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Emerging Innovative technologies and Materials in Hydropower Sector
(A review)

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ABSTRACT

Various technological developments are now occurring in the hydropower sector. New technologies and practices are being developed to improve the hydropower system's adaptability and sustainability. To boost performance, durability, and flexibility, new novel materials that have been discovered through various research projects have also recently been introduced. In addition to improving efficiency, resistance, dependability, and durability, these cutting-edge materials have the potential to have a substantial impact on the hydropower sector's ability to manufacture, install, and transport equipment. Several novel materials are being introduced and numerous studies are continuing in the hydropower industry. Novel materials can be used for both new power plants and restoration projects. This study describes the most relevant novel materials used in various hydropower structure parts and components.

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1. INTRODUCTION

Hydropower is a type of renewable energy source that converts water power into electricity by spinning a turbine and an electric generator. In order to meet the world's energy needs and reduce the temperature rise that is primarily brought on by fossil fuels, the installed hydropower capacity, which was 1308 giga watts (GW) in 2020, is expected to rise by around 60% by 2050. An estimated 1.7 trillion USD in investment is needed to expand hydropower, which will result in the creation of 600 000 specialist jobs. The hydroelectric sector now faces new challenges: In order to provide auxiliary services that can function efficiently on a daily and seasonal basis by taking into consideration the extremely unpredictable nature of wind and solar power generation, flexibility is required.

Pumped hydropower plants must be used to generate and use energy on demand. Larger storage reservoirs are required to minimize floods and droughts. Rural electrification also supports small-scale hydropower plants by connecting energy to already-existing hydraulic structures and insignificant obstacles that are now being used for diverse purposes. The negative consequences of hydropower facilities must be minimized, and they must be environmentally friendly. A number of innovative hydropower technologies are being developed to meet these needs. Due to the larger weight minimization of hydraulic components like turbine runners, Novel materials offer the potential to save manufacturing, labor costs, pollution, waste, and material costs while also improving durability and performance.

2. Research Method

This work is a review paper. Journals, articles and previous project works relevant to the above-mentioned topic were carefully studied and sampled purposefully. Different works were studied and summarized to come up with the information required for the preparation of the paper. This research was conducted using a meta-analysis.

3. Data

data used in this in this document is of secondary origin. Through review of papers, journal, articles, engineering conferences and reports online.

4. Emerging innovative technologies in hydropower

This section of this article discusses current research and development initiatives in the hydropower technology sector. New technology trends that aim to improve the adaptability, effectiveness, and economy of hydropower. These technologies include novel small-scale technologies, variable speed turbines, fish-friendly technologies, flexible hydropower, storage, digitalization, and generators with current-controlled rotors.

4.1 Hydropower Flexibility

Hydraulic turbines must be capable of operating under a variety of different situations in order to meet the varied production of electrical energy needs of renewable energy sources (sun and wind). Because of the limited energy storage capacity and changeable energy market demand, modern hydraulic turbines must operate with a great degree of flexibility throughout a wide aspect of operating conditions that are outside of their best efficiency point (BEP) [1].

Self-induced instabilities that arise during various off-design operating regimes and transient situations, such as start-up, emergency shut-down, load rejections, and runaway, which restrict the operating range of hydraulic turbines [2]. As a result of fatigue damages, the hydraulic turbine's structural integrity and lifetime are both reduced. In order to reduce the consequences, a number of strategies have been explored and created. Depending on the amount of energy pumped into the main flow, they are classified as either active or passive [3].

A) Passive control techniques

While active control techniques need energy for the control loop and auxiliary power, passive control techniques need not. Recently, a variety of passive control techniques have been developed and/or tested. Table 1 lists these passive methods together with their advantages and drawbacks.

Table 1. Passive control methods.

Passive control method	Advantages	Drawbacks
adjustable diaphragm [8]	reducing the draft tube surges on wide range regimes	Extra hydraulic losses
stabiliser fins [4]	reducing the draft tube surge	effective to limited regimes, local hydraulic losses
stator installed immediately downstream to the runner [7]	reducing the draft tube surges	effective to limited regimes, further hydraulic losses
runner cone extensions including freely rotation (FRUCE) concept [6]	reducing the draft tube surge	effective to limited regimes, lateral forces, reduction in kinetic energy recovery within the cone
water injection with flow feedback method (FFM) [8]	reducing the draft tube surge on wide range regimes, no additional volumetric losses, self-regulating	not identified yet
J-grooves [5]	reducing the draft tube surge	effective to limited regimes, further local hydraulic losses

B) Active control techniques

The active flow control techniques typically involve the injection of either water or air while utilizing an outside source of energy. Table 2 lists the primary active control strategies along with their benefits and shortcomings.

