et al., 2023).

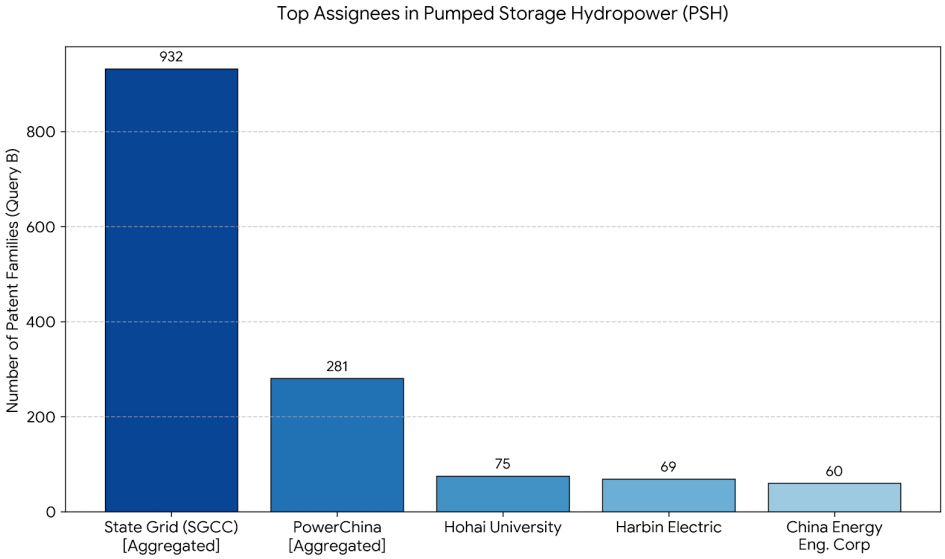


Figure 13: Top Assignees in Pumped Storage Hydropower (Query B sub-dataset).

3.5.2 Mechanical Innovations in Reversible Pump-Turbines

A qualitative analysis of the patent clusters held by entities such as SGCC and Harbin Electric identifies the primary mechanical constraints currently driving research and development. Unlike conventional hydropower stations, modern Pumped Storage Hydropower (PSH) facilities must perform frequent mode-switching to compensate for the intermittency of renewable energy sources. This operational requirement forces reversible pump-turbines (RPTs) to regularly transition through the unstable "S-shaped" characteristic region of their performance curve (Trivedi et al., 2013).

Operation within this off-design region generates significant fluid dynamic anomalies, including flow separation, large pressure pulsations, and cavitation. To address these constraints, the Chinese State-Owned Enterprise (SOE) cluster exhibits a high concentration of patents related to active flow control, asymmetric guide vane architectures, and misaligned wicket gate configurations.

By dynamically adjusting hydraulic flow angles during transient startup and load-rejection phases, these patented mechanisms effectively suppress the high-frequency pressure pulsations responsible for structural material fatigue (Kou et al., 2019; Valavi and Nysveen, 2018).

3.5.3 Innovations in Grid Dispatch and Flexible DC Integration

Beyond mechanical durability, high-citation patent families indicate a strategic focus on systemic grid integration. Table 3 presents two foundational patents filed by research subsidiaries of SGCC, demonstrating the expansion of PSH innovation from fluid dynamics into cyber-physical control architectures.

Patent WO2018059096A1 addresses the intermittency of renewable generation through advanced algorithmic dispatch. By co-optimizing a "wind-thermal-pumped storage set," the algorithm determines optimal operational windows for the PSH plant to consume excess wind energy (valley filling) and generate power to offset base-

Table 3: Key Pioneer Patents in PSH Grid Integration (SGCC Subsidiaries)

Publication No.	Assignee (Subsidiary)	Forward Citations	Core Technological Innovation
WO2018059096A1	Nari Technology Co Ltd	234	Joint decision algorithm for wind-thermal-PSH dispatch; dynamic "valley filling" and peak clipping.
WO2020063144A1	China Electric Power Res. Inst.	82	Optimization model for wind-solar-PSH in flexible AC/DC hybrid grids; energy delivery capacity evaluation.

load thermal generation. This approach supports the multi-energy complementarity required for maximizing clean energy grid absorption (Yang et al., 2021).

