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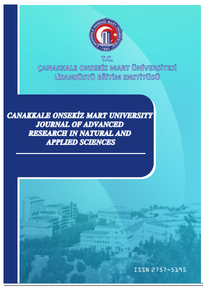

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Optimization Tool for Small Hydropower Plant Resource Planning And Development: A Case Study

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Research Article

Abstract − In recent years, the use of renewable energy sources in electricity networks; has shown a rapid increase thanks to their clean, environment-friendly, and most importantly the supportive policies of the countries. As the production and distribution of energy resources become more complex, there is an increasing need for mathematical modelling and optimization problems, especially for designing clean energy systems and establishing clear and systematic decision-making mechanisms in the operation of these systems. The models created within the scope of this study include decisions such as the capacity of the systems to be created in order to support long-term investment decisions for energy infrastructure planning, and where, how much, and when energy should be generated. In addition to the purpose of the models and the elements they contain, one of the most important factors that complicate the problem is that the problem is stochastic and contains uncertainty. It is possible to get an idea about the electricity market prices and the flow rate and amounts of the rivers that supply water to the production in hydroelectric power plants, with estimation methods, but it is impossible to determine them precisely. All these uncertainties should be taken into account when the capacity of the infrastructure of the energy systems is created. In this respect, in this study, systems are modelled and compared using both deterministic and stochastic programming. The quasi-Newton method is used for nonlinear optimization tasks to plan energy pro-duction under the uncertainties in the nature of renewable energy. In the feasibility study, the Monte-Carlo method, which is a mathematical technique used to predict the possible outcomes of an uncertain event, was applied.

Keywords − *Cost-benefit analysis, cost correlation, cost optimization, net present value, small hydropower plant.*

1. Introduction

The need for energy, which has increased in parallel with production with the Industrial Revolution, has been a current issue since the 18th century (Teck et al., 2019). Every government, every home, every business, and every major issue is underpinned by energy. The increase of power consumption day by day, climate change, and the need to manage diminishing fossil fuels such as natural gas and oil reserves; these three main factors create an enormous problem in power engineering and it gives us reasons to develop power systems and their management, which influence market conditions and to be depended from other countries. But the situation is not easy to understand and resolve as power systems are among the hardest issues that exist for human activities. As seen in Figure 1; according to the International Energy Agency, world energy demand is estimated to increase by approximately 60% in the next 30 years (Kober et al., 2020). The most pressing issue is determining how to fulfil this demand.

Because of the rapid decrease in the number of conventional resources and increasing demand, some countries will not be able to meet the demand by conventional primary resources until 2030 (Matzenberger et al., 2015). As conventional energy sources (fossil fuels) are decreasing day by day, governments should adopt two strategies: reducing energy demand and increasing supply. In this context energy reliability, efficiency and renewable energy are notably relevant. Renewable energy serves two main targets: protecting

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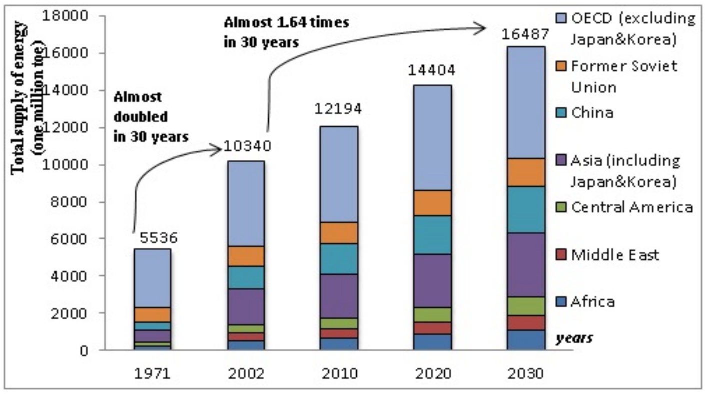

Figure 1. Global energy demand between 1971-2030 (Ranaraja et al., 2020)

the environment with emissions-free energy and generating energy to meet the demand (Davis et al., 2018). The efficiency of energy addresses using energy most accurately without any reduction in production, comfort, and workforce.

Furthermore, currently, a lot of the countries are developing policies and trying to determine attainable targets in this area (Shukla et al., 2017). Comprising features mentioned above, small hydropower plants (SHPP) have been getting attention in both developed and developing countries. Western countries such as North America and Europe have already exploited most of their hydropower potential. However, South America, Africa, and Asia have still substantial unused potential for hydropower. Small hydro can be the cure and help of the insufficient energy in developing countries, as China did with 43000 small schemes and 265 GW of total installed power capacity (Bachir, 2017). In terms of fossil fuel sources, Turkey cannot be considered a rich country; this condition creates economical and political barriers to the development of the country (Kok & Benli, 2017). Beyond these problems; Turkey has a large renewable energy sources potential for electricity generation (Bulut & Muratoglu, 2018). The participation of the private sector in the energy field started a new era in energy generation from renewable sources in Turkey.

Hydroelectric energy constitutes the most important renewable energy source in Turkey (Bulut & Muratoglu, 2018; Erdin & Ozkaya, 2019). Considering its geomorphological structure and climatological/hydrological characteristics, Turkey is among the countries that can be considered lucky in terms of both its head and water level. Disregarding that potential, mainly large-scale hydroelectricity and thermal (non-renewable) has been widely exploited. To handle the potential of other renewables, a feed-in tariff (FIT) scheme has been implemented since 2001 (Kural & Ara, 2020) and it has experienced several revisions over the last decade.

One of the world's biggest problems faced in the 21st century is a secure energy supply (Asif & Muneer, 2007). In our country, where the demand is increasing quite rapidly, meeting the energy demand in a reliable manner as well as peak power is of great importance in terms of ensuring the supply security of the system and hydropower can handle this issue. Large numbers of papers (Alvarez et al., 1994; Asif & Muneer, 2007; Jiang et al., 2018; Marchand et al., 2019; Xu, J., Liu, Z., Jiang, 2021; Y. Yang et al., 2020; Z. Yang et al., 2022) are devoted to solving the generation plan problems. It is important to note that the HPP operating mode should be selected based on uncertain and random factors. Summarizing the above can be noted that despite the efforts of researchers and governments, there are still many unresolved issues, especially to maximize profits through an optimal selection of HPP parameters and operation mode.

