Chapter 7

Worldwide research trends on hydropower

Francisco Manzano-Agugliaro[1], Antonio Zapata-Sierra[1], Alfredo Alcayde[1], Esther Salmerón-Manzano[2]

[1]*Department of Engineering, ceiA3, University of Almeria, Almeria, Spain;* [2]*Faculty of Law, Universidad Internacional de La Rioja (UNIR), Logroño, Spain*

1. Introduction

Hydropower is one of the most important renewable energies in the world [1]. It is the kinetic energy of water mass movement and the potential energy of water available at a certain height. Depending on their functionality, hydroelectric power stations are classified into several types.

Run-of-river (RoR) stations: Operation of the plant is adapted at all times to the flow regime of the river, without alteration. Therefore these plants do not have significant storage capacity and operate continuously, although this varies throughout the year. The energy produced cannot be adapted to the need for electricity demand.

Regulation stations (with reservoir): In this case, it is possible to store water and regulate its operation to meet demand management needs. Storage capacity is achieved by means of a reservoir located upstream of the station, and depending on its capacity there is seasonal, annual, and even hyperannual regulation.

In this last case therefore the potential energy of water can be transformed into kinetic, profitable energy. Hydropower is the energy generated by transforming the power of water into electrical energy. To make this force profitable, large hydraulic basins are built capable of extracting the maximum potential from this renewable, indigenous, and emission-free resource. Fig. 7.1 summarizes this process. Hydropower stations are used to transform the difference in potential energy into electric energy. The dam, located in the usual flow of the river, Fig. 7.1B, accumulates water to from the reservoir, Fig. 7.1A. This allows the water to acquire potential energy. The water behind the dam flows through an entrance that has a protection grid, Fig. 7.1D, and whose flow is regulated by gates, Fig. 7.1C. The potential energy is transformed into kinetic energy as it flows through the channel, Fig. 7.1E. The turbine,

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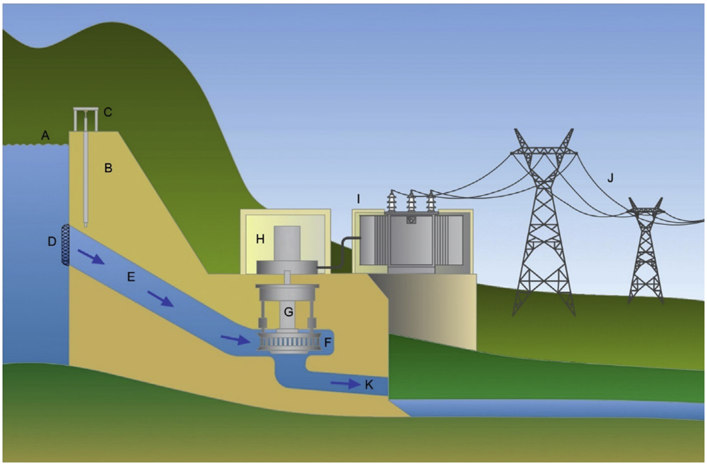

FIGURE 7.1 Hydropower generation.

Fig. 7.1F, is used to transform this kinetic energy into mechanical energy, which is transmitted by the axis, Fig. 7.1G, so that the power generator, Fig. 7.1G, transforms it into electrical energy. The water, once it has given up its energy, is redirected back into the river through the drainage channel, Fig. 7.1K. This water has scarcely any speed and potential energy corresponding to the height of the drainage point. The overall efficiency of the whole process is over 90%, as it uses almost all the potential energy of the water. Efficiency losses are due mainly to load losses in the hydraulic circuit, friction in the rotation of the hydroelectric group, and losses in the electrical equipment.

In parallel with power generation, there are many potential uses of water as a resource. Hydraulic energy can be used directly once it has been transformed into mechanical energy. Fig. 7.2 shows a hydraulic mechanism used as a grinding wheel, where the turbine (A) transmits energy through the axis (D) to the grinding wheel (B). It is observed that a small channel (C) uses the water to cool the axis to avoid heating. In fact, this method was in use until the middle of the 19th century, i.e., water mills [2].

The most widely used turbines are those known as Pelton, Francis, and Kaplan, see Fig. 7.3. For higher falls and lower flow variations the most appropriate turbine is the one invented by James Francis (1849), which is still used today. The turbine invented by Lester Allan Pelton (1870) is suitable for large falls, regardless of the variation in flow. The turbine invented by Viktor Kaplan (1913) is suitable for small falls and variable flows. On the other hand, it is essential that the chosen turbine has the lowest operating and maintenance costs to ensure sustainability. In summary: the Pelton turbine is used in high waterfalls ($H > 200$ m) and with small flow range ($Q < 10\ m^3/s$), the Francis turbine is used in medium waterfalls ($H < 200$ m) and with very wide flow

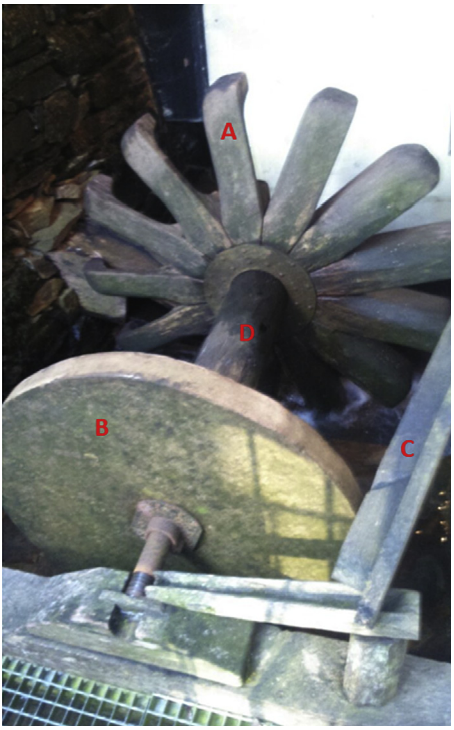

FIGURE 7.2 Hydraulic grinding wheel mechanism.

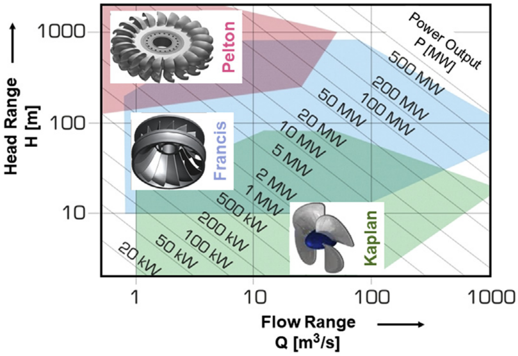

FIGURE 7.3 Electrical power production of Kaplan, Pelton, and Francis turbines.

range (2 $m^3/s < Q < 200$ m^3/s), and the Kaplan turbine is used in small waterfalls ($H < 50$ m) and with medium flow range ($Q > 15$ m^3/s). For a high water flow at low altitude this last turbine is the best option; it can also change the angle of its blades during use.