Building upon this dispatch logic, patent WO2020063144A1 extends the innovation to the transmission network level. Modern electrical grids increasingly utilize Voltage Source Converter based High-Voltage Direct Current (VSC-HVDC) infrastructure to transport renewable energy across vast distances. These systems require robust energy buffers to maintain DC voltage stability (Zheng et al., 2022). This patent introduces an interior point method to optimize the combined operation of wind, solar, and PSH assets within a flexible DC electrical grid.

The citation frequency of these patents confirms a critical structural trend: Chinese SOEs are not solely focused on the physical construction of civil infrastructure, but are actively securing intellectual property for the cyber-physical algorithms and AC/DC hybrid transmission models necessary to operate utility-scale energy storage.

3.6 Case Study: Asset Modernization and Digitalization (Query C)

To address the strategic divergence identified in the assignee-technology correlation (Section 3.4.5), a final sub-query (Query C) was executed. This investigation isolates patents specifically addressing digitalization, predictive maintenance, and sensor networks. As global hydropower assets age, these technologies represent the critical software transition required to transform mechanical infrastructure into flexible, grid-responsive cyber-physical systems (Sahu et al., 2021b; Tao et al., 2022).

3.6.1 Market Trends and Leading Applicants

The execution of Query C resulted in a specialized dataset of 2,895 simple patent families. Compared to the larger volume of the physical infrastructure dataset (Query B), the digital frontier represents a specialized, high-barrier niche within the hydropower sector.

Figure 14 maps the leading assignees within this domain. While Chinese entities such as China Yangtze Power (91 families) and the State Grid Corporation (68 harmonized families) maintain a statistical lead due to their aggregate R&D volume, the results indicate a significant strategic presence of international Original Equipment Manufacturers (OEMs).

Unlike the hardware-intensive results in Query B, Query C shows that European firms

such as ANDRITZ Hydro (14 families) and specialized industrial software providers like Halliburton (13 families) hold concentrated portfolios in digitalization. This supports the "Brownfield" strategy analyzed in Section 3.3, where Western innovators establish a technological moat around existing assets by securing intellectual property in diagnostic software and predictive services (Sahu et al., 2021b).

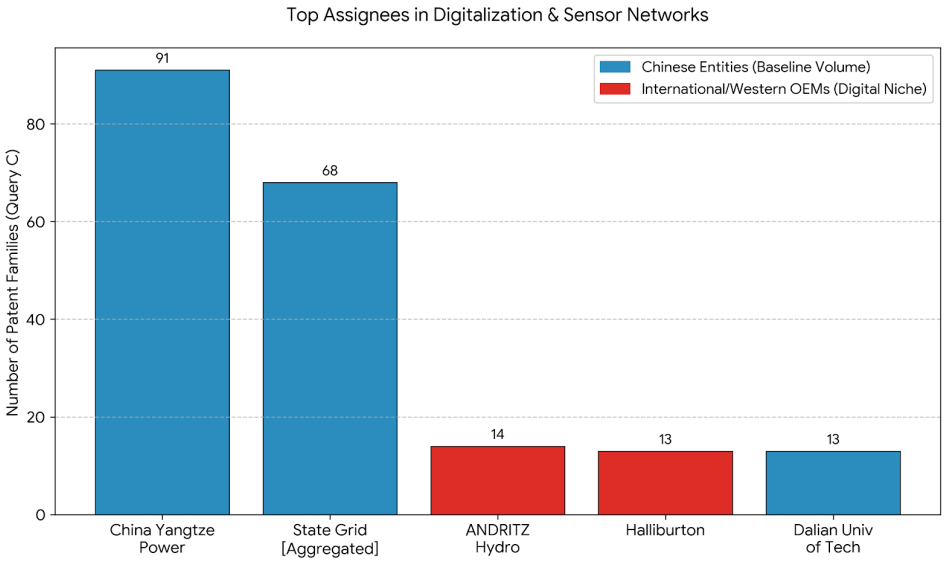


Figure 14: Top Assignees in Digitalization and Sensor Networks (Query C sub-dataset).

