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Virtual Reality-Based Digitalisation Framework for Facility Management in Hydraulic Infrastructures

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Abstract

Hydropower facilities involve complex systems that require precise coordination between mechanical, electrical, and control components. The management and maintenance of such systems are often constrained by physical accessibility, safety risks, and limited visualization of operational interdependencies. These challenges highlight the need for innovative tools that enable efficient supervision, training, and performance monitoring. This study investigates the integration of Virtual Reality (VR) as an interactive and immersive approach to hydropower facility management and training. A virtual hydropower plant was developed using the Unity engine to simulate real-time operational scenarios. The system incorporates two distinct user modes Technician and Managerial Mode, each representing a specific functional domain within a hydropower facility. In Technician Mode, users interact directly with virtual components such as valves, turbines, and generators. The interface provides immediate feedback on system conditions, including valve status, turbine activity, and power output. This mode enables users to perform operational tasks such as opening valves or activating turbines while observing system behaviour through simplified, context-driven interfaces. Its design prioritizes realism, hands-on interaction, and situational awareness for training and maintenance simulation. The Managerial Mode focuses on supervisory analysis and performance evaluation. Instead of physical interaction, users access a dynamic dashboard that visualizes key performance indicators through charts and comparative graphs. These include power generation across turbines, seasonal variations in efficiency, and energy output trends. The interface is designed to support data-driven decision-making, offering managers a high-level overview of operational performance and system reliability.

Keyword: Hydropower Infrastructures, Facility Management, Digitalisation, Virtual Reality (VR)

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Chapter 1 : Introduction

1-1 Chapter overview

In the first chapter of the thesis, the research background, problem statement, research objectives, and scope are explained. This chapter establishes the foundation of the study by explaining the motivation and context behind developing a Virtual Reality-Based Digitalisation Framework for Facility Management in Hydraulic Infrastructures which highlights the significance of the topic and outlining the key goals the research aims to achieve.

1-2 Research Background

The increasing global demand for sustainable and renewable energy sources has positioned hydropower as one of the most reliable and mature technologies for large-scale electricity generation. Unlike intermittent renewables such as solar and wind, hydropower offers stability, storage capability, and flexible load balancing which make it an indispensable component of many national energy portfolios [1]. In addition to electricity production, hydropower facilities play a crucial role in water resource management, flood control, and irrigation, which reinforces their socio-economic importance in both developed and developing regions. However, the effective management of these complex infrastructures remains a persistent challenge. The operation and maintenance of hydropower plants require continuous coordination between civil, mechanical, and electrical subsystems which often rely on site-specific expertise and manual supervision. Traditional facility management practices typically depend on two-dimensional drawings, static documentation, and periodic inspections, all of which limit the potential for real-time understanding and predictive control of plant performance [2].

In recent years, the concept of digitalisation in infrastructure management has gained increasing attention which promotes the integration of advanced digital tools such as Building Information Modelling (BIM), Geographic Information Systems (GIS), Internet-of-Things (IoT) sensors, and real-time simulation platforms [3]. These technologies have enabled the creation of digital twins virtual counterparts of physical systems that replicate and monitor performance parameters [5]. Within this framework, Virtual Reality (VR) has emerged as a particularly powerful medium for visualisation and user interaction. Through VR, users can explore complex environments immersively, which gains both spatial and functional understanding of the underlying systems. For hydropower facilities, this capability is particularly relevant, as it allows for the interactive representation of turbines, generators, penstocks, gates, and control systems, all within an accurate three-dimensional environment [4].

Despite its promise, the application of immersive technologies in the hydropower domain remains limited. Existing digitalisation efforts often focus on data collection and monitoring rather than interactive simulation or experiential training [3]. In this context, VR offers the potential to bridge the gap between engineering analysis and human comprehension. By enabling the simulation of hydropower components and user interaction with them in real time, VR can transform how facility managers and technicians perceive, plan, and respond to operational conditions. For example, users can virtually inspect the spatial relationships between key components, visualise system performance indicators, or experience simulated operational scenarios such as maintenance or emergency responses all within a controlled and safe virtual environment. This enhances not only the educational and training value of the model but also its applicability in decision-support and performance evaluation [4].

1-3 Problem statement

The operation and management of hydropower facilities represent a complex integration of civil, mechanical, and electrical systems that must work in harmony to ensure stable energy generation. Despite being one of the most mature renewable technologies, hydropower continues to face substantial challenges in the areas of monitoring, maintenance, and performance evaluation [5]. The infrastructure associated with hydropower plants like penstocks, turbines, generators, control panels, and auxiliary structures requires continuous supervision to sustain efficiency and operational safety. Traditionally, these processes have relied heavily on manual inspection, two-dimensional documentation, and separate information systems that lack interoperability. As a result, decision-making within hydropower management is often delayed, Incoherent, and dependent on the individual expertise of operators [6].

In many existing facilities, digitalisation remains partial or superficial and primarily focusing on data collection or automation rather than holistic, user-oriented visualisation. While Building Information Modelling (BIM) and sensor-based monitoring systems have advanced the accuracy of design and operation data, these tools are rarely integrated into an interactive environment that facilitates comprehension, prediction, and collaboration [7]. Consequently, a significant gap exists between digital information and user understanding, particularly in conveying spatial relationships, operational dynamics, and system interdependencies. For example, a manager reviewing turbine efficiency data might lack contextual awareness of how structural elements interact within the physical space, while technicians in the field may not have intuitive access to real-time operational feedback. This disconnection limits both the learning potential and the capacity for rapid decision-making [8].

Another key challenge concerns training and knowledge transfer. The management of hydropower plants demands multidisciplinary expertise, yet conventional training approaches often remain static and theoretical. Site visits are expensive, time-consuming, and sometimes hazardous, especially in confined or high-voltage environments. Furthermore, documentation such as schematics, maintenance logs, and operational manuals fails to convey the dynamic nature of hydropower systems. Therefore, there is a pivotal need for an immersive and interactive medium that allows personnel to visualise, experience, and simulate operational procedures safely and intuitively [9].

Virtual Reality (VR) offers a promising response to these challenges. By enabling users to explore and interact with digital representations of hydropower components, VR has the potential to improve comprehension, training, and strategic analysis. However, while VR has been widely explored in architecture, manufacturing, and industrial training, its application in hydropower facility management remains underdeveloped. Existing tools often prioritise visualisation without functional interactivity or realistic representation of operational behaviour. To address this limitation, there is a need for a fully interactive VR-based platform that replicates the structural and operational features of a hydropower plant while accommodating the differing needs of technicians and managers [10].

This research addresses that gap by developing a VR simulation of a hydropower facility in Unity, featuring two distinct modes of interaction. The Technician Mode allows users to move freely within the virtual environment, inspect plant components, and simulate interaction with key elements such as turbines, generators, and control panels. This perspective focuses on operational tasks, maintenance training, and familiarisation with equipment layout. In contrast, the Managerial Mode provides a higher-level analytical interface which incorporates dashboards, comparative performance charts, and seasonal energy data visualisation. This dual-mode structure not only reflects the hierarchical nature of real-world facility management but also enhances communication between operational and administrative levels [11].

1-4 Research's objectives

The main objective of this research is to develop and evaluate a Virtual Reality (VR) model of a hydropower facility that supports both operational training and management-level decision-making. The study seeks to merge technical accuracy with experiential learning by creating a three-dimensional digital representation of a hydropower plant using Building Information Modelling (BIM) software, which will then be integrated into a Unity-based VR environment.

Within this environment, two primary user modes will be implemented. The technician mode will enable users to perform realistic operational procedures such as controlling valves, starting and stopping turbines, and inspecting generator and electrical panels. This mode is intended to simulate field-level operations in a safe and controlled setting, hence, enhancing technical competency and situational awareness.

The managerial mode, on the other hand, will provide an analytical perspective by visualising performance data including turbine efficiency, energy generation, and service coverage through interactive dashboards and visual analytics. This feature aims to support managerial decision-making by presenting complex operational data in an accessible and interpretable form.

To ensure a high degree of realism and user engagement, the VR system will incorporate intuitive interaction mechanisms, including navigation control, camera handling, and collision detection. Furthermore, the research will integrate gamification elements such as progress tracking and feedback systems for promotion of long-term engagement with the training process.

The completed VR model will be evaluated in terms of its functionality, interactivity, and practical relevance for hydropower facility management. The results are expected to demonstrate how immersive simulation and gamified learning can enhance both technical training and strategic decision support within the energy sector.

1-5 Research Questions and Hypotheses

Research Questions

The questions that this thesis aims to address are centred on the design, implementation, and evaluation of a Virtual Reality (VR) model developed from Building Information Modelling (BIM) data for hydropower facility management and training. Specifically, the study investigates how BIM-derived data can be transformed into an immersive VR environment capable of accurately representing and simulating the operational components of a hydropower plant. It further examines the extent to which the technician mode of the system can enhance users' understanding of operational mechanisms and improve their ability to perform practical tasks within hydropower settings.

In addition, the research explores how the managerial mode can facilitate performance analysis and decision-making through the visualisation of key metrics such as turbine efficiency, power generation, and service coverage. The study also evaluates the developed VR model in terms of usability, realism, and functional effectiveness in supporting facility management operations. Finally, it seeks to determine how the implementation of a dual-mode VR framework can contribute to broader digital transformation initiatives in the field of hydraulic infrastructure management which aligns the project with emerging paradigms in digital twins and immersive analytics.

Research Hypotheses

Drawing from the research questions, the following hypotheses guide the study. It is hypothesised that the integration of BIM data into a VR environment will result in an accurate and functionally interactive digital representation of a hydropower facility suitable for operational simulation. It is further anticipated that users engaging with the technician mode will demonstrate a greater understanding of hydropower system operations compared to those trained through conventional, non-immersive approaches.

Moreover, it is hypothesised that the managerial mode of the VR model will enhance decision-making effectiveness by enabling intuitive visual analysis of energy generation, service coverage, and seasonal performance data. The model is also expected to be perceived as both highly usable and realistic by technical and managerial participants, thus validating its potential for application in real-world facility management contexts. Finally, the research assumes that the dual-mode VR framework represents a scalable and adaptable approach to digital transformation in hydraulic infrastructure management which aligns with the principles of digital twin technologies and immersive data-driven analysis.

1-6 Significance of the Study

This study advances the digitalisation of hydropower facility management by introducing a dual-mode Virtual Reality (VR) system that unites both technical interactivity and managerial analysis within a single immersive framework. Previous research has largely focused on the visualisation of power plants or operator training in isolated environments, with limited integration between engineering data and managerial decision-making processes [12–14].

The key significance of the project lies in its two-mode structure. The technician mode allows users to interact with hydropower components such as turbines, valves, and electrical panels which simulates realistic maintenance and operational procedures. The managerial mode introduces analytical dashboards that present critical indicators such as energy generation, service coverage, and demand–supply gaps through interactive charts.

This dual-mode integration offers a holistic view of hydropower operations which address a major gap in prior studies where the managerial and analytical dimensions of VR facility management were often excluded [15,16].

Ultimately, this work provides a replicable foundation for immersive facility training, system optimisation, and strategic decision support which contributes to the sustainable digital transformation of hydraulic systems.

1-7 Thesis Organization

This thesis is organized into several chapters to ensure a logical flow of content and clarity in presenting the research. Chapter 1 introduces the research background and outlines the rationale for undertaking this study. Chapter 2 provides a comprehensive literature review related to the topic, identifying research gaps and theoretical foundations. Chapter 3 presents the case study that supports the practical context of the research. Chapter 4 explains the research methodology and the approach adopted for developing and implementing the proposed framework. The subsequent chapters present the results and discussion, where the findings are analysed and interpreted. Finally, the last chapter offers the conclusion and recommendations for future research, summarizing the key contributions and implications of the study.

Chapter 2 : Literature review

2-1 Chapter Overview

This chapter delves into several key topics within the realm of Building Information Modelling (BIM) as applied to infrastructure projects. It examines how BIM is revolutionizing the planning, design, and management of infrastructure through advanced visualization, improved data integration, and collaborative workflows. The chapter also explores the role of Virtual Reality (VR) in enhancing project visualization and stakeholder engagement, allowing immersive experiences that aid in decision-making and design validation. Furthermore, it discusses the various software tools and emerging technologies that support BIM implementation, highlighting their capabilities in streamlining processes, improving accuracy, and fostering innovation in infrastructure development. Together, these topics provide a comprehensive overview of the technological advancements shaping the future of infrastructure projects.

In addition, this chapter presents a literature review focusing on the digitalization of hydraulic infrastructures, adopting a pyramidal approach to structure the analysis. It begins by outlining the foundational concepts and general advancements in digital transformation within the hydraulic sector, progressively narrowing down to more specialized applications such as smart water management, digital twins, and sensor-based monitoring systems. The review highlights key research contributions, technologies, and methodologies driving innovation in hydraulic infrastructure management, emphasizing their impact on efficiency, sustainability, and resilience. This pyramidal approach provides a clear and systematic understanding of how digital tools are being integrated at different levels of hydraulic infrastructure development and operation.

2-2 BIM in Hydraulics Infrastructures

Building Information Modelling (BIM) has emerged as one of the most transformative technologies in the design, construction, and management of complex infrastructure systems. Initially developed for the architectural and structural sectors, BIM has increasingly found application in hydraulic infrastructures, such as dams, powerhouses, spillways, tunnels, and penstocks, due to its ability to integrate multidisciplinary data into a single coordinated digital environment [17,18]. In hydropower projects, where civil, mechanical, and electrical components must operate in perfect synchronization, BIM provides a unified platform that ensures spatial accuracy, design coherence, and information continuity throughout the project lifecycle.

Lifecycle Benefits of BIM in Hydraulics Infrastructure

1. **Planning & design**

BIM facilitates advanced 3D modelling and spatial coordination between hydraulic structures and electromechanical systems. Traditional two-dimensional drawings often fail to capture the spatial interdependencies between components such as turbines, gates, valves, and pipelines. BIM models, by contrast, allow for precise clash detection and hydraulic pathway simulation, minimizing design conflicts before construction begins [20]. This reduces the risk of costly redesigns and rework, which are common in large-scale hydropower facilities due to their geometric and mechanical complexity. Additionally, integrating geospatial and topographic data enhances the accuracy of terrain modelling and flow simulations which ensures hydraulic efficiency and system integrity from the conceptual stage.

2. **Construction phase**

BIM supports schedule integration (4D BIM) and cost management (5D BIM), enabling real-time tracking of construction progress and expenditure [21]. The model serves as a central information repository that links design intent with construction execution. For hydropower plants, where multiple contractors may operate simultaneously across civil and electro-mechanical domains, BIM ensures coordinated communication and documentation. This phase also benefits from the use of BIM in prefabrication and assembly planning, which can improve safety, reduce on-site congestion, and streamline complex installation processes, such as turbine or gate mounting. Sustainability and Lifecycle Analysis.

3. **Operation and Maintenance (O&M) phase**

The operation and maintenance (O&M) phase represent one of the most critical applications of BIM in hydraulic infrastructure. Once construction is completed, the BIM model evolves into an as-built digital twin, reflecting the exact conditions of the physical facility [21]. This digital twin can then be used to monitor performance, plan maintenance schedules, and store operational data for predictive analytics. For example, information related to turbine efficiency, valve operation, and reservoir management can be integrated with the BIM model to enable data-driven maintenance strategies and failure diagnostics. The interoperability of BIM with IoT and sensor technologies further extends its capabilities which allows real-time monitoring and automated control systems to be visualized and managed within a single digital framework [22].

4. Lifecycle phase

BIM thus acts as the central digital backbone of hydropower facilities beginning as a design coordination tool which transforms into a construction management platform and ultimately serving as a dynamic facility management system during operation. This continuity of data across project stages not only enhances efficiency but also supports long-term sustainability and resilience of water infrastructure. The integration of BIM with Virtual Reality (VR), as applied in this study, elevates this lifecycle model by transforming the digital twin into an immersive environment where both technicians and managers can visualize, interact with, and evaluate hydropower system performance in real time.

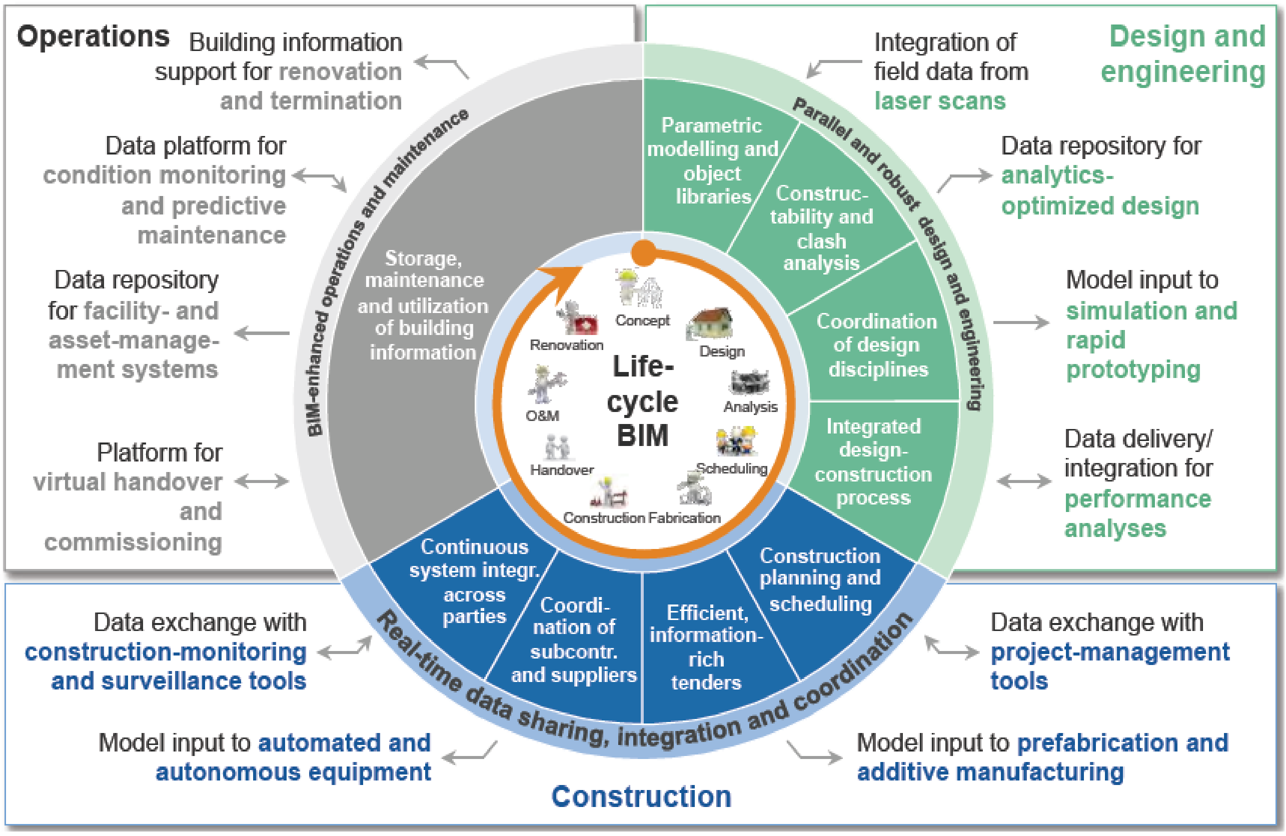

Figure 2-1 BIM Workflow: Supporting Design, Construction, and Operational Intelligence

2-3 VR in Infrastructures

Virtual Reality (VR) is rapidly gaining traction in the infrastructure sector as a powerful tool for visualization, collaboration, safety planning, and decision support. Unlike traditional 2D representations, VR offers immersive, interactive environments that enhance stakeholder understanding and engagement across different infrastructure lifecycle stages [23]. From early-stage design to maintenance and training, research shows VR not only streamlines complex processes but also fosters safer and more informed infrastructure development outcomes [24].

A recent study demonstrated significant benefits when integrating BIM (Building Information Modelling) with VR for urban infrastructure projects. The combined VR–BIM solution reduced design conflicts and iterations by 37%, increased stakeholder engagement by 62%, and enhanced spatial awareness by 48%. Additionally, it helped achieve a 20% reduction in greenhouse gas emissions, underscoring VR's potential for sustainable and inclusive infrastructure planning [25].

Safety planning and workspace optimization benefit greatly from immersive simulations. In one case, BIM-based VR was employed to simulate construction activities, integrating worker and manager input to optimize workspace planning and safety. The real-world case study revealed significant improvements in how safety-critical information was communicated and embedded within Health and Safety Plans [26].

Other research highlights VR combined with real-time tracking (e.g., RFID systems), enabling visualization of worker and equipment positions within virtual jobsite environments. This approach improved situational awareness and supported hazard avoidance—especially valuable during preconstruction safety planning [27].

VR is proving invaluable in the structural health monitoring of infrastructure—particularly for aging structures. One experimental VR environment allowed multiple experts to virtually visit a footbridge, viewing sensor-based structural behaviour captured via LiDAR, UAV photogrammetry, and Finite Element Analysis (FEA). This immersive multi-user setting significantly reduced the need for physical site visits, accelerated assessments, and improved collaborative decision-making [28].

The virtuality continuum, defined by Milgram & Kishino (1994), is a scale of transition between the virtual and real environments, often called mixed reality (MR). Depending on the user environment, augmented, mixed and virtual reality is defined [29].

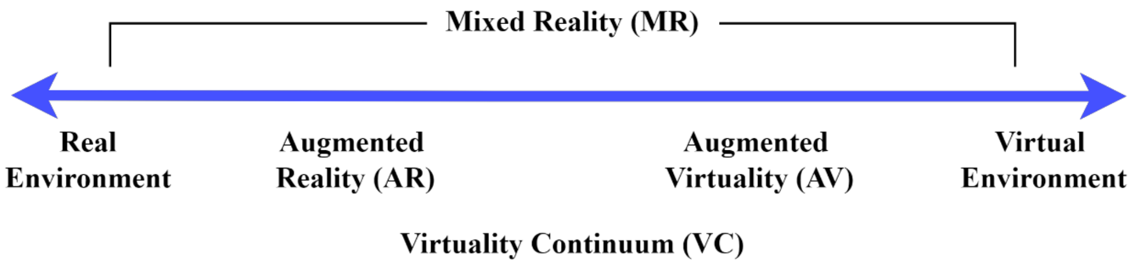

Figure 2-2 Virtuality Continuum: Mapping the Shift from Reality to Full Immersion

2-3-1 Key Applications of VR in Civil Engineering

1. Design Visualization & Review

VR headsets let engineers, architects, and clients walk through virtual models of infrastructure before it's built [30]:

- Roads, bridges, tunnels, and buildings can be explored at full scale.
- Helps detect spatial errors, visibility issues, or design flaws early in the process [31].
- Engineers can view imported BIM models (from Revit or Civil 3D) in VR using Unity [32].

2. Construction Planning & Simulation

- VR helps simulate construction site layouts and phasing.
- Teams can practice workflows, crane positioning, or site logistics virtually.
- Potential hazards or access issues can be resolved early [33].

3. Safety Training

- Workers can train for high-risk scenarios (like confined space entry or heavy equipment operation) in a risk-free virtual environment.
- Simulations help improve muscle memory and situational awareness [34].

4. Stakeholder Communication

- Non-engineers (like city officials or the public) can understand complex projects better by "walking through" them in VR.
- Interactive elements (like buttons or scenario toggles) built in Unity make these walkthroughs engaging and informative [35].

5. Digital Twins & Real-Time Monitoring

- VR environments can be synced with IoT data to visualize real-time status of infrastructure (e.g., bridge stress or water flow in a dam).
- Enables immersive inspection and monitoring [36].