Currently, the most common use of hydraulic energy is the production of electricity by establishing artificial heights of water in a riverbed. This difference in height allows the water to be channelled through a pipe to a turbine at the base of the waterfall, which is mechanically connected to an electric generator.

Roughly speaking, considering the average global annual rainfall levels and the average height of the land above ground, it can be estimated that hydraulic potential is equivalent to almost twice the annual energy consumption in the world. However, installed hydropower generation capacity in the world today is approximately 1292 GW, with an annual production of 4200 TWh according Ref. [3], which is only 10% of the usable hydraulic potential. Large hydroelectric power plants have been developed for some time, and therefore much of the research is focused on the development of small hydropower.

The cost of a kilowatt-hour obtained by a hydropower system depends on the installation's cost, which must be absorbed over its lifetime; on the operating cost; and on the energy produced, which depends largely on the water flow at the plant location. At this point, hydrological studies for long return periods are essential [4]. The installation cost basically depends on the cost of the following elements: civil works (access, reservoirs, channels, pipes, buildings, etc.), machinery (turbines, generators, gearboxes, etc.), electrical system (power lines, transformers), control, regulation, and protection system. Equipment costs can be considered as a fixed amount for a given power plant capacity. However, it is estimated that civil works can account for two-thirds of the cost of the installation. But this can vary considerably from one place to another and may be from 80% to only 25%, for example, in the last-mentioned scenario if the power plant can run on existing dams or reservoirs [5]. This threshold can establish the difference between project and nonproject feasibility.

Some authors argue that these types of facilities have minimal impact on the environment, except when the catchment requires the construction of large marshes, which can have high negative effects locally especially on river ecosystems. Only influences arising from the manufacturing stage of the equipment and systems for converting and transporting these energies (blast furnaces in the manufacture of steel or other materials, manufacture of components, etc.) can be included in the impact assessment. The assessment of negative impacts can only include those derived from the manufacturing process of the systems and equipment for the conversion and transport of these energies (blast furnaces in the manufacture of steel or other materials, manufacture of components, etc.). However, it must be considered that the same impacts also occur in the manufacture of equipment for the exploitation of nonrenewable energies. In any case, they are much lower than those of nonrenewable energies. Compared to other energies, hydropower generation has low CO_2 and CH_4 emissions and no emissions of particles, or SO_2, or NO_x.

In this chapter we will focus on studying the indexed scientific publications related to the subject of hydropower. For some authors, science is what is published in scientific journals [6]. Scientific journals, conferences, or books attain some prestige if they are indexed in scientific databases. These databases can be considered the basis of science since they collect all the scientific knowledge that in one way or another is available to researchers around the world. A bibliometric analysis of these publications aims to identify the issues that most concern scientists, but also respond to the key interests of countries and scientific research institutions in this field.

2. Data

In this chapter, all the scientific production data collected in the Scopus database with the search term "Hydropower" have been analyzed. So, the following search string was used: TITLE-ABS-KEY ("Hydropower"), of which more than 23,000 results were obtained in the period between 1969 and 2019. Fig. 7.4 shows two detected periods over these publications: in the first period, from 1969 to 2000, there was a relatively low scientific production, around eight publications per year. Thus, at the end of this period, the number of publications per year reached 200. The second period, from 2001 to 2019, may be considered with higher growth, reaching 100 publications per year. Therefore, at the end of this second period, the number of publications per year reached 2000. These data are in line with major bibliometric laws such as Price's law on the increase of scientific literature [7]; Bradford's law on the dispersion of scientific literature [8]; and Lotka's law on author productivity [9]. The previous background research affirms that in the output of a given scientific field, after a linear period of scientific productivity, there is a period of exponential growth.

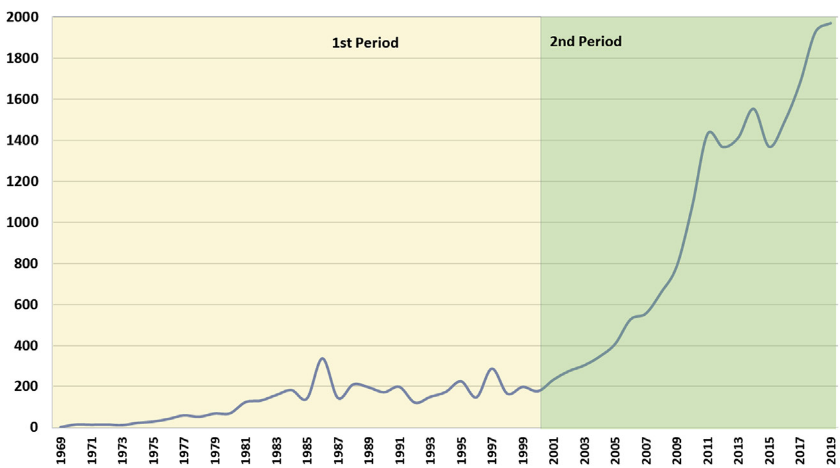

FIGURE 7.4 Periods of worldwide scientific production in hydropower.

3. Results

3.1 Subjects from worldwide publications

Publications indexed in scientific databases are categorized when they are indexed. Fig. 7.5 shows the main subject categories in which publications related to hydropower are indexed by Scopus. The leading category is Engineering with just over 28% of the total publications, as expected. The second category in ranking order of number of publications is Environmental Science (20%), followed by Energy (16%). This is worthy of reflection since hydropower is considered a renewable energy in some countries according to the installed power [10]. However, for many sectors this energy can disturb the ecosystem, hence the significant publishing output related to hydropower in the Environmental Sciences category. The fourth and fifth categories are Earth and Planetary Sciences (11%) and Social Sciences (5%). The categories with 4% are Agricultural and Biological Sciences, and Computer Science.

This analysis of the subject categories would not be complete if their evolution over time were not analyzed. In Fig. 7.5, one can see how the category of Engineering has dominated the topic more or less clearly during the whole period studied until 2016, with the exception of 1999. From 2016 onwards, the category of Environmental Science begins to lead the topic. In fact, in the last year studied, 2019, the Environmental Science category has about 150 more publications, which is 20% more than the Engineering category.