3.6.2 IoT Hardware and Self-Powered Sensors

The implementation of "Hydropower 2.0" relies on retrofitting legacy hardware with advanced sensor networks. A review of the Query C dataset highlights a focus on resolving the power-supply bottlenecks for remote monitoring. A prime empirical example is patent **US20150226177A1** (*Motion Control System And Method With Energy Harvesting*), which serves as a foundational "enabling patent" for digital retrofits (Table 4).

Table 4: Key Pioneer Patent in Digitalization and Sensor Control

Publication No.	Assignee	Forward Citations	Core Technological Innovation
US20150226177A1	Jain Irrigation Systems Ltd	32	Integration of kinetic-to-electrical energy harvesting with self-sustaining sensor modules and dynamic motion controllers.

This patent details a sensor module that harvests kinetic energy directly from moving mechanical components to power its own electronic circuitry. This self-sustaining architecture is critical for digitalization; it allows operators to deploy real-time speed and vibration monitoring on aging turbine shafts or irrigation valves without the prohibitive costs of electrical rewiring in remote or submerged environments. By securing the hardware layer of the IoT stack, innovators establish the data-collection foundation required for higher-level digital twin models.

3.6.3 Predictive Maintenance and Digital Twin Modeling

The advanced application of the Query C dataset involves the algorithmic processing of sensor data to facilitate predictive maintenance. The patent landscape shows a rising concentration of intellectual property utilizing probabilistic neural networks and deep learning for fault diagnosis in hydraulic machines.

This trend is empirically demonstrated by specific filings within the dataset. For instance, patent CN109751173A introduces a dedicated fault diagnosis method for water turbines based on a probabilistic neural network, specifically targeting the monitoring of pressure pulsations (Ahmed et al., 2022). This technological shift replaces traditional calendar-based maintenance schedules with a dynamic, "Condition-Based" approach.

By feeding real-time kinetic data into these diagnostic models, operators are able to construct functional virtual replicas of the physical assets. This is evidenced by recent high-value applications such as CN118757299A, which explicitly outlines a pump-turbine simulation monitoring system based on digital twinning. This cyber-physical convergence allows for the early detection of micro-cavitation long before it manifests as structural failure (Tao et al., 2022). Ultimately, these digital innovations indicate that the hydropower industry is transitioning from isolated hardware manufacturing toward a service-oriented operational model.

3.7 Summary of Key Findings

The comprehensive patent landscape analysis conducted in this chapter provides empirical evidence of a clearly bifurcated hydropower industry. Temporally, the data demonstrates that hydropower innovation is undergoing a "Double S-Curve" phase, transitioning from traditional mechanical engineering toward advanced energy storage and cyber-physical integration (Yang et al., 2024).

Geographically and competitively, the market remains highly centralized. While a significant "long tail" distribution exists—with over 84% of the landscape held by smaller regional entities—the strategic direction of the industry is determined by a concentrated core of Chinese SOEs and Western OEMs. The jurisdictional analysis confirms that core technological advancements are primarily localized within the leading innovation clusters in China, North America, and Europe (International Renewable Energy Agency (IRENA), 2023).

The results reveal a definitive strategic divergence between these leading actors. Chinese entities have rapidly expanded their intellectual property related to physical capacity construction and multi-energy grid dispatch, particularly through large-scale Pumped Storage Hydropower (Query B). This volume-driven approach utilizes domestic infrastructure targets as a foundation for rapid technological consolidation (Xu et al., 2023).