Table 2. Active control methods

Active control method	Advantages	Drawbacks
tangential water injection at the cone wall [10]	reducing the draft tube surge	further volumetric losses
air injection/admission [9]	reducing the draft tube surges on a variety of regimes	Extra losses, self-excitation amplification at a few operating points
water injection with flow feedback method and additional energy (FFM+) [11]	reducing the draft tube surge	not identified yet
axial water injection with high/low velocity [11]	reducing the draft tube surge	volumetric losses (additional)
inverse modulate water jet [13]	reducing the draft tube surge, modulated frequency targets a specific value	extra volumetric losses
water jet with tangential component [12]	reducing the draft tube surge	volumetric losses (additional)
water injection at the trailing edge of the wicket gates [15]	reducing RSI effects	volumetric losses (additional)
two-phase air-water injection [14]	reducing the draft tube surge on wide range regimes	extra losses

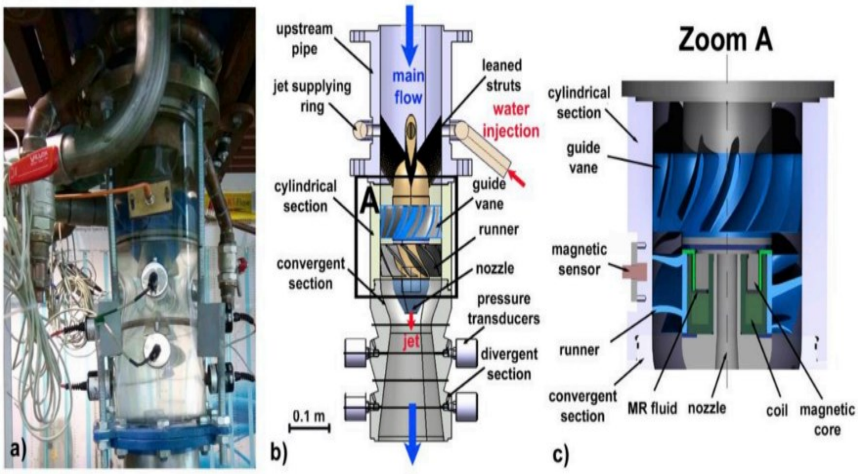

Figure 1. Swirl generator test rig designed to investigate different control techniques; a) photo of the test section installed on test rig; b) axial water injection [44]; c) magneto-rheological control technique [45].

4.2 Hydropower digitalisation

In order to deliver enhanced grid supporting services without compromising the reliability and stability of stations, real-world data must be collected and processed in order to modify the existing operating conditions of hydropower turbines.

Real-world (big) data on the actual working condition of the turbines must be obtained and elaborated in order to expand the capacity of hydropower facilities to provide sophisticated grid supporting services without jeopardizing their safety and efficacy. This emerging technology aims to support hydropower facilities in fulfilling the demands of the future electrical power system (EPS) by offering quick frequency containment reserve (FCR), frequency restoration reserve (FRR), and black start in emergencies.

This innovative idea has not yet been explored and builds on the knowledge gained from recent research projects [1], where a thorough sequence of tests and experiments were used to analyze the phenomena that needed to be managed and regulated. Such advanced technological development will add to the hydropower industry's "digitalization," which would change how projects are designed, run, upgraded, and maintained.

In many cases, the hydropower infrastructure that is already in place was built decades ago. As a result, their equipment has less digitalization than the systems and components used in the operation and maintenance (O&M) of contemporary renewable energy sources (RES), such as wind turbines. The potential to digitise the operation of hydroelectric equipment is provided by the refurbishment and upgrading of the current fleet. Rehabilitation and digitalization entail increasing overall efficiency and, thus, the amount of energy produced, in addition to extending lifespan and resolving cyber security issues. According to current projections, the 1225 GW of built hydropower capacity around the world could improve yearly production by 42 TWh [10], translating to $5 billion saving in annual operational and a considerable decrease in emissions of greenhouse gas.