For the purposes of this study, objective research is defined as research that aims to develop short- and long-term planning models for price takers generating in the market environment while pursuing profit maximization while taking into account energy market conditions, uncertainties, and joint working opportunities. To achieve the stated goal four main tasks need to be considered:

- development of stochastic optimization algorithm for hydroelectric power plant;
- a cost-benefit analysis (CBA) to measure the benefits of a decision;
- presentation of CBA findings of total project costs for installed power capacity and reservoir alternatives; establishing a long-term SHP to evaluate qualifications and find the best alternative;

- synthesis of a model for the benefit of hydroelectric power plant operators; testing of models during the solution of optimization tasks; description of the volume and resources of information required; the possibility of applying models has been proven by the Quasi-Newton method.

The first chapter describes the topicality of the study, formulates the goal and tasks of the work. The chapter contains an introduction to the problem and deals with the research methods which are used for the acquisition of the results of the work, as well as the basic levels of research. Chapter two describes general knowledge about small hydropower plants and their equipment. Chapter three starts with information about SHPP design and continues to describe the formulation of SHPP operations. Also, feasibility scenario the Chapter offers an optimization technique purposeful by maximizing income for hydropower which has limited water to use. The economic part of the feasibility study of power plants in terms of a particular feed-in tariff and market conditions is formulated. Chapter four presents the application of the considered methods with examples and a case study for a Turkish SHPP. The suggested algorithm of power plant working condition optimization is approbated on the Saf HPP. Chapter five represents conclusions and devoted an outline of the future work. Finally, several conclusions and suggestions for future work are given and the solution algorithm is presented to solve the hydropower generation coordination problem at market conditions.

1.1 The objectives of power supply development

Sustainable energy is the model of energy acquired from non-exhaustible resources so the provision of this model of energy distributes the needs of the present without compromising the ability of future generations' capacity to satisfy their own. Electricity generation, distribution, and consumption have many unfavourable environmental consequences at the global, regional, and local levels, including indoor air pollution in global warming, blighted area communities, and land degradation. Green energy organizations are needed to direct all of these towards environmental sustainability (Zhang et al., 2021). The sustainability topic covers the three pillars of issues – environmental, economic, and social– and includes issues such as indigenous peoples, downstream flow regimes, resettlement, infrastructure safety, water quality, sedimentation, and erosion (Ranjbari et al., 2021).

Sustainability prevents the rising of oil prices; it helps provide cheap and environment-friendly energy. Overall, the sustainable development of the hydropower sector is based on three important principles: (Zhang et al., 2021)

- economic sustainability means delivering the maintenance of the renewable resource base, and the use of non-renewable resource rents to encourage structure the improvement of other factors of generation. Cost-benefit analysis and evaluation of long-term economic performance are the keys to the achievement of economic sustainability;
- social sustainability is based on how effective regions and countries are in the building of new projects, which means people involvement during erection and generation for working and improvement of self-knowledge.
- the avoidance of unavoidable environmental causes such as biodiversity loss and the buildup of persistent pollutants is essential for ecological (environmental) sustainability. Technology and economics are also related to resource management, decision-making, acquisitions, etc (Alterach et al., 2010). Figure 2 represents a definition of the space of feasible solutions, considering the legal, technical, and economic aspects or boundary conditions.

Hydropower energy technologies are important contributors to sustainable energy because they help to provide global energy security by lowering reliance on fossil fuels and giving chances to reduce greenhouse gas emissions. Sustainable energy sources and efficient use of energy as a whole cannot be considered separately. The basic aim of sustainable energy sources and efficient use of energy is a reduction of carbon dioxide emissions. Small-scale hydropower is a promising alternative for producing inexpensive and sustainable energy in rural or developing areas. The case study of this thesis aims at investigating the useful tools for operation and management for small-scale hydropower in rural areas for sustainable development. (Demirtas, 2013)

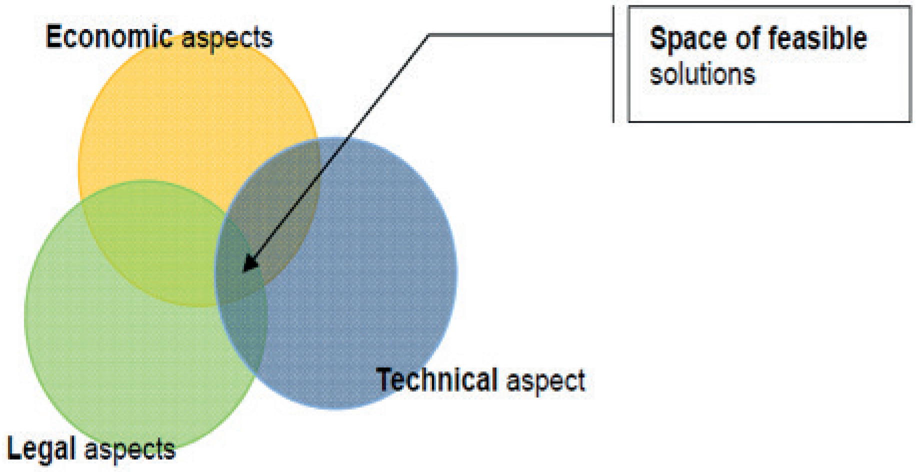

Figure 2. The space of SHPP feasible solutions (Alterach et al., 2010)

A sustainable hydropower project is possible, but it needs careful system design and proper planning to control the objections (Kaunda et al., 2012). The hydropower projects which are planned well can contribute to the supply of sustainable energy. It is important that up-to-date information (knowledge) is necessary for investors, energy planners, and other stakeholders to make informed decisions concerning hydropower projects. Hydropower can considerably provide towards diminishing effects of global warming and mitigation of climate change, increased national energy access and security, creation of economic opportunities, and thus completely leading to sustainable development (De Jong et al., 2018).

1.2 Hydropower in Turkey

The technical potential provided current and expected local economic conditions in developing technology but can be part of the so-called developed and economically feasible hydropower potential of increasing energy prices, technical and economic potential of the technical potential of the approach. Figure 3 shows Turkey's annual energy generation percentages.