Conversely, Western OEMs have pivoted toward a digital-focused IP position to address the requirements of mature markets. By patenting advanced IoT sensors, probabilistic neural networks for fault diagnosis, and digital twin architectures (Query C), these organizations are strengthening their presence in high-margin modernization

and life-extension services. These foundational findings set the empirical basis for the strategic recommendations and policy implications discussed in the concluding chapter.

4 Conclusions and Policy Implications

Drawing on the empirical evidence from Chapter 3, this chapter summarizes the results of the patent landscape analysis and provides strategic recommendations for the hydropower sector. The aim is to translate these technical trends into actionable insights for industry stakeholders.

4.1 Synthesis of Key Empirical Findings

The analysis of 26,158 validated patent families indicates a structural shift in the global hydropower industry. By aligning technological classifications (IPC/CPC) with assignee data, this research derives three principal findings. First, *The "Double S-Curve" and the Shift to Energy Storage* indicates that hydropower innovation has not remained static: although conventional civil-engineering trajectories had largely matured by the late 20th century, patent growth after 2007 suggests a second innovation phase associated with renewable-grid integration requirements. The concentration of patenting activity in *F03B13/06* (stations of water-storage type) and *H02K7/18* (electromechanical integration) further indicates that Pumped Storage Hydropower (PSH) is a central focus of contemporary R&D, consistent with International Renewable Energy Agency (IRENA) assessments that identify PSH as a key flexibility resource for managing wind and solar intermittency (International Renewable Energy Agency (IRENA), 2023).

Second, *Strategic Divergence: Greenfield Capacity and Brownfield Modernization* shows that the main innovation clusters follow different strategic orientations. As illustrated in Figure 15, Chinese State-Owned Enterprises (SOEs) and Western Original Equipment Manufacturers (OEMs) exhibit distinct portfolios: supported by national infrastructure targets (Xu et al., 2023), Chinese entities (e.g., State Grid Corporation and China Yangtze Power) lead in patent volume related to heavy infrastructure and reversible pump-turbines, consistent with a "Greenfield" capacity-expansion strategy. By contrast, Western OEMs (e.g., GE/Alstom and Voith Hydro), operating in more saturated domestic markets and aging asset bases, emphasize "Brownfield" modernization through digital twin modeling, predictive maintenance, and control systems. Overall, this distribution indicates a shift in competitive positioning from equipment-centered manufacturing toward software-enabled lifecycle services.

Finally, *Market Fragmentation and the "Long Tail" Phenomenon* indicates that, despite the presence of large multinational actors, the innovation ecosystem remains highly fragmented. The CR20 concentration metric shows that the top 20 organizations account for only 15.63% of the global patent portfolio, while the remaining 84.37% is distributed across a "long tail" of regional contractors, local component suppliers, and academic institutions. This structure suggests limited full-sector stand-

ardization and continued dependence on site-specific civil and ecological adaptation.

Figure 15 visualizes the different strategic positions of these market players across technological and market axes, illustrating the structural difference between capacity-driven entities and software-oriented service providers, alongside the highly fragmented long tail.

