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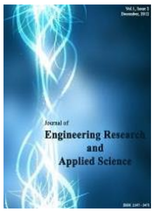

Levelized Cost of Hydropower Projects for Sustainable Electricity Generation

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Abstract
Well-planned hydropower projects can contribute to a sustainable energy supply. Energy planners, investors, and other stakeholders need up-to-date knowledge to make informed decisions about hydropower projects. Hydropower is sensitive to environmental influences and climate change. Although global potential is expected to increase slightly with global climate change, some countries will face declining potential and increased risks. Adaptation measures are necessary to ensure sustainable hydropower utilization. Hydropower costs are generally low but depend heavily on location. The levelized cost of electricity (LCOE) for the rehabilitation and modernization of hydropower facilities ranges from as little as USD 0.01/kWh for additional capacity of an existing hydropower project to approximately USD 0.05/kWh for a more expensive modernization project, assuming a 10% capital cost. The levelized cost of electricity (LCOE) for large hydropower projects typically ranges between USD 0.02 and 0.19/kWh, assuming a 10% capital cost. This makes the best hydropower projects the most cost-effective electricity generation option available today. Levelized costs of electricity (LCOE) for small hydropower plants in developing countries range between $0.02 and $0.10 per kilowatt-hour. This makes small hydropower a very cost-effective option for supplying electricity to the grid. For very small hydropower plants, costs can be higher, resulting in LCOEs of $0.27 per kilowatt-hour or more.

Keywords: *life cycle costs; hydropower projects; renewable energy; sustainable electricity*

1. Introduction

Historically, the development of hydropower has had many driving forces, depending on the economic and social conditions in different regions of the world [1]. A hydropower project has always been carefully assessed, from the initial investment decision to commercial operation, and due to its considerable scale and associated risks, it has required the application of internationally recognized environmental and social standards [2]. Hydropower plants are unique compared to other conventional power generation methods such as thermal or nuclear power. Hydropower plants are always tailor-made, site-specific projects [3]. They require large capital investments, offer relatively low operating costs, and a long lifetime of 40 to 50 years, which can often be extended to 100 years through modernization or upgrades [4]. A hydropower project therefore results in very competitive electricity costs and thus attractive returns [5]. Another key difference lies in the financial modeling of a hydropower plant: While other traditional power plants largely consider fuel costs and therefore depend on their volatility, hydropower does not have such a cost component. The development of hydropower projects is generally a challenging task associated with numerous risks and uncertainties. These risks are related to the hydrology and geology of a potential site, the licensing and permitting process, construction in a remote location with difficult transportation conditions, environmental and social risks, and financial risks due to long payback periods and uncertain electricity tariffs [6-13].

2. Feasibility study and economic drivers

One of the most complex and critical phases of project development is the feasibility study, as this is where the majority of the investigations, planning, and design studies are conducted. The outcome of this phase also provides the green light for an investment decision and initiates implementation [1-5]. When a company considers a new investment in a hydropower plant, it must first answer the question of whether and when this investment will be profitable. This is of utmost importance for hydropower projects, as they require enormous initial investments and complex implementation before any money flows from the sale of electricity. Therefore, the first step is to determine whether the market demand for electricity is (and will

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be) large enough to absorb hundreds of megawatts at a reasonable price [6-8].

If the answer is yes, the planning process begins with an evaluation of available potential sites and plant configurations for a hydropower plant in the region [2]. This evaluation typically covers a broad range of topics and requires the involvement of experts from various disciplines. A preliminary assessment can identify several promising sites based on a rough understanding of the load profile and installed capacity, as well as basic technological concepts [1].