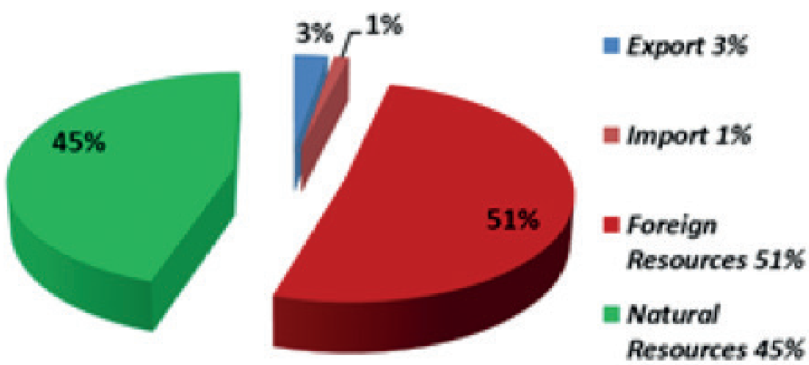

Figure 3. Turkey's annual energy generation percentages (*Ministry of Energy and Natural Resources, 2022*)

As a result of climate change, and due to the effects of Covid-19; electricity production in Turkey decreased by 16% in HPPs in 2021 compared to the previous period (Coban, 2021). As seen in Figure 3, developing domestic and renewable energy resources is very important for Turkey in ensuring sustainable development because the country imports 51% of the total energy it consumes, according to the statistical data of the General Directorate of Renewable Energy. The country's premier domestic and renewable energy resource is hydropower. Figure 4 below presents the distribution of Turkey's installed power resources as of the end of 2021. About 46% of the installed capacity belongs to renewable energy sources. The renewable installed capacity of a very large portion is constituted by hydraulic capacity. The share of solar and geothermal power is limited. The share of natural gas is 27% (Ministry of Energy and Natural Resources, 2022).

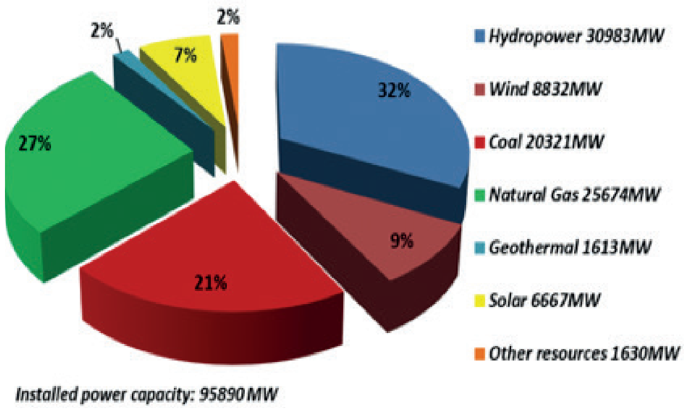

Figure 4. Turkey's installed power as distributed among resource types (*Ministry of Energy and Natural Resources*, 2022)

- Turkey's annual potential hydroelectric energy capacity is 128 billion kWh. Nevertheless, only 36% of this capacity is being used; currently, the amount of electricity annually produced from hydroelectric power plants is 46 billion kWh. Also, many hydropower plants are under construction by the private and the public sector. (Yuksel et al., 2017)
- Especially Northern of the country (the Black Sea region) is rich in terms of altitude and rivers. Most of the Black Sea region is hilly; it can be possible to develop higher heads by way of non-expensive civil works so that smaller flow rates are needed to achieve the power aimed at. Renewable energy will play a critical role as Turkey's development for accession to the European Union is in progress.(Yuksel et al., 2017)
- Turkey has about 1.5% of the world's total hydroelectric potential, with an average altitude three times higher than the European average, with an average elevation of 1132 m, and the location, the country is ringed on three sides by seas, is highly favourable for hydroelectric power production. This topography favours the formation of high gradient mountain streams, which are applicable locations for small-scale hydropower development. (Kaygusuz, 2018)
- Turkey, which has the sixth-largest electricity market in Europe, has a rapid growth rate in electricity consumption above the GDP per capita growth as a result of population growth, economic, and industrialization growth in the last two twenty years (M. Şahin, 2021).
- Privatization efforts of the government were notably fruitful in Turkey's hydropower environment. The very quick growth in the number of privately financed small to medium-sized hydroelectric power plants helped the country to develop a more secure, efficient, and reliable energy supply as well as progress towards its goal of producing 100% of its total energy from renewables by 2050 (Coban, 2020a).
- Turkey has Europe's highest hydroelectric potential with its 216 billion kWh/year technical hydropower potential and the economically viable potential is 140 billion kWh/year; but was using only 24.58% (67,259 GWh) of hydropower potential as of the year 2015 (Bilgili et al., 2018; Erat et al., 2021). However, many European countries are trying to reach the production target of over 70% of their economically viable hydroelectric potential. (Lund & Østergaard, 2018).

The support scheme and the day-ahead market:

Unfortunately, Turkey's markets are still inadequate when compared to the EU countries that are leading the utilization of renewable energy sources. For example, according to the German Renewable Energy Law for different energy sources government offers different feed-in tariffs. Still, the Turkish government guarantees to purchase the produced electricity for 10 years and offers a feed-in tariff of 7.3\$cents (6.4€cents)/kWh (Yalılı et al., 2020). In addition, the Law provides additional bonus income for each domestically produced component of mechanical or electro-mechanical equipment used in power plants. This is called "local contribution" (Yalılı et al., 2020). The feed-in tariff for some of the European countries is shown in Table 1.

Table 1

Feed-in tariff rates in Europe €c/kWh (Legal Sources on Renewable Energy, 2021)

Country	Biomass	Biogas	Hydropower	Wind	PV
Lithuania	8.6	8.6	7.0	7.5	44.0
Latvia	18.5	19.5	18.8	10.5	42.6
Germany*	5.76	8.3	3.5 – 12.5	3.5-19	8.92
Turkey	10.4	10.4	6.4	6.4	10.3
Turkey*	11.8	13.3	9.5	9.5	15.2

Germany*: offshore wind €ct 3.5 – 19 per kWh, onshore wind €ct 4.72 – 8.66; Turkey*: with an additional payment for "Made in Turkey" components

Every day, the national load distribution center publishes a demand forecast determined on an hourly basis for the next day on the Market Management System. Participants need information such as seasonal conditions, precipitation, various factors such as occupancy rates, and system constraints when the dam produces electricity for the next day considering their estimates. The aim is to increase production at times when the demand is high and to reduce and stop production at times when the demand is low. As in all markets, in the electricity market, if the demand is greater than the supply, the price increases at that time; night hours, weekends, and holidays represent examples of electricity prices going down. Market participants can submit hourly, block, and flexible bids at the day-ahead market. The amount and price of bids can differ for different hours. The maximum and minimum amount of power and price that can be traded is determined by the Market Financial Settlement Center (C. Şahin, 2021). Figure 5 abstracts the process of the day-ahead electricity market.