Tools That Bridge BIM and VR

- **Unity + Unity Reflect / Pixyz**: Import Revit, Rhino, or IFC models into Unity for VR interaction [37].
- **Enscape / Twinmotion**: Real-time rendering with VR output from Revit or SketchUp [38].
- **Unreal Engine**: An alternative to Unity with high visual fidelity for large-scale projects [39].

2-4 Software & Technologies

The software and technologies used in this thesis are introduced and briefly explained which includes Autodesk Revit, Unity and VR headset.

2-4-1 Revit

Autodesk Revit and Its Application in Civil Engineering

Autodesk Revit is a powerful Building Information Modelling (BIM) software that has significantly transformed civil engineering practices. By enabling the creation of intelligent 3D models, Revit enhances design accuracy, collaboration, and project efficiency across various civil engineering disciplines [40].

Structural Modelling and Analysis

Revit allows civil engineers to design and analyse structural components such as beams, columns, and foundations within a unified environment. The software's parametric modelling capabilities ensure that any changes made to the design are automatically updated across all views and documentation, reducing errors and saving time [41].

Reinforcement Detailing

With Revit, engineers can model reinforcement for concrete structures in 3D, facilitating accurate placement of rebar and other reinforcing elements. This detailed modelling aids in generating precise construction documents and schedules, improving the constructability of designs [42].

Quantity Takeoffs and Cost Estimation

Revit’s ability to generate comprehensive schedules and quantity takeoffs directly from the model assists engineers in accurate cost estimation and resource planning. This feature streamlines the budgeting process and enhances project cost control [43].

Clash Detection and Coordination

The software supports interdisciplinary collaboration by allowing multiple stakeholders to work on the same model. This collaborative environment helps in early detection of clashes between structural, architectural, and MEP systems, reducing the likelihood of costly on-site conflicts [44].

4D Scheduling and Project Management

Revit integrates time-related information with the 3D model, enabling 4D scheduling. This integration allows project managers to visualize construction sequences, monitor progress, and optimize project timelines effectively [45].

Visualization and Presentation

Revit's advanced rendering tools help civil engineers create realistic visualizations of their products. These visualizations are instrumental in stakeholder presentations, design reviews, and obtaining project approvals [46].

Benefits Summary

- Enhanced collaboration through cloud-based model sharing
- Improved accuracy due to parametric consistency
- Efficient design documentation and quantity takeoffs
- Support for sustainable design and energy analysis

Benefits of Using Revit in Civil Engineering

- **Enhanced Collaboration**: Revit's cloud-based platform allows for real-time collaboration among project teams, improving communication and coordination.
- **Improved Accuracy**: The parametric nature of Revit ensures consistency across all project documentation, reducing errors and rework.
- **Efficiency in Design and Documentation**: Automation of routine tasks and the ability to generate documentation directly from the model accelerate the design process.
- **Sustainability Analysis**: Revit supports energy analysis and sustainable design practices, aiding engineers in creating environmentally responsible projects

2-4-2 Unity

Unity is a real-time 3D development platform originally popularized by game developers but now widely used in architecture, engineering, and construction (AEC) industries, including civil engineering. It enables immersive visualization, simulation, and interactive design review, making it a valuable tool for planning, communication, and decision-making in infrastructure projects.

Key Applications in Civil Engineering

1. **3D Visualization and Immersive Walkthroughs**

   Unity allows civil engineers and stakeholders to experience infrastructure projects in real-time, interactive 3D environments. Roads, bridges, tunnels, and buildings can be rendered with high fidelity, offering virtual walkthroughs that enhance spatial understanding and design validation before construction begins [47].

2. **Simulation of Construction Processes**

   Civil engineers can use Unity to simulate construction sequences, equipment movement, and site logistics. These simulations help identify potential scheduling conflicts or spatial inefficiencies, enabling better planning and safer operations on-site [48].

3. **Digital Twins and Smart Infrastructure**

   Unity supports the creation of digital twins—virtual replicas of real-world infrastructure. These twins can be integrated with sensor data (e.g., from IoT devices) to monitor structural health, traffic flow, or environmental conditions in real time. This improves maintenance and operational decision-making [49].

4. **Public Engagement and Communication**

Unity-powered applications can be deployed on the web or mobile, helping communicate complex civil engineering projects to non-technical stakeholders. These apps are often used in public consultations, city planning presentations, and investor meetings [50].

5. **AR/VR Integration**

Unity seamlessly supports augmented and virtual reality. Civil engineers can review BIM models (imported from Revit or other platforms) in VR, enabling immersive design critique, error detection, and enhanced team collaboration especially useful for remote teams [51].

Unity's Role in the Civil Workflow

Unity doesn't replace tools like Revit or Civil 3D, but rather enhances them through real-time rendering, user interaction, and simulation capabilities. Using tools like Unity Reflect or third-party plugins (e.g., Pixyz, BIM2Unity), engineers can import BIM and CAD models directly into Unity while preserving metadata.

Table 2-1 Comparison between Unity vs. other VR pipelines

Feature / Capability	Unity (VR)	Enscape / Twinmotion / Lumion (VR)
Custom Interactions	Full scripting — grab objects, open doors, trigger events, multi-user	Limited or predefined
Game-Like Mechanics	Supports full gameplay, puzzles, simulations	Not designed for interactivity
Multiplayer / Collaboration	Build your own or use frameworks (Photon, Normcore, etc.)	No or very limited support
Device Compatibility	Wide support (Quest, Vive, Pico, XR Toolkit)	Often limited (usually only tethered desktop VR)
Performance Optimization	Full control over LODs, occlusion, asset loading	Preset optimizations only
Extendibility	Add AI, physics, custom tools, UI, animation logic	Not possible
Speed to Result	Slower (build pipeline, testing, scripting)	Instant preview and VR launch
Live Revit Sync	Possible via Unity Reflect or custom tools	Built-in or direct plugin support
Real-Time Rendering	Real-time, programmable shaders, particles	Real-time, but limited to presets

2-4-3 Blender

Blender is a free, open-source 3D creation suite that enables artists, designers, and developers to create detailed models, animations, textures, and visual effects. It supports the entire 3D pipeline from modelling and sculpting to texturing, lighting, rendering, and animation. For immersive environments such as hydropower plants, industrial sites, or training simulations, Blender provides a highly flexible platform to design realistic assets before bringing them into a game engine like Unity.

Applications in Immersive Environment Creation

1. **3D Modelling and Scene Building**
2. Blender allows the creation of precise models of mechanical, architectural, and natural elements. For example, in a hydropower simulation, you can model turbines, valves, control panels, and entire facility layouts with accurate dimensions [52].
3. **Texturing and Material Creation**
4. Using Blender's Principled BSDF shader system, developers can simulate real-world surfaces from painted steel to weathered concrete. Adding grunge, rust, and water stains enhances realism, which is essential for believable immersive environments [53].
5. **Lighting and Atmosphere**
6. Blender's physically based lighting lets creators test day/night cycles, indoor illumination, or environmental effects before moving to Unity, ensuring a consistent visual tone [54].
7. **Animation and Simulation**
8. Moving parts like rotating turbine blades, opening valve wheels, or swinging panel doors can be animated in Blender. Physics simulations (fluids, smoke, cloth) can also be baked and exported for playback in Unity [55].

Interaction and Integration with Unity

- **Asset Export**: Blender's native. blend files or exported. fbx and. obj formats integrate directly into Unity. Materials and animations can be preserved during export.
- **Optimized Workflows**: Models can be UV-unwrapped, textured, and baked in Blender to reduce performance overhead in Unity.
- **Interactive Environments**: While Blender handles the visual creation, Unity adds interaction such as clicking a valve to open it, triggering a turbine spin, or showing water flow.
- **Consistent Scaling**: By matching units (meters in Blender and Unity), assets maintain accurate proportions for VR/AR immersive experiences.

2-5 Previous Research on BIM & VR in Infrastructure

Alves de Sousa and et al, conduct research on a virtual reality (VR) based training system designed for maintenance and operation of hydroelectric units of energy (HUE) which leverages non-immersive VR techniques to enhance technical training. The main objectives are to develop modules for maintenance and operation that improve understanding, reduce risks, and lower operational costs associated with traditional training methods. A case study approach was employed, focusing on the Tucurui hydroelectric plant in Brazil, which has 23 HUEs with an installed capacity of 8370 MW. The VR system (Virtual Generator Unit - VGU) was developed using Delphi language and OpenGL-based components (GLScene), running on standard PC hardware. The system includes three main modules: educative, maintenance, and operation. The maintenance module offers three training modes automatic, guided, and exploratory which adapts to the trainee's knowledge level. Data collection involved integrating technical manuals, CAD models, and real operational procedures into the virtual environment. They report that the VR-based training system effectively enhances learning by providing immersive, practice-oriented experiences that surpass traditional manual and theoretical methods. Implemented interactive VR modules enabling trainees to virtually assemble/disassemble components, perform maintenance steps, and visualize operational dynamics. The system allows real-time simulation of contingencies such as short circuits and operational procedures like startup/shutdown sequences. The training modules aim to improve technical skills, safety awareness, and comprehension of electromechanical behaviours without risking real equipment or environment [56].

Lai and et al, address the challenges of data interoperability and collaboration in building design using Building Information Modelling (BIM). The primary objective is to develop a BIM-based platform that facilitates seamless data exchange, collaborative design, and project management across multiple disciplines and software tools. The study emphasizes the importance of a unified data exchange that can interpret, modify, and synchronize heterogeneous BIM data models. The research adopts a design and development approach, creating a BIM-based platform with five core data-processing engines. Data collection involved importing IFC files exported from commercial BIM tools (ArchiCAD, Tekla Structures, MagiCAD) for a case study. The case study is a multi-story library building at Shanghai Jiao Tong University to validate the platform's effectiveness. The platform's functions include interpreting IFC data, visualizing models in 3D using OpenGL, combining partial models, extracting specific elements, and supporting communication via BCF. The proposed BIM-based platform successfully resolves key data interoperability issues in multidisciplinary building design like interpreting heterogeneous IFC data models with data integrity during exchange and simplification of complex workflows like model merging and partial extraction without data loss or misrepresentation. The case study confirmed the platform's capability to handle large, detailed models accurately, supporting project management activities such as clash detection and design review [57].

Tong and et al, explores the integration of Building Information Modelling (BIM), Virtual Reality (VR), and Geographic Information Systems (GIS) technologies to enhance water environmental in-situ monitoring and management. The primary objective is to develop a comprehensive digital model that combines geographic data, water quality monitoring information, equipment status, and surrounding environment to improve visualization, remote control, and management of Automatic Water Quality Monitoring Stations (AWQMS). Compilation of geographic information, water quality data, monitoring equipment details, interior layouts, and surrounding environment data were gathered for data collection. Autodesk Revit for 3D BIM modelling, 3D MAX for rendering and light-weighting, GIS platforms for spatial analysis, VR engine (UE4) for immersive visualization, and service-oriented architecture (SOA) for data interaction were used for analysis. The case study model of Gulao AWQMS located in Jiangmen city, China. The integration of BIM, GIS, and VR technologies offers a powerful toolset for environmental monitoring infrastructure management. The approach enhances visualization, remote control, and data analysis capabilities, promoting more scientific and aesthetic management of water quality stations. Lightweight optimization techniques (mesh optimization) ensure models are web-compatible without losing essential details. The data interaction through SOA architecture facilitates real-time access to water quality metrics and historical trends remotely [58].

Zhang et al, addresses the need to improve design efficiency and promote intelligence in hydropower engineering throughout its entire life cycle, including planning, construction, and operation. The main objectives are to develop an integrated BIM-based technological system architecture—termed HydroBIM—that supports digital design, intelligent construction, and smart operation management of water conservancy and hydropower projects. The research employs a system architecture design based on independent intellectual property, integrating multiple technologies and standards (including IFC). Data collection involved investigations of over 200 water conservancy and hydropower projects domestically and internationally. The research confirms that integrating BIM with complementary digital technologies creates a comprehensive management system (HydroBIM) that significantly enhances the efficiency, safety, and intelligence of hydropower engineering projects. The HydroBIM platform supports seamless collaboration across disciplines and project stages, enabling real-time decision-making and risk management. Technologies such as BIM + GIS, BIM + IoT, BIM + VR, cloud computing, and digital twins synergistically contribute to comprehensive project management [59].

Inzerillo et al, explores the application of Building Information Modelling (BIM) integrated with Virtual Reality (VR) for infrastructure projects, focusing on enhancing design, construction, and maintenance processes. The primary objectives are to demonstrate BIM's potential benefits in infrastructure development, analyze a case study of the Riyadh North-South railway station, and identify best practices for successful implementation. Case study analysis focusing on the design and modelling process of the Riyadh North-South railway station using BIM. The case study demonstrates that adopting advanced BIM practices can lead to more sustainable, efficient, and smarter urban infrastructure networks. Project drawings, Revit software for 3D modelling, Enscape for rendering, Photoshop for post-processing images, and Lumion for outdoor visualizations were utilized. The integration of BIM with VR technologies offers substantial benefits for infrastructure development, including improved accuracy, collaboration, and stakeholder communication. The case study demonstrates that adopting advanced BIM practices can lead to more sustainable, efficient, and smarter urban infrastructure networks [60].

Raya and Gupta address the challenges faced in rural infrastructure (RI) projects, such as resource mismanagement, poor documentation, stakeholder communication issues, and delays. It introduces a novel framework called Rural Building Information Modelling (R-BIM), adapted from urban BIM applications. The research emphasizes leveraging digital tools to overcome typical rural construction hurdles, aiming for efficient, participatory, and sustainable infrastructure development. A case study approach that applied R-BIM was a rural water management project in Rajasthan, India. Data collection involves stakeholder engagement through participatory planning, surveys, technical assessments, and resource estimation. BIM tools (AutoCAD, Infraworks, Autodesk BIM 360) for modelling and visualization, PERT for scheduling, EVA for performance evaluation were utilized for analysis. The R-BIM framework demonstrates significant potential to improve rural infrastructure project management by integrating participatory planning, visualization, scheduling, safety, and capacity building. EVA validation showed the project experienced delays and budget overruns but achieved approximately 78% of planned work at the 135th day. Compared to a non-R-BIM scenario, the project with R-BIM was completed faster (163 vs. 195 days) and with better performance indices [61].

2-6 Previous Research on Hydraulic Infrastructures

Zhang and et al, address the integration of Building Information Modelling (BIM) with 3D web-based Geographic Information Systems (GIS) specifically for hydraulic and hydropower engineering projects. The main objectives are to develop an integrated methodology and a BIM/GIS Integration Platform (BGIP) that can incorporate detailed micro- and macro-information into a unified environment without requiring standard conversions or plug-ins. The study proposes an integrated approach involving geometric visualization, coordinate transformation, rendering techniques, and information retrieval. Data collection involved parsing IFC files, building a geospatial database, and creating terrain and imagery datasets from sources like ASTER GDEM and satellite imagery. The approach utilizes web technologies such as WebGL, Cesium, GeoServer, and BIMserver for model display, data sharing, and interaction. The process includes hierarchical IFC parsing, geometric rendering at different levels of detail, and coordinate transformation based on WGS84 standards. A prototype system (BGIP) was developed with a three-layer architecture: presentation (HTML5/JavaScript), application (PHP/JavaScript), and data (relational, geospatial, BIM databases). The case study focused on the Nuozhadu hydropower project in Yunnan, China, integrating BIM models with terrain and imagery data for visualization and management. The proposed methodology successfully integrates BIM and GIS data into a unified web-based environment suitable for hydraulic and hydropower engineering projects. It enhances visualization, data management, safety monitoring, and decision-making processes without requiring standard conversions or additional plugins. The system improves project efficiency, reduces information omissions, and supports real-time interaction in complex infrastructure environments [62].

Bergsager discusses the application of Building Information Modelling (BIM) in dam and river basin projects, emphasizing digitalization and use of BIM in design, construction, and rehabilitation phases. The primary goal is to showcase how fully integrated BIM workflows can improve project control, visualization, collaboration, and efficiency. The Case studies are based on Norconsult's projects including the Vamma 12 hydropower project (2015-2019), Songa dam rehabilitation, and Mjåvatn dam in Norway. It can be concluded that by adopting the fully integrated BIM workflows, Outcomes like Improved control over costs and quantities via continuous scanning, reduced errors and collisions through early detection in the 3D model, Enhanced visualization for stakeholder communication and landscaping, streamlined construction processes with direct data transfer to machinery, and efficient final documentation and potential coupling with O&M software for ongoing operations are expected to be happened [63].

Kong and et al, explores the application of immersive virtual reality (VR) systems to assist in maintenance decision-making for hydropower stations. The primary goal is to develop a virtual environment that accurately replicates real hydropower equipment and facilities, enabling virtual rehearsal of maintenance tasks. The physical and design data through spot photography, 3D modelling software, and assembly constraints to produce precise virtual models were gathered. The study contributes to the advancement of digital twin concepts and intelligent maintenance in the hydropower industry which the Immersive virtual reality systems are effective tools for planning and optimizing hydropower station maintenance. The virtual simulation was used to plan the repair process, which was then executed physically, resulting in a reduction from 50 days to 4 days [64].

De Paola and et al, introduce DyEHS, a novel digital tool designed to optimize water distribution network (WDN) design by integrating multiple advanced technologies within the AutoCAD Civil 3D (C3D) environment. The primary goal is to enhance the efficiency, accuracy, and flexibility of hydraulic infrastructure modelling through seamless integration of Building Information Modelling (BIM), hydraulic simulation, and optimization algorithms. The Harmony Search algorithm initializes with random solutions satisfying hydraulic constraints, then iteratively improvises new solutions considering existing ones, updating the solution set based on cost and hydraulic performance. Each candidate solution undergoes hydraulic analysis via EPANET 2.2 embedded within Dynamo, verifying constraints like pressure and flow. The workflow automation like data transfer, file generation, simulation execution, and result processing were done by Dynamo. The development of DyEHS demonstrates a significant advancement in automated water distribution network design by integrating BIM, hydraulic simulation, and metaheuristic optimization within a unified platform. The tool improves design efficiency, accuracy, and adaptability, supporting sustainable development goals through optimized infrastructure planning. Moreover, its seamless integration within Civil 3D enhances user experience and encourages adoption in engineering practice. The approach fosters innovation by enabling dynamic adjustments and real-time visualization, ultimately leading to more reliable and cost-effective water systems [65].

Wei and et al, explores the development and application of digital twin technology within the field of hydropower stations and water conservancy systems in China. Its main objectives include constructing a comprehensive digital twin platform for reservoirs, enhancing real-time monitoring, safety assessment, flood forecasting, and decision support, aligned with China's "14th Five-Year Plan" for smart water conservancy. Real-time hydrological sensors (water levels, rainfall, dam monitoring), remote sensing satellite imagery, and existing databases from water resource agencies were utilised for data collection. The HEC-RAS for hydraulic flow simulation, AI algorithms for data processing, GIS for spatial analysis and model surface reduction and texture compression to optimize performance were employed. The 3ds Max for virtual environment creation, Unity with C# scripting for interactivity, and WebGL export for browser-based access were used. The research demonstrates that that digital twin technology can significantly enhance water resource management, flood prevention, and dam safety in hydropower stations. Moreover, cost-effective modelling strategies such as model facet reduction and texture compression—improve system performance without sacrificing accuracy. The Integration of BIM, GIS, AI, and hydraulic models enhance the virtual representation of reservoirs and water systems [66].

2-7 Previous Research on Digitalisation of Hydraulics infrastructures

Giovanni and correa focus on the digitalization and modernization of the Paulo Afonso IV hydroelectric power plant in Bahia, Brazil, utilizing Building Information Modelling (BIM) technology. The primary objective was to develop a comprehensive BIM model of the entire plant, based on laser scanning data, to support asset management, maintenance, and future upgrades. They employ Action-research approach involving iterative cycles of planning, execution, follow-up, and evaluation. The data collection compromise of Ground scanning with RIEGL VZ-400i lidar scanner over 30 days; aerial scanning using DJI Phantom 4 Pro drone with lidar RIEGL minVUX-1UAV, completed in one day. The Manual conversion of point clouds into 3D models using Autodesk Revit 2021; management of large datasets via Autodesk Construction Cloud. They conclude that the scan-to-BIM methodology is feasible for hydropower plants, though conversion from point cloud to model remains labour-intensive. The resulting BIM As-Is model enhances asset management, safety, and modernization planning. The generated model (10TB data) effectively captures all plant systems and can be used for operational and upgrade purposes. The process demonstrated that integrating laser scanning with BIM enhances plant documentation, safety training, and future modernization efforts [67].

Baldissin and et al, investigate the application of Building Information Modelling (BIM) combined with Augmented Reality (AR) technology to support the modernization of the São Simão Hydropower Plant in Brazil. The primary goal is to develop and evaluate an AR tool that overlays BIM data onto the physical infrastructure, enabling users to identify interferences between existing structures and future project modifications. Their case study is a São Simão, Hydropower Plant in Brazil, operating since 1978. The Unity game engine used to create AR experiences; integration required custom solutions due to incompatibility with standard BIM formats. Multiple BIM data sources from different suppliers; formats tested included IFC, FBX, and Navisworks NWD files via PiXYZ Studio used for best compatibility. AR Capabilities like Image tracking, plane tracking, and cloud point scanning using SDKs such as AR Foundation/ARCore, Vuforia, Wikitude, and EasyAR tested. The study demonstrates that integrating BIM with AR can significantly aid in infrastructure modernization projects by providing real-time interference detection. Combining multiple AR tracking techniques improves positional accuracy but still faces inherent limitations due to hardware and data compatibility issues. The research contributes to advancing AR-BIM integration methodologies within the context of large-scale industrial infrastructure [68].

Li and et al, focus on developing and applying a BIM-based digital seepage control technology for large hydropower projects, exemplified by the Yangfanggou Hydropower Station. The primary objectives are to achieve precise, real-time supervision of grouting operations, enhance data analysis and visualization, and improve safety and quality in seepage control. A comprehensive digital grouting system based on modular MVC architecture using Kotlin, React, PostgreSQL, and RESTful APIs was developed. key grouting parameters (pressure, flow, density, lifting) via integrated monitoring instruments connected through IoT networks were collected, over 20,000 grouting holes with detailed tracking and visualization. The digital system effectively monitored key grouting parameters in real time with alarms triggered by threshold breaches especially seepage flow and pressure indicators were well below standard limits. The visualizations based on 3D geological models allowed intuitive understanding of the seepage control process. This integrated approach reduced manual workload, minimized data tampering risks, and enhanced decision-making accuracy [69].

Moraes and et al, focus on developing a methodology for creating optimized virtual environments (VEs) of hydroelectric power plants (HPPs) using 3D modelling and virtual reality (VR) technologies. The primary goal is to facilitate training, maintenance, and operational procedures remotely, reducing reliance on physical trips and resource-intensive activities. The research emphasizes improving visual quality, modelling efficiency, and reusability of components to support multiple power plant simulations. The Scene Modelling approach focused on three main environments per plant: Electrical Gallery, Mechanical Gallery, and Power Transformers Courtyard. The Unity 3D's Editor Windows was used to automate scene setup, including positioning objects, applying textures, and generating control panels. The proposed methodology effectively streamlines the creation of detailed virtual environments of hydroelectric plants, supporting training and operational activities. This approach demonstrates practical benefits in industrial VR applications, emphasizing reusability, scalability, and high graphical fidelity [70].