During this phase, technical, geological, and hydrological studies are conducted to gather all possible information and identify various options for a potential power plant location and configuration [1]. This allows for a rough economic evaluation and preliminary calculations of the project economics, especially the investment budget. If certain locations and configurations meet the investor's requirements, more detailed studies are conducted for the selected sites. This pre-feasibility study also follows a step-by-step process [3]:

- Engineering studies are based on the use of available information to evaluate existing technologies and the feasibility of hydropower utilization at a specific location. This typically requires multiple site visits, preliminary design preparations, hydrological estimates, geological assessments, and a complete technical proposal for the power plant [1].
- Preliminary calculation of the project budget for each site and estimation of electricity costs in terms of annual costs per kilowatt hour;
- Assessment of the permit requirement for all locations;
- Analysis of potential social and environmental risks and options for mitigating them.

Successfully identifying and evaluating alternatives requires experienced and qualified specialists in hydropower project development. If these skills are lacking, it is recommended to engage a specialized consulting firm that can conduct appropriate studies based on its experience in planning, engineering, and construction. The latter is particularly important for determining potential schedules and cost estimates. Table 1. Shows the typical costs of a hydroelectric power plant.

Table 1. Typical costs of a hydroelectric power plant.

Type of hydropower	**Investment costs, $/kW**	**OPEX, %/year of CAPEX**	**Capacity factor (%)**	**LCOE, $/kWh**
Large hydropower	940-8400	2-2.5	25 to 90	0.02-0.9
Small hydropower	1300-800	1-4	20 to 95	0.02-0.27
Upgrade	500-1000	1-6		0.01–0.05

Source: [1-4]

Finally, the feasibility study is conducted to analyze the preferred option and further minimize risks. This generally includes [1]:

- Technical and financial assessment of the preferred option;
- Final assessment of the budget and financing options;
- Detailed understanding of the permitting process and social and environmental risks.

The feasibility study should provide clear conclusions regarding the investment decision, the type of technology, location, schedule, and a comprehensive economic evaluation [1]. Although the final report may be prepared by a third party, the final decision rests with the project developer. Therefore, at each of these stages, the alternatives should be examined thoroughly enough to assess their suitability for the stated objective. If any of the alternatives do not meet the requirements of the feasibility study, they should be eliminated. This funnel approach minimizes potential risks, saves money and time during project execution, and thus maximizes the return on investment (ROI) [1].

Typical capital costs for a large hydropower plant depend on the country and location and can vary considerably. They range from US$940 to US$8,400 per kilowatt of installed capacity, with the average being approximately US$2,800/kW (see Table 1). It is important to note that there is no significant relationship between the EPC company and the OEM manufacturer involved in the project and the cost of the installed kilowatts: in most cases, costs are determined by local regulations, land availability, permitting procedures, and general construction practices [1-4]. Furthermore, economies of scale typically play an important role, resulting in lower costs per kilowatt of installed capacity for larger power plants of comparable type [5-8].

While operating and maintenance costs account for approximately 2% of annual investment costs, fuel costs (a key cost factor for thermal power plants) are eliminated. The variable cost component is therefore much more stable, as it is not affected by volatile fuel prices. The capacity factor of a hydropower plant is another variable to consider and can be as high as 25% depending on the operating mode (peak or base load). This results in a levelized cost of electricity of approximately US$0.02 to US$0.19 per kilowatt-hour [2, 4], which represents the break-even point for an investor: the selling price of the electricity must be above this value to achieve a positive return [1].

Knowing the investment and operating costs of a future project allows an investor to calculate and analyze the project's net present value and explore various financing options to estimate the return on investment and payback period. Another issue that is inevitably gaining importance today is the life cycle cost of carbon emissions, i.e., the total CO_2 emissions associated with the design, construction, and operation of a hydropower plant. Although the plant's operation is carbon-free, some emissions are still generated, mainly due to concrete production, material delivery to remote locations, and the potential impact on vegetation damaged by the reservoir [1-4].

3. Design and construction

Once the feasibility study is completed and the investment decision has been made and approved, the investor must select a project developer capable of preparing a detailed design and subsequently constructing a hydropower plant. Typically, a tender process begins with the investor issuing a request for proposals, allowing companies to propose their solutions and prices [1]. This is usually done with the help of a technology and engineering firm, a specialized company that helps the investor specify their requirements in detail, often already during the feasibility study. There are only a few large and world-renowned players who act simultaneously as owners, partly as investors, and partly as project planners and managers [2-6].