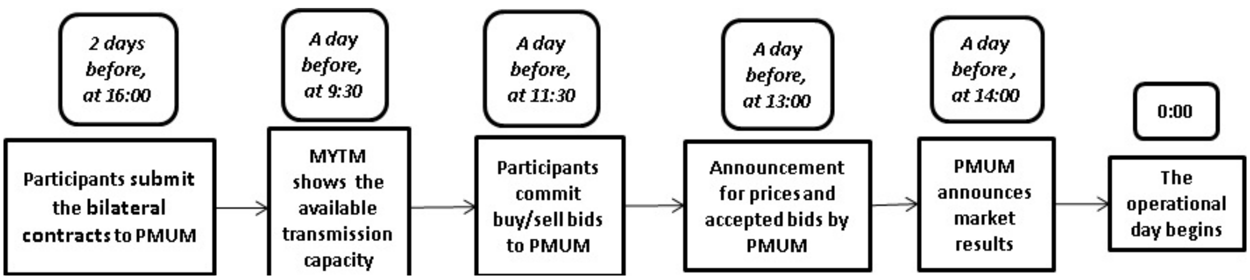

Figure 5. A timeline of the Turkish day-ahead market

1.3 The methodology of a cost-benefit analysis

The CBA is the heart of a feasibility study for a small hydropower project (Wendle, 2019). The costs and benefits that an investment project will provide over its entire life are determined in monetary terms. The discount rate plays a critical role in the choice of whether or not a proposed project is economically feasible and should accordingly be carried out. Furthermore, the longer the life of an investigated power plant project, the greater the impact that the discount rate has on costs and future benefits (Wendle, 2019). The main objective of the CBA is to provide alternatives that are economically best appropriated for the improvement of an aging hydropower plant. The primary objective of the analysis is to collect all the costs associated with all the alternatives and to determine the relationship between the returns and the investment. The initial stage of this analysis is to calculate the total cost for each alternative, then the present worth of the revenues is calculated and the relationship established; if the alternative is economically viable and is best suited for both the investment or returns ratio and the reliability of the unit, then the project application stage begins (Wendle, 2019).

Figure 6 summarizes the economic methodology for calculating the annual net income. To estimate the annual net benefit, project operating and maintenance expenses are subtracted from the sum of reve-nues, which are gross electricity generation, project services, and additional incomes. Additional annual benefits relate to being in coalition with irrigation companies, other energy producers, and fishermen. Annual benefits of the project consist of revenues from benefits such as river transportation, water supply, irrigation, and flood control. Annual costs of operation represent interest payment, past and future investment costs on the project, and current operation and maintenance costs. (Bin, 2021)

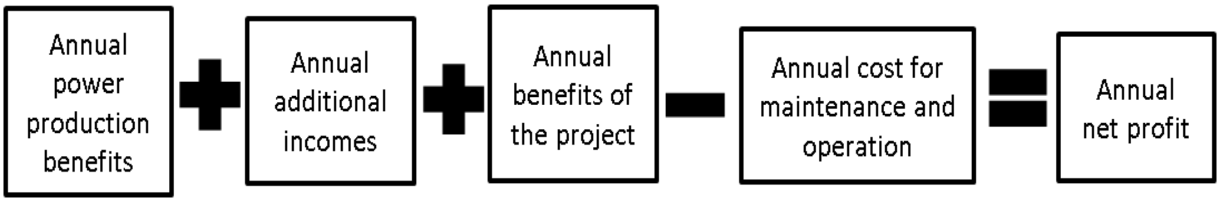

Figure 6. An income calculation of a hydropower plant

A thorough search and review have been carried out for relevant published reports and journal papers; several studies exist that reveal the costs of production for run-of-river, storage, and pumped-storage hydropower plants (Belbo, 2016; Kotchen et al., 2006; Wessel et al., 2020; Yildiz & Vrugt, 2019). One of the existing cost equations and associated work is summarized below.

The authors of (Kotchen et al., 2006) draw on three studies of environmental constraints, which are, firstly, electricity production costs, secondly, air quality benefits, and, thirdly, recreational fishing benefits on hydroelectricity production costs and benefits related to the run of river flow. The authors investigated the economic impact of increases in electricity production from other resources. As a result, the best approximate calculation offers that the aggregate benefits are more than two times as large as the producer's costs.

A review of the literature shows that several empirical equations have been developed worldwide to estimate electromechanical costs, civil works, and overall project costs. However, each of these studies has certain limitations about being applied to the prediction of costs for new hydropower projects in the United States. Particularly, the cost of a hydropower project is nonlinearly correlated to installed capacity and head; also it is very sensitive to the evolving technologies and site-dependent.

2. The Basics of SHPP Design and Operation

The choice of the most appropriate sites for the hydropower exploitation depends upon the relationship between the construction, operation, and maintenance costs of the entire system and the income from energy selling plus the additional benefits, such as creating a coalition with a public trader and/or local consumers (Sun et al., 2021). According to the hydropower equation (2.1), the power generated is proportional to the product of the head and the release via the turbines, with precise values set by turbine design (Bachir, 2017).

$$P_t = \rho u h \text{ (kgm)}, \tag{2.1}$$

Where;

P_t -potential energy;

ρ - the density of water in kilograms.1000/m^3;

u - the amount of water;

h - the height difference between inlet and outlet in meters.