Ai and Li introduce a Virtual Reality (VR) based on diagnosis scheme designed for hydro-power facilities, aiming to enhance fault diagnosis accuracy and efficiency. The primary objectives are to develop an intuitive, immersive diagnostic environment that integrates facility information, diagnostic knowledge, and expert reasoning methods, thereby assisting maintenance experts in fault detection and analysis. The research adopts a system design approach, integrating VR technology with fault diagnosis models to create an interactive diagnostic environment. The information gathered are facility operational data, failure phenomena, maintenance records, and expert knowledge from the Gezhouba hydropower station. The analysis employs visualization of 3D models, animation simulations, fault tree analysis, and knowledge bases to support diagnosis. The developed VR-based diagnosis scheme provides an effective tool for assisting experts in fault detection and analysis in hydro power facilities. It enhances understanding through immersive visualization, supports knowledge sharing, and streamlines maintenance decision-making. The integration of expert knowledge with VR technology offers a promising direction for future intelligent maintenance systems [71].

Liu explores the applications of virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies in the production and operation of hydropower stations. Its primary objectives are to identify key application scenarios, analyse technological methods, and evaluate the benefits of VR-based solutions for training, operation, maintenance, emergency response, and remote diagnosis. The Modelling Techniques are Geometry-Based Modelling and Rendering (GBMR): Suitable for large-scale scenes; relies on geometric data. Image-Based modelling and Rendering (IBMR): Uses real images for scene realism but requires significant storage. Hybrid modelling: Integrates GBMR and IBMR to leverage advantages of both. Virtual reality technologies hold substantial promise for transforming hydropower station production through immersive training, enhanced operation, maintenance, and safety protocols. Despite current technical challenges, ongoing developments in graphics processing, networking, AI, and big data will facilitate broader adoption. These applications can lead to safer, more efficient operations, better talent cultivation, and improved emergency preparedness [72].

Paola and et al, address the challenge of digitally managing hydraulic infrastructures more effectively through advanced technological tools. Its primary objective is to develop an integrated approach combining AI, BIM, VR, and digital modelling to enhance the design, visualization, and management of water systems such as aqueducts, water networks, and sewers. The approach combines AI-driven algorithms with parametric modelling tools like Dynamo and VIKTOR for creating complex 3D hydraulic infrastructure models. Models are imported into the SmartVerse VR platform for immersive visualization and interaction. Techniques include laser scanner surveys for real-time data acquisition, AI for optimization and predictive analytics, and Unity engine for developing immersive virtual environments. The study confirms that integrating AI, BIM, VR, and digital modelling transform hydraulic infrastructure management into a more efficient, immersive, and sustainable process. It demonstrates the potential for real-time visualization, predictive analytics, and automated system optimization to revolutionize design, maintenance, and training practices. These technological advancements support smarter decision-making, reduce costs, enhance safety, and promote sustainability in water infrastructure projects [73].

Bao focuses on developing a three-dimensional visual simulation system for major water conservancy projects based on Virtual Reality (VR) technology. The primary objectives are to improve the predictability, efficiency, and visualization of hydraulic engineering design, construction, and management processes. Digital photography, satellite imagery, aerial photos, and 3D modelling technologies to gather terrain, hydrology, and structural data were utilized for data collection. Modelling Process involved collecting basic data, constructing 3D models, optimizing models, real-time rendering and interactive visualization. The study demonstrates that VR-based 3D visual simulation improves the visual clarity and understanding of complex hydraulic systems compared to traditional 2D plans. The system enables dynamic simulation of construction sequences and internal behaviours of water projects. The integration of digital models with VR technology provides an intuitive platform that enhances understanding, collaboration, and decision-making efficiency [74].

Chapter 3 : Research Methodology

3-1 Chapter overview

This chapter outlines the methodological framework adopted to develop the Virtual Reality-Based Digitalisation Framework for Facility Management in Hydraulic Infrastructures. The workflow consists of four main phases: (1) BIM modelling and setup, where the hydraulic infrastructure was digitally constructed using Building Information Modelling tools; (2) importing the BIM model into Unity and configuring the project environment to support real-time interaction; (3) creation of the VR model, integrating navigation, interface elements, and facility management functionalities; and (4) model testing and evaluation, conducted to assess usability, performance, and alignment with facility management objectives. Each step was designed to ensure technical accuracy, immersive quality, and practical relevance to the operational needs of hydraulic infrastructure management.

3-2 Revit modelling & BIM setup

The first phase of the methodology consisted of the creation of a detailed Building Information Model (BIM) of the hydropower facility using Autodesk Revit. BIM technology provides a parametric and information-rich modelling environment which enables precise digital representation of both geometric and non-geometric aspects of infrastructure (Eastman et al., 2011). The hydropower plant components including turbines, penstocks, intake structures, and control buildings were modelled based on engineering drawings, design specifications, and site data.

During this stage, the Level of Development (LOD) of the BIM model was defined to ensure that it contained sufficient detail for both visualization and integration into a virtual reality (VR) environment. Metadata such as material specifications, operational parameters, and maintenance information were embedded in the model to support its use as a digital twin. In addition, quality control measures such as clash detection and constructability checks were conducted within Revit to identify and resolve conflicts prior to VR integration (Sacks et al., 2018).

The BIM setup stage thus established a reliable digital foundation for subsequent visualization and simulation tasks. By ensuring accuracy and interoperability, the model not only facilitated VR development but also demonstrated the potential of BIM as a central tool in the digitalisation of hydropower assets.

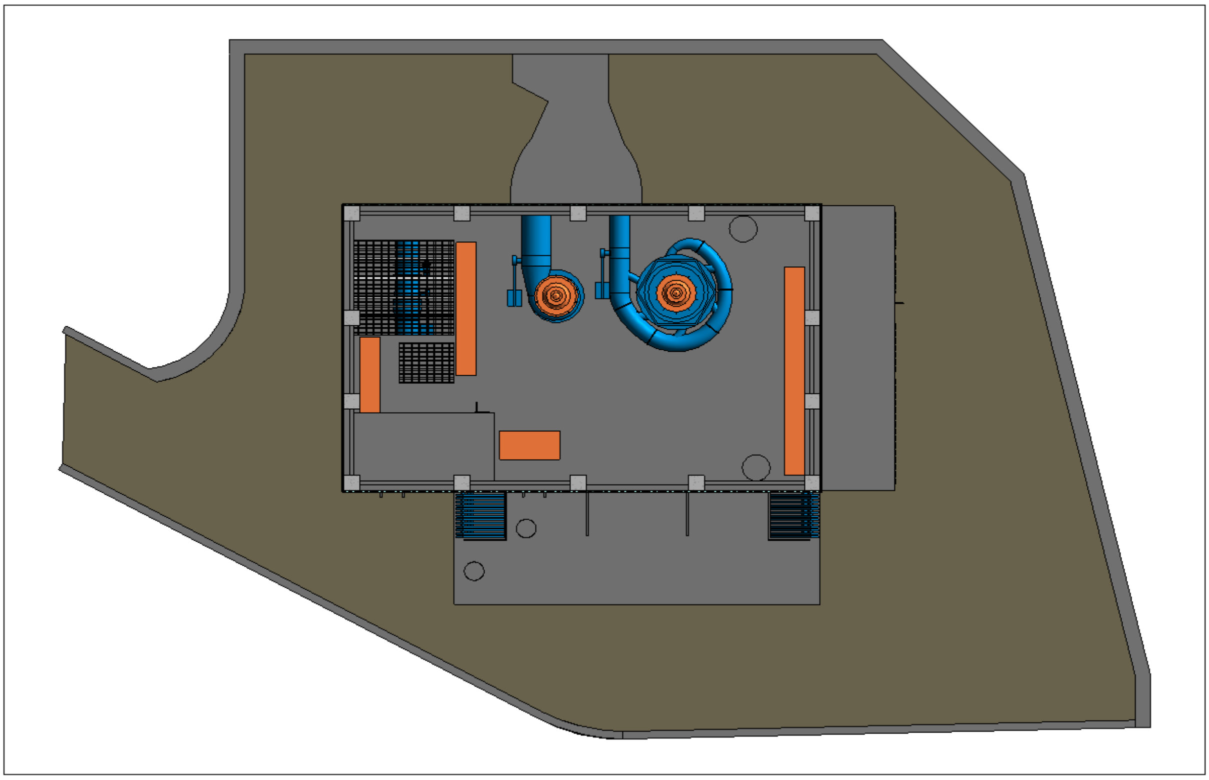

Figure 3-1 Revit Modelling & BIM Setup

3-3 Importing to Unity & Project Setup

Following the completion of the BIM model, the next step involved its transfer into Unity, a real-time 3D development engine widely applied in immersive visualization research (Jerald, 2015). As Revit models are not directly compatible with Unity, the geometry was exported using intermediate file formats such as FBX or IFC. The conversion process included geometry optimisation, polygon reduction, and the adjustment of materials to ensure efficient real-time rendering. While FBX preserves the geometry effectively, it does not retain the parameters of the BIM model or the associated textures, which may require additional adjustments during the import process.

To prepare the hydropower model for simulation in Unity, Blender was used as an intermediate platform for component refinement. Specific elements such as valves and turbine blades were manually separated from the imported FBX model to enable individual manipulation and animation. Circular components often exhibited misaligned pivot points due to export inconsistencies; these were corrected using Blender's Origin to Geometry and Set Origin tools.

Once the model was imported, a Unity project was configured to support immersive visualization. This included establishing correct scaling, lighting, and physics properties, as well as integrating interaction frameworks such as the XR Interaction Toolkit to enable Virtual Reality headset compatibility (Unity Technologies, 2022). Scene organisation and project structuring were carried out to balance rendering quality with performance requirements.

This phase effectively transformed the static BIM model into a dynamic digital environment, laying the foundation for immersive navigation and interactivity. It also ensured that technical constraints such as frame rate stability and hardware limitations were addressed at an early stage.

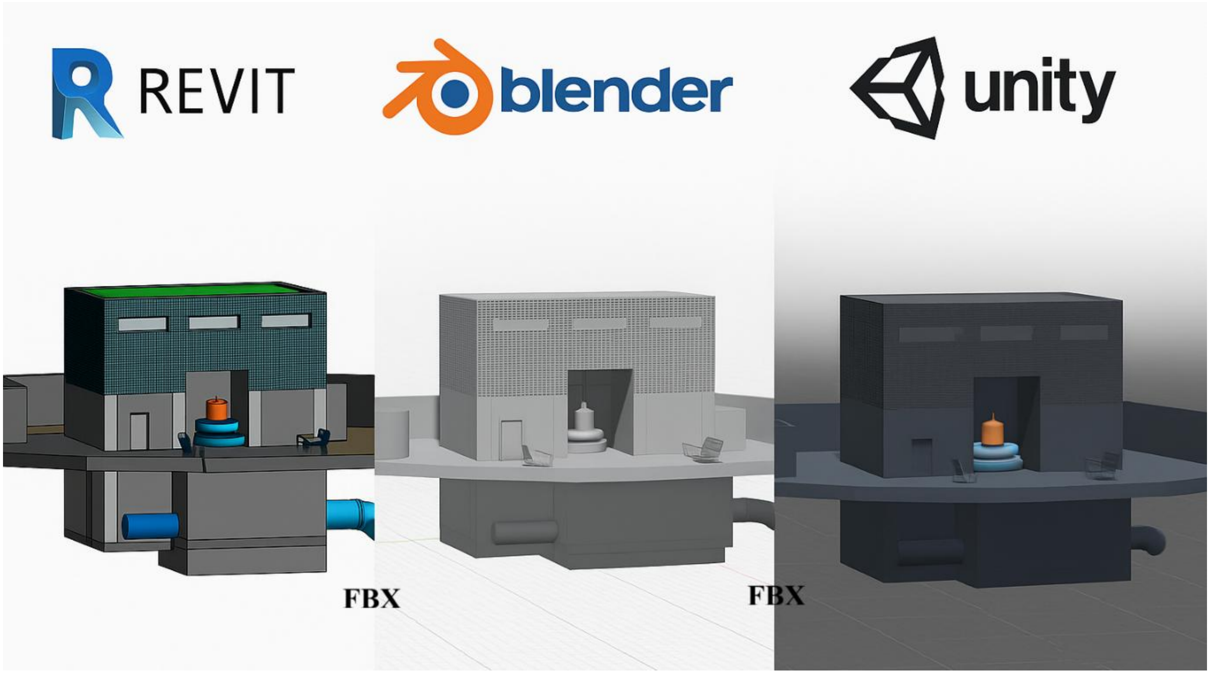

Figure 3-2 Interoperability pipeline: Revit → Blender → Unity (FBX workflow)

3-4 Creation of VR Model in Unity

The third stage of this research involved the creation of an interactive virtual reality (VR) model of the hydropower facility using Unity. At this stage, the imported 3D model was enhanced with interactive and visual elements to replicate realistic plant operations within a virtual environment. The functionality of the system was developed through custom C# scripting, allowing users to control key hydropower components such as valves, turbines, and electrical panels. In this stage, material properties were carefully assigned to all structural and mechanical components to improve surface realism and distinguish between metallic, concrete, and fluid elements. Additionally, the player object was enhanced with movement control scripts and a designated player spawn system which allows users to seamlessly enter and navigate the virtual scene from predefined starting points within the facility.

Two operational modes were implemented to address different aspects of facility management and system analysis. The Technician Mode was designed to simulate practical, hands-on operations, enabling users to move within the plant environment, open and close valves, start and stop turbines, and observe the dynamic responses of the system. This mode focuses on the operational layer of the hydropower facility and supports understanding of real-world maintenance and control procedures.

The Managerial Mode, on the other hand, focuses on strategic monitoring and assessment. It includes a dashboard interface that displays performance indicators such as turbine efficiency, power generation, service coverage, and the energy demand–supply gap. This mode provides a data-driven overview of the system's performance which supports management-level evaluation and decision-making.

By combining both operational and analytical perspectives within a unified virtual environment, the developed VR model functions as a digital twin of the hydropower facility. It serves as a comprehensive platform for training, operational planning, and performance analysis, bridging the gap between digitalisation and practical engineering applications.

3-5 Model Test & Evaluation

The final phase of the methodology focused on testing and evaluation of the developed virtual hydropower model to ensure that all components operated according to design requirements. This phase aimed to verify the accuracy of system interactions, evaluate user interface functionality, and assess the overall performance and usability of the model. The testing procedure was conducted iteratively, allowing for refinement of scripts, object behavior, and interface responsiveness.

Functional testing was first performed within the Technician Mode, where all mechanical and electrical operations were verified through direct interaction. This included assessing the correct rotational behaviour of valves, validating turbine start/stop sequences, and confirming the real-time response of the generator and electrical panels. Each interactive element was examined to ensure it reflected accurate operational feedback, such as the visual motion of turbine blades, valve positioning, and display of system messages.

The Managerial Mode underwent testing to evaluate data presentation accuracy and interface usability. The dashboard panels were reviewed to confirm correct activation through user input, proper chart loading for each turbine, and accurate visualization of performance indicators such as service coverage, seasonal power output, and energy demand–supply gap. Navigation between panels and back-end functionality were optimized to provide a seamless user experience with minimal latency or display errors.

3-6 Flowchart

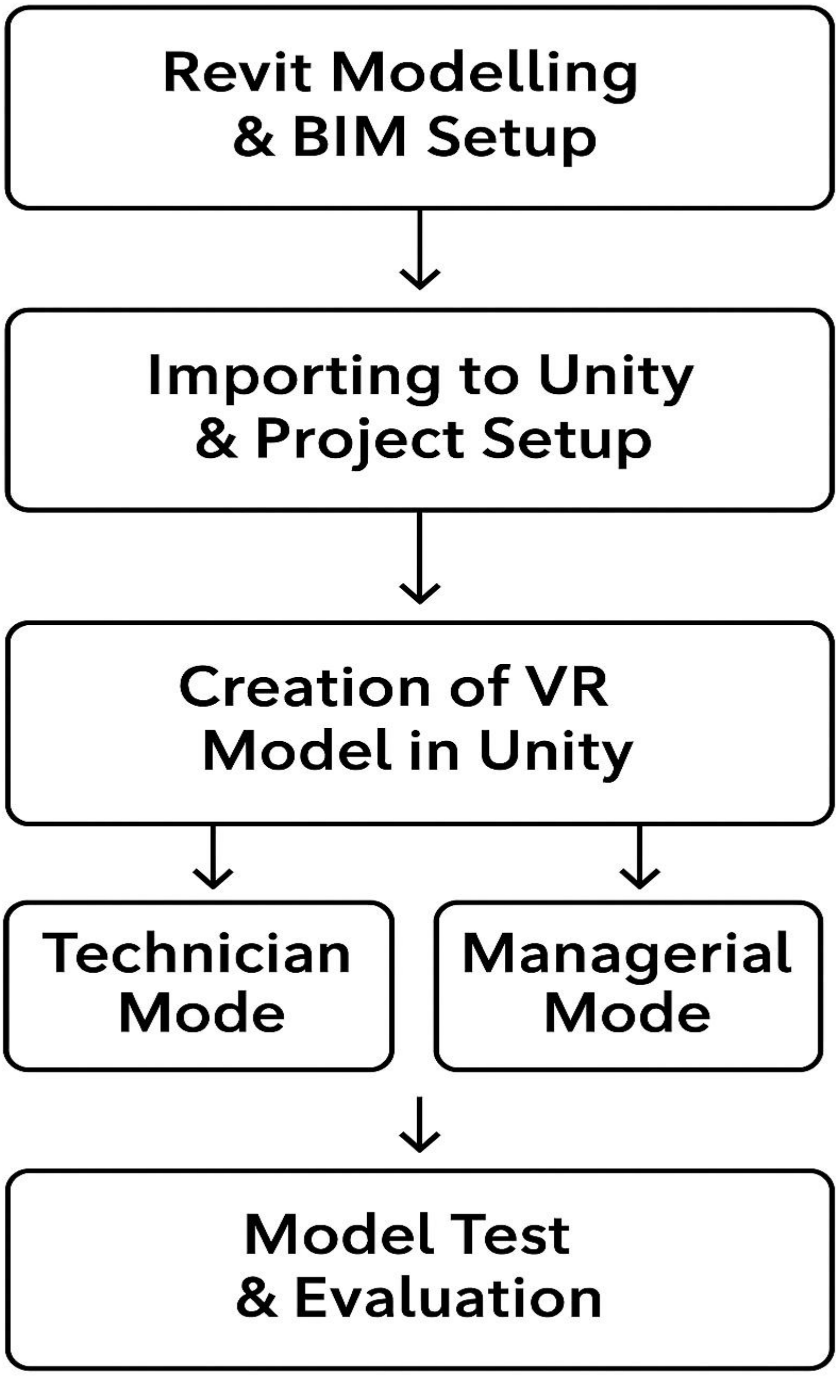

Figure 3-3 Methodology Flowchart for VR-Based Hydropower Facility Development

Chapter 4 : Case study

4-1-1 Hydropower plant

Hydroelectric power (hydropower) is a renewable energy source where electrical power is derived from the energy of water moving from higher to lower elevations. It is a proven, mature, predictable and price competitive technology. Hydropower has the best conversion efficiencies among all known energy sources (about 90 % efficiency, water to wire). It requires relatively high initial investment but has a long lifespan with very low operation and maintenance costs. Our case study is hydropower plant located in Campolattaro (BN), Italy.

4-1-2 Concept of Hydroelectric Power Generation

Hydropower is produced as the energy extracted from water moving from higher to lower locations. It is the volume of the water flow and the change in elevation from one point to another which define the amount of available energy in a particular system.

Hydroelectric power plants therefore are located on or near a water source. The change in elevation is what is known as head. In general, the greater the water flow and the higher the head, the more electricity a hydropower plant can produce. From an elevated source, water flows through a pipe, or penstock, then pushes against and turns blades in a turbine to spin a generator to produce electricity.

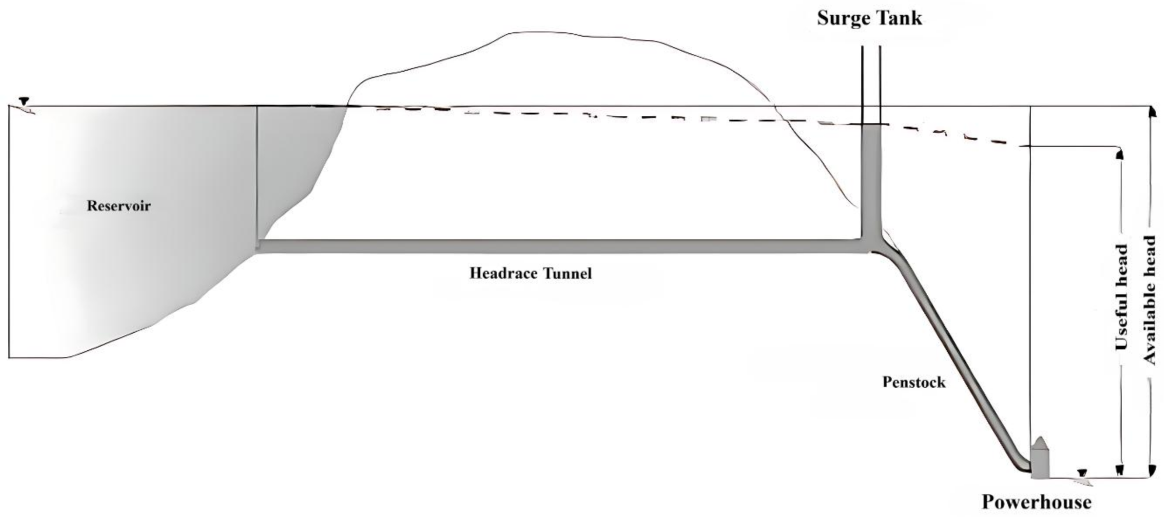

Figure 4-1 Schematic diagram of a hydroelectric power generation system

The diagram above depicts a typical hydroelectric power plant structure and its major components.

4-1-3 Hydropower plant components

Reservoir: A reservoir is a large, elevated water storage basin that accumulates potential energy by holding water at a higher elevation. It regulates seasonal flow variations, ensures consistent turbine operation, and supports multipurpose uses such as flood control, irrigation, and drinking water supply. In hydroelectric systems, the reservoir's elevation directly influences the available head and energy output. It is located on the Tammaro River with a capacity of up to 156 million m^3.

Headrace Tunnel: A Headrace tunnel is a reinforced underground conduit that transports water under high pressure from the reservoir to the surge tank or penstock. It is engineered to withstand significant internal forces and minimize hydraulic losses. Tunnel lining materials and geometry are optimized to balance structural integrity and flow efficiency, especially under heads exceeding 500 meters. The Steel pipeline (DN 1800–2200 mm) over 7.3 km long, designed for 7.6 m^3/s flow.

Surge Tank: A surge tank is a vertical shaft connected to the pressure tunnel or penstock that stabilizes pressure fluctuations caused by rapid changes in turbine load. It prevents water hammer and structural damage by absorbing excess energy during transient conditions. Surge tank design is governed by stability criteria such as the Thoma equation, and modern simulations allow for more precise sizing. It is 72 m high, 2.2 m diameter shaft to absorb pressure fluctuations and prevent water hammer.

Penstock: A penstock is a pressurized pipeline that delivers water from the surge tank to the turbines. It must be designed to handle high flow rates and pressure heads while minimizing energy losses due to friction and turbulence. Material selection, diameter, slope, and anchoring are critical to ensure hydraulic efficiency and structural safety, especially under dynamic load conditions. The Penstock is 546 m steel conduit delivering water to turbines.

Powerhouse: The powerhouse is the facility where turbines and generators convert the kinetic and potential energy of water into electrical energy. It houses mechanical and electrical systems including control units, transformers, and safety mechanisms. The layout and integration of components are optimized for operational efficiency, maintenance access, and grid connectivity.

Available Head: Available head is the total vertical distance between the reservoir surface and the turbine axis. It represents the theoretical maximum energy potential of the system, assuming no losses. This gross head is a key parameter in calculating the power output and sizing hydraulic components.