3.1. Tendering procedure

The general contractor implements the turnkey project. For the investor, a "one-stop shop" may be a preferred solution: a company or joint venture that assumes full responsibility for the entire project as a single entity. It would be responsible for all design, material procurement, and on-site construction work up to commissioning. An EPC would outsource parts of the work to subcontractors but would remain the client's central point of contact. However, the general contractor bears all risks and can therefore increase the project price. Separate contracts are concluded for different parts of the plant project, such as detailed design, procurement of key equipment, waterway construction, etc. Although the client has full responsibility here, this can be a demanding activity that requires experience and expertise. The investor either outsources project management to a consultant or manages the project with its own project management team [1].

Traditionally, large hydropower projects are implemented on a turnkey basis under an EPC contract. Often, a joint venture is formed between a construction company and a major equipment manufacturer (hydro turbine and generator), which wins the contract due to significantly more favorable terms, relevant references, and a better schedule. Once the contract has been awarded to the main contractor (or a project manager), the project must be financially closed to secure budget allocation (usually through debt financing due to the high investment values). There are two main options for financing a hydropower project [1-5]:

- Corporate financing: A lending institution provides the investor with financing that enables the project developer to implement the hydropower project and service the debt. The lender considers the company's ability to make interest payments and repay or refinance the debt.
- Project financing: The focus is on generating cash after project completion. Project assets can be used as collateral to reduce the lender's risk.

3.2. Construction

The construction of a hydroelectric power plant includes the following essential steps, which may partially overlap [1]:

- Detailed planning of a project, preparation of important design drawings and specifications for the procurement of major and minor equipment and systems;
- Site preparation activities;
- Civil engineering work begins with detailed planning, site preparation, and infrastructure

development. Major civil engineering projects include the construction of dams, penstocks, and waterways, as well as ancillary facilities, the power plant, and the plant foundations. These projects require manufacturer information on foundation loads and system dimensions.

- The installation of large-scale facilities involves erecting supports and delivering equipment to the construction site. Since most large hydropower plants are located in remote areas, delivering equipment, especially bulk items such as turbines, generators, and transformers, can be challenging. Specialized road surveys, precise planning, and the expertise of specialized logistics companies play a critical role and can lead to significant project delays.
- Electrical and mechanical work is performed around the main equipment to establish auxiliary equipment, also known as the "balance of plant." This includes auxiliary pumps, motors, electrical systems, instruments, control rooms, etc.
- Commissioning phase, which includes all necessary testing procedures to verify the construction work, equipment, and grid connections. During this phase, the guaranteed parameters of the power plant must be maintained.
- Finally, commercial operation begins after all testing procedures have been successfully completed and the generated electricity is fed into the grid.

Once financing is secured and the EPC contract is signed, the general contractor begins the detailed design, which forms the basis for the construction of the power plant. Detailed design, carried out by an EPC company, serves to prepare the relevant drawings for the construction and erection of foundations, structures, and buildings, as well as for the fabrication and installation of main and auxiliary equipment, etc. Typically, some of the work is subcontracted to other companies specializing in specific areas: civil engineering, structural engineering, electrical engineering, mechanical engineering, plant engineering, etc. After the design is complete, the EPC company orders long-term components such as hydropower turbines, generators, and valve blocks and establishes the specifications for other equipment. On-site work for a hydropower project includes several key phases [1]:

- Site preparation, i.e., clearing the site for temporary worker accommodation. For large hydropower projects, the number of workers employed on a construction site can reach several thousand at peak times. This requires specially designed and built warehouses with all necessary services for the entire life cycle, from construction to commissioning.
- Local supply chains should be established in parallel with the construction of the depot. These should ensure the supply of electricity and utilities during the construction period, as well as the delivery of materials and equipment. Since most large hydropower projects are located in remote areas, transportation options are often limited and difficult: Separate roads are typically built to ensure the delivery of heavy materials. In addition, some sites may be equipped with newly constructed concrete plants to enable on-site production.
- In order to minimize damage to the water source (especially downstream) and the natural environment, excavation and earthworks are usually carried out in stages.