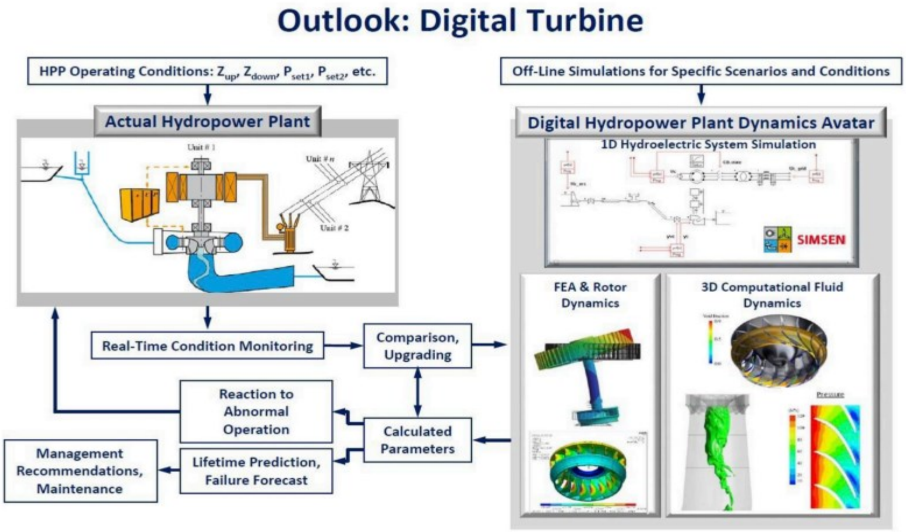

Figure 2. Information flow & exchange of a Digital Avatar for hydropower plant dynamics. Source [46]

4.3 Generators with current-controlled rotors

The energy conversion components experience additional wear as a result of the frequent starts and stops needed to provide secondary regulation. Inspections used to inform the maintenance engineer when maintenance work was necessary. currently, condition monitoring serves to alert users about the components' states. Condition-based maintenance is being tested as the next stage. The availability and affordability of sensors, data collecting, and data analysis are all increasing at the same time. Each large-scale hydroelectric power plant has sensors for vibration, voltage, temperature and current. But frequently, these sensors are merely employed to trip the unit and protect the system. If the units status could be actively sensed by the components, the advantage that is offered would be increased. As a result, the components would report as well as counteract, for instance, vibrations. In this manner, the system would be able to self-heal in some way when issues first arise.

Segmented rotors [16] and current-controlled rotor magnetization equipment may offer such a tool for producing air gap unbalances. Modern power electronics with current-controlled power supplies provide new options for controlling electrical equipment. Lower maintenance and investment costs may be possible when the idea of a segmented rotor is combined with novel theories of excitation [17]. The most obvious use of a segmented rotor system is to reduce undesirable forces as they arise inside the generator. Power electronic converters open up new options for electrical equipment. There is still much to learn, and fresh ideas should enhance the integration of electrical machines and power electronics.

4.4 Small-scale hydropower technologies

Small-scale hydropower is crucial to rural electrification and mini-grid strategies. In particular, the enhanced designs of gravity hydraulic machines turbines (like very low head turbines and hydrokinetic turbines), and (water wheels and Archimedes screws), and advanced designs and operation strategies for pumps as turbines (PATs), are being developed.

The environmental effects of building dams that prevent their licensing make it difficult to create new large-scale hydropower projects. Small-scale hydropower is typically more environmentally benign and may be able to provide a different clean energy option in the market for intermittent electricity. Small hydro's present operational and policy structure does not ensure favourable economic terms or a quick payback [18]. combined installations-operation with other energy technologies such as photovoltaic (PV) and optimised operation and control technologies could also increase its profitability. Small-hydro plays an important role in rural electrification strategies and mini-grid and it is particularly important in developing countries to support economic activities in remote areas.

4.4.1 Novel designs of gravity hydraulic machines

Gravity water wheels and Hydrodynamic screws are examples of gravity hydropower converters that have recently seen improvements in environmental impact, cost-effectiveness, especially on fish populations, as well as attractive efficiency [19]. In terms of more contemporary scientific endeavors, gravity water wheels have undergone significant testing. Depending on head differences and the maximum flow rate per metre width, they are classified as overshot, breastshot, and undershot water wheels [20]. Gravity machines' maximum hydraulic efficiency may surpass 80%, while average global efficiency values fall between 50 and 70 percent. The price of water wheels is lower than that of hydrodynamic screws and 33-60% less than that of Kaplan turbines [21]. When it is possible to renovate old water mills and turn them into desirable educational, tourist, and recreational destinations, water wheels can be helpful.