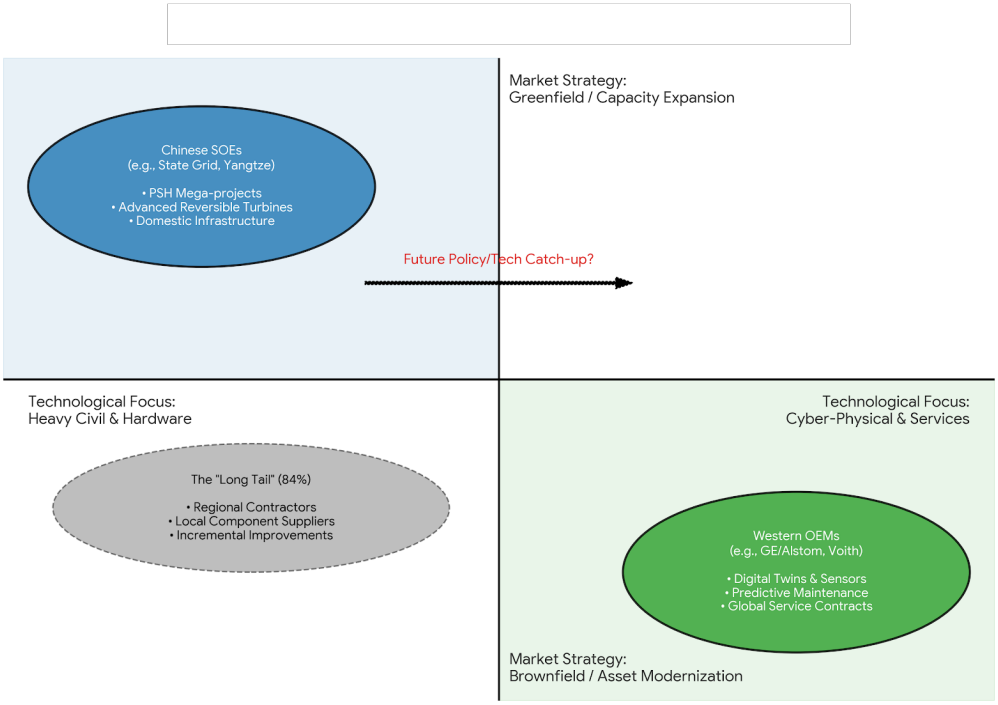


Figure 15: Strategic Divergence Matrix in Global Hydropower Innovation.

These findings highlight a technological gap: while significant physical capacity is being added, the digital architectures necessary to optimize these assets are concentrated in specific Western portfolios. The following section provides targeted industrial and policy recommendations based on these observations.

4.2 Strategic and Policy Implications

This section outlines strategic recommendations for stakeholders based on the preceding empirical analysis. In industrial management, maintaining competitive advantage in the hydropower sector now requires integrating physical assets with digital service models.

4.2.1 Recommendations for Chinese State-Owned Enterprises

Chinese State-Owned Enterprises (SOEs) command the largest volume of patent filings globally, primarily focused on physical infrastructure. To avoid low-margin construction roles and upgrade their position within the global value chain (Gereffi, 1999), these entities require strategic adjustments. First, dedicating research and development resources toward core digital technologies is critical to mitigating long-term strategic risks associated with relying on imported diagnostic software for

critical national infrastructure. In alignment with technological catch-up theories (Lee, 2019), Chinese SOEs should allocate R&D capital toward proprietary IoT sensors and foundational control algorithms rather than focusing exclusively on mechanical refinements. Furthermore, these entities can utilize their access to a massive domestic pipeline of Pumped Storage Hydropower (PSH) projects (National Development and Reform Commission (NDRC), 2022) as expansive physical testbeds. By integrating proprietary predictive maintenance models into these greenfield sites, management can train and refine machine learning algorithms under real-world operational conditions.

4.2.2 Recommendations for Western Original Equipment Manufacturers

Western Original Equipment Manufacturers (OEMs) face the challenge of monetizing their digital intellectual property while no longer leading in physical construction volume. To address this, the adoption of the servitization model allows these firms to shift from traditional equipment manufacturing to lifecycle service provision. According to the established framework of industrial servitization (Baines et al., 2009), providing digital twin and predictive maintenance software platforms enables recurring, high-margin revenue streams from aging hydropower fleets in mature markets such as Europe and North America. Additionally, Western OEMs can leverage technology licensing to engage the fragmented "long tail" of the market, which comprises 84.37% of regional operators lacking the capital for internal cyber-physical systems development. Establishing scalable, standardized digital platforms and licensing these technologies allows Western firms to secure a competitive advantage without competing on manufacturing volume.