In mountainous regions, various methods are used, primarily blasting or special tunnel boring machines. The construction process can vary depending on the type of construction. However, it usually takes place in several phases [1]:

- Construction of temporary waterways to divert water around the construction site;
- Construction of dams, including main and secondary dams (where applicable);
- Construction of the turbine room structures (either in a separate building or in the rock);
- Construction of large water inlets and pressure pipes;
- Construction of concrete structures, valves, overflows, etc.

After the completion of the main construction work—that is, the proper erection of all foundations to support the main and auxiliary equipment—the mechanical and electrical systems are installed. Their delivery to the construction site is subject to transportation restrictions, so it's important to ensure good transport links to the construction site in advance.

3.3. Commissioning

Commissioning is typically performed by an EPC with the support of the equipment manufacturers' procurement engineers or by a specialized company under a separate contract. This process requires extensive expertise to inspect the manufactured equipment and ensure the required level of quality [1]. Before commissioning, the commissioning engineer collects all necessary information, such as quality certificates, test procedures, test results from the equipment installers, and other relevant documents. Although the main tests usually include performance guarantees, the hydropower plant must meet additional requirements [2-13]:

- Dry test: After installation, the device is tested under dry conditions to verify basic functionality.
- Wet and stress tests: with water collected in the tank;
- Performance test: verification of the hydraulic efficiency of the turbine and the electrical efficiency of the generator as well as the overall performance of the plant in accordance with the values and conditions specified in the contract;
- Functional and reliability testing: This takes up to 30 days to ensure that all systems are functioning properly.

All of these procedures are typically carried out according to the terms of the contract and are subject to penalties. Depending on the contract, different conditions and warranties may be agreed upon during the negotiation process prior to signing the EPC contract. At the end of the commissioning phase, the operator must submit detailed test reports with all results, as well as all operation and maintenance manuals and documentation, including working drawings. The Certificate of Completion issued by the owner confirms acceptance of the project and is usually associated with the release of the EPC from its final payment obligations [2].

4. Lifecycle management

The average lifetime of hydropower plant systems and components under normal operating and maintenance conditions is summarized in Table 2. These values can vary considerably from plant to plant, depending on site-specific conditions such as water quality and chemical composition, climatic conditions, plant operating profile, and operation and maintenance practices. Although the average values given provide an indication of the frequency and extent of major rehabilitation and modernization work, these must be evaluated and planned based on actual conditions.

Table 2. Average lifetime of components and systems of hydropower plants

Part or system	Years
Steel structures for waterways (pressure pipes, valves, grates, etc.)	60-80
Concrete structures for waterways	70-100
Major mechanical equipment, including hydraulic turbine, generator, valve block	40-50
Mechanical BOP systems (pumps, cooling and compressed air systems, HVAC, etc.)	30
Transformers, high and medium voltage switchgear and associated equipment	30-40
Instrumentation, control and protection systems	20
Remaining electrical BOP (LV AC and DC power supply, emergency diesel generator)	30
External transmission lines	70

Source: [1-4]

4.1 Operational and maintenance activities and costs

Operation and maintenance activities aim to ensure the safety, availability, and reliability of a hydropower plant so that it can produce electricity as planned. Since operation and maintenance costs account for the largest share of operating costs, careful planning is important during the design and construction phases [1-4].