The quantity of water falling (2.2) is called flow. When water supplies u discharge rate some time interval, m^3/s:

$$Q = \frac{u}{t} \tag{2.2}$$

In order to obtain the water velocity required to produce energy from a water turbine with the help of water force, a drop height or the kinetic and pressure energy of the water is absolutely needed. The maximum active hydraulic power (installed power) capacity that a facility can produce is expressed in the formula (2.3) below.

$$P = \eta \rho g Q h, \tag{2.3}$$

Where;

P - the power output, measured in Watts;

η - the efficiency rate of the generator and turbine;

Q - the water flow rate m^3/s;

g - the acceleration of gravity, $9.81 m/s^2$

The real-life model of a power plant is more complicated. Because n is a function of the head-pond of water. This phenomenon can be taken into account when choosing concrete equipment.

2.1 An overview of SHPP optimization procedures

The optimization task of power plant management can be identified with multi-parameter, linear or non-linear, dynamic, stochastic, discrete variables (Asif & Muneer, 2007; Mahmoudimehr & Sebghati, 2019). No commonly accepted solution to this task. Many simplified approaches are applied. Depending on the objective function, the restrictions on the types and designs, the mathematical task after its formulation can be solved by using the mathematical programming 0method. A wide range of mathematical programming methods is described in the literature. There are optimization studies in the fields of water resources management and power generation using the solver application, and some of the most frequently used programming models are summarized below.

An optimization model has been developed in the article (Benli & Kodal, 2003) investigated the optimum plant pattern with the Non-Linear Optimization method they developed in the South-eastern Anatolia Region in their study. The model inputs were transferred to the MS-Excel solver program and the LINDO software package under water potential, crop yield, adequate and limited irrigation conditions. With the same objective function and constraints, they tried to determine the optimum planting area distribution with linear and nonlinear models and showed that the net income obtained from the nonlinear model was higher under limited irrigation conditions.

The article (Arai et al., 2011) simulated a study in Bangladesh using an Excel Solver application to demonstrate the impact of electricity generation on economic growth. For various power generation schemes, a solver for nonlinear problems in the model was used and six steps were followed. i) the constants and settings were set, ii) a price system calculation was obtained, iii) income and final demand were calculated, iv) production demand was calculated, v) the equilibrium was solved and, vi) future electricity prices and capital accumulation were calculated. Upon comparing the results for various established models, the electricity generation capacities and applicable planning and operating policy were obtained.

The paper (Tiainen et al., 2008) investigates the optimization of the energy production of a Finnish head-dependent reservoirs in light of market conditions based on the Nord Pool Spot hourly energy price. The optimization algorithm's objective function is to maximize the income in a given period, with the hourly-changing the inflow, electricity price and the current generator states as inputs while keeping the head between the required limits. With varied inflow levels and pricing data, the technique is examined using genetic algorithm-based and steepest ascent-based optimization algorithms. The reservoir was filled to the maximum before the peak time and the head was allowed to drop when the price was high. The optimization is implemented in three versions – Steepest Ascent Hill Climbing, Genetic Algorithm, and Simulated Annealing. The results are compared the income had improved approximately by 0.5-10%.

The authors of (Wu et al., 2008) present the cost of reliability by considering the stochastic nature of power systems in the long term. Random outages of transmission lines and generating units as well as load forecasting errors are designed as scenario trees in the Monte-Carlo simulation. The hourly unit commitment problem is used to solve the reliability model in a successful way. They have applied the Monte-Carlo method to simulate potential contingencies in uncertain security-constrained unit commitment.

The authors of (Desreumaux et al., 2014) aimed to develop a new method to compute the cost-to-go function efficiently and to reduce the computation time of the Stochastic Dynamic Program algorithm applied to a hydropower system optimization. The objective function of the one-stage optimization problem that is solved to evaluate the cost-to-go function includes the summation of two terms, the current benefits function, and the expected water value function.

The article (Howard, 2006) describes the formulation of a hybrid two-stage hourly hydropower generation optimization model that is established on an MS-Excel solver. The first stage determines the hourly total powerhouse discharge that maximizes generation revenue within the operating limitations and constraints, namely the quadratic optimization model. The second stage is a non-linear postprocessor, which disaggregates the optimized plant discharge and simulates the operation of the project using the suitable non-linear curves. The method was used to determine plant and unit operations to maximize revenue.

The authors of (Najarchi & Haghverdi, 2020) would like to attain optimal operation of the hydropower plant, which is a multistage and nonlinear combinatorial optimization problem with many constraints and can be presented as finding a water level change sequence that satisfies all constraints to maximize the annual income by electricity generation. As a result, they found that the differential evolution algorithm is preferable to dynamic programming since it provides a new approach for multi-reservoir combined optimal operation and has better calculation speed.

The nonlinear monthly optimization model proposed by the authors of (Barros et al., 2001) has been developed for the operations and management of a large-scale hydropower system and applied to the hydropower system of Brazil. Their model can be used by two different approaches, a linear approach and a nonlinear one. The linearized model replaces the energy production and tailrace functions by their corresponding average values in a seven-year planning time horizon. Their results showed that the linearized model produced 1.5% and 0.5% more energy.

The authors of (Enoksson & Svedberg, 2015) concentrate their self in master thesis more on the mathematics on a two-stage stochastic optimization model. The objective function aims to maximize the income. The authors developed a model that uses public data that are directly observable from the electricity market for hydropower optimization which takes hydrological uncertainty into account. They have tested different methods which are the normalization approach, where the assumption that inflow to the reservoirs is outcomes from a normal distribution for each time step, and the Bootstrap approach, where scenarios are created by randomly sampling inflows from the historical observations. The author's recommendation is to use one of these two inflow distribution methods.

The article (Soares & Carneiro, 1991) proved the influence of several factors including water inflow seasonality, head-pond, discount rate, and system design on a deterministic optimization. The result showed that these factors have a great effect on the long-term optimization for CBA of hydrothermal power plants. To model the stochastic factors, they have used a deterministic approach because authors could not compute in a stochastic way.Summarizing above, it can be concluded that the HPP optimization problems can be considered as multi-objectives, non-linear and stochastic. These keywords form a base of the algorithm which has been chosen in this study.

3. General mathematical programming

It is assumed that the profit (3.1) of the power facility is any function of head pond, water discharge, market prices, etc. can be defined as below.

$$R_{i\Delta} = \varphi(C_t, D_t, U_{it}, H_{it}, K_t, CH_t, Inv_t, P_{it}, \rho_{it}, OM_t, A_{it}) \tag{3.1}$$

where;

$R_{i\Delta}$ – the profit.