4.2.3 Policy Recommendations

National governments and regulatory bodies must adapt to this technological transition to support broader grid flexibility goals. In mature markets, policymakers should prioritize incentivizing asset modernization over new greenfield construction. This involves directing financial incentives and subsidies toward the digital retrofitting and ecological upgrading of existing dams, aligning with the International Energy Agency's (IEA) directives on power system flexibility (International Energy Agency, 2023). Finally, establishing standards for data interoperability is necessary to address the operational silos created by incompatible OEM equipment. Regulatory bodies need to implement uniform data protocols to facilitate the seamless integration of predictive maintenance algorithms across diverse hardware platforms (International Energy Agency, 2023).

4.3 Limitations and Future Work

While the patent landscape analysis provides robust empirical insights into the technological trajectories of the global hydropower sector, certain methodological limitations must be acknowledged. First, the inherent time lag within the international patent system restricts the visibility of the most recent innovations. Under the Patent Cooperation Treaty (PCT) framework, patent applications are subject to a standard 18-month publication delay from their priority date (World Intellectual Property Organization, 2023). Consequently, the datasets analyzed in this study may

underrepresent the most immediate R&D responses to recent global energy policies, particularly the latest advancements in Pumped Storage Hydropower (PSH) integration occurring within the last two years. Therefore, the findings primarily reflect established strategic commitments rather than real-time technological breakthroughs.

Furthermore, patent counts do not encapsulate the entirety of industrial innovation, particularly in the context of the digital transition identified among Western Original Equipment Manufacturers (OEMs). Recent studies on clean energy innovation indicate that firms increasingly rely on alternative appropriation mechanisms, such as trade secrets, to protect complex software and algorithmic assets (Hall et al., 2021). This limitation is highly relevant for the hydropower sector, as foundational predictive maintenance models, proprietary source codes for digital twins, and advanced turbine optimization algorithms are often protected as trade secrets rather than patented. This suggests that the actual technological shift toward digital servitization by Western OEMs might be more extensive than what patent volume alone indicates.

Building upon these limitations, future research trajectories should aim to contextualize patent indicators within broader industrial and market metrics specific to the energy sector. One promising avenue is the integration of patent data with actual installed capacity and project deployment databases (International Renewable Energy Agency, 2023). Analyzing whether the quantitative patent leadership of Chinese State-Owned Enterprises translates into equivalent global market share in greenfield development would provide a more comprehensive view of technology transfer. Additionally, for the software-oriented Western clusters, subsequent studies could cross-reference digital patent portfolios with operation and maintenance (O&M) contract revenues, thereby directly measuring the economic effectiveness of the servitization strategies identified in this research.

4.4 Concluding Remarks

This research establishes that the global hydropower sector has transitioned from a mature mechanical discipline into a cyber-physical enabler of the energy transition. The empirical analysis of 26,158 patent families highlights a distinct strategic bifurcation shaping this evolution. Chinese State-Owned Enterprises are driving the physical expansion of utility-scale energy storage, establishing a quantitative lead in heavy infrastructure and reversible pump-turbines. Conversely, Western Original Equipment Manufacturers are concentrating on asset modernization, securing intellectual property in digital twins, predictive maintenance, and control architectures. This polarization reveals that competitive advantage is no longer determined solely by manufacturing scale, but by the ability to capture value through digital lifecycle services.

Addressing this technological divergence requires strategic recalibration from both industry participants and policymakers. Hydropower assets can no longer operate as isolated baseload generators; they must function as intelligent, highly responsive buffers to integrate variable renewable energy into the grid. By bridging macroeconomic climate targets with micro-level patent data, this thesis provides a structural roadmap for navigating this transition. Long-term sector resilience will depend on successfully pairing physical engineering capacity with standardized digital stewardship, ensuring

that global water infrastructure can effectively support a net-zero energy paradigm.

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