4.4.2 Advanced operation and design of pumps as turbines

PAT (Pump as turbines) are hydraulic pumps that operate as turbines in reverse mode. By connecting an induction motor that acts as a generator, they produce energy instead of consuming it. The main benefits of using hydraulic pumps as turbines include their mass production, small size, quick delivery, ease of maintenance, accessibility to spare parts, and lower installation costs [22]. The price is five to ten times less than that of conventional turbines. This is especially important in the context of micro hydropower schemes with installed power less than 100 kW, where the acquisition of the turbo-generator unit often accounts for 35% of the whole scheme cost [23].

Despite the advantages of using pumps as turbines (PATs), their market share in hydro turbines has just recently become insignificant. This is mainly due to the pump makers' and hydropower consulting firms' lack of expertise or interest in the subject, and partially due to the PAT's design and operation's few remaining technical issues. Even if there are a few examples of larger installations, most PAT-based schemes currently in use have nominal powers below 20 kW. Off-grid rural electrification projects in remote locations without access to local hydro turbine suppliers and energy recovery in pressurized water networks are PATs' two most notable fields of application [24].

4.5 Fish-friendly hydropower technologies

In order to get over the constraints on fish passages, recent efforts have focused on developing fish-friendly turbines for hydro plants with relatively higher head. The Alden and Minimum Gap Runner turbines were consequently introduced. The Alden turbine functions, particularly with head fluctuations of up to 25 m. The Alden turbine is a relatively new concept for a fish-friendly turbine. To reduce fish mortality, the shaft, which revolves around a vertical axis, has just three blades. Furthermore, it rotates at a slower rate than conventional turbine technology (120 rpm in the model).

The Alden turbine was initially developed and tested using computational fluid dynamics (CFD) and experiments at a pilot scale in the Alden research facility. A real-world model has been built and tested (1:8.71 scale). The results indicate that for fish under 20 cm, commercially available systems are expected to have a maximum hydraulic efficiency of 93.6% and fish passage survival rates of 98% or higher [25].

The Kaplan turbine has been upgraded to become the Minimum Gap Runner (MGR) turbine. Its construction reduces the distances between the hub and the adjustable runner blade as well as between the discharge ring and the blades. These modifications decreased fish damage and mortality while increasing turbine efficiency [25].

5. Novel materials

5.1 Novel materials for turbines and hydraulic equipment

Turbine in hydropower plant is the element responsible for converting waterpower into mechanical power. When working with water flow, a turbine's blades revolve around the rotation axis. The two types of hydraulic turbines are action turbines, which take advantage of the flow velocity, or the kinetic energy and flow momentum of the water and reaction turbines, which primarily take advantage of the pressure of the water. Only very low-head applications (< 5 m) are suitable for using gravity machines, which take advantage of the weight of water [26]. Hydrokinetic turbines, like wind turbines, harness the kinetic energy of rivers.

Austenitic steel alloys with a chromium content of 17% to 20% (> 12%; the minimum chromium composition should be 12% to provide atmospheric corrosion resistance) are frequently used for high-head turbines in order to increase the life span of the runner blades and improve the stability of the protective film.As an alternative, martensitic stainless steel, which has double the strength of austenitic stainless steel, can be used to create the blades. Stainless steel or Corten steel is typically used to make low-head machines. Typically, reinforced polymers, carbon fiber (CF), or fiber glass are used to create hydrokinetic turbines [27].

In general, the materials used to construct turbines for high-head applications must be able to withstand high stresses caused by water pressure as well as erosion, fatigue and cavitation. Low-head turbines do not undergo significant pressures or stresses, but their power to weight ratio is very low. The main goals of the materials selected are to be lighter and more resistant to wear and fatigue. Additionally, particularly in remote locations, a heavy turbine weight can dramatically raise transportation and installation expenses. Therefore, it's critical to minimize the weight of the turbine in order to increase the economic viability of very low-head applications [28].

By reducing the impacts of cavitation, erosion, corrosion, and fatigue, novel materials can offer a longer service duration for hydro equipment [29]. Cavitation happens when the liquid's pressure varies quickly, leading to the creation of voids and bubbles. Particularly in reaction turbines, the collapse of such gaps can result in powerful shockwaves due to the shift in fluid pressure. Components are damaged by silt erosion due to particle collisions on the substance. The process of repeating cyclic stresses, such as those caused by load changes and vibrations, is known as fatigue. The biofouling problem also affects the hydropower sector (the development of invasive organisms like zebra mussels on facilities like turbines as a result of bacterial build up). The joined effects of air and oxygen, known as corrosion, can be reduced by adopting new materials in place of steel. Stainless steels are complex alloys that predominantly consist of Cr and Ni with trace amounts of Mo, C, Mn, N, Ti and N. Based on their solubility, these elements can precipitate as secondary particles such as sulfides, carbides, and nitrides, improving the mechanical properties and corrosion resistance of the installed components.