C_t – electricity market prices, Eur/MWh;

D_t − risks ratio for year "t";

U_{it} – the number of units;

H_{it} – the head-pond, m;

CH_t – the catchment area, ;

K_t – the discount factor for year "t";

i – the number of the option (alternatives);

Inv_t – the cost of construction.

P_{it} – the installed capacity;

OM_{it} – operations and maintenance costs in year "t";

ρ_{it} – efficiency of turbine and generators;

A_{it} – capacity of the reservoir, ;

t – the time interval, t (year);

A given set of input parameters is known in the deterministic situation, while some of these parameters are uncertain and/or probabilistic in the stochastic case. In this case, the random $R_{i\Delta}$ optimization problem can be formulated as an average profit maximization task as follows:

$$M[R_{i\Delta}] = \Delta t \int_{-\infty}^{+\infty} \dots \int \varphi \begin{pmatrix} P_{it}, U_{it}, H_{it}, C_t, A_{it}, \rho_{it}, \\ OM_t, D_t, K_t, CH_t, Inv_t \end{pmatrix} dF \tag{3.2}$$

Where;

F – a multidimensional probability distribution function (Antans Sauhats et al., 2016; R. Varfolomejeva et al., 2014).

The objective function presented in the form (3.2) is not only difficult for maximization, but also very complex to calculate (Antans Sauhats et al., 2016).

3.1 Constraints of SHPP operation

The main constraints of HPPs operation can be classified into four groups: (Yuan et al., 2021)

I. The reservoir storage volume limits:

The head-pond means the difference in height. It is assumed that H can be any value lying within the domain [H_{min}, H_{max}], where H_{min}, H_{max} are positive constants (3.3) specified in the operation plan:

$$H_{i,min}^t \le H_i^t \le H_{i,max}^t, \qquad \forall i \in I,\ \forall t \in T \tag{3.3}$$

where H represents the water level (3.4); the min and max are the allowable lowest and highest-level during time t respectively (3.5, 3.6). is reservoir level at the beginning of period *t*;

$$H_i^t + A_i^t - Q_i^t = H_i^{t+1} \tag{3.4}$$

$$H_i^t = H_i^{t-1} + \sum_{t=1}^{T} A_i^t - \sum_{t=1}^{T} Q_i^t \tag{3.5}$$

$$H_{i,max}^t \geq H_i + \sum_{t=1}^{T} A_i^t - \sum_{t=1}^{T} Q_i^t \geq H_{i,min}^t \tag{3.6}$$

$\forall i \in I,\ \forall t \in T$

Where;

T,t - the index and set of hours;

I,i - the index and set of the reservoir;

A_t^i - the water flow rate into the reservoir at hour t;

H_i^t - the water level at hour t;

Q_i^t - the volumetric discharge at hour t.

The rate of A water flowing into the dam is a positive variable. It is straightforward to extend water flow can be a deterministic function of t or to follow a stochastic process. The water level relationship can be reformulated as the sum of the initial level storage and the difference between the flow and discharge from periods 1 to T as follows:

II. The water discharge from the reservoir:

Water discharge is the rate of the water flowing through the turbine. It is assumed that *Q* can be any value residing within the domain [Q_{min}, Q_{max}], where Q_{min} is zero, and Q_{max} (3.7) is determined by the turbine's head.

$$Q_{i,min}^t \leq Q_i^t \leq Q_{i,max}^t, \quad \forall i \in I,\ \forall t \in T \tag{3.7}$$

where Q_{min} and Q_{max} are water discharge's the lower and the upper limits, respectively. In the case study, the minimum water discharge was considered negligible.

III. The power generation:

P is a function (3.8, 3.9) of the head-pond and reservoir release *Q*:

$$P_i^t = n_i^t Q_i^t \Delta H_i^t, \qquad \forall i \in I,\ \forall t \in T \tag{3.8}$$

$$0 \leq P_i^t \leq P_{i,max}^t, \quad \forall i \in I,\ \forall t \in T \tag{3.9}$$

Where;

ΔH_i^t - the water head at hour t;

n_i^t - the overall efficiency of the power plant at hour t;

$P_{i.max}^t$ - the maximum power generation at hour t.

IV. Minimum power generation:

The minimum production (3.10) must be set to a certain amount of the maximum production on each unit, taking into account the efficiency of the turbine and generator, and the cavitation.

$$\%R \cdot P_{i,min}^t \leq P_i^t \leq P_{i,max}^t \tag{3.10}$$

where *R* is each unit's minimum electricity generation.

The objective function for deterministic approach:

To maximize power generation as one of the operational goals, a way to achieve this is to use water overhead to increase power generation while reducing wastewater. The only way to maximize revenue with the deterministic method is to maximize energy production because electricity prices are fixed.

Mathematically, optimization problem (3.12) can be formulated as:

$$R = \text{Max}\left(E(\vec{Q}) \cdot c - Ex\right) \quad (3.11)$$

$$I(P_1, P_2, \dots, P_t) = \text{Max} \sum_{t=1}^{T} \sum_{i=1}^{n} P_i^t(\vec{Q}) \cdot c^t \quad (3.12)$$

Where E is the total amount of produced electrical energy as a function of i and t are the index of the reservoir and time, respectively; I_j is income, P is the generated power of the hydropower plant in kWh, Q is the water flow through the turbine in m³/s, c is constant electricity price, Ex represents the expenses; namely interest payments, operations and maintenance costs. According to equation (3.11), the decision variable is the hydroelectric output depending on the reservoir release.

The objective function for stochastic approach:

The purpose of the SHPP owner is to maximize profit from all price forecast scenarios that the turbines/generators are only run during peak load hours, as the prices are higher. SHPP should stop generating power during a period of low price and accumulate water in the reservoir. It is required to consider restrictions and limitations on the natural water flow on small rivers and the possible amount of water that may be consumed by a SHPP during the day. The operation of a reservoir for a hydropower plant is a complex endeavor. The variation of the water pressure on the SHPP is caused by the variation of the upstream and downstream water levels. This is due to the use of water through SHPP's turbines. Therefore, the variation of the water level should be limited from the top and bottom (Berry, 2003; Coban et al., 2015).