Future operation and maintenance personnel are typically comprehensively trained by the EPC and, in particular, the OEM prior to plant commissioning to participate in commissioning and testing. All equipment and systems are supported by an operation and maintenance manual provided by the manufacturer and/or the EPC. The operation and maintenance costs of a hydropower plant can be divided into two main categories [2]:

- Costs for electrical and mechanical equipment. The recommended annual budget for maintenance of electromechanical equipment is 2.0 to 2.5% of the original investment cost, of which 40% is allocated for annual maintenance and the remaining 60% is set aside in a reserve fund for future renovations and upgrades.

- Construction costs are limited to approximately 0.4 to 0.6% of the original investment cost and are used for underground work, reservoir and construction site maintenance, etc.

5. Hydropower as part of a sustainable energy system

Hydropower generation is currently the most widely used renewable energy technology worldwide. As a historically established and mature technology, hydropower offers many advantages over other electricity generation sources, especially thermal power plants: it is renewable, clean, largely carbon-free, and easily integrated into the electricity grid, often promoting its stability [6]. Hydropower is ideal for covering peak loads and compensating for intermittent energy sources such as wind and solar. In standby mode, it can be switched on and supplying electricity within 15 to 30 seconds [7]. Depending on the country, hydropower can be used either primarily for baseload or peakload generation [4-8].

The operational flexibility of hydropower can act as a catalyst for a sustainable electricity generation system by:

- Ensuring stable and large-scale baseload capacity in areas with high water resource potential;
- Acts as a grid balancing technology to compensate for variable energy sources such as solar and wind power;
- Enable energy storage by collecting the potential energy of water in reservoirs or using excess energy from variable sources in pumped storage.
- Use of excess energy to produce hydrogen as one of the possible energy sources of the future.

However, hydropower can also have negative impacts, particularly at the local level, where dams, spillways, diversions, and changes in river flow can disrupt ecosystems and cause problems [6]. Some of the potential issues discussed at the international level are presented in the following case study.

CO_2 or other greenhouse gas emissions: Hydropower technology does not emit carbon dioxide, nitrogen oxides, hydrocarbons, or particulate matter during operation. However, this figure is underestimated because, as with many other technologies, CO_2 emissions are very high, especially during the construction phase. They arise mainly from the production and consumption of concrete, the manufacture and delivery of equipment, etc. However, given the long lifetime of hydropower plants, which can be up to 80 years, CO_2 emissions per kWh produced are among the lowest of all renewable technologies [6].

Most estimates of life-cycle greenhouse gas emissions from hydropower range between 4 and 14 g CO_2 equivalent per kWh of electricity generated. However, in some scenarios, there is a risk of significantly higher greenhouse gas emissions [10]. In addition, the reservoir could be responsible for the release of methane, a greenhouse gas with a far greater impact than CO_2 . Causes could include changes to the river ecosystem caused by the construction of the reservoir or its chemical composition. Although the construction of hydropower plants can strengthen local economies and provide a flexible and reliable source of electricity, concerns remain about their long-term sustainability. One aspect to consider is the impact of climate change on hydropower generation. These studies are particularly important because hydropower systems have long lifetimes and can last for multiple generations, and long-term climate variability can therefore have significant impacts on projects currently under development [6].

6. Hydropower for electricity generation in Turkey

Following the establishment of the National Water Corporation (DSI) in 1954, projects were better financed and annual production increased significantly. Nevertheless, today approximately 60% of the country's hydropower potential remains untapped. Regarding the situation in this country, contrary to popular belief, Turkey is neither a country with abundant freshwater resources nor the richest country in the region in this regard [14-20]. Turkey is located in a semi-arid region and has only about one-fifth of the water available per capita. This is much more than the 2,000 m^3 per capita in Turkey. Turkish water is not always in the right place at the right time to meet current and expected needs. Some regions of Turkey, such as the Black Sea region, have abundant but unusable freshwater, while some of the more densely populated and industrialized regions, such as the Marmara and Aegean regions, experience a freshwater shortage [14-17].