5.2 Novel materials for dams and hydraulic structures

A dam is a hydraulic structure that blocks a river's water flow and creates an artificial basin upstream. It is referred to as a weir or barrier when a dam is constructed to control the water level of a river upstream without creating a sufficient artificial basin to store a sizable amount of water. Infrastructures that can be used for irrigation, electricity generating, flood control, and water delivery are reservoirs. Dam safety has dramatically increased, particularly since the 1990s. However, dam engineers are constantly looking for new technology to build dams that are more secure, cost-effective, and environmentally benign.

New dam materials have just been introduced. Glass fiber (GF-reinforced concrete) is a cement-based composite containing alkali-resistant GFs dispersed at random throughout the final product for appurtenant dam constructions. This has a strong resistance to abrasion and cavitation and it can be used as surface protection, for instance, on concrete composites likes spillway and others. Similar to the steel in reinforced concrete, the fibers support the tensile stress, extending the life of the structure. A precast concrete structure with conductive carbon fibres (CFs) can offer real-time load information on the structure, allowing for the early detection of issues before stress or cracking is obvious to the naked eye [30].

The rock-bolted underpinning system is another invention. A link to the riverbed is provided by an underpinning system that is rock-bolted and GPS-guided. The structure can be installed and fastened more easily as a result. With the help of numerous rock bolts, each of which is capable of supporting heavy loads, each piece is fastened to an existing dam or the riverbed. Metal rock bolts have been utilized in dam construction as well as mining for many years [31]. Pultruded composite rock bolts may also be essential in particular applications, and their modest weights can lessen their negative effects on the environment.

The layers of very huge rock boulders from quarries are used to create rock-filled concrete dams, which are subsequently filled with self-compacting concrete with a high fluidity. Advantages of rock-filled concrete include reduction in cement/concrete quantity and the absence of the need of compaction of concrete, in addition to the reduction of cracking risk of concrete during construction and heat effects. Finding self-compacting concrete that is strong enough and has a high viscosity is difficult. This process is an alternative to roller-compacting dry, low-cement concrete, in which the concrete is layered and subsequently compressed using vibrating rollers, as in the case of soil compaction. The advantage of rock-filled concrete dams is that they can be built upon and overtopped without fear of failure. Consequently, river diversion works such as diversion tunnels can be strictly controlled. Since cemented rockfill is the one with higher deformation modulus than conventional rockfill, it is less likely to cause substantial deformation in rockfill dams, which has advantages for the economy and lowers thermal impacts during construction [32]. The cemented material dam idea was put forth in 2009 with the promise of cost savings of 10% to 20% and a shortened construction time. In comparison to concrete, cemented material requires less processing, grading, screening, and mixing. For instance, based on the new concept of trapezoidal cemented sand-gravel dam and the facing symmetrical hardfill dam, the roller compacted concrete method has been improved during the past few decades. Cemented soil dams and the concrete-face rockfill dams add cement to a nearly untreated soil material, in contrast to roller compacted concrete, which employs chosen cement-sand-gravel combinations as traditional concrete. The symmetrical or trapezoidal shapes served as a compensating factor for the decreased resistance.

Another trend being developed to cover dam surfaces is bituminous conglomerate. A mixture of modified bitumen and aggregates makes up a modified bitumen sealing membrane (MBSM). The waterproofing activity is carried out by the binder stratifications of the modified bitumen sealing membrane, which, in terms of resistance to mechanical impacts, are comparable to a layer of 3 cm thickness in bituminous conglomerate [33]. Care must be given at the horizontal connection on the dam crest, which should eventually be reinforced, to prevent the strata from sliding downward and forming streams and infiltrations. Because the layers turn to plastic at a particular self-weight, bituminous material can only be used to build dams up to a certain height.

The advancement of concrete and the use of chemical adjuvants in injection technology with the goals of self-compaction, tightening, viscosity reduction, flexibility, quick placement, enhanced thermal behavior and fracture healing is a significant theme. Over the past few decades, this field has seen significant advancements.