Useful Head: Useful head is the effective vertical distance available for energy conversion after accounting for hydraulic losses due to friction, turbulence, and structural inefficiencies. It determines the actual power delivered to the turbines and is used in performance calculations and efficiency assessments.

4-1-4 Overview of Turbines

In hydropower, turbines convert the energy from flowing or falling water into mechanical energy, which is then converted into electricity by a generator. The most common types of turbines used in this project are Francis Turbine and Pelton Turbine.

The Francis turbine is one of the most used water turbines in hydropower plants. Invented by James B. Francis in the 19th century, it is a reaction-type turbine that combines both radial and axial flow concepts. Water enters the turbine radially and exits axially through a spiral casing and guide vanes that control the flow direction and velocity [78].

Francis turbines are widely used because of their high efficiency (up to 95%), compact design, and ability to operate over a wide range of flow rates and heads. They are best suited for medium-head applications, typically between 10 to 300 meters. These turbines are fully submerged in water and are typically housed within a concrete powerhouse structure [78].

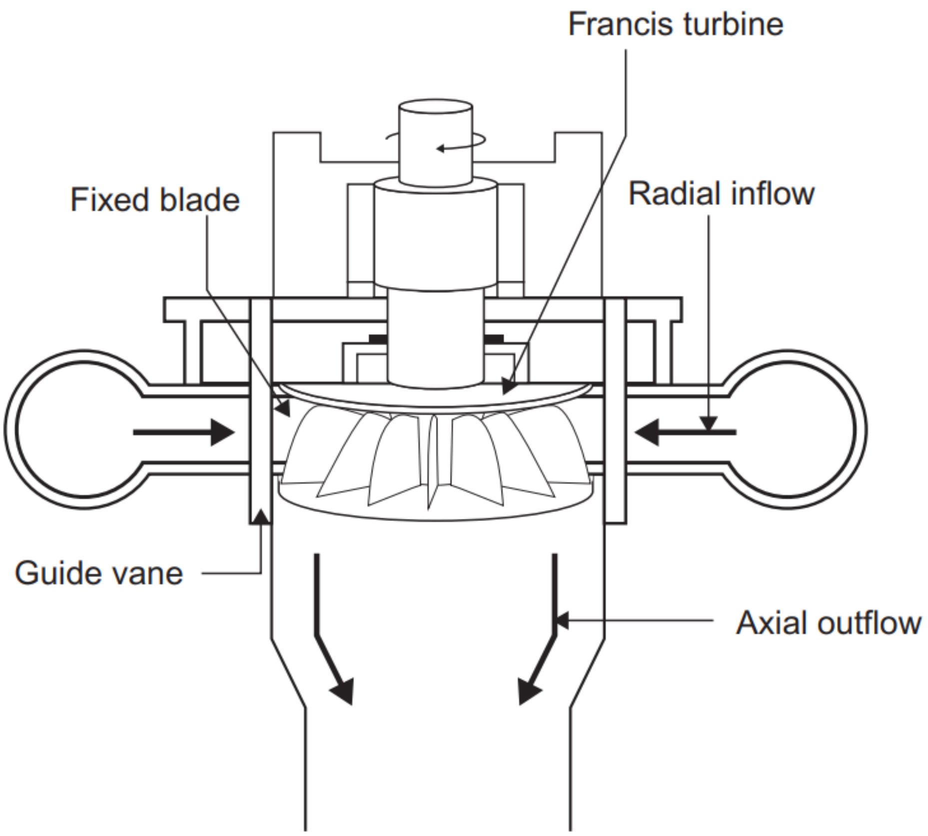

Figure 4-2 Francis Turbine Scheme

The Pelton turbine is an impulse-type turbine, invented by Lester Allan Pelton in the 1870s. It is specifically designed for high-head, low-flow conditions. Unlike reaction turbines, the Pelton turbine operates with water jets at atmospheric pressure. High-velocity water jets are directed at spoon-shaped buckets mounted on the perimeter of a wheel. These jets cause the wheel to spin, transferring kinetic energy from the water to mechanical energy.

Pelton turbines are typically used in mountainous areas or places where water can be channelled from high elevations. They are known for their simple construction, reliability, and very high efficiency in high-head situations [81].

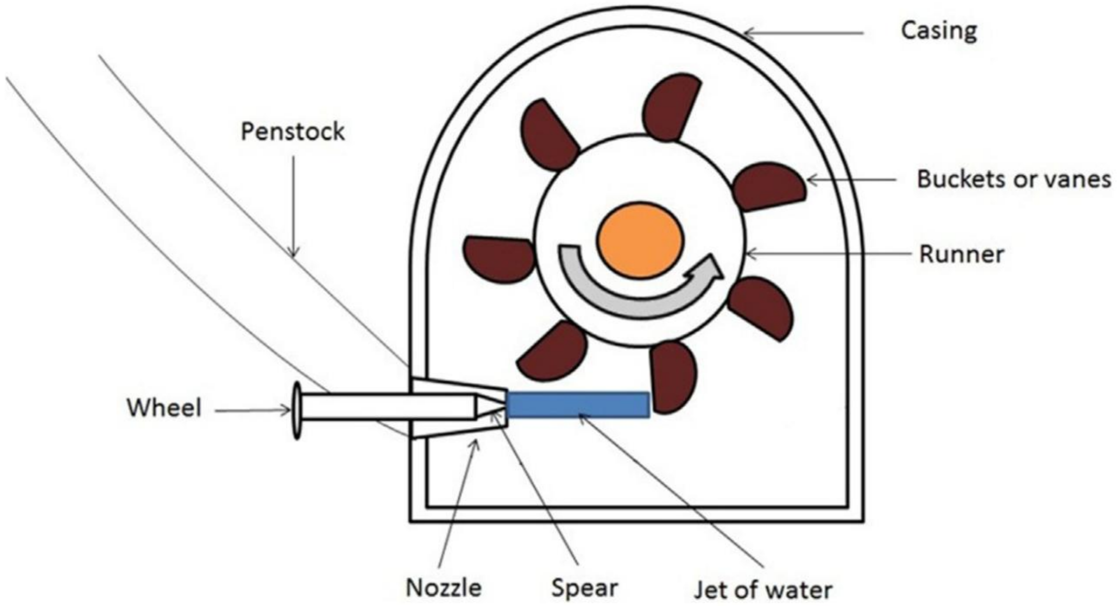

Figure 4-3 Pelton Turbine Scheme

Table 4-1 Technical Comparison between Turbines

Feature	Francis Turbine	Pelton Turbine
Type	Reaction (mixed flow)	Impulse
Water Flow	Enters radially, exits axially	Directed as high-speed jets onto buckets
Head Range	10 – 300 meters	Above 300 meters
Flow Rate	Medium	Low
Efficiency	High (up to 95%)	High (especially at design point)
Best for	Medium-head, medium-flow	High-head, low-flow
Construction	More complex, enclosed in a spiral casing	Simpler, exposed buckets and no casing
Maintenance	More demanding (submerged components)	Easier access and simpler parts
Typical Application	Dam-based, reservoir systems	Mountainous terrain, run-of-river
Orientation	Horizontal or vertical	Mostly horizontal

4-1-5 Power Generation Capacity of Turbines

The mathematical equation for the generation of electrical power in hydropower turbine is given as follows: $\boldsymbol{P = \rho \cdot g \cdot H \cdot Q . \eta}$

where P represents the electrical power produced, ρ is the density of water (1000 Kg /m^3); g is Acceleration gravity (9.81 m /s^2); H is the net available head (m); Q is the water flow rate (m^3/s) the different between spring & Autumn seasons is due to the irrigation needs ; and η is the efficiency of the turbine-generator system (typically 95 %).

4-1-6 Energy Supply of Francis Turbine

Table 4-2 Francis Turbine Power Calculation

Parameters	Value	
Acceleration Gravity (m/s^2)	9.81	
Discharge (flow rate) (m^3/s)	Spring	7.6
	Autumn	5.4
Head (m)	103	
Density (Kg /m^3)	1000	
Efficiency (-)	0.95	
Power (MW)	Spring	7.30
	Autumn	5.18
Number of people served (by the turbine)	Spring	9885
	Summer	8715
	Autumn	6863
	Winter	6979

The power production of turbine was calculated based on some coefficient and proportions which means firstly, the energy consumption of 60 million inhabitants was extracted from Terna website then converted proportionally for 10 thousand inhabitants. the energy consumption is a 3-hour period within a day. after that, the gap between energy consumption and production were calculated for each season. Moreover, the number of people served by the turbine are also computed by proportion of energy consumption of 10 thousand people and power production of a turbine. the difference in the population is due to the discharge flow and consumption pattern.

Table 4-3 Energy Supply of Francis Turbine (Spring)

Time Spring	Energy Consumption 10 thousand (MW)	Generated power	Gap (MW)	Energy Production (MW)
00:00	6.35	7.30	-0.94	6.28
03:00	5.49	7.30	-1.80	5.43
06:00	6.17	7.30	-1.13	6.10
09:00	8.59	7.30	1.29	8.49
12:00	8.52	7.30	1.22	8.42
15:00	8.37	7.30	1.08	8.28
18:00	8.10	7.30	0.80	8.00
21:00	8.12	7.30	0.82	8.02
24:00	6.72	7.30	-0.58	6.64

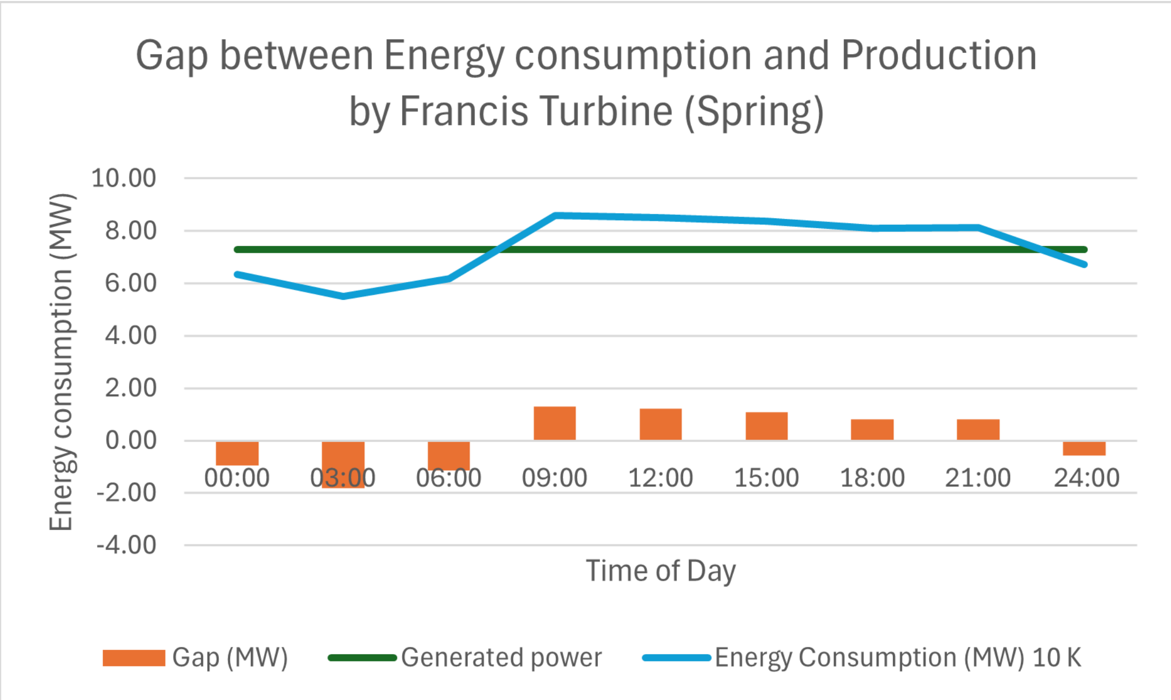

Figure 4-4 Gap between Energy Consumption & Supply (Francis Turbine) in Spring

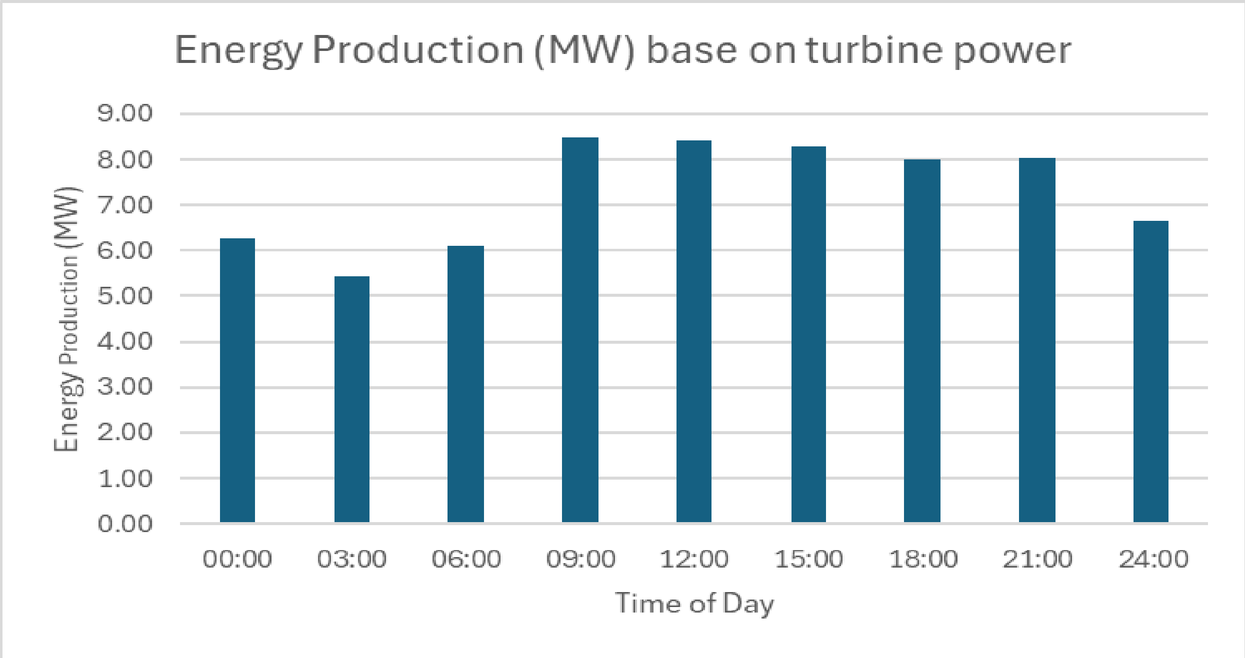

Figure 4-5 Corresponding Energy Production of Francis Turbine (Spring)

Table 4-4 Energy Supply of Francis Turbine (Summer)

Time Summer	Energy Consumption 10 thousand (MW)	Generated power	Gap (MW)	Energy Production (MW)
00:00	7.38	7.30	0.08	6.43
03:00	6.41	7.30	-0.88	5.59
06:00	6.84	7.30	-0.45	5.96
09:00	9.29	7.30	1.99	8.10
12:00	9.78	7.30	2.49	8.52
15:00	9.74	7.30	2.45	8.49
18:00	9.33	7.30	2.03	8.13
21:00	9.07	7.30	1.77	7.90
24:00	7.49	7.30	0.20	6.53

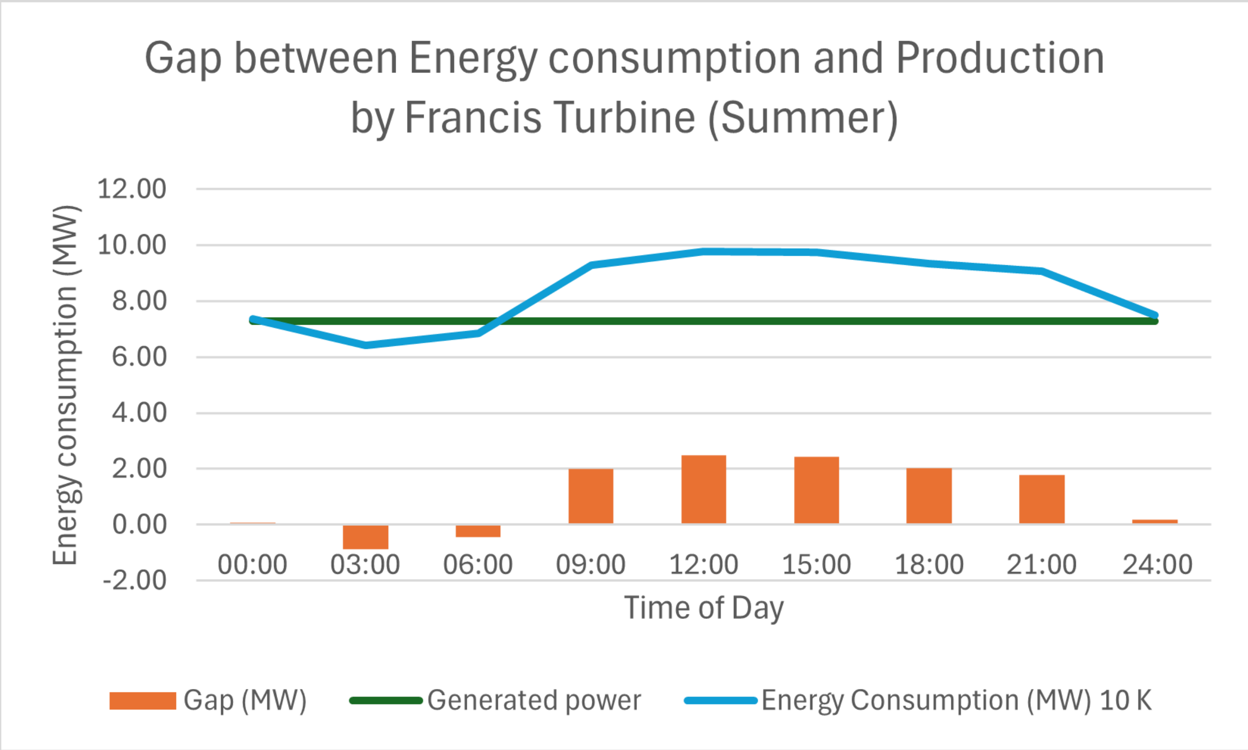

Figure 4-6 Gap between Energy Consumption & Supply (Francis Turbine) in Summer

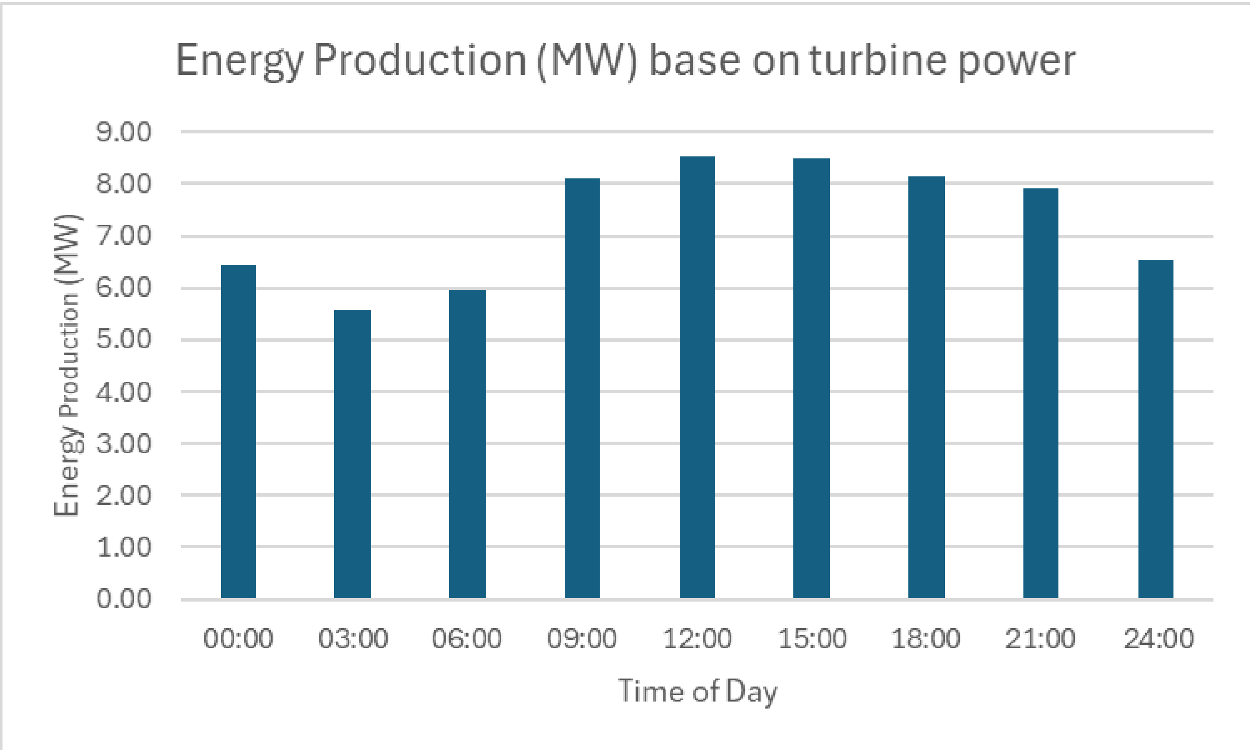

Figure 4-7 Corresponding Energy Production of Francis Turbine (Summer)

Table 4-5 Energy Supply of Francis Turbine (Autumn)

Time	Energy Consumption 10 thousand (MW)	Generated power	Gap (MW)	Energy Production (MW)
Autumn				
00:00	6.16	5.18	0.98	4.23
03:00	5.35	5.18	0.17	3.67
06:00	6.43	5.18	1.25	4.41
09:00	9.05	5.18	3.87	6.21
12:00	8.98	5.18	3.79	6.16
15:00	8.75	5.18	3.56	6.00
18:00	8.70	5.18	3.52	5.97
21:00	8.25	5.18	3.06	5.66
24:00	6.30	5.18	1.12	4.32