Turkey has significant hydropower capacity estimated at 433 TWh per year, of which approximately 214 TWh per year are considered economically viable (2022). At an average elevation of 1,100 meters above sea level, sufficient head is available for expansion in many regions, including the Black Sea region, the Mediterranean, and Eastern Anatolia. The geographical location offers significant opportunities for hydropower development [15].

Turkey produces more than 77 billion kilowatt-hours of electricity from hydropower annually [15], which accounts for 26% of its total electricity production [14]. Due to rapid urbanization and industrialization, Turkey's energy consumption is increasing by an average of 5.7% annually. Electricity consumption peaked at 126.9 billion kilowatt-hours in 2002, but is expected to reach 374 billion kilowatt-hours by 2022. It is projected to increase to 628 billion kilowatt-hours by 2030 [14-17]. The total gross hydropower potential and total electricity generation capacity amount to just under 50,000 MW and 112 TWh per year , respectively. On average, 36% of the total gross potential could be economically utilized. Currently, only about 14% of the total hydropower potential is utilized. The National Development Plan aims to fully utilize the hydropower potential by 2030. The contribution of small hydropower plants to total electricity generation is estimated at 4%. There are still some rivers whose small-scale hydropower potential has not yet been fully exploited. Since total energy losses in hydropower generation were approximately 3.6 TWh in 1985 , another goal is to improve hydropower generation. Figure 1 shows the distribution of licensed electricity generation by source in 2023.