In addition, efforts are being made to construct inflatable rubber weirs, especially for use in small hydropower sectors and with head heights under 3 m. The elastic, elliptical inflatable weirs can be inflated with air, water, or a combination of the two. They are made of rubberized material that is attached to a sturdy concrete base. When sediment flushing is needed, the structure can be inflated to act as a weir and deflated when not in use. The cost is typically lower than that of standard weirs of the same size. Steel clapping plates were used to connect rubber bodies. Although they might corrode, research is being done to develop GF-reinforced polymer composites to replace steel [34].

Investigations are also being done on novel surface treatments and coatings for hydraulic infrastructure and waterways. New canal coatings, like penstocks, reduce surface friction, which increases electricity output. Although concrete-lined tunnels are typically coated with steel or polyethylene reinforced by fiberglass, epoxy-based coatings may reduce friction losses and guard against future deterioration.

5.3 Novel materials for bearings

The shafts of the spinning components are supported by bearings, which are essential parts of hydraulic turbine units because they reduce friction (and the need for lubricant) and maintain shaft alignment. Because of the severe contact pressure circumstances (above 30 MPa) throughout a 40-years lifespan, hydropower turbine bearing operation is difficult. The most common hydrodynamic sliding bearings fall into three groups: shaft bushings, thrust bearings, and journal bearings [35].

The main causes of maintenance issues and expenses are friction and wear. Therefore, to decrease friction, wear, maintenance interventions, and expenses, as well as to increase machine performance, the majority of turbines employ pressurized oil inorder to lubricate the turbine bearings. Nonethless, oil leakage from hydraulic turbines may cause some operational and maintenance issues as well as harmful effects on the environment. Therefore, Eco tribology—the use of environmentally friendly tribological technology and components (such as bearings) is seen as an efficient strategy of engineering to increase the sustainability of hydropower applications [36].

The idea of eco-tribology in the hydropower sector has developed quickly recently, notably in the bearing context, in an effort to avoid the potential risk of oil spillage from hydropower units. With better or comparable tribological performance to the conventional lubricants, ecological/vegetable lubricants, water-based lubricants and self-lubricant bearings (with tribo-materials) have been created.

Although ecological/vegetable oils are biodegradable they have the drawback of degrading more quickly when combined with water than other mineral oils, which reduces their mechanical qualities. Vegetable oils also cost more than mineral oils, and if some materials are exposed to them, they may be vulnerable to degradation.

The low viscosity of water makes it possible for bearings to run in a boundary or mixed lubrication regime for comparatively longer periods of time, especially when low sliding speeds and start/stop cycles are taken into account. According to Ingram and Ray, water-lubricated guide bearings increase overall plant efficiency by reducing friction losses and maintenance when compared to oil-lubricated guide bearings since they are less expensive, nontoxic, and have a higher heat capacity. A water-lubricated guide bearing that was created especially for a multi-nozzle vertical Pelton turbine was detailed in detail by Oguma et al. Due to its low viscosity, high volatility and solvent character (corrosiveness) water is a poor lubricant for demanding technical applications. Low viscosity has the potential to greatly increase friction and lower the bearings' actual wear life. Because of this, using water-based lubrication poses significant engineering issues, particularly in terms of selecting a material for bearing surfaces that can guarantee a lifespan of 40 years and a friction coefficient below 0.1[37].

Bearings that self-lubricate have also been developed in order to reduce the need for lubricants. Generally, they are constructed of bronze or Teflon (a metal-based material) (plastic-based). The thrust bearings for runners, trunnion bearings and wear plates on spillway gates in turbines are likewise made of composite materials and self-lubricating polymers. Technology for coatings made of diamond-like carbon has also advanced dramatically in the past ten years. Self-lubricating bearings used to control the guide vanes and turbine blades are among the most affected components. However, due to the prevalence of intermittent solar and wind power plants with unpredictable output, conditions of operation of the hydropower plants are becoming more variable in response to the grid requirements [38].

5.4 Novel materials for sealing

A sealant joins parts, reduces water leakage, and guards against water and dirt infiltration. The biggest difficulty is sealing the turbine's main shaft. The sealing process should ideally be finished, but because it is expensive, the main goal of shaft sealing is to keep leakage to a manageable level.