The Energy category has always been in third place, except for the period from 2000 to 2006, when it was second only behind the Engineering category. The category of Earth and Planetary Sciences has always been in fourth place; however, it should be noted that from 2005 to 2019 it had an average growth

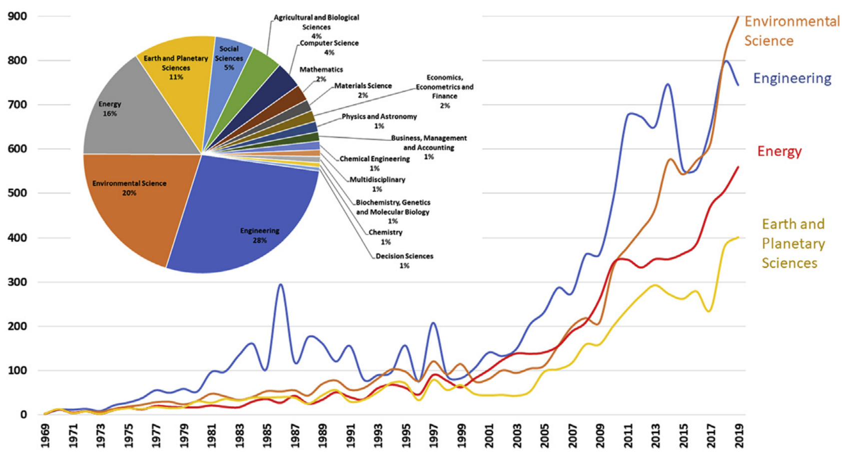

FIGURE 7.5 Distribution and evolution of Scopus categories on hydropower.

rate of 13% per year. This may be due to studies on water as a resource, i.e., hydrology. Some examples of this issue in this category are that one of the biggest changes in river hydrology when a dam is built is deviation from the normal hydrograph [11], or how climate change-induced hydrological change will reduce hydropower generation [12].

The type of publication is an index of the maturity of the technology studied, where a high percentage of books would indicate that the topic is well known, and a high percentage of conference publications would indicate the opposite, a very new technology. In this study, books account for only 1%, book chapters 3%, conference papers 25%, and articles 68% (article 65% and review 3%). Therefore it can be considered that although hydropower is a mature technology, it is still of great interest to researchers.

3.2 Countries, affiliations, and their main topics

The research of hydraulic energy arouses the interest of almost all countries, and therefore it is a technology that is geographically distributed worldwide. Fig. 7.6 shows in a worldwide map by color intensity the number of publications of the 160 countries that have contributed to this topic. With more than 1000 publications are China (30%) followed by the United States (12%), then by more than 3% are Germany, the United Kingdom, India, and Brazil. With just over 2% are Norway, Canada, and Switzerland, and with more than 1% are Italy, Austria, Sweden, France, Australia, Spain, Turkey, Japan, Russian Federation, Netherlands, Iran, and Romania. It can be concluded that the countries that contribute most in this field are those that have this resource available, as expected. The data from publications are certainly correlated in most cases with the hydropower installed capacity. This installed hydropower capacity is led by the countries with more than 10 GW installed: China (356.40 GW), Brazil (109.06 GW), United States (102.75), Canada (81.39 GW), India (50.07 GW), Japan (49.91 GW), Russia (49.86 GW),

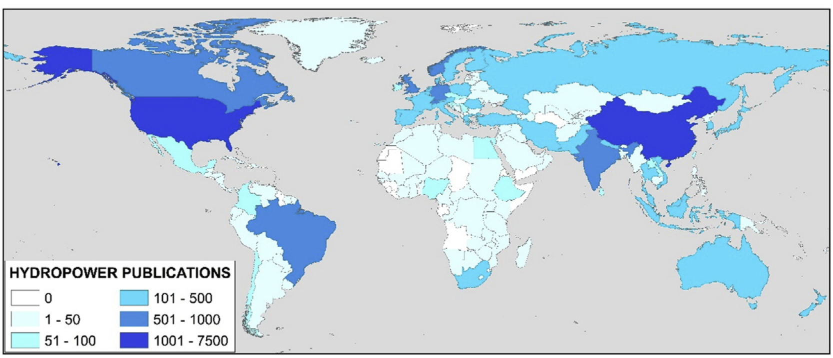

FIGURE 7.6 Worldwide geographical distribution of the scientific production of hydropower.

Norway (32.67 GW), Turkey (28.50 GW), France (25.56 GW), Italy (22.59 GW), Spain (20.41 GW), Switzerland (16.86 GW), Vietnam (16.76 GW), Sweden (16.48 GW), Venezuela (15.39 GW), Austria (14.54 GW), Iran (12.17 GW), Mexico (12.13), and Colombia (11.92 GW). From this list the United Kingdom did not have a relevant position in terms of publications; however, its total hydropower generation is 7.770 GWh, its total hydropower installed capacity is 4.71 GW, and its pumped storage hydropower installed capacity is 2.83 GW.

If country analysis is important, no less so are the institutions that research this topic. Fig. 7.7 shows the top 28 affiliations that do research on hydropower, which are those with at least 100 publications. If the first 15 are analyzed by their first four keywords, then Table 7.1 is obtained. These are led by Wuhan University. Note that all of the affiliations in Table 7.1 are from China except one from Norway in ninth place. The most commonly used keywords in these publications are: Hydroelectric Power, Hydroelectric Power Plants, and Hydropower Stations. It should be noted that the most cited publication with the keyword Hydroelectric Power is a paper dealing with hydrology [13]. The most cited publication with the keyword Hydroelectric Power Plants is a review of the state of the art of this technology and its future in China [14] and the publication related to Hydropower Stations is one related to the Stability Analysis of Jinping, the first hydropower station [15]. In the fourth keyword, some differentiation between the research of these centers or universities can be seen. It seems that the topic of Rock Mechanics, and to a lesser extent Reservoirs (water) and Optimization, dominates. There are major challenges for the development of hydropower projects. The first to be assessed are the complicated geological conditions found during construction.

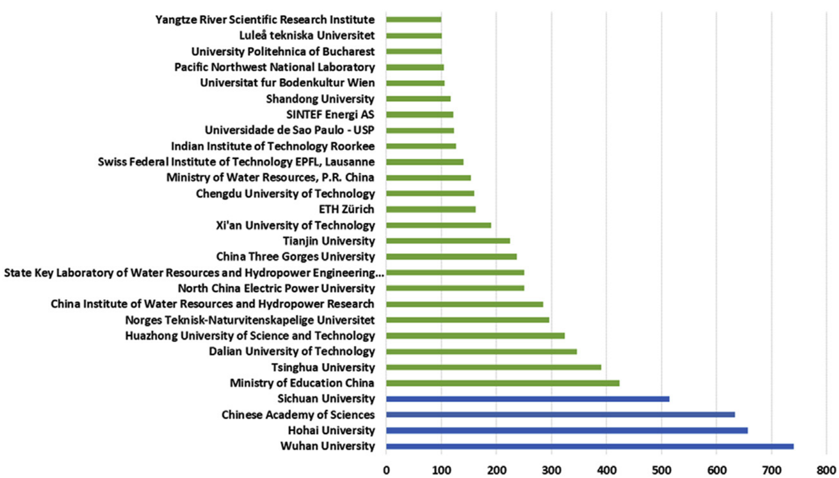

FIGURE 7.7 Main institutions in the scientific production of hydropower.