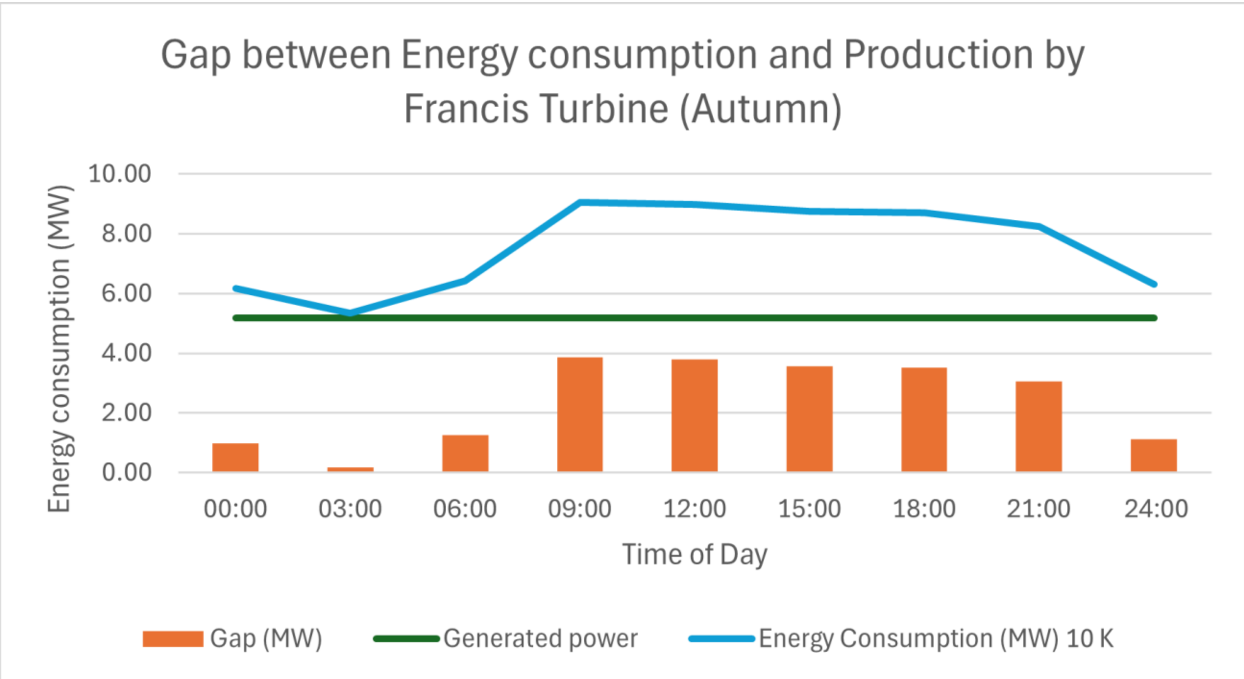

Figure 4-8 Gap between Energy Consumption & Supply (Francis Turbine) in Autumn

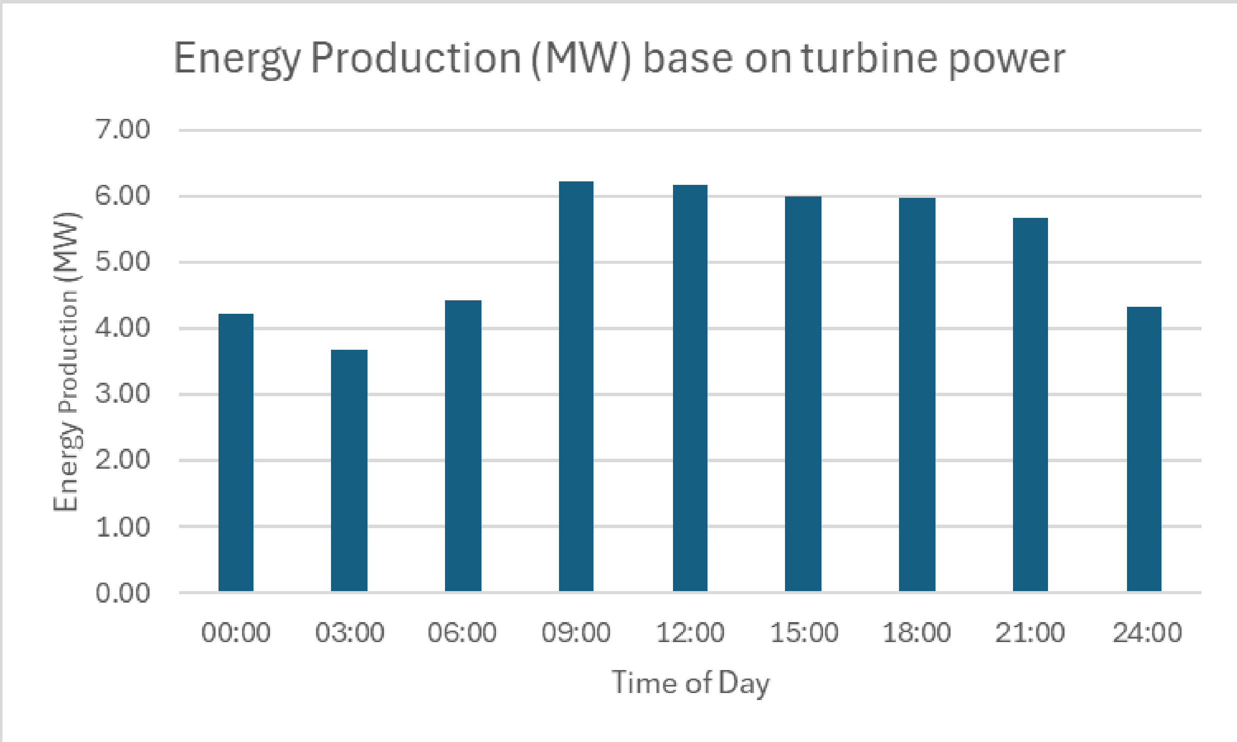

Figure 4-9 Corresponding Energy Production of Francis Turbine (Autumn)

Table 4-6 Energy Supply of Francis Turbine (Winter)

Time	Energy Consumption 10 thousand (MW)	Generated power	Gap (MW)	Energy Production (MW)
Winter				
00:00	6.10	5.18	0.92	4.26
03:00	5.29	5.18	0.11	3.69
06:00	6.29	5.18	1.10	4.39
09:00	8.80	5.18	3.62	6.14
12:00	8.51	5.18	3.33	5.94
15:00	8.34	5.18	3.16	5.82
18:00	8.77	5.18	3.59	6.12
21:00	8.13	5.18	2.95	5.68
24:00	6.60	5.18	1.41	4.60

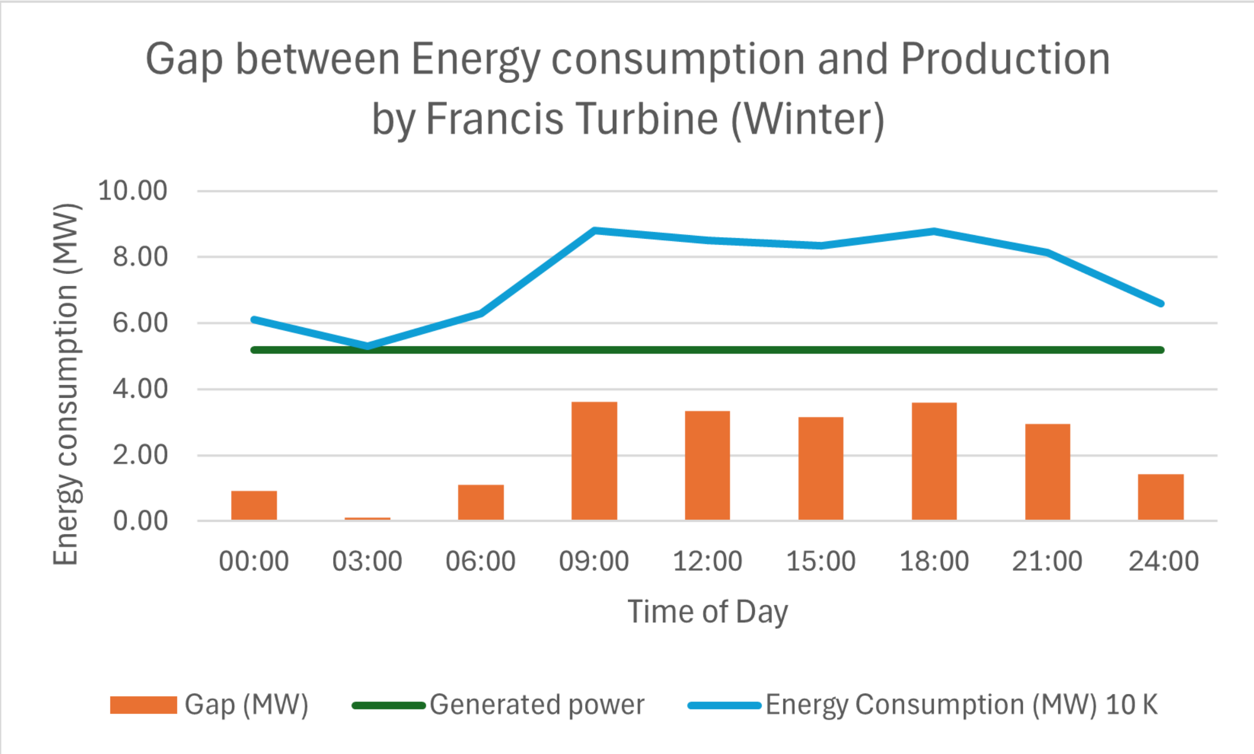

Figure 4-10 Gap between Energy Consumption & Supply (Francis Turbine) in Winter

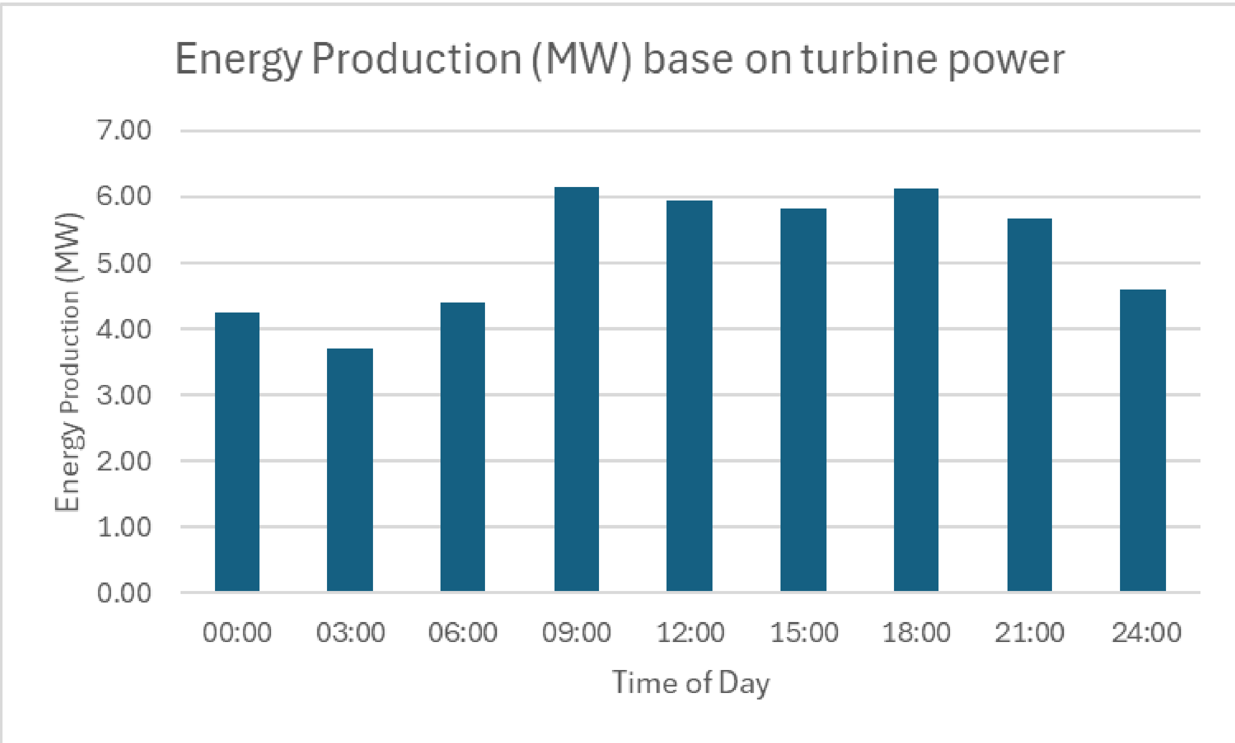

Figure 4-11 Corresponding Energy Production of Francis Turbine (Winter)

4-1-7 Energy Supply of Pelton Turbine

Table 4-7 Pelton Turbine Power Calculation

Parameters	Value	
Acceleration Gravity (m/s^2)	9.81	
Discharge (flow rate) (m^3/s)	Spring	7.6
	Autumn	5.4
Head (m)	103	
Density (Kg /m^3)	1000	
Efficiency (-)	0.90	
Power (MW)	Spring	6.91
	Autumn	4.91
Number of people served (by the turbine)	Spring	9364
	Summer	8256
	Autumn	6501
	Winter	6612

Although Pelton and Francis turbines may operate under identical hydraulic parameters such as outflow rate, gravitational acceleration, net head, and fluid density their power output can differ due to inherent differences in energy conversion mechanisms. Pelton turbines are impulse machines that convert kinetic energy from high-velocity water jets, while Francis turbines are reaction machines that utilize both pressure and velocity energy within a fully flooded runner. Under matched conditions, Francis turbines generally achieve higher mechanical efficiency due to smoother energy transfer and reduced hydraulic losses. Experimental studies have shown that at comparable heads and flow rates, the efficiency of Francis turbines can exceed that of Pelton turbines by 2–5%, resulting in slightly higher power output [82,83]. This difference is attributed to the continuous flow regime and optimized blade geometry in Francis turbines, which reduce turbulence and improve torque generation [84,85].

Table 4-8 Energy Supply of Pelton Turbine (Spring)

Time Spring	Energy Consumption 10 thousand (MW)	Generated power	Gap (MW)	Energy Production (MW)
00:00	6.35	6.91	-0.56	5.95
03:00	5.49	6.91	-1.42	5.14
06:00	6.17	6.91	-0.75	5.77
09:00	8.59	6.91	1.67	8.04
12:00	8.52	6.91	1.61	7.98
15:00	8.37	6.91	1.46	7.84
18:00	8.10	6.91	1.18	7.58
21:00	8.12	6.91	1.21	7.60
24:00	6.72	6.91	-0.19	6.29

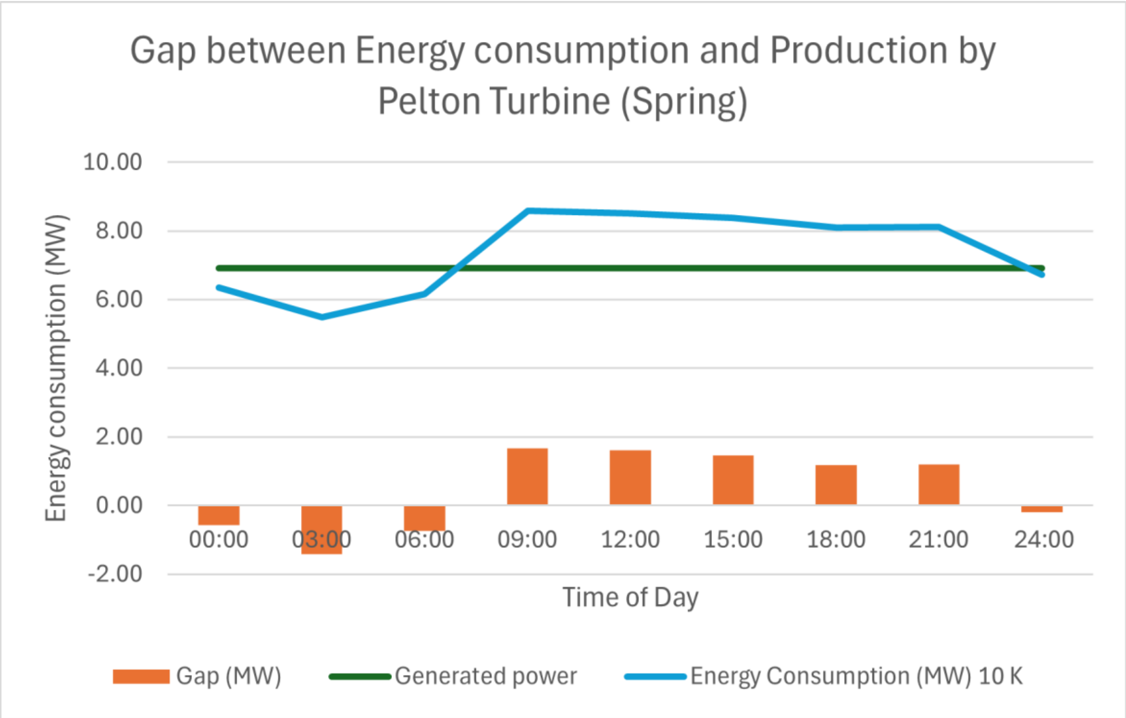

Figure 4-12 Gap between Energy Consumption & Supply (Pelton Turbine) in Spring

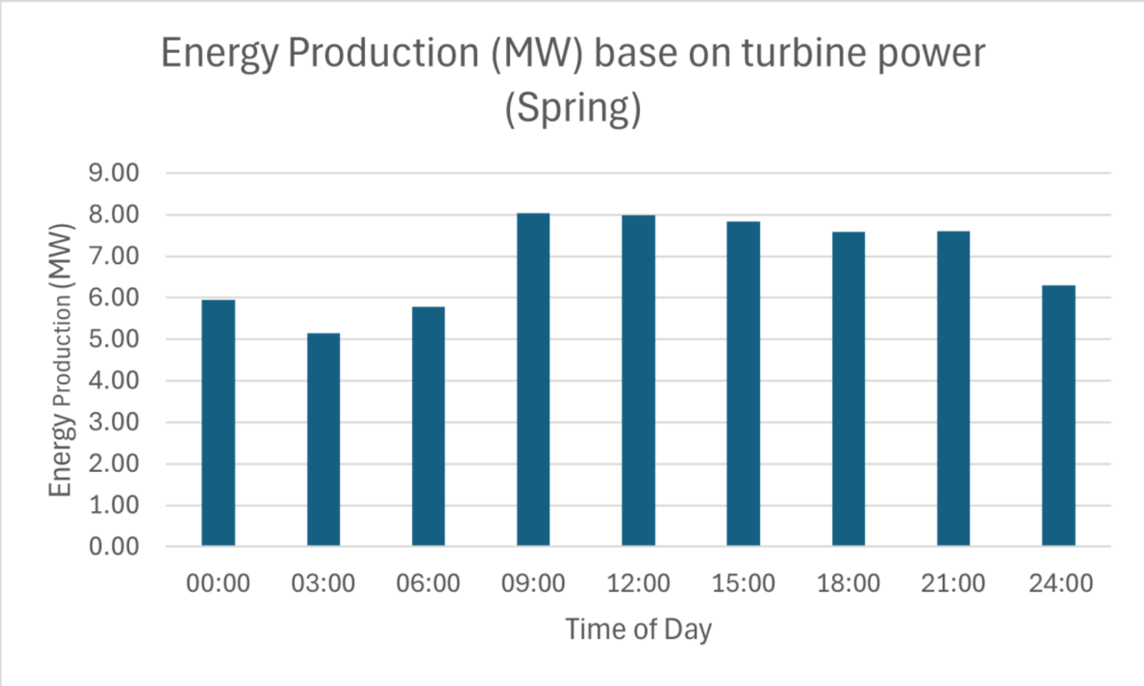

Figure 4-13 Corresponding Energy Production of Pelton Turbine (Spring)

Table 4-9 Energy Supply of Pelton Turbine (Summer)

Time Summer	Energy Consumption 10 thousand (MW)	Generated power	Gap (MW)	Energy Production (MW)
00:00	7.38	6.91	0.47	6.09
03:00	6.41	6.91	-0.50	5.29
06:00	6.84	6.91	-0.07	5.65
09:00	9.29	6.91	2.38	7.67
12:00	9.78	6.91	2.87	8.08
15:00	9.74	6.91	2.83	8.04
18:00	9.33	6.91	2.42	7.70
21:00	9.07	6.91	2.16	7.49
24:00	7.49	6.91	0.58	6.19

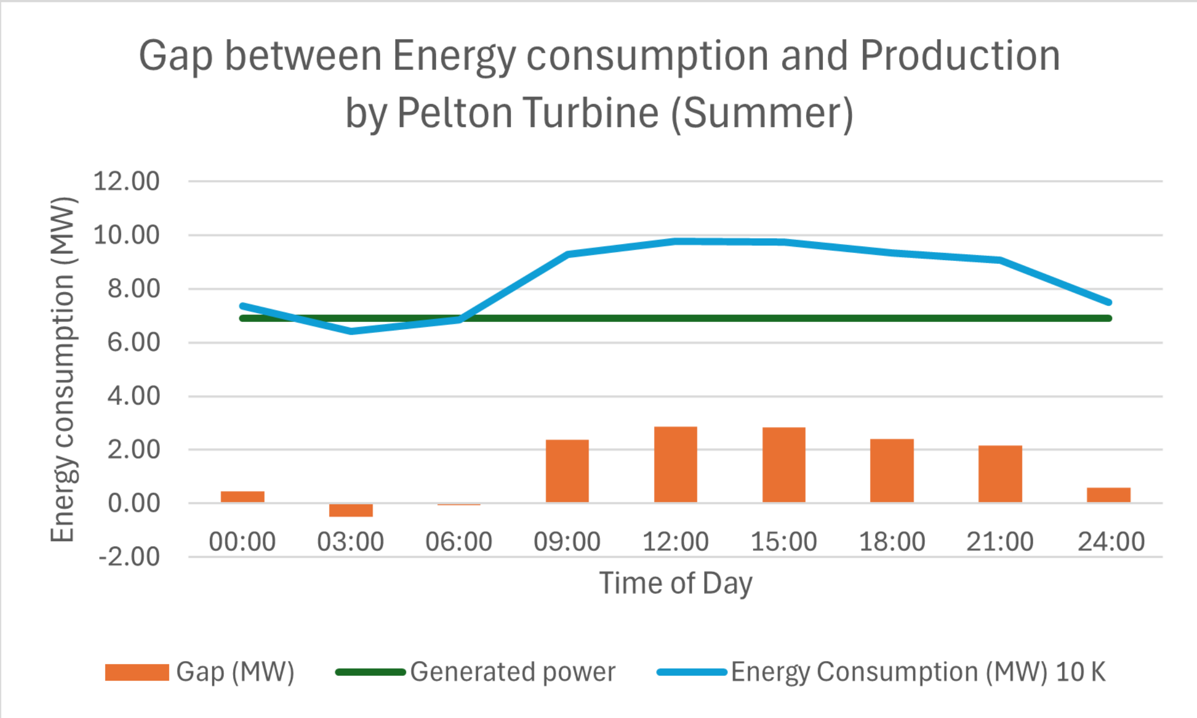

Figure 4-14 Gap between Energy Consumption & Supply (Pelton Turbine) in Summer

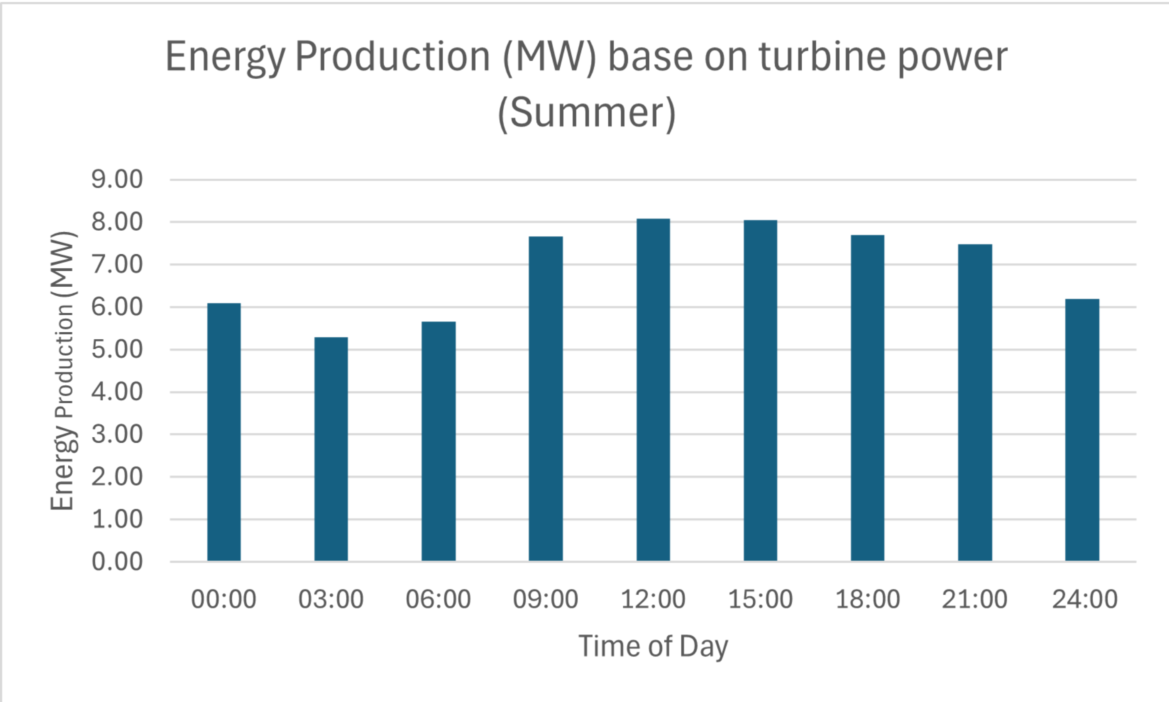

Figure 4-15 Corresponding Energy Production of Pelton Turbine (Summer)