Compression packing was employed in the first hydraulic turbine to seal the turbine shaft. Early packing, however, necessitates a sizable volume of water for cooling. Novel materials, lubricants, and blocking agents have been created as compression packing devices have advanced in order to increase the packing life by using less cooling water. Over time, a number of technologies have been created, such as carbon-segmented rings and elastomeric radial sealing components [39]. As an effective long-term sealing option for hydraulic turbines, mechanical sealing of axial faces is gaining popularity. As a sealing face, soft carbon graphite is frequently combined with a hard-facing substance (e.g., alumina ceramic). Even though alumina ceramic is a fairly effective insulator, its thermal properties and pressure-velocity (PV) performance are subpar. By dividing the pressure at the sealing contact by the mean face diameter of the mechanical seal's rotational velocity, the PV performance is calculated. The life lifetime is shortened due to significant wear and heat generation when the PV value exceeds the limit set on the sealing face pair [40]. Novel materials, like SiC, have been created to get around the PV restriction. SiC increases the PV performance by two to three times, produces 60% less heat, and requires less cooling water.

5.5 Novel materials for ocean hydropower and hydrokinetic turbines

In oceanic environments, hydropower plants turn the energy of waves and tidal movements into electricity. Low head turbines in the tidal context utilize tidal ranges' potential energy, whereas hydrokinetic turbines utilize tidal flows and ocean currents' kinetic energy. Hydromechanical devices in the context of wave energy transform the oscillatory motion of waves into mechanical energy [41].

Seawater is corrosive, and the oceanic climate is extremely harsh and unpredictable. Tidal energy converters are subject to fatigue stress as well, although maintenance activities must be sparse due to the difficulty of accessing submerged installations in high-energy regions. As a result, and because local loading phenomena like turbulence and wave-current interactions are still poorly understood, rotors are frequently overdesigned—up to 30% in some cases—in order to achieve the necessary endurance. In terms of cost, performance, and material use, this is inefficient. In order to lower costs and improve durability, innovative materials with improved strength, fatigue, and anti-corrosion qualities are being developed. The majority of the prototypes created so far are fibber composites like glass fibbers (GFs) and carbon fibbers (CFs) that have an epoxy resin matrix infused in them. Due to their significantly lower rotational speed when compared to traditional high-head turbines like the Francis and Pelton turbines, these innovative materials are primarily practical and cost-effective. Epoxies are typically chosen for underwater applications because, among the thermoset resin systems available, they offer exceptional resistance to hydrolytic breakdown and progressive moisture absorption when the chemistry is tuned [42]. Thermoplastic polymers and vinyl ester resins were also taken into consideration. The latter offers the possibility of recycling but calls for different manufacturing procedures that are more expensive. In the context of ocean hydropower, Table 3 compares conventional materials with composite materials [43].

There are many other material choices available, however the majority of developers have chosen fiber composites, typically with CF reinforcements for enhanced fatigue resistance, because to their mechanical performance, durability, and ease of manufacturing complex geometries.

Table 3. Material properties for tidal turbines, based on Ref.43

Material	Density (gcm^{-3})	Elastic modulus (GPa)	Tensile strength (MPa)
CF composite	1.60	145	1240
GF composite	2.10	45	1020
Al alloys	2.70	70	300-550
Ti alloys	4.50	114	1170
Stainless steel	7.75	193	750-850
Carbon steel	7.85	207	400-500

Figure 3. Sabella D10 tidal turbine dockside in Brest before installation. Source (energylivenews.com)

6. Discussion

There are several Emerging technological trends and novel materials aimed at increasing hydropower's sustainability, efficiency, resistance, reliability, lifespan, flexibility, and cost-effectiveness.

Strategies to combat climate change must use a significant portion of renewable energy (RES). New hydropower technologies must offer greater flexibility across a wider variety of hydraulic conditions due to the variable generation of RES.

Stabilizer fins, J-grooves, an adjustable diaphragm installed in the draft tube cone, axial water injection with high/low velocity and low/high discharge, two-phase air-water injection along the axis, air injection/admission, axial water injection with a counter-flow tangential component, tangential water injection at a cone wall, ejector power plants for the excess flow rat, and hydroelectric energy systems are some of the most notable flexibility technologies.

The other technological development in the hydropower industry is hydropower digitalization. By gathering and analyzing real-world data to modify the actual operating conditions of hydropower turbines, advanced grid-supporting services can be offered without jeopardizing the dependability and safety of stations. According to estimates, implementing hydropower digitalization could increase current hydropower energy production by a total of 42 TWh. An increase like this might result in $5 billion in annual operational savings and a considerable drop in greenhouse gas emissions.