TABLE 7.1 Main affiliations and their main keywords.

Affiliation	Country	N	Keywords			
			1	2	3	4
Wuhan University	China	740	Hydroelectric Power	Hydroelectric Power Plants	Hydropower Stations	Rocks
Hohai University	China	657	Hydroelectric Power	Hydroelectric Power Plants	Hydropower Stations	Rock Mechanics
Chinese Academy of Sciences	China	633	Rock Mechanics	Hydroelectric Power	Rocks	Hydroelectric Power Plants
Sichuan University	China	515	Hydroelectric Power	Hydroelectric Power Plants	Hydropower Stations	Rock Mechanics
Ministry of Education China	China	424	Hydroelectric Power	Rocks	Rock Mechanics	Hydropower Stations
Tsinghua University	China	390	Hydroelectric Power	Hydroelectric Power Plants	Hydropower Stations	Reservoirs (water)
Dalian University of Technology	China	346	Hydroelectric Power	Hydroelectric Power Plants	Optimization	Optimal Operation
Huazhong University of Science and Technology	China	324	Hydroelectric Power	Hydroelectric Power Plants	Optimization	Scheduling
Norges Teknisk-Naturvitenskapelige Universitet	Norway	296	Hydroelectric Power	Hydropower	Hydroelectric Power Plants	Commerce

Continued

TABLE 7.1 Main affiliations and their main keywords.—cont'd

Affiliation	Country	N	Keywords			
			1	2	3	4
China Institute of Water Resources and Hydropower Research	China	285	Hydroelectric Power	Hydroelectric Power Plants	Reservoirs (water)	Hydropower Stations
North China Electric Power University	China	251	Hydroelectric Power	Hydroelectric Power Plants	Optimization	Wind Power
State Key Laboratory of Water Resources and Hydropower Engineering Science (Wuhan University)	China	251	Hydroelectric Power	Hydroelectric Power Plants	Hydropower Stations	Rocks
China Three Gorges University	China	237	Hydroelectric Power	Hydropower Stations	Hydroelectric Power Plants	Hydropower Projects
Tianjin University	China	225	Hydroelectric Power	Hydroelectric Power Plants	Hydropower Stations	Optimization
Xi'an University of Technology	China	190	Hydroelectric Power	Hydroelectric Power Plants	Reservoirs (water)	Hydropower Stations

Therefore rock mechanics plays a critical role in the design and construction of hydropower projects [16]. As mentioned earlier, a dam stores water in a reservoir, from which the water flows through pipes to electricity-generating turbines. The amount of electricity produced is determined by the volume of water flow and the height from the top of the turbines to the surface of the water at the base of the dam. Therefore the reservoirs produced by hydroelectric dams are essential to determine the energy capacity of the hydroelectric plant. The methods for finding the best solution (the so-called optimal one) vary according to the complexity of the problem to be studied [17]. Most of these techniques are inspired by biological or physical processes, and try to simulate the behavior of these processes that favor the search and detection of better solutions in an iterative way [18]. The most widespread of these techniques are genetic algorithms, based on the mechanism of natural evolution of species [19].

An interesting feature of Table 7.1 is Wind Power from the North China Electric Power University, i.e., a study related to the incentive policy system for the renewable energy power generation in China [20]. Another keyword is Commerce from the Norges Teknisk-Naturvitenskapelige Universitet (Norway). In this last case, one of the most cited works deals with the water level of reservoirs in relation to climate change and the deregulation of the electricity market in Norway [21].

3.3 Keywords from worldwide publications

For a scientific study, the title, the abstract, and the keywords are the most important basis for indexing. In fact, if authors want to make it as widely known as possible, they should pay particular attention to the words used in these indexing fields. On the other hand, they are important to serve as a basis for those who want to continue researching the same topic, since they are the ones used in the search terms in scientific databases. One of the most important aspects for the authors of the study is to choose words that best represent the research and technology that supports it, the keywords.

In this study, just over 40,000 keywords were obtained as a result of extracting this information from all the scientific publications analyzed. Table 8.2 shows the most frequent keywords in the publications related to hydropower. It is striking that the search term ranks third after Hydroelectric Power and Hydroelectric Power Plants, maybe because some journals do not allow to list as a keyword something that is included in the title of the work. Related to these concepts are others like: Hydropower Stations, Hydropower Plants, or Hydroelectric Power Plant. The second set of most important keywords is related to natural resource itself: Reservoirs (water), Rivers, Dams or Water Resources. The third set could be related to Rock Mechanics or Rocks. Finally is a fourth set related to the environmental issue Climate Environmental Impact. To have a general view of the most frequent keywords in all the analyzed publications, a cloud word is represented in Fig. 7.8.

TABLE 7.2 Top 20 keywords related to hydropower.

Rank	Keyword	N
1	Hydroelectric Power	7474
2	Hydroelectric Power Plants	4246
3	Hydropower	2826
4	Reservoirs (water)	1813
5	Rivers	1650
6	Hydropower Stations	1530
7	Hydropower Plants	1423
8	Optimization	1410
9	Hydroelectric Power Plant	1284
10	Dams	1242
11	China	1206
12	Climate Change	1155
13	Water Resources	1136
14	Water Supply	1084
15	Rock Mechanics	1038
16	Wind Power	988
17	Rocks	971
18	Water Management	946
19	Sustainable Development	918
20	Environmental Impact	888

3.4 Worldwide research trends: cluster analysis

However, the previous analysis of keywords would not be exhaustive if it were not done accurately and considering the relationship between all the published works. For this purpose, the clusters in which all the publications can be grouped have been detected by using Gephi software. Fig. 7.9 shows the clusters found and the relationship between them. Of these, only eight clusters are meaningful since their relative importance is greater than 1%, and among these they account for 99.1% of the studies. The names of the clusters have been set according to the most frequent keywords of each cluster. The 20 keywords of each cluster are listed in Tables 8.3–8.6.