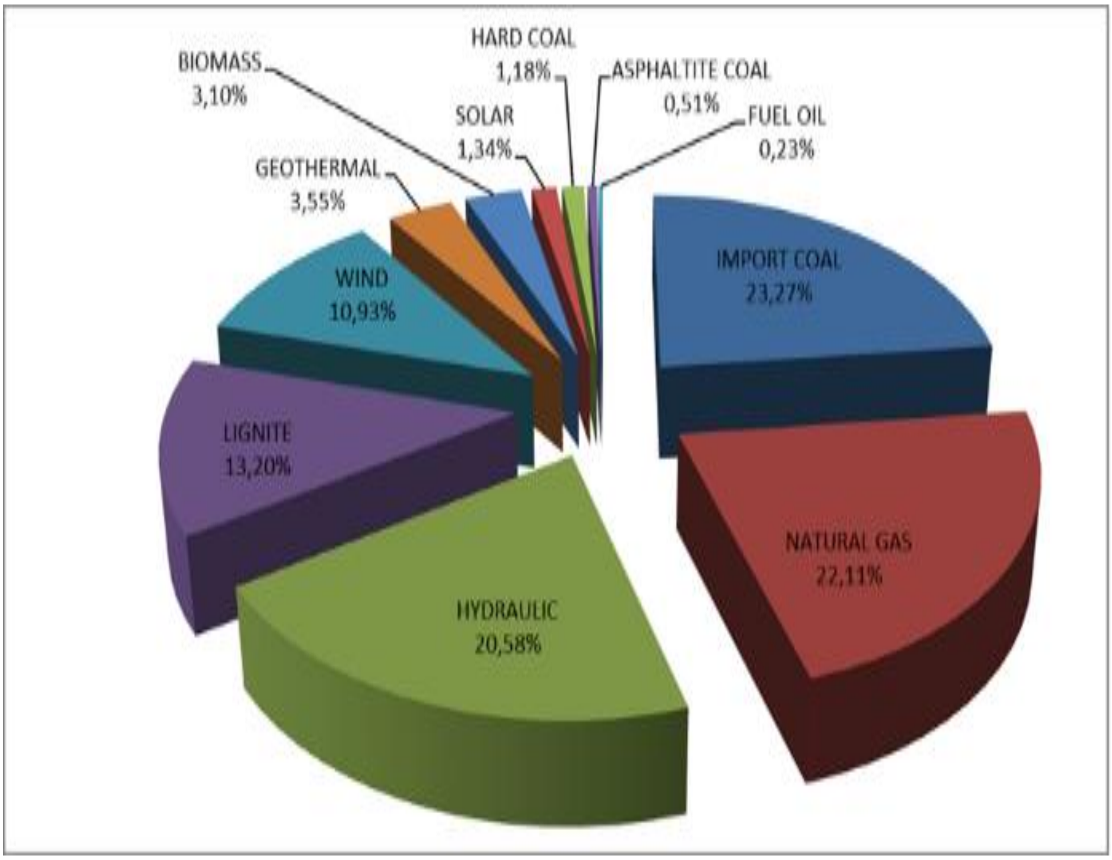

Figure 1. Distribution of licensed electricity generation by source in 2023.

Among other renewable energies, hydropower contributes the most to electricity generation in Turkey and worldwide. The installed hydropower capacity was increased to 32,000 MW by the end of 2022, but the 2030 targets aim to increase this number to 46,000 MW. Since the country has high hydropower potential due to its geological structure, Turkey is making great efforts to turn this potential into an advantage. In addition to the currently operating hydropower plants (HPs), work is underway to increase the installed capacity by 6,500 MW of licensed HPPs and 3,500 MW of pre-licensed HPP projects . Furthermore, combined heat and power plants, as a fully domestic energy source, generate electricity at a lower cost than modern renewable energy sources. Figure 2 shows Turkey's licensed electricity production per year (GWh).

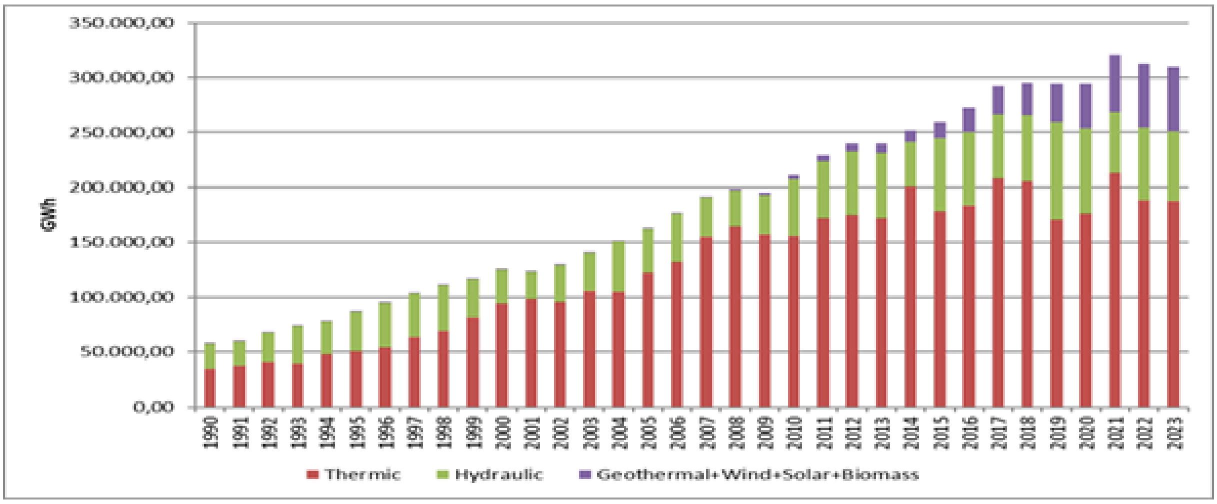

Figure 2. Licensed electricity generation in Turkey per year (GWh).

Since only about 25% of the practical and about 50% of the economic potential have been secured so far, the potential for future developments is greater. Numerous estimates of the future penetration of hydropower exist, almost all of which predict a significant global increase. Some hydropower companies forecast an even higher market potential of 8,750 TWh / year by 2050. Recent studies show that hydropower could double by 2050, reaching a total capacity of 2,000 GW, or about 7,000 TWh . The majority of this development would come from large hydropower plants in developing and emerging countries (Fig. 3).