Energy storage, like that offered by pumped hydropower storage (PHS), is required to offset the rise in variable RES in power networks. Fixed or variable speed turbines can help PHS plants run in both pump and turbine modes for peaking regulation. Electronic converters allow for speed modification in any of the two modes listed below. Electric machines that are fed by AC currents into both the stator and the rotor windings are known as double-fed induction machines, converter-fed synchronous machines, and synchronous machines whose stator is powered with a variable frequency. The German Goldisthal PHS facility, which was built in 2004 and has four 265 MW pumped-storage units, was the first significant variable-speed hydropower plant in Europe. Two of the units are connected to the grid via a doubly-fed induction machine.

Improved control of electrical equipment is possible with new power electronics and current-controlled power supply; during start and stop phases. For instance, the two pump-turbines of the hydropower project Frades II in Portugal are controlled by an AC excitation system, which also regulates the power of the induction-motor generator's rotor.

Small-scale hydropower is crucial to rural electrification and mini-grid plans. In particular, the enhanced designs and operation techniques for pumps as turbines (PATs) as well as unique designs of gravity hydraulic machines (like water wheels and Archimedes screws) and turbines (like extremely low head turbines and hydrokinetic turbines) are being developed. PATs are typical pumps with a turbine mode of operation. Deriaz turbine is one of the additional PAT designs that is now being developed, despite the fact that it is typically utilized in large hydropower facilities.

The sustainability of a hydropower plant is increasingly taken into account during the design phase due to environmental concerns. For low head applications, fish-friendly turbines include Archimedes hydrodynamic screws, water wheels, and Vortex turbines. For higher heads, Alden turbine and minimal gap runner turbine are also suitable.

In addition to greater efficiency in reaction turbines and free surface turbines (such as the vortex turbine, Archimedes screw, and water wheels), the use of innovative materials for turbines and hydraulic equipment can also reduce weight and increase lifespan. However, the spinning reserve, which ensures hydropower flexibility, would decrease as a result of the lighter turbine runners. Prior to now, some hydraulic machines even flywheels have been combined to improve the spinning reserve, which is important for frequency management.

Additionally, new materials for dams have been created, including GF, CF, and materials made of cementitious rockfill and soil. They lengthen the structure's lifespan, lessen distortion, and make installation easier. The mechanical reaction may be enhanced by the cemented rockfill material's higher modulus compared to the rockfill material. The advantage of cemented rockfill or soil dams over rockfill embankment dams is that they have stronger material erosion resistance, allowing for overtopping with little chance of failure during extreme floods. Another emerging technique to streamline waterproofing is to coat the dam surface with bituminous conglomerate.

PCD bearings and PTFE have been introduced in the bearing assembly industry to increase performance and decrease the requirement for oil, boosting the plant's environmental sustainability and virtually eliminating wear. SiC has been used in seals to increase their PV performance by two to three times while producing 60% less heat, decrease the amount of cooling water needed for the sealing faces, and reduce wear from abrasion and erosion. The primary method of lowering oil-related pollution is lubrication consisting of water and vegetable oil.

The idea of eco-tribology in the hydropower sector has developed quickly recently, notably in the bearing context, in an effort to avoid the potential risk of oil spillage from hydropower units. Self-lubricant bearings (with tribo-materials) and ecological/vegetable lubricants, all of which offer superior or comparable tribological performance to conventional lubricants, have also been created.

Advanced composite materials, such GF and CF-reinforced polymers, can lower prices and boost durability in ocean environments. Study examples with specific applications on hydrokinetic devices have already been described in the literature. Real Tide, a current EU H2020 project, is dedicated to enhancing our knowledge of composite blade materials in order to increase the reliability of tidal turbines. To create materials with a lesser environmental effect, the durability of substitute composites based on basalt or natural fiber reinforcing is also being investigated.

7. Conclusion

There are various technological advancements taking place in the hydropower industry right now. Hydropower is becoming more adaptable and eco-friendlier thanks to the development of new technology and sustainable practices. Additionally, new materials have recently been created to improve performance, durability, and reliability. The constraints, innovation trends, and emerging innovative materials and technology in the hydropower sector are covered in the article. It mostly covers diverse research projects and findings in numerous hydropower-related fields. It is obvious that the future role of hydropower depends on more than only the new materials and technological developments discussed in this article. Other scientific fields' knowledge advancements are also significant and may lead to better services.

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