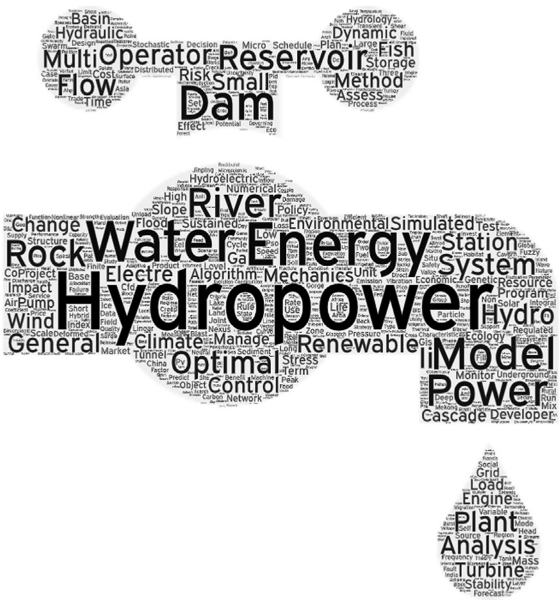

FIGURE 7.8 Cloud of keywords from the scientific production of hydropower.

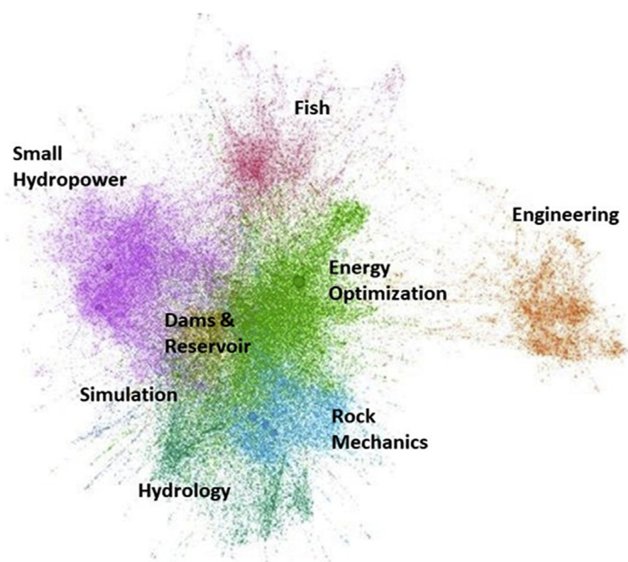

FIGURE 7.9 Relationship between hydropower publications.

TABLE 7.3 Main clusters (Fig. 7.6), weight, and names.

Cluster name	Weight (%)	N
Small Hydropower	26.5	3021
Energy Optimization	21.7	2469
Rock Mechanics	12.7	1448
Dams & Reservoir	10.9	1251
Engineering	10.8	1224
Fish	9.1	1031
Hydrology	5.9	675
Simulation	1.5	174
Agriculture	<1	<100

TABLE 7.4 Small Hydropower cluster.

Keyword	N
Renewable Energy	366
Small Hydropower	137
Sustainability	79
Micro-hydropower	74
Turkey	73
Sustainable Development	69
Climate Change	67
Hydropower Plant	64
China	62
Energy	60
Small Hydropower Plant	55
Hydropower Development	51
Life Cycle Assessment	50
Environmental Impact	45
Rural Electrification	43

TABLE 7.4 Small Hydropower cluster.—cont'd

Keyword	N
Optimization	40
Electricity	40
Biomass	40
Pump as Turbine	38
Energy Policy	37

TABLE 7.5 Energy Optimization cluster.

Keyword	N
Reservoir Operation	286
Optimization	152
Cascade Hydropower Stations	148
Optimal Operation	112
Genetic Algorithm	111
Multi-objective Optimization	95
Cascade Reservoirs	73
Hydropower Station	71
Hydropower Plant	61
Wind Power	57
Hydropower Generation	54
Renewable Energy	50
Dynamic Programming	49
Climate Change	48
Particle Swarm Optimization	47
Simulation	45
Hydropower Engineering	44
Uncertainty	44
Electricity Market	41
Unit Commitment	39

TABLE 7.6 Rock Mechanics cluster.

Keyword	N
Rock Mechanics	239
Jinping II Hydropower Station	92
Numerical Simulation	84
Microseismic Monitoring	77
Underground Caverns	71
Underground Powerhouse	69
Rockburst	67
Hydraulic Engineering	56
Stability	53
Slope Engineering	49
Rock Slope	47
Hydropower Station	42
Stability Analysis	40
Deep Tunnel	39
High Geostress	35
Baihetan Hydropower Station	32
Back Analysis	29
Tunneling Engineering	25
Numerical Analysis	23
In-situ Stress	23

The cluster designated as Small Hydropower is the most important in terms of size with 26.5% of the total output. It should be noted that according to the installed capacity, it is considered as small hydropower or not, depending on the country. For example, this can range from $\leq$10 MW in some European countries such as France, Norway, Czech Republic, Spain, or Italy; $\leq$25 MW in India; $\leq$30 MW in Brazil; $\leq$50 MW in New Zealand; and $\leq$100 MW in the United States [10]. Installation of this type of energy solution usually involves a relationship between the head and the discharge or available flow, and according to these two parameters the turbine is usually chosen (Pelton, Francis, Kaplan, or crossflow) [22]. Then, in areas with little rainfall, that is, when there is not much available flow, the ideal for this technology is the mountainous areas, since they combine the availability of scarce water resources with the necessary minimum head. The expression for installed power is given in Eq. (7.1):

$$P = \gamma \cdot Q \cdot H \cdot A \tag{7.1}$$

where:

- P is the power (kW),
- Q is the equipment flow (m^3/s),
- H is the existing net water head (m),
- γ is the specific weight of water (at 4°C, 9.807 kN/m^3), and
- A is the efficiency factor of the plant.

The Small Hydropower cluster is surrounded by the Fish, Agriculture, Dams & Reservoir, and Hydrology clusters. The production of hydraulic energy in general, and particularly minihydraulics, depends to a great extent on rainfall. For example, in Spain, the average annual rainfall is 700 mm for an area of 500,000 km^2 in an average year, which is about 350 km^3/year. But, of course, the distribution of these resources is very unequal in time and space. The inequality in time is a consequence of the great fluctuations in the flow of rivers at different times of the year. The irregularity in space is very evident if we consider that the potential resource (approximately 30% of rainfall) varies from one basin to another. For example, the basins in the north of Spain produce more than a third of the contribution of the rivers in 10% of the country's surface area, while the remaining 90% are not in such a favorable situation in terms of water resources and already fall into the category of semiarid region.