The main criterion (the objective function) of the optimization task is income maximization (3.13, 3.14); at market conditions, mathematically, optimization problem can be formulated as:

$$I(P_1, P_2, \dots, P_j) = \sum_{j=1}^{J} I_j(c_j, P_{SHPP\,j}) \rightarrow \max \quad (3.13)$$

$$I\left(P_1, P_2, \dots, P_j\right) = argmax \sum_{j=1}^{J} I_j\left(c_j, P_{SHPP\,j}\right) = max \sum_{j=1}^{J} c_j \cdot \left(9{,}81 \cdot \eta_{turb} \cdot \eta_G \cdot Q_j \cdot H_j\right) \quad (3.14)$$

Where;

P_{SHPP} - SHPP produced electricity, kWh;

P_j - produced electricity at j-time;

c_j - the electricity market price at the period j, EUR/kWh;

H_j - the headwater level at the intake in m;

Q_j - water inflow through the turbine, m³/s;

η - the efficiency factor of the components: $\eta_{И} = \eta_{turb} \cdot \eta_G$, where η_{turb} - turbine efficiency factor; η_G - generator efficiency factor (Grigoriu & Popescu, 2010; A. Sauhats et al., 2014).

$I_j\,(c_j, P_j)$ - the income from the sales of electricity, that is gained on power facility during the time interval Δt_j by known market price c_j, €;

It is necessary to determine the operating schedule of the SHPP, providing the maximum revenue per regulatory cycle *T*, hour. The first statement can be applied considering the water level limitations and the usage condition *Wj* of the set water amount in the reservoir (3.15): (Renata Varfolomejeva, 2014)

$$\sum_{j=1}^{J} Q_j \cdot \Delta t_j = W_J \tag{3.15}$$

Where;

T – the regulation cycle duration: $T = \sum_{j=1}^{J} \Delta t_j$

Q_j - the water flow through the SHPP flap during the time interval Δt_j, m³/s;

W_j - the set amount of water (m³) that could be passed through the SHPP flap per regulation cycle T.

The time interval equals to Δt_j = 1 hour at the daily regulation cycle of SHPP. The power generation on SHPP during to the *j-th* interval Δt_j is defined as: $P_j \cdot \Delta t_j$. At the known natural inflow of the river Q_{flow}, the used water flow in each time interval of regulation is determined by the value Q_j that depends on the usage of water reservoir capacity (m³) (Renata Varfolomejeva, 2014; Renata Varfolomejeva et al., 2013)

3.2. An overview of the optimization tools

An optimization is a key tool in designing and planning. The purpose of this study can be considered as targeted to not only methodology and algorithm but also the software creation. In this direction, we needed to go a long way. The necessary steps for creating optimization software for power plants are summarized in Figure 7.

The selected path is exhibited by red colour. In the first stage stochastic approach is preferred. Secondly, the time-average method has been applied. The following three steps are associated with optimization procedure selection. A big number of variants are existed and are used. We have selected a mixture of them: linear for part

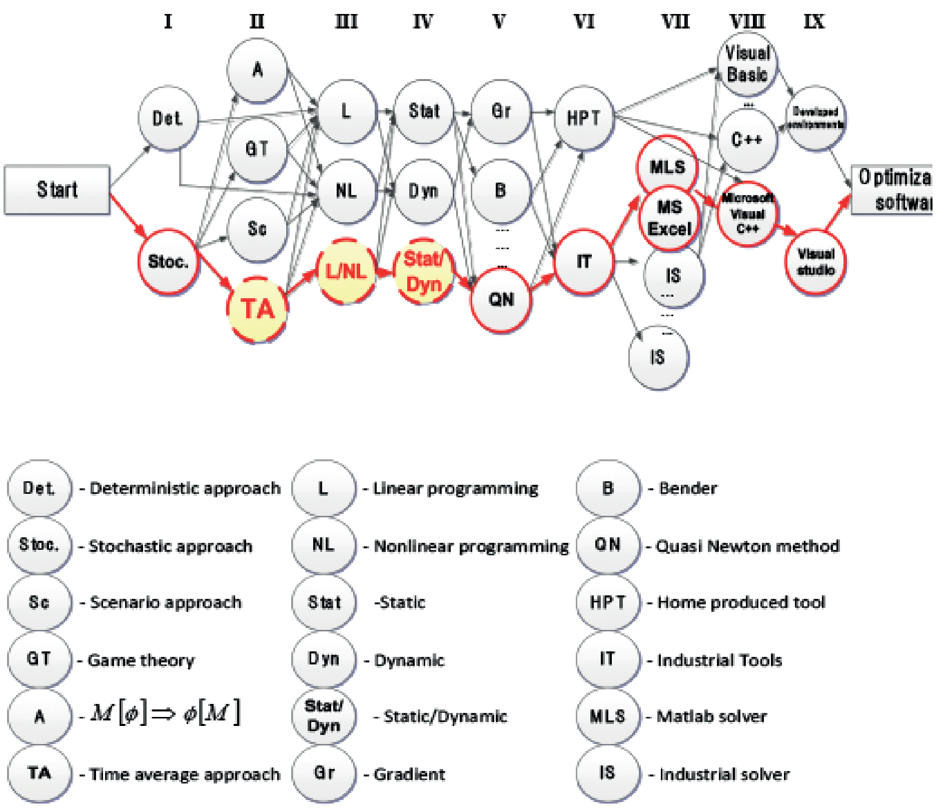

Figure 7. The necessary milestones for creating optimization software of power plants (R. Varfolomejeva et al., 2015)

of tasks and non-linear when accuracy is needed; statistic task statement is applied, but to do enlargement of variables number a dynamic nature of the problem is considered. The Quasi-Newton method is selected for the maximization problem solution (Coban, 2020b; Khaniya et al., 2020). The last three steps are related to software development. The choice of MATLAB and MS-Excel solvers, as well as was determined by university resources.