Table 4-10 Energy Supply of Pelton Turbine (Autumn)

Time Autumn	Energy Consumption 10 thousand (MW)	Generated power	Gap (MW)	Energy Production (MW)
00:00	6.16	4.91	1.25	4.01
03:00	5.35	4.91	0.44	3.48
06:00	6.43	4.91	1.52	4.18
09:00	9.05	4.91	4.14	5.89
12:00	8.98	4.91	4.07	5.84
15:00	8.75	4.91	3.84	5.69
18:00	8.70	4.91	3.79	5.66
21:00	8.25	4.91	3.34	5.36
24:00	6.30	4.91	1.39	4.10

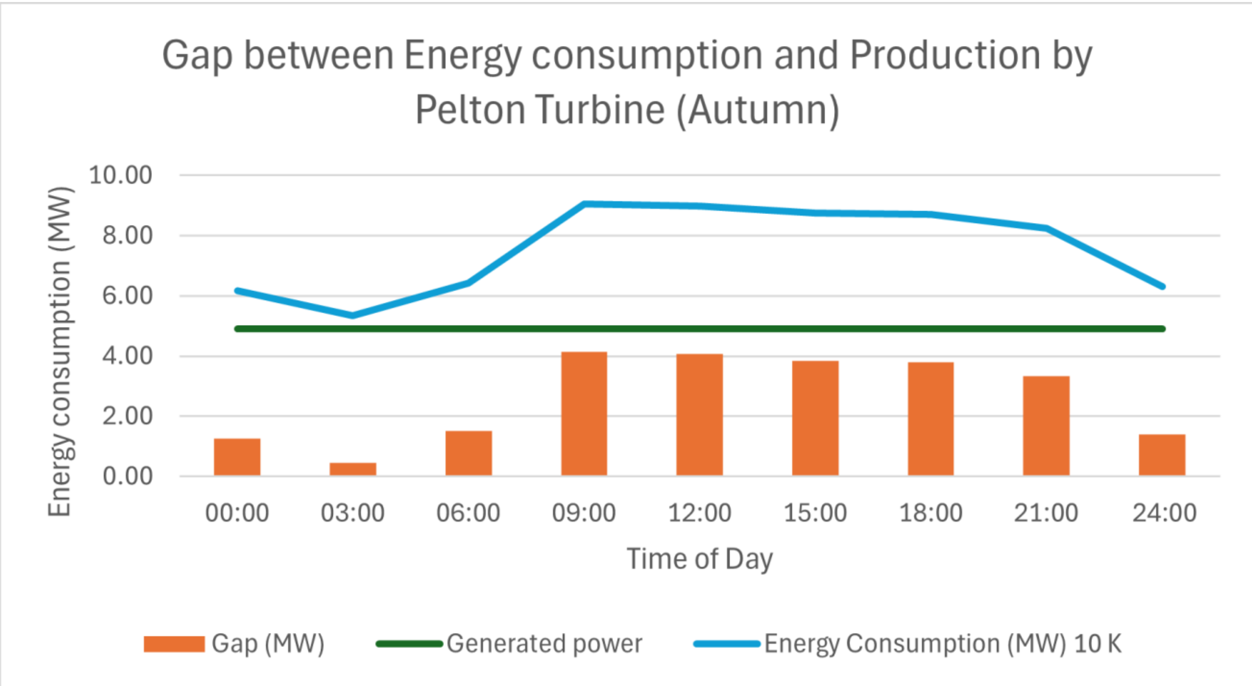

Figure 4-16 Gap between Energy Consumption & Supply (Pelton Turbine) in Autumn

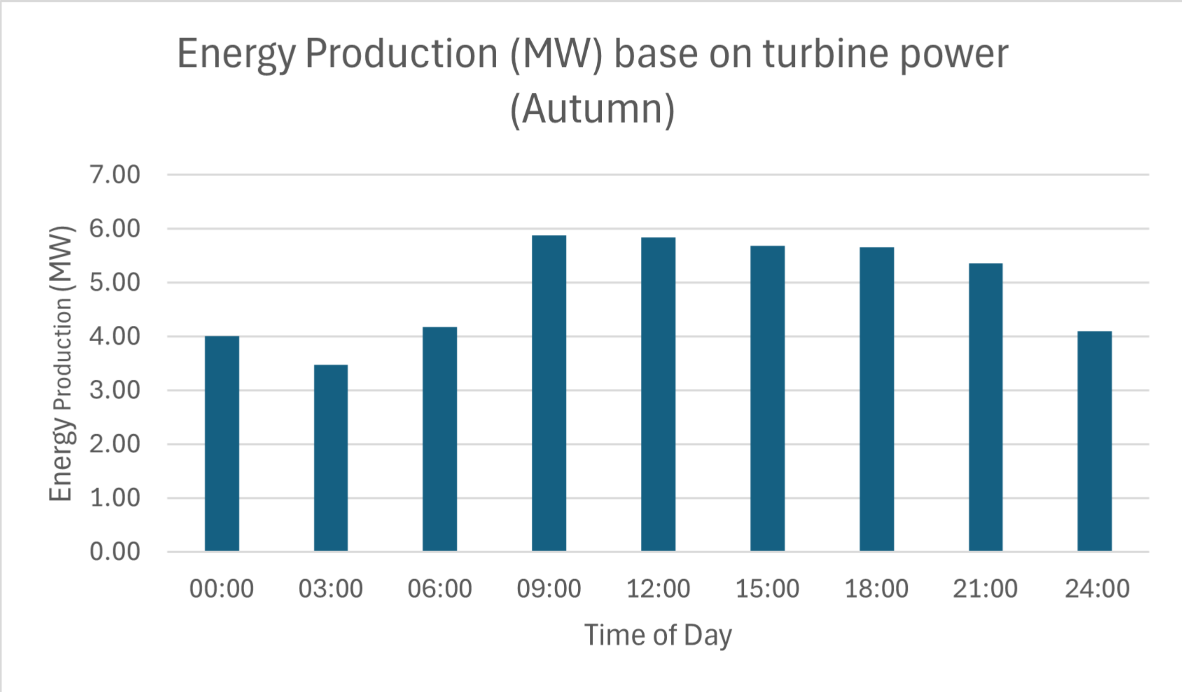

Figure 4-17 Corresponding Energy Production of Pelton Turbine (Autumn)

Table 4-11 Energy Supply of Pelton Turbine (Winter)

Time Winter	Energy Consumption 10 thousand (MW)	Generated power	Gap (MW)	Energy Production (MW)
00:00	6.10	4.91	1.19	4.04
03:00	5.29	4.91	0.38	3.50
06:00	6.29	4.91	1.38	4.16
09:00	8.80	4.91	3.89	5.82
12:00	8.51	4.91	3.60	5.63
15:00	8.34	4.91	3.43	5.51
18:00	8.77	4.91	3.86	5.80
21:00	8.13	4.91	3.22	5.38
24:00	6.60	4.91	1.69	4.36

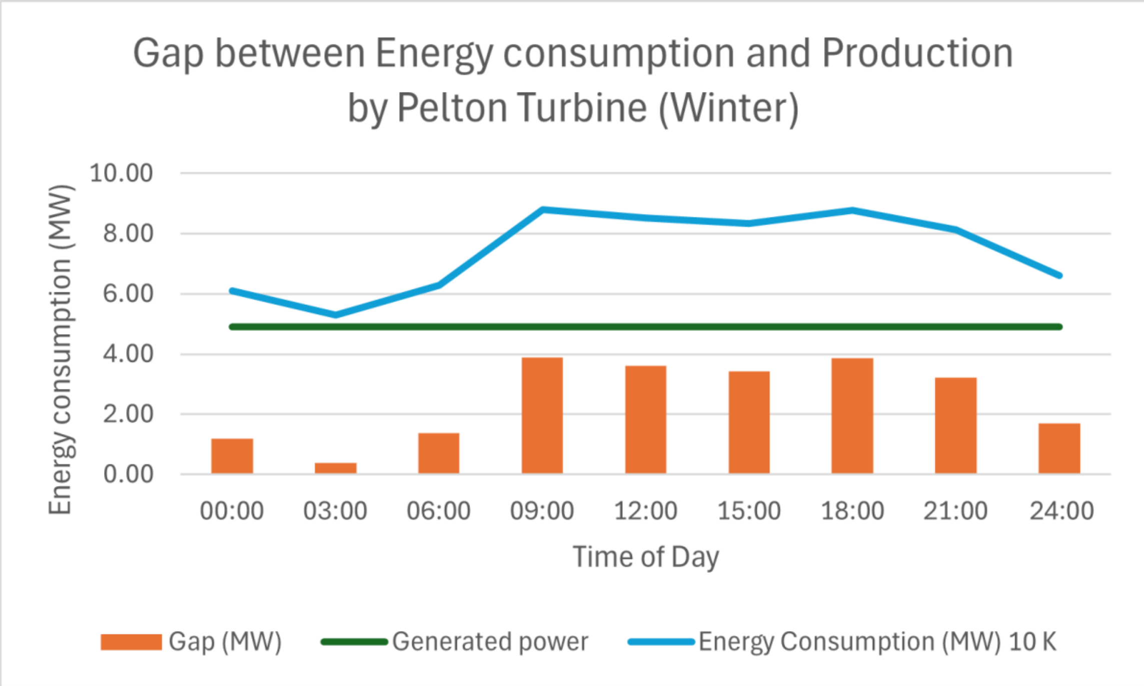

Figure 4-18 Gap between Energy Consumption & Supply (Pelton Turbine) in Winter

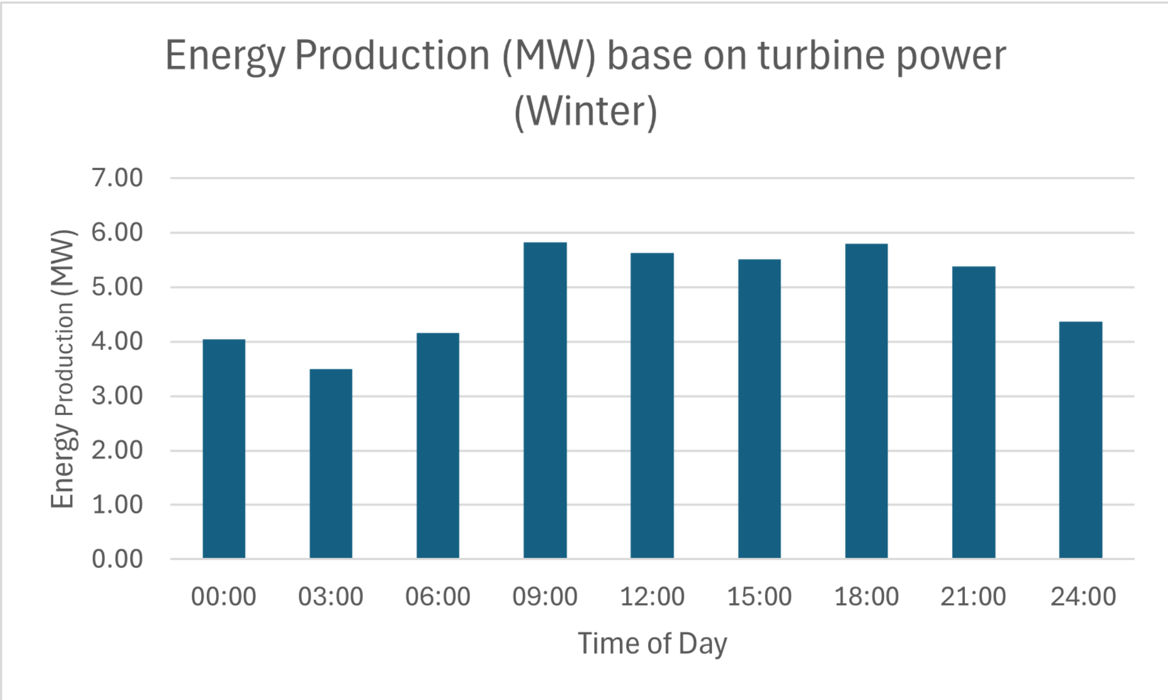

Figure 4-19 Corresponding Energy Production of Pelton Turbine (Winter)

Chapter 5 : Results and Discussion

5-1 Chapter overview

This chapter presents results and findings of the VR based digitalisation of hydropower facility management; it highlights the implementation of two distinct user modes within the developed VR-based digitalisation framework: Technician Mode and Managerial Mode. Technician Mode was designed to simulate the hands-on, field-level activities typically performed by maintenance engineers and operators which emphasizes routine operational procedures and the technical maintenance responsibilities associated of hydropower infrastructure. In contrast, Managerial Mode was tailored to support facility managers and planners by providing tools for evaluating system performance, comparing turbine efficiency, and facilitating data-driven decision-making.

5-2 Application Setup

The virtual reality (VR) environment developed for this project operates in two distinct configurations: Technician Mode and Managerial Mode, each designed to simulate different aspects of hydropower facility management. The Technician Mode serves as the default environment when the simulation begins, enabling direct interaction with the physical components of the hydropower plant. Conversely, the Managerial Mode provides a high-level analytical interface that allows users to review operational data and visualize system performance through graphical dashboards.

Table 5-1 Overview of Technician Mode vs. Managerial Mode

Mode / Feature	Technician mode	Managerial Mode
Purpose	Operational and maintenance simulation	Monitoring and analytical decision support
Activation	Default mode at simulation start	Activated by pressing the **“M”** key
Interaction Type	Physical interaction with components (valves, turbines, panels)	UI-based interaction through charts and dashboards
Player Setup	First-person player controller with camera and physics-based movement	Static camera; no player or movement system
Controls	WASD navigation, jumping, crouching, and “E” key for interaction	Mouse-based UI navigation (button clicks, chart viewing)
Collider Usage	Box or mesh colliders	No colliders
Camera Configuration	Player-attached camera	Stationary camera

5-3 Technician Mode

The Technician Mode represents the operational and maintenance layer of the virtual hydropower facility. It is designed to replicate, as realistically as possible, the routine tasks and decision-making processes that a field technician would undertake within an actual hydropower plant. Within this mode, the user assumes the role of an on-site operator, which navigate the digital twin of the power station through a first-person interface. The environment provides access to interactive components such as valves, turbines, and electrical panels, each of which responds to user inputs in a manner consistent with real-world engineering behaviour.

This mode emphasizes procedural understanding, situational awareness, and safety-oriented actions. For example, a technician may approach a valve, press an interaction key, and observe the corresponding mechanical response in the turbine system. The simulation reflects the sequence of physical operations opening valves, initiating turbine rotation, and synchronizing generators accompanied by visual alerts and dynamic user interface feedback. These elements communicate vital information such as valve position, turbine activity, and power output which allows the user to grasp the cause/effect relationship between operational decisions and system behaviour.

The Technician Mode serves as an immersive training tool that promotes experiential learning. It allows users to explore potential faults, system responses, and safety protocols without the risks or costs associated with real equipment. The mode's integration of physical simulation and digital feedback forms a vital component of the facility's digital twin which bridges the gap between theoretical knowledge and operational practice. In this way, Technician Mode not only enhances technical competence but also contributes to a deeper understanding of hydropower system dynamics and facility maintenance processes.

5-3-1 Basic Player Movement with WASD & Arrow keys

In the virtual hydropower, the player movement system forms the foundation of the interactive environment which enables the user to explore the digital model of the power station. The player represents the technician's point of view and is controlled through a simple, yet effective movement mechanism implemented using the standard **WASD** and **arrow keys**. This control setup ensures intuitive navigation and accessibility which replicates the experience of moving through an industrial workspace.

```
float x = Input.GetAxis("Horizontal");
float z = Input.GetAxis("Vertical");
Vector3 move = transform.right * x + transform.forward * z;

float currentSpeed = isCrouching ? crouchSpeed : speed;
controller.Move(move * currentSpeed * Time.deltaTime);
```

Figure 5-1 Directional movement script

The player movement was implemented using Unity's Character Controller component, which provides smooth and collision-aware motion within the 3D environment. The script interprets the keyboard inputs W and Up Arrow for forward movement, S and Down Arrow for backward motion, and A/Left Arrow and D/Right Arrow for lateral movement. These inputs are processed in the **Update()** function to ensure real-time responsiveness.

```
void Update()
{
    HandleMouseLook();
    HandleMovement();
    HandleCrouch();
}
```

Figure 5-2 Unity's frame-based input handling via the Update() method

5-3-2 Camera Control

In this environment, the camera system functions as the user's visual and perceptual interface with the 3D world. It determines how users observe and interact with digital representations of turbines, generators, and control panels which ensures that the virtual experience closely resembles real-world inspection and monitoring conditions.

The camera is configured as a child object of the player controller which means it automatically follows the technician's body movement across the virtual space. This design ensures that the visual perspective remains stable and aligned with the player's position which creates a first-person view of immersive simulation environments. Horizontal and vertical rotations of the camera are managed through mouse input which allows the user to freely look around the environment.

Overall, the camera control system serves a dual purpose: functional navigation and task precision. In technician mode, precise camera control allows close inspection of equipment and instruments, supporting actions like reading indicators, observing turbine operation, and locating electrical components. In managerial mode, the camera can transition to more static or top-down viewpoints which assists in visualization of operational data and the analysis of overall plant performance.

```
void HandleMouseLook()
{
    float mouseX = Input.GetAxis("Mouse X") * mouseSensitivity * Time.deltaTime;
    float mouseY = Input.GetAxis("Mouse Y") * mouseSensitivity * Time.deltaTime;

    xRotation -= mouseY;
    xRotation = Mathf.Clamp(xRotation, -90f, 90f);

    cameraTransform.localRotation = Quaternion.Euler(xRotation, 0f, 0f);
    transform.Rotate(Vector3.up * mouseX);
}
```

Figure 5-3 Mouse-based camera control in Unity

5-3-3 Collider

In unity, collider represents simulation of the boundaries and physical interactions between the player and the surrounding environment. The collider system ensures that objects behave realistically within the digital space which prevents the player from walking through walls, machinery, or other physical structures. It forms the invisible green layer that defines how entities within the simulation occupy and respond to spatial constraints.

Different colliders were implemented for this project, like Trigger Colliders, Mesh Colliders and Capsule Collider. Due to the complexity of elements inside the hydropower like generator rotors, valve assemblies All components were assigned a mesh collider (script) which closely follow the object's actual 3D geometry. The player object has a Capsule Collider surrounding the virtual body and represents a standing human figure. It ensures that the player maintains proper contact with the ground and cannot pass through solid structures. It works in conjunction with the Rigidbody component, which governs physics-based motion and collision response. In the hydropower facility, trigger colliders are used to define interaction zones for example, when the player approaches the generator, control panels, or turbine area, a message or UI prompt ("Press E to Inspect") shows up.

```
using UnityEngine;

[ExecuteInEditMode]
Unity Script (1 asset reference) | 0 references
public class AddMeshCollidersToAllChildren : MonoBehaviour
{
    [Tooltip("Set to true if you want the mesh colliders to be convex (required for moving objects).")]
    public bool convex = true;

    Unity Message | 0 references
    void Start()
    {
        AddMeshCollidersRecursively(transform);
    }

    2 references
    void AddMeshCollidersRecursively(Transform current)
    {
        // If this GameObject has a MeshFilter and no Collider yet
        if (current.GetComponent<MeshFilter>() && current.GetComponent<MeshRenderer>())
        {
            if (!current.GetComponent<Collider>())
            {
                MeshCollider meshCollider = current.gameObject.AddComponent<MeshCollider>();
                meshCollider.convex = convex;
            }
        }

        // Recurse through children
        foreach (Transform child in current)
        {
            AddMeshCollidersRecursively(child);
        }
    }
}
```

Figure 5-4 Mesh Collider's script

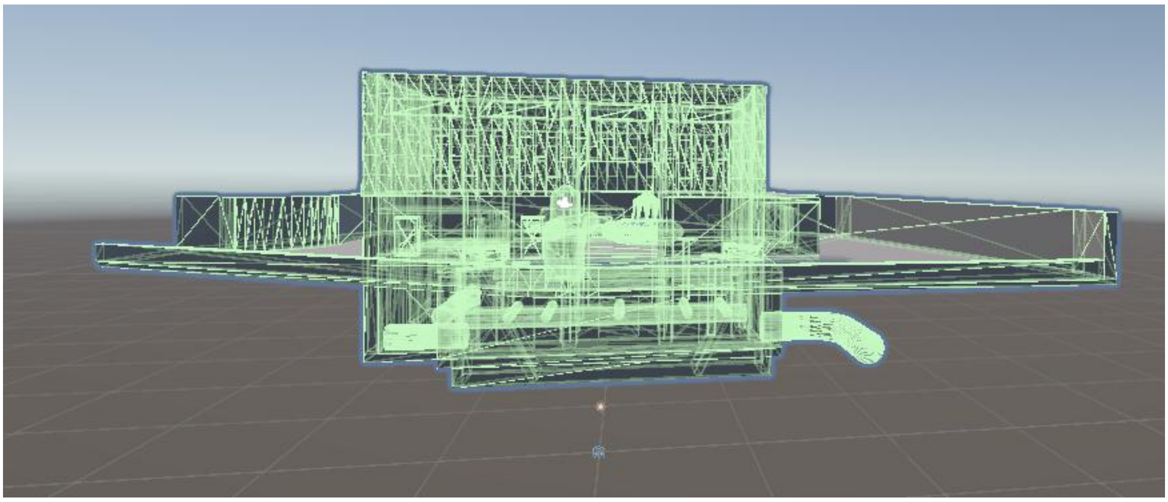

Figure 5-5 Mesh Collider of Hydropower in Unity

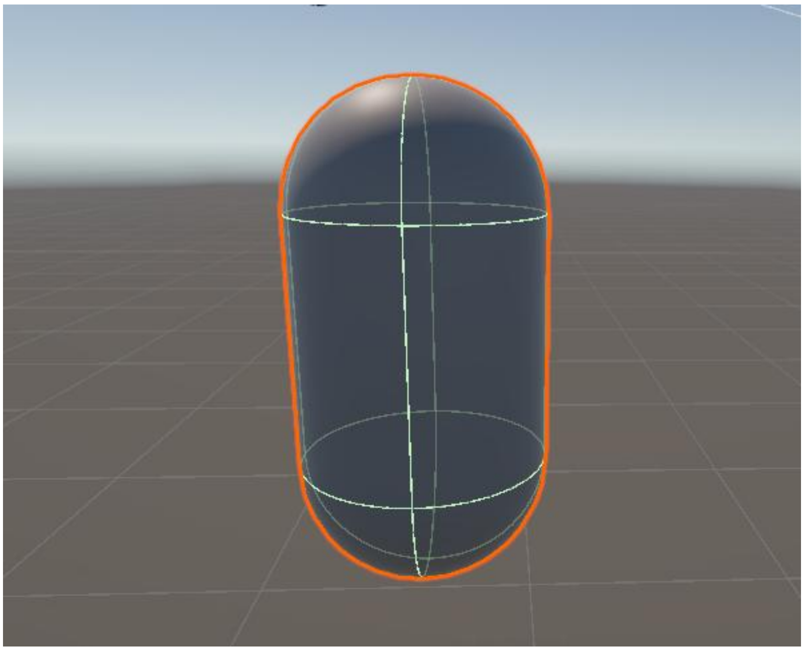

Figure 5-6 Capsule Collider of character

5-3-4 Gravity

Gravity serves as a physical force that governs the player's motion and object interactions, In Unity's physics engine, gravity is an ever-present downward acceleration that continuously influences any object associated with a Rigidbody component. It is expressed as a constant vector acting along the negative Y-axis (commonly set to $-9.81\ m/s^2$) which closely replicates the gravitational force experienced on earth.