The most cited studies referring to small hydropower are the case studies of specific areas generally for the support of rural electrification or sustainable energy, as in the case of Ethiopia where the 85% of the population lives in places where access to electricity is less than 2% [23]. In the case of India, small hydropower capacity was estimated at 10,000 MW, and growth was 28% in the period 1999–2004, reaching 1693 MW in 2004, and yet there is still a considerable amount of potential to be developed [24,25]. A parallel scenario occurred in Turkey, where the small hydropower potential for 2005 was 8.7 TWh and 7.7% of that total was used [26]. In addition, the Turkish government has given a strong stimulus to the increase of power generation from renewable energy sources through publication of the Turkish Renewable Energy Law. Turkey aimed to connect to the grid by 2020 its full hydropower potential by building smaller hydropower stations. China also focuses on the possibility of rural electrification through small hydropower. A summary of the statistics of small hydropower stations of various scales in China showed that mini (0.5 MW), micro (0.5–10 MW), and small (10–50 MW) had an installed capacity of 73,829 MW for the year 2105 [27]. As a significant contribution to environmental aspects, the two following policies can be mentioned, "National Small Hydropower Ecological Protection Project" and "Replace Firewood with SHP." The main idea was to reduce the consumption of wood for cooking, and to offer alternative energy to farmers and thus protect forest areas [28]. In Greece, an economic study showed that for the small hydropower stations studied in that country, the values of the expected internal rate of return were higher than 18% for the majority of cases [29]. Many of these studies, as expected, also focus on the environmental impact [30]. The interruption of fish migration routes is one of the most obvious impacts of damming a river. However, the possible effects of dams depend on the nature of the dam, the river, and its fauna, so it is difficult to make global assumptions. The dam is a barrier to movement that must be crossed to prevent the upstream spawning population from perishing [31]. The main species of fish studied in this regard is salmonid such as *Salmo salar*, or Atlantic salmon [32], and *Salmo trutta* [33].

The second cluster according to importance with 21.7% is the one focused on Optimization, which could be considered as the central cluster in hydropower research. The main keywords are: Optimization, Optimal Operation, Genetic Algorithm, Multi-objective Optimization, Dynamic Programming, Particle Swarm Optimization, or Simulation. Constant progress in computer hardware and software has enabled researchers to address problems applied to renewable energy in general and hydropower in particular with these optimization methods [34]. There are many of these optimization-based energy models for energy planning models, energy supply/demand models, forecasting models, renewable energy models, and emission reduction models [35]. An example of optimization is the case of Brazil, which is full of natural water resources and has one of the largest hydroelectric systems in the world. It has an installed capacity that produces 92% of the nation's electrical energy. The system consists of 75 hydroelectric plants and a combination of storage tanks and RoR plants. A proposal for the optimization of operations of large-scale hydropower systems [36] were objectives to minimize the loss of the stored potential energy, to minimize the sum of the squares of storage deviations from targets, to maximize total energy production, to minimize total spilled energy, to minimize energy complementation, and to maximize the profit derived from the secondary energy. This cluster is opposed to that of small hydropower; one could say that it is the least related. It should be noted that this cluster is the one that links the research of the Engineering cluster with the rest. As an example of this relationship, one can cite the study concerning the parameters identification of hydraulic turbine governing systems [37].

The third cluster with 12.7% is focused on rock mechanics, as shown by some of the main keywords: Rock Mechanics, Microseismic Monitoring, Underground Caverns, Rockburst, Stability, Rock Slope, Stability Analysis, or High Geostress. This research is based on the fact that if the correct geomechanical characterization of the rocky masses is carried out, it is possible to differentiate them according to their behavior, which would allow proposing and applying engineering solutions adapted to the requirements of the design of the works of the dam, guaranteeing its economic viability and the integral safety of the construction. Highlights include site-specific studies, such as Jinping II hydropower station, which has 4800 MW of installed capacity. During the excavation of deep underground tunnels, rockbursts are carried out, which are sometimes a serious danger. The research provides a direct case history to help predict and support rockburst disasters, and contribute to the excavation of deep buried tunnels in dam construction, for example, engineering rock mechanics at the underground hydropower plant in Jinping I [38]. Other examples are the two headrace tunnels and the drainage tunnel excavated at the Jinping II hydropower station, where triaxial rockburst tests were carried out in the laboratory to simulate the process of marble rockbursting during the excavation of a tunnel [39].

The fourth cluster with 10.9% is focused on Dams & Reservoir and their possible impacts. It can also be considered as the central zone of the set of published works on hydropower. This cluster highlights terms from specific geographical locations in China, Brazil, Cambodia, or Laos. Also, these first 20 keywords are specific river areas such as the Amazon, Nile, Congo, or Mekong rivers, or even Lancang river (upper half of Mekong river). These rivers are among the longest in the world, and their problems are often transnational. For instance, the Mekong river runs through China, Myanmar, Laos, Thailand, Cambodia, and Vietnam. The most cited works of this cluster study the environmental impacts [40], its restoration [41], or the connectivity of the river itself [42] (Table 7.7).

The fifth cluster is the Engineering cluster with 10.8%. This cluster is located somewhat outside the core of papers, linked to the core of papers through the Optimization cluster. It is quite focused on the topic of turbines: Francis Turbine, Hydro-turbine Governing System, Hydraulic Turbine, and Hydro Turbine. The main idea is to select the appropriate type of turbines, and the economical size for a hydropower station. Not surprisingly, one of the most cited works in this field is related to the optimization of turbines [37]. Here, the first step is the identification of parameters for advanced control system design, and they could also be used in condition inspection, fault diagnosis, and performance prediction. It should be noted that one of the most difficult challenges is the identification of the parameters of the hydroturbine's steering system. On the other hand, this cluster also joins the Fishes cluster, this is because there are numerous studies of fish behavior in relation to passage through hydropower turbines. Of course, there are classic hydraulic engineering problems such as cavitation. In some of the hydropower sites where the height is relatively low and the discharge is of medium or high order, it is difficult to use a pulse-type turbine, as sufficient speed may not be achieved to drive it. For this reason, they are usually considered to be reaction turbines of high speed with a medium to low head. These turbines, when closed, operate at variable pressure, and are more prone to cavitation. This is the case of the

TABLE 7.7 Dams & Reservoir cluster.

Keyword	N
Dams	59
Climate Change	54
Mekong	42
China	39
Reservoir	36
Hydropower Dams	36
Renewable Energy	29
Hydropower Development	26
Hydroelectric Dams	26
Development	26
Brazil	25
Resettlement	24
Energy	23
Amazon	22
Mekong River	19
Environmental Impact	18
Cambodia	18
Laos	18
Lancang River	16
Conservation	15

Francis turbine [43]. Another problem studied is the water hammer. It is important to mention the research that, considering the nonlinear characteristics of the hydraulic turbine and the inelastic effect of the water hammer, developed a system for simulating hydraulic transients in hydroelectric power plants [44] (Table 7.8).