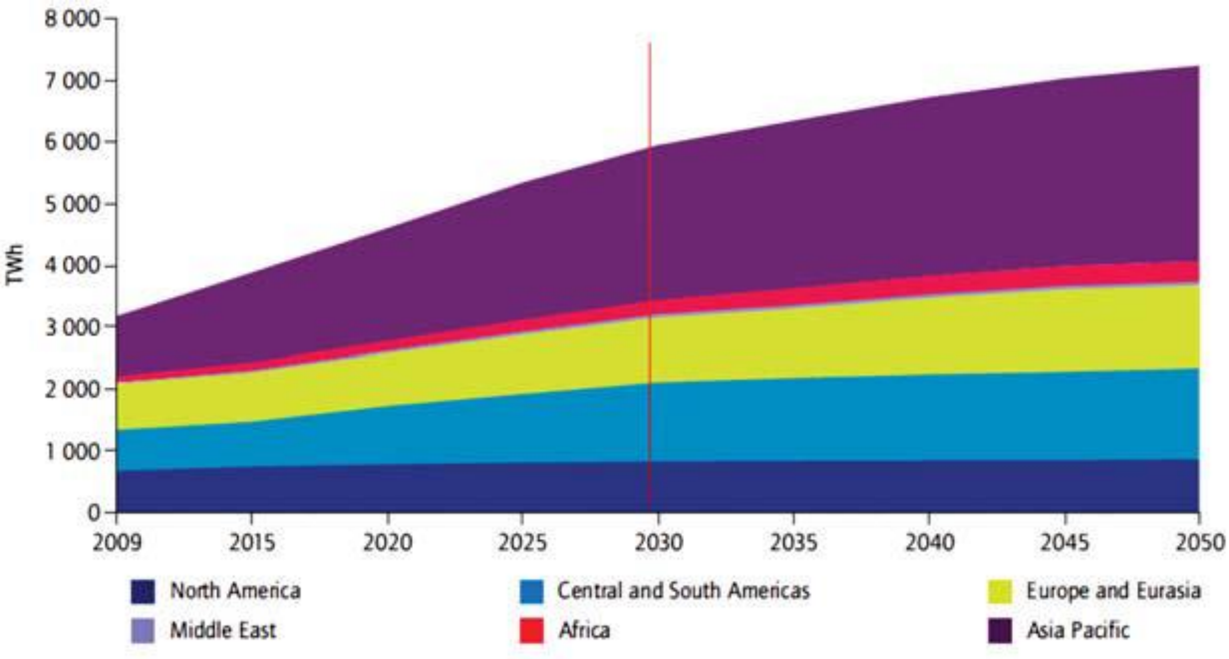

Figure 3. Roadmap for hydropower production until 2050 [3].

7. Conclusion

Turkey utilizes approximately 30% of its hydropower potential. The untapped potential consists of small-scale hydropower projects. At the end of 2022, the installed capacity of Turkish hydropower plants was 13,393 MW. The Turkish Ministry of Energy has decided to utilize the entire hydropower potential for both large-scale and small-scale hydropower projects. However, many projects violated the local population's right to access water and ignored the protection of river ecosystems. Within just a few years, the rapid expansion of hydropower has become an example of how renewable energy policies can fail without a balanced approach to the use of diverse renewable energy sources combined with energy efficiency.

Hydropower is an important energy source for Turkey because it is renewable, clean, and environmentally friendly. Turkey's hydropower potential can meet 40% to 60% of its electricity needs by 2030. By evaluating small hydropower plants, Turkey can meet a significant portion of its total electricity needs from its own hydropower resources. To date, only 5% of the economically viable potential of small hydropower plants has been developed. If Turkey's remaining hydropower potential were fully utilized, approximately 20 TWh of electricity could be generated annually , which is equivalent to almost 10% of the country's annual electricity demand. Currently, only 30% of the economically viable hydropower potential is usable in Turkey. If Turkey could effectively utilize its remaining hydropower potential with a hydropower capacity of 100 TWh /year

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