The gravity system also plays an important functional distinction between the two primary modes of this simulation. In Technician Mode, gravity is fully active which ensures that the player experiences real-world physics as they navigate the hydropower facility. Conversely, in Managerial Mode, where interaction focuses on data analysis and turbine performance visualization, gravity and movement physics are intentionally disabled which allows for a fixed-camera perspective suited to examining dashboards and statistical charts.

```
void HandleMovement()
{
    // --- Ground Check ---
    isGrounded = controller.isGrounded;

    if (isGrounded && velocity.y < 0)
    {
        velocity.y = -2f; // keep player stuck to ground
    }

    // --- Directional Movement ---
    float x = Input.GetAxis("Horizontal");
    float z = Input.GetAxis("Vertical");
    Vector3 move = transform.right * x + transform.forward * z;

    float currentSpeed = isCrouching ? crouchSpeed : speed;
    controller.Move(move * currentSpeed * Time.deltaTime);

    // --- Jump Logic ---
    if (Input.GetButtonDown("Jump") && isGrounded && !isCrouching)
    {
        velocity.y = Mathf.Sqrt(jumpHeight * -2f * gravity);
    }

    // --- Gravity Application ---
    velocity.y += gravity * Time.deltaTime;
    controller.Move(velocity * Time.deltaTime);
}
```

Figure 5-7 Gravity-based vertical motion

5-3-5 Jumping & Crouching

The inclusion of jumping and crouching within the technician mode of the hydropower virtual environment facilitates enhancing the interactivity of user experience. These movements replicate fundamental human actions required during facility inspections and maintenance operations which enable users to navigate tight spaces, step over minor obstacles, or reach elevated platforms in a manner consistent with real-world physical behaviour.

The jumping provides the player with the ability to temporarily overcome gravitational constraints which allows brief vertical displacement before naturally returning to the ground. Technically, this is achieved through the application of an upward impulse to the player’s Rigidbody component when the designated jump key (spacebar) is pressed.

Conversely, the crouching allows the player to reduce their standing height temporarily which simulates the act of bending or lowering the body to pass beneath obstacles, inspect lower machinery parts, or operate controls situated near the ground level. Crouching is achieved by dynamically adjusting the character collider's height and the camera's position within the player's hierarchy. When the crouch key (the **C** Control key) is pressed, the system gradually interpolates the collider size and camera offset to reflect the lowered posture.

```
// --- Jump ---
if (Input.GetButtonDown("Jump") && isGrounded && !isCrouching)
{
    velocity.y = Mathf.Sqrt(jumpHeight * -2f * gravity);
}

// --- Crouch ---
if (Input.GetKeyDown(KeyCode.LeftControl) || Input.GetKeyDown(KeyCode.C))
    isCrouching = true;
else if (Input.GetKeyUp(KeyCode.LeftControl) || Input.GetKeyUp(KeyCode.C))
    isCrouching = false;

float targetHeight = isCrouching ? crouchHeight : standHeight;
controller.height = Mathf.Lerp(controller.height, targetHeight, Time.deltaTime * cro

float targetCamY = controller.height / 2f;
Vector3 camPos = cameraTransform.localPosition;
camPos.y = Mathf.Lerp(camPos.y, targetCamY, Time.deltaTime * crouchTransitionSpeed);
cameraTransform.localPosition = camPos;
```

Figure 5-8 Jump and crouch mechanics

5-3-6 Component Controls

This part of the project introduces component control systems and operational interfaces that indicate the real-world operational processes. These include the opening and closing of valves, the start/stop of turbines, and the monitoring of system parameters through electrical panels and generator dashboards. Each of these interactive modules has been carefully designed to reflect the logical and procedural workflow of hydropower plant operation. Within the simulation, player (technician) can approach machinery, initiate or halt turbine functions, regulate water flow through valve manipulation, and observe corresponding system responses in real time. The dashboards and status panels provide continuous feedback on mechanical performance, power output, and system stability.

5-3-6-1 Opening / closing Valves

The valve control system has been developed to authentically replicate the mechanical behaviour of hydraulic gates in a hydropower facility. The valve model used is of the counterbalance type, which operates similarly to the door of a washing machine rotating outward around a fixed hinge instead of following a purely vertical or linear motion. This design allows the virtual valve rotation to accurately represent the physical characteristics and movement of real industrial valves. Within the Unity environment, the player can interact with the valve by approaching it and pressing a designated key (E), which triggers a smooth and realistic opening sequence. The animation is governed by a controlled rotation around a pivot point that mirrors the mechanical hinge mechanism.

```
void Update()
{
    // Toggle valve when player presses E
    if (isPlayerNearby && Input.GetKeyDown(KeyCode.E))
    {
        isValveOpen = !isValveOpen;
        targetValveAngle = isValveOpen ? valveOpenAngle : 0f;
        Debug.Log(isValveOpen ? "Valve opened!" : "Valve closed!");
    }

    // Smoothly rotate valve (Y-axis)
    currentValveAngle = Mathf.MoveTowards(
        currentValveAngle,
        targetValveAngle,
        valveTurnSpeed * Time.deltaTime
    );
    transform.localRotation = Quaternion.Euler(0, currentValveAngle, 0);
}

void OnTriggerEnter(Collider other)
{
    if (other.CompareTag("Player"))
        isPlayerNearby = true;
}

void OnTriggerExit(Collider other)
{
    if (other.CompareTag("Player"))
        isPlayerNearby = false;
}
```

Figure 5-9 Player-triggered valve control

5-3-6-2 Start/stop Turbine

The operation of the turbines in this virtual hydropower facility has been designed to reflect the dynamic relationship between mechanical activation and hydraulic input. Once the valve is opened, allowing water to flow through the penstock, the turbine automatically begins to rotate which replicates the physical behaviour of energy transfer from fluid motion to mechanical rotation. In this project, the turbine start / stop mechanisms are directly controlled by player interactions within the Unity environment which simulates a technician’s field operations. By pressing a specific interaction key near the turbine or its control valve, the user can visualise the Activation / deactivation of turbine .

```
void Update()
{
    // --- Valve Toggle ---
    if (isPlayerNearby && Input.GetKeyDown(KeyCode.E))
    {
        isValveOpen = !isValveOpen;
        targetValveAngle = isValveOpen
            ? valveOpenAngle
            : 0f;

        Debug.Log(isValveOpen
            ? "Valve opened!"
            : "Valve closed!");
    }

    // --- Valve Rotation ---
    currentValveAngle = Mathf.MoveTowards(
        currentValveAngle,
        targetValveAngle,
        valveTurnSpeed * Time.deltaTime
    );

    transform.localRotation = Quaternion.Euler(
        0, currentValveAngle, 0
    );
```

Figure 5-10 Valve toggle Interaction

The rotational behaviour of the turbine blades is governed by a dedicated script that activates when the valve reaches an open state. This link ensures that turbine motion cannot occur without proper hydraulic input which reflects the real-world interdependence between flow control and mechanical performance. Furthermore, in order to ensure the physical accuracy, each turbine's rotation axis and pivot point are precisely aligned with its geometric center, which produce a smooth and consistent spin pattern that mirrors the movement of real Francis and Pelton turbines.

```
    // --- Turbine Spin ---
    if (turbineBlades != null)
    {
        float targetSpeed = isValveOpen
            ? maxTurbineSpeed
            : 0f;

        float accel = isValveOpen
            ? spinAcceleration
            : spinDeceleration;

        currentSpinSpeed = Mathf.MoveTowards(
            currentSpinSpeed,
            targetSpeed,
            accel * Time.deltaTime * 100f
        );

        turbineBlades.localRotation *= Quaternion.Euler(
            0, currentSpinSpeed * Time.deltaTime, 0
        );
    }
}
```

Figure 5-11 Turbine spinning's logic

5-3-6-3 Status dashboard of Electrical Panels

The electrical panel status dashboard serves as a critical interface between the hydropower facility's physical components and the digital monitoring system developed in Unity. In each electrical panel the operational states of valves, turbines and their corresponding power output are visually presented which allows the technicians to assess system's performance in real time.

Each panel is designed to activate through direct player interaction that simulates a real-world technician approaching and inspection of an electrical cabinet. When the user presses the interaction key (E) near a panel, the UI panel appears that displays information on turbine status (running or stopped), valve position (open or closed), and generated power (in megawatts). The status dashboard of electrical panels bridges the mechanical and digital dimensions of the hydropower system that embodies the essence of digitalization in facility management.

```
public TextMeshProUGUI turbineStatusText;
public TextMeshProUGUI turbineRPMText;
public TurbineController turbineController; // Reference to your turbine logic

void Update()
{
    if (playerInRange && Input.GetKeyDown(KeyCode.E))
    {
        if (technicalUIPanel != null)
        {
            bool isActive = technicalUIPanel.activeSelf;
            technicalUIPanel.SetActive(!isActive);
            Debug.Log("Toggled UI panel");

            if (!isActive && turbineController != null)
            {
                turbineStatusText.text = turbineController.isValveOpen
                    ? "Turbine Active"
                    : "Turbine Idle";

                turbineRPMText.text = turbineController.currentSpinSpeed.ToString("F
            }
        }
    }
}
```

Figure 5-12 Electrical Panel UI Toggle Based on Player Proximity

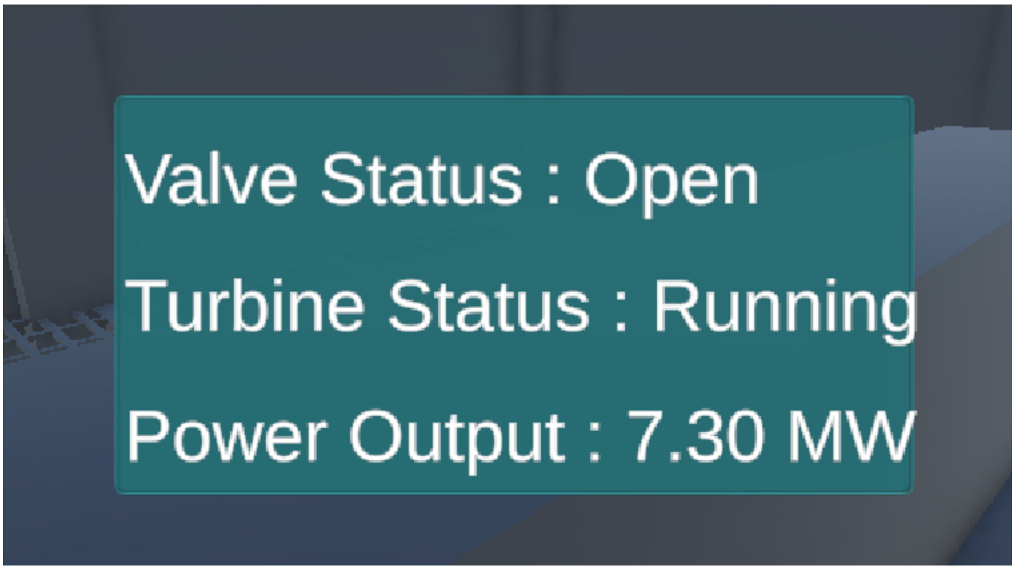

Figure 5-13 Electrical Panel operational display

5-3-6-4 Status dashboard of generator

The generator status dashboard represents one of the most crucial components of the hydropower facility's virtual monitoring system. Its main purpose is to provide user the real-time insights of the operational condition of the generator and its synchronization with the active turbines.

When the player approaches the generator and interacts using the designated input key, the corresponding UI panel is displayed. This interface immediately assesses the current operational state of the turbines and valves which verifies whether conditions are suitable for generator activation. For example, if the turbines are inactive or the valves remain closed, the dashboard issues a warning message which indicates that synchronization cannot proceed until the hydraulic system is fully operational. Conversely, when one or both turbines are running, the dashboard dynamically updates to reflect generator activity, accompanied by the combined power output. To enhance the interpretability of data, visual hints such as color-coded alerts and text feedback are incorporated into the design. A red indicator suggests a stopped turbine or closed valve, while green indicates active power generation.

```
public class GeneratorUIController : MonoBehaviour
{
    [Header("Turbine References")]
    public ValveAndTurbine francisTurbine;
    public ValveAndTurbine peltonTurbine;

    [Header("UI Elements")]
    public GameObject generatorUIPanel;
    public TextMeshProUGUI alertText;

    private bool isPlayerNearby = false;
    private bool isPanelVisible = false;

    void Start()
    {
        if (generatorUIPanel != null)
            generatorUIPanel.SetActive(false);
    }

    void Update()
    {
        if (isPlayerNearby && Input.GetKeyDown(KeyCode.E))
        {
            isPanelVisible = !isPanelVisible;
            generatorUIPanel.SetActive(isPanelVisible);

            if (isPanelVisible)
                UpdateGeneratorStatus();
        }
    }
```

Figure 5-14 Generator UI Controller Script for Player Interaction and Status Display

Figure 5-15 Generator Operational Display

```
public void UpdateGeneratorStatus()
{
    bool francisRunning = francisTurbine != null && francisTurbine.IsTurbineRunn
    bool peltonRunning = peltonTurbine != null && peltonTurbine.IsTurbineRunning

    string message = "";

    if (francisRunning && peltonRunning)
    {
        message = " Both Francis and Pelton Turbines are Running\nPower Output:
        alertText.color = Color.green;
    }
    else if (francisRunning)
    {
        message = " Francis Turbine Running\nPower Output: 7.30 MW";
        alertText.color = Color.green;
    }
    else if (peltonRunning)
    {
        message = " Pelton Turbine Running\nPower Output: 6.91 MW";
        alertText.color = Color.green;
    }
    else
    {
        message = " No Turbines Running\nPower Output: 0 MW";
        alertText.color = Color.red;
    }

    alertText.text = message;
}
```

Figure 5-16 Conditional Logic for Displaying Turbine Status and Power Output

5-4 Managerial Mode

The Managerial Mode provides a complementary perspective focused on performance monitoring, strategic assessment, and decision support. Unlike the hands-on interactivity of the Technician Mode, this mode adopts a higher-level view which enables users to analyse the operational data of the hydropower plant through an interactive dashboard. The user interface presents a set of panels that visualize key indicators such as turbine efficiency, seasonal variations in power generation, and the comparative performance of different turbine types, such as Francis and Pelton turbines. These visualizations are represented through charts and graphs derived from the operational data simulated within the system.

This mode is intended to support facility managers and planners in understanding broader operational trends rather than individual equipment performance. The dashboard design allows users to switch between various analytical views which facilitates quick evaluations of total energy output, maintenance requirements, and resource efficiency. In addition, the system can be extended to integrate predictive insights that help anticipate performance changes over time. By focusing on data visualization rather than physical interaction, the Managerial Mode transforms the virtual environment into a platform for informed decision-making and long-term operational planning.

```
    public void ActivateManagerMode()
    {
        Debug.Log("🔷 Switched to Manager Mode");

        isManagerMode = true;
        technicianModeRoot.SetActive(false);
        managerModeRoot.SetActive(true);

        if (technicianCamera) technicianCamera.enabled = false;
        if (managerCamera) managerCamera.enabled = true;

        Cursor.lockState = CursorLockMode.None;
        Cursor.visible = true;
    }

    public void ActivateTechnicianMode()
    {
        Debug.Log("🛠 Switched to Technician Mode");

        isManagerMode = false;
        technicianModeRoot.SetActive(true);
        managerModeRoot.SetActive(false);

        if (technicianCamera) technicianCamera.enabled = true;
        if (managerCamera) managerCamera.enabled = false;

        Cursor.lockState = CursorLockMode.Locked;
        Cursor.visible = false;
    }
}
```

Figure 5-17 Runtime Mode Switching Logic Between Technician and Manager Views

Figure 5-18 Managerial mode interface showing buttons for Turbines

Francis Turbine Performance Overview

The Francis turbine, as one of the most widely used reaction turbines in medium-head hydropower plants, plays a critical role in ensuring reliable energy generation and community service continuity. Within this project, the turbine's operational performance is analysed through three major indicators: the number of people served, seasonal power output, and the energy consumption–supply gap. These parameters collectively represent both the social and technical effectiveness of the turbine system and are visualized interactively within the virtual reality (VR) managerial mode. The VR environment provides users with the ability to explore these dynamic relationships in a digitalized facility management framework which connects the understanding between physical processes and operational outcomes.

5-4-1-1 Service Coverage of Francis Turbine

The Francis turbine demonstrates seasonal variations in service coverage, with the number of people served fluctuating according to hydrological and demand conditions. The highest service level occurs in spring (9,885 people), followed by summer (8,715 people), while the lowest values are observed in autumn (6,863 people) and winter (6,979 people). The superior coverage during spring resulting from the increased water availability from snowmelt and elevated river discharge, which enhances generation capacity and grid stability. Conversely, the reduced service in autumn and winter caused by the diminished water inflow which leads to a decrease in generation efficiency and limiting the extent of supplied regions.

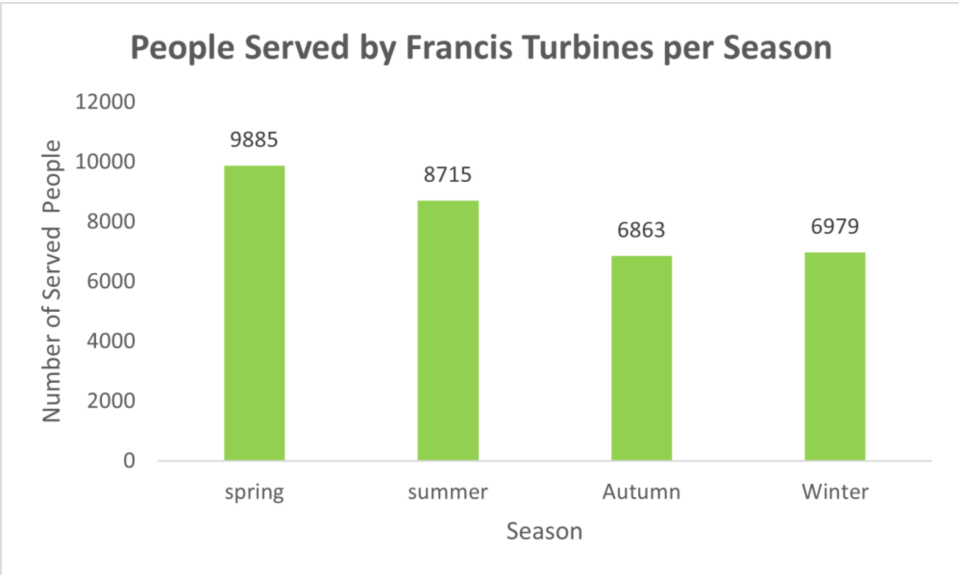

Figure 5-19 Francis Turbine's Service Coverage

5-4-1-2 Power output of Francis Turbine

This Figure illustrates the seasonal variation in the power output of the Francis turbine which highlights the influence of hydraulic conditions on energy generation. During summer, the turbine reaches its maximum recorded output of 7.3 MW which reflects favourable flow rates and head pressure due to increased water availability. In contrast, winter performance declines to 5.18 MW which representing roughly a 29% reduction in output. This reduction is consistent with seasonal decreases in river discharge and higher water viscosity caused by lower temperatures, both of which diminish turbine efficiency.

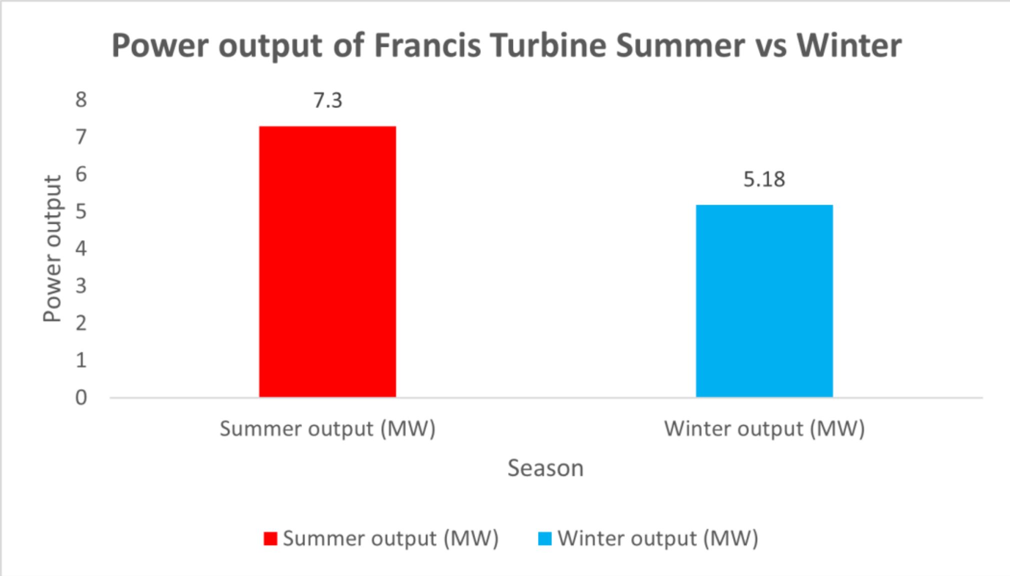

Figure 5-20 Power output of Francis Turbine Per Season

The results confirm that, while the Francis turbine remains operationally stable across all seasons, its energy yield is highly sensitive to hydrological changes. These findings highlight the importance of real-time monitoring and adaptive facility management capabilities that are enhanced in this project through the virtual reality environment which allows operators to visualize performance fluctuations and adjust operational parameters accordingly.

5-4-1-3 Gap Between Energy Consumption and Production per season (Francis)

Finally, the Figure 5-21 illustrates the seasonal fluctuation in the energy gap between consumption demand and supply for the Francis turbine system. The data reveal a pronounced variation across seasons, with the smallest gap recorded during spring (0.08 MW) and summer (1.08 MW), compared to substantially higher deficits in autumn (2.37 MW) and winter (2.24 MW). The reduced gap in spring and summer primarily results from increased water outflow due to irrigation activities, which enhances turbine discharge and stabilizes electricity production. During these periods, the hydropower facility operates near optimal flow conditions which allows the generated power to closely match consumer demand. In contrast, autumn and winter exhibit reduced flow rates and lower reservoir replenishment, which constrains turbine output and widen the supply–demand gap. This pattern highlights the dependency of hydropower efficiency on seasonal hydrological cycles. Through the VR-based monitoring platform developed in this project, such disparities can be visualized interactively which enables managers to notice supply shortages and adjust operational schedules or load distributions proactively.