The sixth cluster, with a relative weight of 9.1%, is focused on fish. This cluster is closely related to the Small Hydropower and Engineering clusters. Here the main topics are fish migrations with keywords like: Migration, Downstream Migration, or Fish Migration. These are mainly for salmon (*S. salar*) or Atlantic salmon [45], but also the Pacific salmon [46]. There are four primary passage routes downstream migrating fish can pass through the

TABLE 7.8 Engineering cluster.

Keyword	N
Hydropower Station	63
Hydropower Plant	57
Francis Turbine	49
Hydropower Unit	45
Stability	35
Hydraulic Structure	30
Vibration	27
Hydro-turbine Governing System	27
Hydraulic Transients	26
Surge Tank	25
Numerical Simulation	24
Hydraulic Turbine	23
Hydro Turbine	22
Hydroelectric Power Generation	22
Simulation	22
Water Hammer	22
Fault Diagnosis	21
Transient Process	20
Finite Element Method	19
Hydropower House	19

dams: turbine, juvenile bypass, spillway, and surface passage, save for some passage routes through navigation locks. In this cluster, emphasis is placed on the detail of the fish passage or fishway through hydropower turbines. The fish sensory system employs its side line system to detect obstacles and change its orientation. But in the fast passage times and complex pressure regimes of turbine systems, this sensory response system may not be successful. The effects of preexisting stress profiles on turbine run performance (particularly as they affect trajectories) are not known, but may be important [31]. Some countries, such as France, which has more than 1700 small hydropower plants, have specific legislation regulating the passage of fish in this type of facility, the small hydropower plants [47]. The French Environment Code (Article L 432-6) requires that any hydrological plan in watercourses or parts of them must include facilities to ensure the passage of migratory fish. This law considers as diadromous migratory species: salmon (*S. salar* L.), sea lamprey (*Petromyzon marinus* L.), allis shad (*Alosa alosa* L.), sea-run brown trout (*S. trutta* L.), sturgeon (*Acipencer sturio* L.), and European eel (*Anguilla anguilla* L.), and as migratory species in rivers: brown trout (*S. trutta* L.), northern pike (*Esox lucius* L.), and European grayling (*Thymallus thymallus* L.).

In this sense also exists Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Here, river continuity plays an important role for migratory species in rivers.

The other cluster that has links with this one is Dams & Reservoir. In this regard, it should be noted that in 2014 the construction of 3700 large dams worldwide was planned, each of them with a capacity greater than 1 MW. This was predicted to reduce the number of large rivers still flowing freely by approximately 21% [48] (Table 7.9).

The cluster that focuses on hydrology has a relative importance of 5.9%. Hydrology studies water, its occurrence, distribution, circulation, and properties, including precipitation, runoff, soil moisture, evapotranspiration, and equilibrium of glacial areas. Hydrology's spatial variation is driven by the complex interactions between climate, geology, topography, and vegetation at multiple spatial and temporal scales. The potential effects of climate change have a direct impact on hydrology and therefore on the water resources available for all types of applications and in particular hydropower. On the other hand, climate-related changes in flow regimes of glacier-fed streams have direct consequences on freshwater availability, irrigation, and hydropower potential [49]. This is why this cluster is linked to the clusters of Dams & Reservoirs (Water Resources), Agriculture (Water Management), and Rock Mechanics. It is therefore not surprising that the topic of glaciers is so present [49], as well as high mountain areas such as the Alps [50] or the Himalaya [51] (Table 7.10).

The cluster that focuses on simulation has a relative importance of 1.5%. The use of simulation in engineering has allowed the generation of variable values and in this way the experiments do not need to be repeated in the laboratory. In this way, a wide range of possibilities can be covered without the need for real experimentation. Naturally, the difficulty resides in making the mathematical models close to the reality to be studied. Therefore the Simulation cluster is between the Hydrology cluster, the Dams & Reservoir cluster, and the Small Hydropower cluster. Significant examples of this are hydrological studies in Sweden such as assessments by global climate models, dynamical downscaling, and hydrological modeling [52]. The Nordic perspective on the effects of climate change on water resources is particularly relevant to hydropower production and less so to water supply, as is the case in

TABLE 7.9 Fish cluster (12).

Keyword	N
Hydropeaking	166
Fish Passage	55
Dams	28
Migration	26
Reservoir	26
Atlantic Salmon	23
Telemetry	20
Downstream Migration	18
Acoustic Telemetry	17
Environmental Flows	16
Fishway	15
River Restoration	15
Regulated Rivers	14
River Regulation	14
Salmon	13
Salmo Salar	13
Turbine	13
River	12
Ecohydraulics	12
Fish Migration	12

TABLE 7.10 Hydrology clusters.

Keyword	N
Climate Change	184
Water Resources	131
Renewable Energy	30
Hydrology	23
Hydrological Modeling	23

Continued

TABLE 7.10 Hydrology clusters.—cont'd

Keyword	N
Water Management	16
Adaptation	15
Himalaya	15
Hydropower Generation	13
Glaciers	13
Climate Change Impacts	12
Reservoir	12
Reservoir Operation	11
Water-energy Nexus	11
Alps	11
Streamflow	10
Uncertainty	9
Electricity Market	9
Water Supply	9
Optimization	9

southern Europe. The study for Sweden proved that the chronology of the extreme values shows a general trend from spring to other seasons in the north, where the return periods related to rain floods in summer and winter decrease. It should be pointed out that both extreme events and return periods are the basis of design of any major hydraulic project [53].

The purpose of the reservoir operating rules is to guide and manage the reservoir system in such a way that the release made benefits the objectives of the system, in line with certain existing inputs and storage levels. Genetic algorithms have been successfully used to optimize the reservoir operating rule curves in Taiwan [54], given that these rule curves traditionally are derived through intensive simulation techniques. Related to small hydropower, several numerical investigations were carried out by different researchers on the efficiency of pumps as turbines [55] (Table 7.11).

Finally, the smallest cluster among all is the one focused on aspects related to agriculture and soil fertility. The main keywords related to this topic are: Soil Fertility, Soil Nutrient, and Inorganic Phosphorus. This cluster is located between the clusters of Hydrology, Dams & Reservoirs, and Small Hydropower. The link with these clusters essentially concerns the competitiveness of

TABLE 7.11 Simulation clusters.

Keyword	N
Numerical Simulation	14
Total Dissolved Gas	12
Hydraulic Characteristics	6
Hydraulics	6
3D Numerical Simulation	6
Flood Discharge Atomization	6
Water Temperature	6
Hydropower Station	5
Model Test	5
Diversion Channel	5
Environmental Hydraulics	5
High Dam	5
River Ice	5
Spillway Tunnel	5
Supersaturation	5
Two-phase Flow	4
Bilevel Multi-objective Model	4
Fuzzy Random Environment	4
Fuzzy Random Variable	4
Multi-level Intake Structure	4

water for irrigation or hydropower [56]. Another major line of research is how catchments affect nutrients in sediments, e.g., the study of the vertical distribution of sediment grain size in the Dongfeng reservoir, Hongyan reservoir, and Wujiangdu reservoir on the Wujiang river. Due to the hydropower cascading, the reservoir downstream had a smaller grain size, and thus the reservoir sediments had a higher adsorption rate to superimpose phosphorus from the water [57].

The most serious human disturbance in river basins is the construction of dams. Since sediment microbes play an important role in riparian ecosystems, their longitudinal distribution pattern and responses are an interesting scientific issue. The bacterial communities in riparian sediments along the Lancang

TABLE 7.12 Agriculture cluster.

Keyword	N
Slope	4
Soil Fertility	2
Ecological Restoration	1
Hydropower Construction	1
Corridor	1
Stability	1
Disturbance	1
Guandi Hydropower Station	1
Biology Technology	1
Dangerous Rocks	1
Eco-landscape	1
Engineered Eco-restoration	1
Fractionation	1
General Block Theory	1
Hydropower Construction Region	1
Inorganic Phosphorus	1
Microbial Community Structure	1
Microbial Functional Diversity	1
Soil Enzyme	1
Soil Nutrient	1

river and their responses to dam construction were investigated [58]. They found that bacterial diversity gradually increased along the river, from top to bottom, and that community composition differed significantly between mid-high and downstream sites (Table 7.12).

3.5 Perspectives and challenges

Water and energy availability poses a fundamental issue in ensuring the satisfaction of basic human needs and the development of economies worldwide. On the other hand, large volumes of water are required for the hydropower plant turbines to operate. Traditionally, a large part of the world's population has suffered from serious water shortages. But today another kind of poverty is emerging, energy poverty. In the near future the demands for energy will be even higher and climate change will further aggravate the problem. Furthermore, with more extreme climates the demand for energy will increase. The great challenge of hydropower research is to make energy generation compatible with environmental conservation.

In particular, in hydropower, it will be necessary to study the scenarios that will allow the current plants to remain in use, since the current climate change forecasts indicate that there will be less rain and therefore less runoff in the rivers, less water in the reservoirs, and therefore less hydropower generation will result. This scenario can be particularly accentuated in Latin America, where 60% of energy is produced in this way, and in Asia, where hydroelectric power has grown considerably in recent years.

In the literature reviewed, it has been observed that there are still large projects for the use of hydropower. The Democratic Republic of Congo has suffered a serious energy crisis. For instance, by 2017, hydropower accounted for more than 90% of national electricity production. Less than 10% of the population nowadays has access to electricity, making the Democratic Republic of Congo the country with the largest number of nonelectricity users in Africa after Nigeria. Its hydropower resources are estimated at approximately 100,000 MW. The Inga 3 dam has the potential to provide enough energy for the Democratic Republic of Congo and it could become an electricity exporter [59]. Given the precarious state of the power grid and the dispersed nature of the country's population centers, decentralized solutions represent the most cost-effective way to overcome grid constraints and provide electricity access to the huge proportion of the population currently without it.

The way in which Africa meets the energy needs of a young, rapidly growing, and increasingly urban population is crucial to the economic and energy future of the continent and the world.

Uncertainty about the effects of climate change on the hydrology of regions highlights the need to create a diverse energy mix and improve regional connections. Planning and investment decisions on energy infrastructure must be climate resilient. The increased frequency and intensity of extreme weather events, such as droughts and floods, will lead to greater variability in the output of hydropower generation. For example, in Zambia the severe drought in 2015, due to a strong El-Niño, led to a decrease in production at the largest hydropower plant, resulting in power cuts [60]. One of the largest sources of electricity in Zambia is the Kariba hydropower plant. The low rainfall, which resulted in low water levels in the catchment area, has reduced the capacity of the plant by less than half. In fact, it was reduced from 2337 to 1080 MW to ensure a continuous power supply [61].

However, there are still challenges related to this technology, such as, for example, in large cities. The incorporation of small turbines in the route of the downpipes of residential buildings of a certain height can allow the use of the potential energy of the water drained by gutters, bathrooms, and kitchens. This energy, stored in small accumulators, can allow self-consumption in residents' associations, providing sufficient electricity for lighting doorways, stairs, and other small devices.

In geographic areas of high water scarcity, ensuring hydroelectric power production represents a challenge that must be addressed through strategic and integrated planning approaches. This would require joint national or regional renewable energy plans and hydrological plans.

There are technical simplified applications for small hydraulics that can still be studied and improved. For example, in relation to intake and storage works, there are inflatable dams or dikes on the market that require limited infrastructure and hydraulic works and can be regulated based on the level of the open channel upstream of the dam. In addition, there is the possibility of using plastic pipes for the forced ducts that can work at the optimum pressure of 16 bar, are easy to install and adapt to the terrain, and have lower pressure losses than other materials. For falls from 1 to 10 m a simple and often insufficiently studied solution is to use siphon turbines.

One of the major perspectives of this work, and of which scarce research has been observed, is that hydropower plants can play a key role in managing the energy system for the integration of other renewable energies. This technology offers great flexibility to the energy system, for example, in the integration of renewable energies, reducing when there is an excess of wind energy or returning to its maximum capacity when the solar energy is in temporary shortage.

4. Conclusions

Hydropower is a process of generating electricity with zero emissions into the atmosphere. In addition, all the water used in the process is returned to the river or reservoir in its original state and with its quality intact. On the other hand, rivers are a source of biodiversity and an important part of the natural heritage. The large numbers indicate that large hydroelectric plants account for only 10% of installations but generate 90% of hydroelectric energy.

In this chapter, it was found that there are major related lines of research that are closely linked to each other. However, it has been seen how engineering is a subject that is already somewhat unrelated to the central core of these investigations. The latter may be due to the great maturity that exists in this technology. It has been seen that there is a great sensitivity among researchers for natural ecosystems, and how to make them compatible with hydropower.

As a general conclusion of this chapter, it is understood that the general principles for hydropower development must be sustainable. In addition, this sustainability must contemplate climate change scenarios and be respectful of the possible ecological effects they may cause. Therefore measures must be taken to adopt an approach that integrates environmental corrections. In this way, the negative effects of hydropower are mitigated, and local communities are affected as little as possible.

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