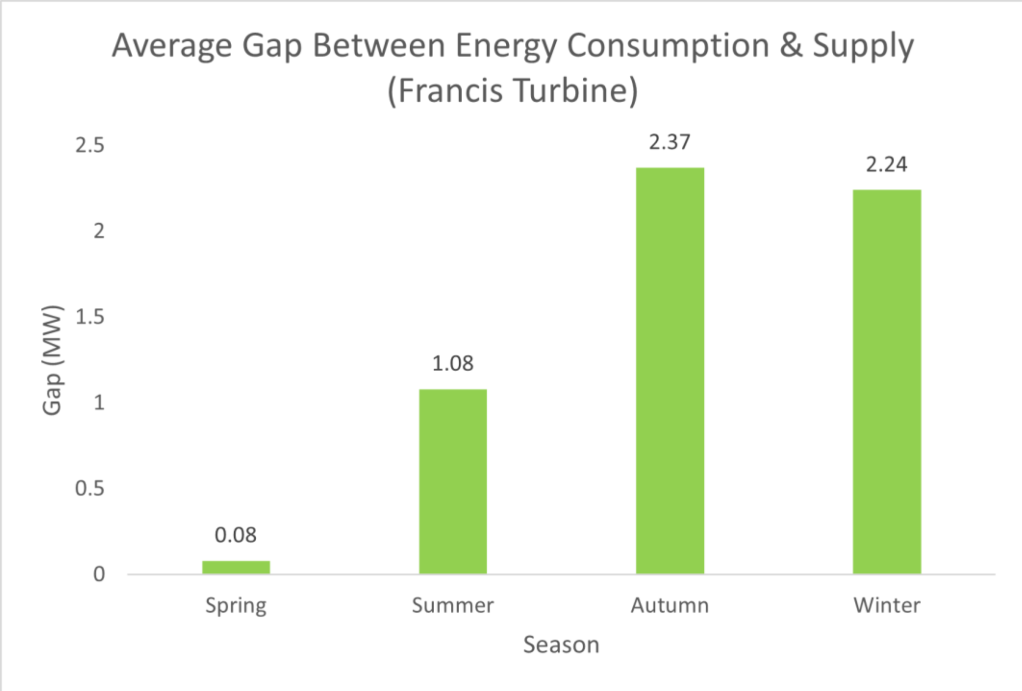

Figure 5-21 Gap Between Energy Consumption & Supply (Francis Turbine)

5-4-2 Pelton Turbine Performance Overview

The Pelton turbine, characterized by its impulse-based design, plays a complementary role in the hydropower facility's energy generation strategy, particularly in regions with high head and low flow conditions. Its operational dynamics are well-suited for seasonal variability which offers efficient performance during periods of fluctuating water availability. Within the virtual simulation environment, the Pelton turbine's behaviour is modelled to reflect real-world conditions, including jet velocity, runner interaction, and mechanical output. This allows for a detailed analysis of its contribution to the overall energy mix and its capacity to support population-level energy demands.

5-4-2-1 Service Coverage of Pelton Turbine

As illustrated in following Figure, the number of individuals served by the Pelton turbine exhibits marked seasonal variation. The highest service coverage is observed in spring, with approximately 9,364 people benefiting from the turbine's output. This is followed by summer, serving 8,256 individuals. In contrast, autumn and winter show reduced service levels, with 6,501 and 6,612 people served, respectively. These fluctuations are indicative of the turbine's sensitivity to seasonal hydrological inputs, particularly the availability of high-pressure water sources required for optimal impulse generation.

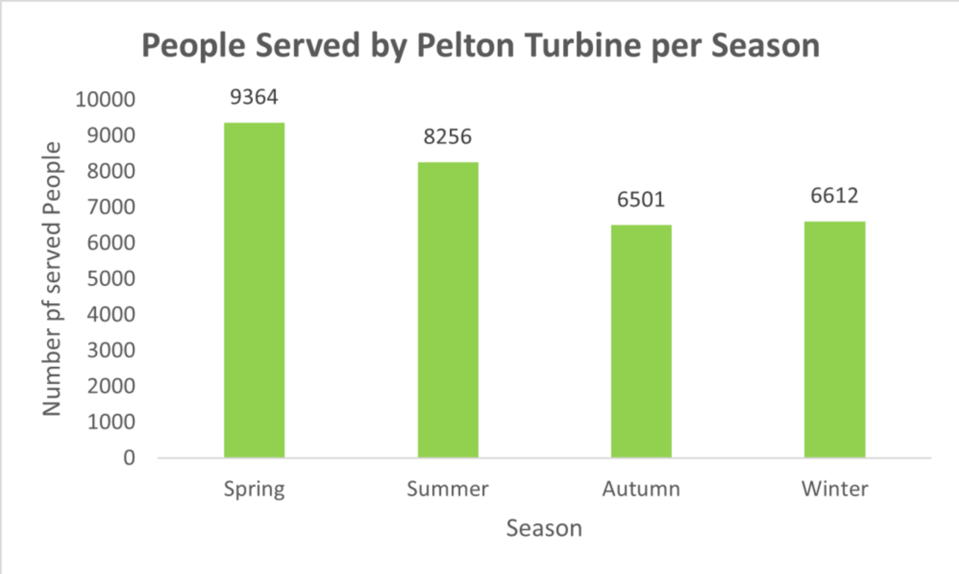

Figure 5-22 Pelton Turbine's Service Coverage

5-4-2-2 Power output of Pelton Turbine

Figure 5-23 presents a comparative analysis of the Pelton turbine's power output across summer and winter seasons. During summer, the turbine achieves a peak output of 6.91 MW, attributed to favourable hydraulic conditions such as increased head and reduced flow turbulence. Conversely, winter output declines to 4.91 MW which represents a reduction of approximately 29%. This decrease aligns with seasonal limitations in water pressure and jet force, which directly impact the turbine's mechanical efficiency. The data underscores the importance of seasonal planning in hydropower operations, particularly for impulse turbines whose performance is closely tied to environmental conditions.

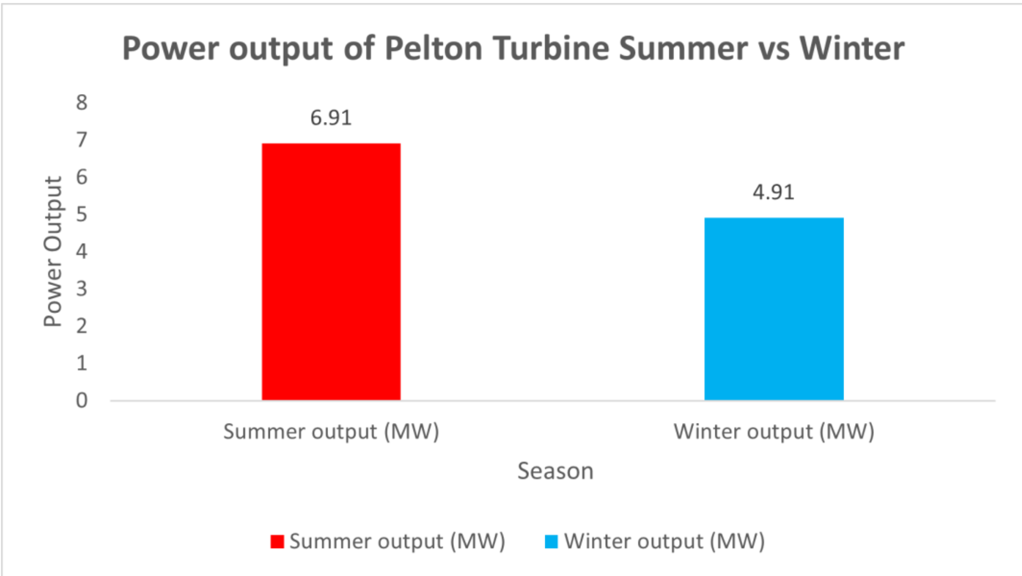

Figure 5-23 Power output of Pelton Turbine Per Season

5-4-2-3 Gap Between Energy Consumption and Production per season (Pelton)

The Figure 5-24 presents the average gap between energy consumption and supply for the Pelton turbine. The results indicate a minimal gap in spring (0.47 MW) and summer (1.46 MW), followed by a sharp increase in autumn (2.64 MW) and winter (2.52 MW). The smaller discrepancies in spring and summer can be attributed to higher outflows driven by irrigation demand, which enhance turbine performance and reduce the mismatch between energy supply and consumption. Conversely, during autumn and winter, reduced discharge capacity and increased energy demand widen the gap which indicates a less efficient operational balance. Within the VR management system, this data is integrated into interactive dashboards which users can visualize real-time performance fluctuations and develop optimized management strategies that respond dynamically to seasonal hydrological conditions.

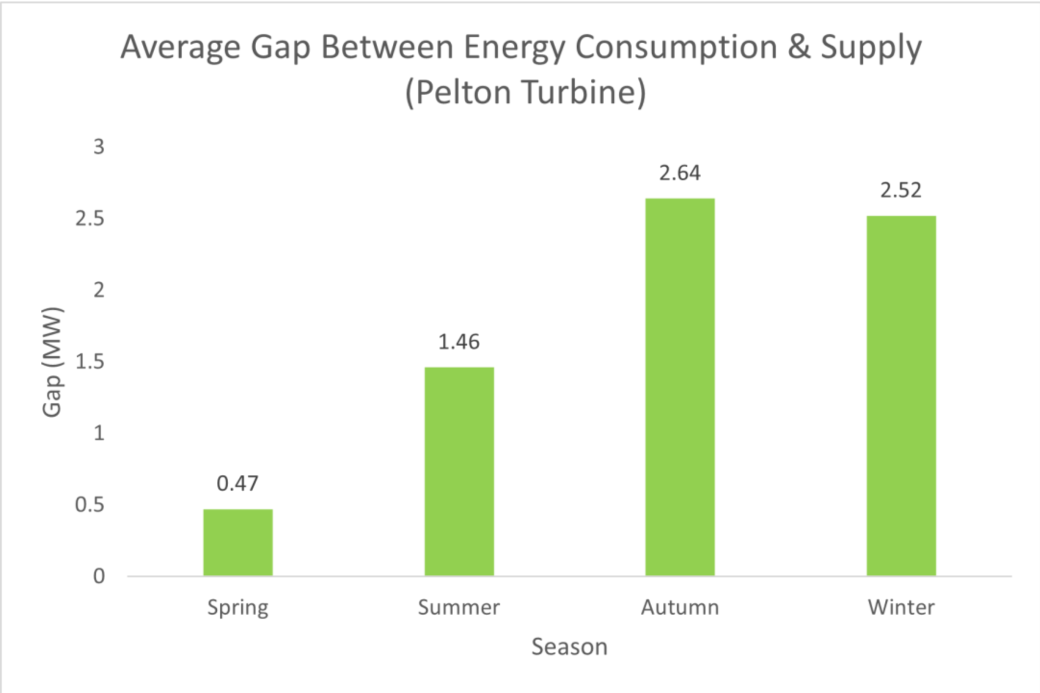

Figure 5-24 Gap Between Energy Consumption & Supply Pelton Turbine

5-4-3 Performance Comparison of Turbines

This section presents a comparative evaluation of the Francis and Pelton turbines in terms of their operational performance, service coverage, seasonal power output, and the balance between energy consumption and supply. The comparison aims to highlight how each turbine type responds to varying hydraulic and seasonal conditions within the same hydropower infrastructure. The Francis turbine, being a reaction type, operates efficiently under medium head and flow conditions, while the Pelton turbine, an impulse type, is optimized for high-head, low-flow scenarios. By examining their respective service coverage levels, the seasonal fluctuations in power output, and the gaps between generated and consumed energy, this analysis provides a comprehensive understanding of their complementary roles in maintaining system reliability. Through data visualization and simulation within the virtual reality environment, users can observe how each turbine's performance adapts to seasonal variations which offers valuable insights for improving energy management strategies and optimizing hydropower operations across different demand and flow regimes.

5-4-3-1 Service coverage Comparison

The comparative analysis of service coverage between Francis and Pelton turbines across seasonal variations reveals a consistent trend: both turbine types serve a greater number of people during spring and summer than in autumn and winter. This increase is attributable to higher outflow rates during the warmer seasons, which enhance the operational capacity of the turbines. Specifically, Francis turbine consistently outperform Pelton turbine in terms of service coverage, which can be attributed to their superior hydraulic efficiency and adaptability to variable flow conditions.

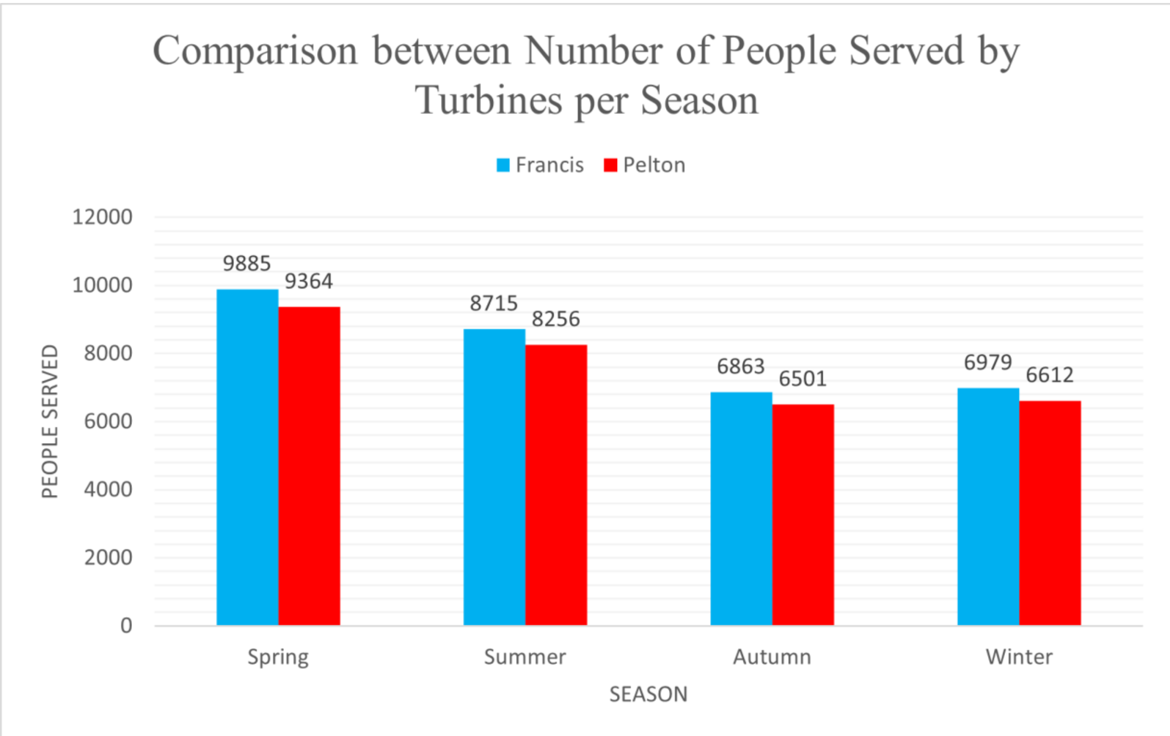

Figure 5-25 Service Coverage Comparison of Turbines

5-4-3-2 Seasonal Power Output Comparison

The seasonal power output data further supports the efficiency advantage of Francis turbines over Pelton turbines. In both summer and winter, Francis turbine demonstrates higher power output, with a more significant difference during the summer season. This performance differential is mainly due to the higher energy conversion efficiency of Francis turbines, which are better suited to handling moderate to high flow rates with minimal energy loss. The elevated summer output correlates with increased water availability which reinforces the role of seasonal hydrological conditions in turbine performance. These findings highlight the operational benefits of deploying Francis turbines in regions with significant seasonal flow variation.

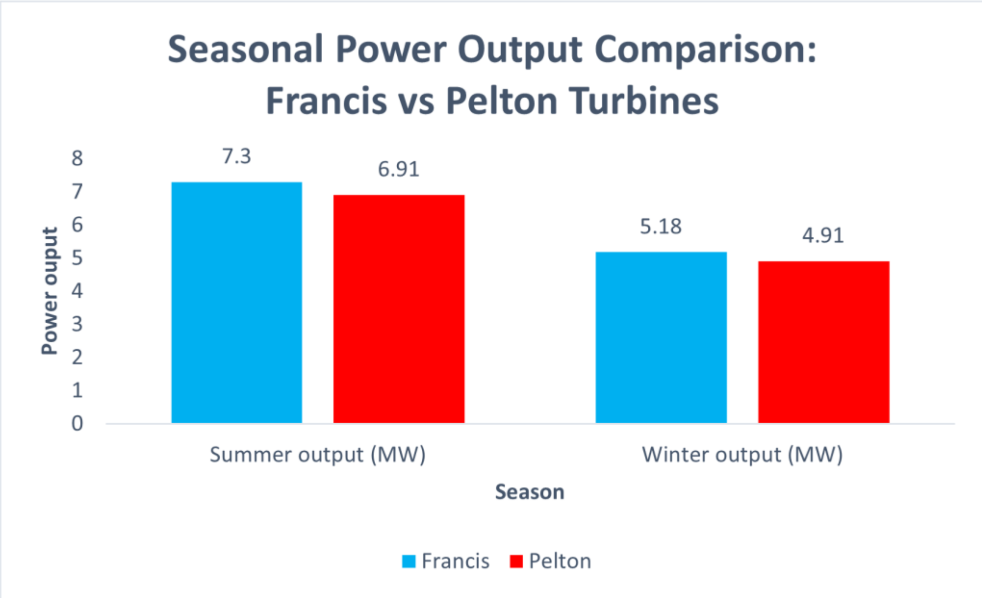

Figure 5-26 Seasonal Power output comparison of Turbines

5-4-3-3 Energy Consumption & Supply Gap Comparison

The analysis of the average gap between energy consumption and supply across seasons reveals a marked reduction in spring, particularly for Francis turbines. This reduction is closely linked to increased outflow rates during spring, which enhance generation capacity and narrow the supply-demand gap. Across all seasons, Francis turbines exhibit a consistently smaller gap compared to Pelton turbines which reflects their higher efficiency and better alignment with consumption patterns. The data suggest that turbine selection plays a critical role in minimizing energy deficits, especially in seasons where water availability fluctuates. Optimizing turbine deployment based on seasonal flow dynamics can thus contribute to more balanced and reliable energy provision.

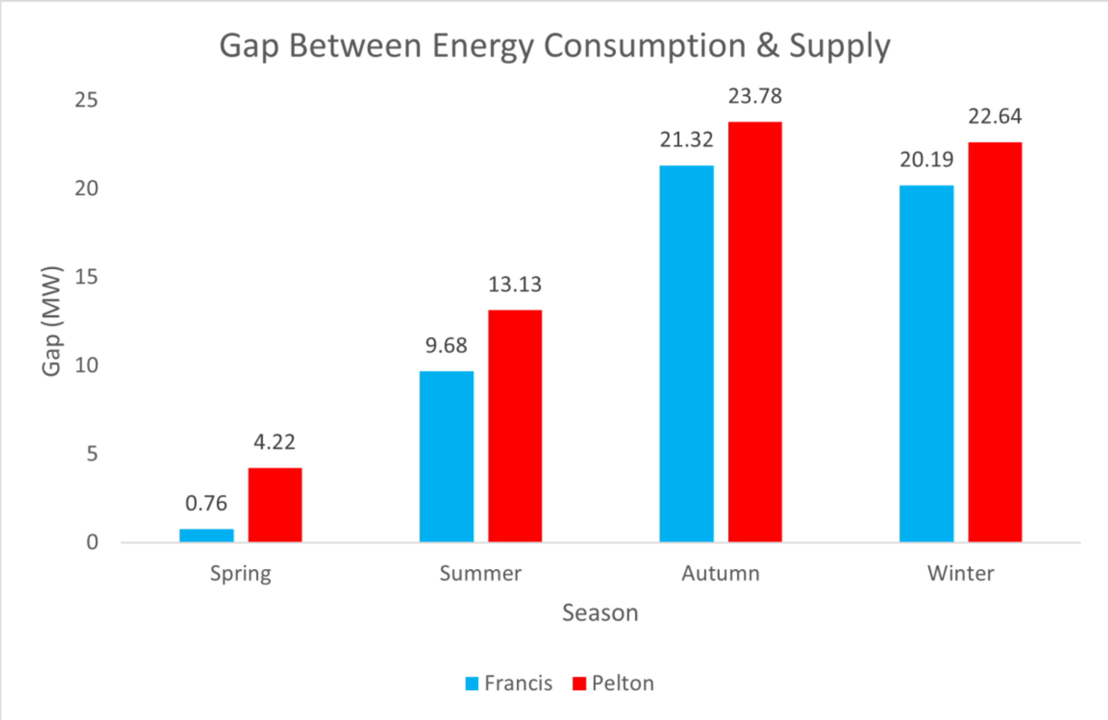

Figure 5-27 Gap Between Energy Consumption & Supply (Both Turbines)

Chapter 6 : Conclusion & Future Research

6-1 Chapter overview

This chapter presents the overall conclusion of the study which provides a comprehensive summary of the key findings and outcomes achieved throughout the project. It reviews the main objectives, highlights the significance of implementing virtual reality (VR) for hydropower facility management, and reflects on the performance of the developed simulation system. In addition, this chapter outlines future recommendations for enhancing the functionality, realism, and applicability of the system, offering potential directions for continued research and technological development in digital hydropower management.

6-2 Summary of the Project

This project developed a virtual reality (VR) environment for the digitalization and management of hydraulic infrastructures which integrates both technical and managerial perspectives. The simulation aimed to enhance understanding, operation, and monitoring of critical components such as turbines, valves, generators, and electrical panels. Through the use of Unity, interactive control systems were designed to replicate real-world functionalities including valve rotation mechanisms, turbine start/stop procedures, and dynamic status dashboards which allows users to experience realistic facility management processes within a controlled digital space.

Two operational modes were established: Technician Mode and Managerial Mode. Technician Mode focused on hands-on interaction with hydraulic components which provides immersive engagement with the mechanical and electrical systems. Managerial Mode, on the other hand, offered a broader overview of system performance through visualized data dashboards and charts that enables the evaluation of service coverage, energy output, and operational efficiency. This dual-mode framework ensured that both on-site maintenance activities and high-level decision-making processes could be simulated within a single integrated environment.

Performance analysis concentrated on Francis and Pelton turbines, comparing their seasonal behaviour in terms of power output, service coverage, and energy consumption–supply balance. The results demonstrated complementary performance patterns between the two turbines: the Francis turbine exhibited superior output during high-flow seasons (spring and summer), while the Pelton turbine maintained efficient operation in low-flow, high-head conditions (autumn and winter). Seasonal variations in population served and power generation highlighted the adaptability of both turbines under fluctuating hydraulic and energy demand conditions. Furthermore, the analysis of the energy consumption–supply gap indicated reduced inefficiency during irrigation periods, when higher water discharge supported stronger power generation. Overall, the system's digital replication provided valuable insights into performance optimization and infrastructure management under varying operational constraints.

The integration of VR as a visualization and management tool underscores its potential in modern facility management. By combining data-driven dashboards, user interaction, and physical process simulation, this approach facilitates not only improved operational awareness but also enhanced training, safety, and strategic planning. In summary, this project successfully demonstrated how digitalization through immersive virtual environments can transform traditional hydropower operations into smarter, more sustainable, and interactive systems.

6-3 Future Research & Recommendations

While the developed VR system presents a comprehensive digital framework for hydraulic infrastructure management, several directions for future research and development are recommended to expand its functionality and impact.

Integration with Real-Time Data:

Future iterations could connect the virtual model to live sensors and Supervisory Control and Data Acquisition (SCADA) systems which allows real-time monitoring of parameters such as flow rate, pressure, and energy production. This connection would enhance operational accuracy and enable predictive maintenance strategies based on live performance indicators.

Advanced Interaction and Haptic Feedback:

Incorporating haptic feedback devices and gesture-based interfaces would further improve realism in technician interactions, particularly for simulating maintenance tasks such as valve adjustments or turbine inspections.

AI-Driven Optimization:

Implementing artificial intelligence algorithms could support automatic fault detection, performance prediction, and decision-making assistance for energy balancing and maintenance scheduling. This would shift the system from a reactive to a proactive management model.

Expanded System Components:

Additional hydraulic and electrical subsystems such as spillways, penstocks, or control gates could be integrated to provide a more holistic representation of dam and power plant operations.

Collaborative and Remote Access Features:

Enabling multi-user or networked VR environments would allow technicians and managers to collaborate remotely within the same virtual infrastructure, fostering improved communication and decision-making.

Training and Educational Applications:

Beyond operational management, the system could be adapted for academic and professional training, offering scenario-based simulations for emergency response, load management, and equipment diagnostics.

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