3.3. SHPP optimization tasks mathematical restatement and reformulation

It is assumed that an electric power system includes consumer Cons, generation companies Gcom, and power network Pnet (3.16):

$$Own(G_{com}, P_{net}, C_{ons}) \tag{3.16}$$

In general, each of these contains many objects managed by different owners (3.17):

$$\begin{aligned} &G_{com}(g_{com1}, \dots, g_{comn1}) \\ &P_{net}(p_{net1}, \dots, p_{netn1}) \\ &C_{ons}(c_{ons1}, \dots, c_{onsn1}) \end{aligned} \tag{3.17}$$

Each owner strives to increase their own profit (or reduce expenses) (3.18):

$$R\left(Own_j\right) \Rightarrow \max \tag{3.18}$$

In the general case, it is assumed that the owner's profit is any of the following nonlinear functions: parameters Π and configuration Σ of the owned objects (3.19);

$$\Sigma_{i\_};\ \ \Pi_i \tag{3.19}$$

The part configuration and parameters may change over time (3.20):

$$\Gamma(t) = \Sigma_i(t);\ \ \Pi(t) \tag{3.20}$$

Parameters and configurations depend on uncertain and random events and processes (solar radiation, wind speed, ambient temperature, etc.); and they must be selected (in the design phase) before the experiment begins. Considering the parameters listed above, the optimization objectives are formulated as follows:

$$\begin{aligned} &R(Own_1) = F_1\left(\Sigma, \Pi, \Sigma_{i-}, \Pi_{i-}, t, \Gamma(t)\right) \Rightarrow \max \\ &\vdots \\ &R(Own_n) = F_{n\Sigma}\left(\Sigma, \Pi, \Sigma, \Pi\ , t, \Gamma(t)\right) \Rightarrow \max \\ &\text{subject to: } \delta\left(\Sigma, \Pi, \Sigma_{i-1}, \Pi_{i-1}\ , t, \Gamma(t)\right) \ni \Omega \end{aligned} \tag{3.21}$$

Due to each optimization function contains random time processes *Γ(t),* and profit *R* is time-dependent the form (3.21) cannot be solved. It is necessary to take into account to select indicators that allow describe profit by one number; to create an appropriate statistical model of random processes *Γ(t);* and to choose planning period length. Performance of these steps allows to express the owner's profits in form (3.2). Using (3.2), it can be re-formed (3.21):

$$\begin{aligned} &M[R(Own_1)] \Rightarrow \max \\ &\vdots \\ &M[R(Own_n)] \Rightarrow \max \\ &\text{subject to: } \delta \ni \Omega \end{aligned} \tag{3.22}$$

where *M* is the mathematical expectation of the value.

For the following reasons, statement (3.22) describes an extremely complex problem.

- Equation (3.2) contains a very large integral and highly complained probability distribution function that should describe a multidimensional random process Γ(t);
- The solution of (3.22) is concerned with all owners' decisions. In the event that there is insufficient knowledge regarding the behaviour of rivals, each owner must make own judgments.
- The objective functions of (3.22) are non-linear in the general case and contain discrete variables that describe the configurations of the power system objects under optimization. A large number of configuration variants can be generated.
- Long term planning covers time horizons between 10 and 40 years Meanwhile, the operation conditions are changed each hour.
- The impact of random processes should define the future. Named difficulties lead us to search for appropriated simplifications. Figure 8 represents the proposed general optimization modelling approach.

Analyzing expressions (3.2) and (3.22), the stochastic approach leads to the formulation of an objective function that is extremely complex in terms of required computational effort and wide scope of input data. To estimate the expected profit according to (3.22), the multidimensional integral must be calculated. It should be added that since the typical planning horizon is thousands of hours going into a corresponding dimension of the integral, the size of the integral may be too large for the problem under consideration. The difficulty of computing the integral (3.2) can be considered as the main reason for applying the scenario approach. (Antans Sauhats et al., 2015; R. Varfolomejeva et al., 2015).

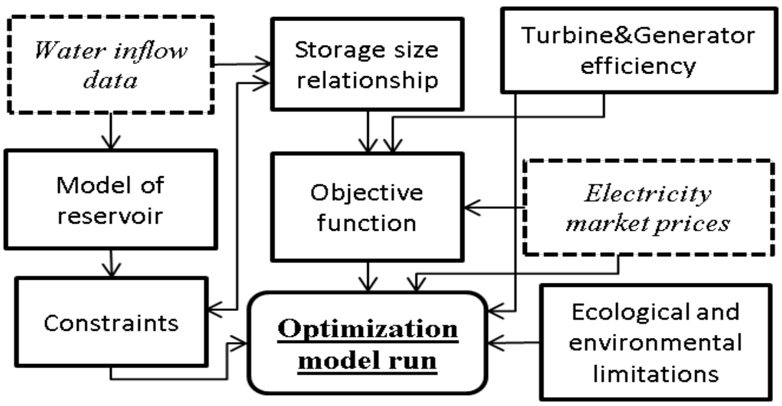

Figure 8. Optimization simulation flow chart

3.4. Decomposition approaches for optimization

It is assumed that the power facility is a player in the day-ahead market. To investigate long-term planning issue; it is necessary to formulate the time period of years profit maximization problem. The profit for the planning period can be calculated as the sum of the annual profit (3.23).

$$R_{\Sigma} = \sum_{j=1}^{N_T} M[R(Own_i)]_j \tag{3.23}$$

NPV is the difference between the present value of the investment's cash inflows and the present value of the cash outflows. Each year's profit is used when calculating the NPV (3.24) and can be expressed as:

$$NPV = \sum_{j=1}^{J} \frac{CF_j}{(1+d)^j} = \sum_{j=1}^{8760} \frac{(W_{ej} \cdot C_{ej}) - E_{xj}}{(1+d)^j} \tag{3.24}$$

Where;

CF_j - net the cash inflow during period j;

d - the discount rate; it is supposed that d is constant during planning time.

j - the number of lifetime periods e.g. years, months;

W_{ej} - produced power at hour j;

E_x - the expenses.

C_{ej} - electricity market prices at hour j;

the sum of daily profits represents each annual profit R_i:

$$R_i = \sum_{K=1}^{365} \sum_{J=1}^{24} M[R(Own_i)]_j \tag{3.25}$$

Analyzing (3.25), the profit of the day is linked with water amount into the reservoirs at the start and the end of the day under the study. The main objective of the model is to estimate the annual income and expenditure of storage facility projects during their lifetime. These parameters can then be used to calculate the payback period, NPV, and IRR for feasibility assessment. Consequently, a simplified profit-based optimization algorithm is presented by the structure of the algorithm in Figure 9.

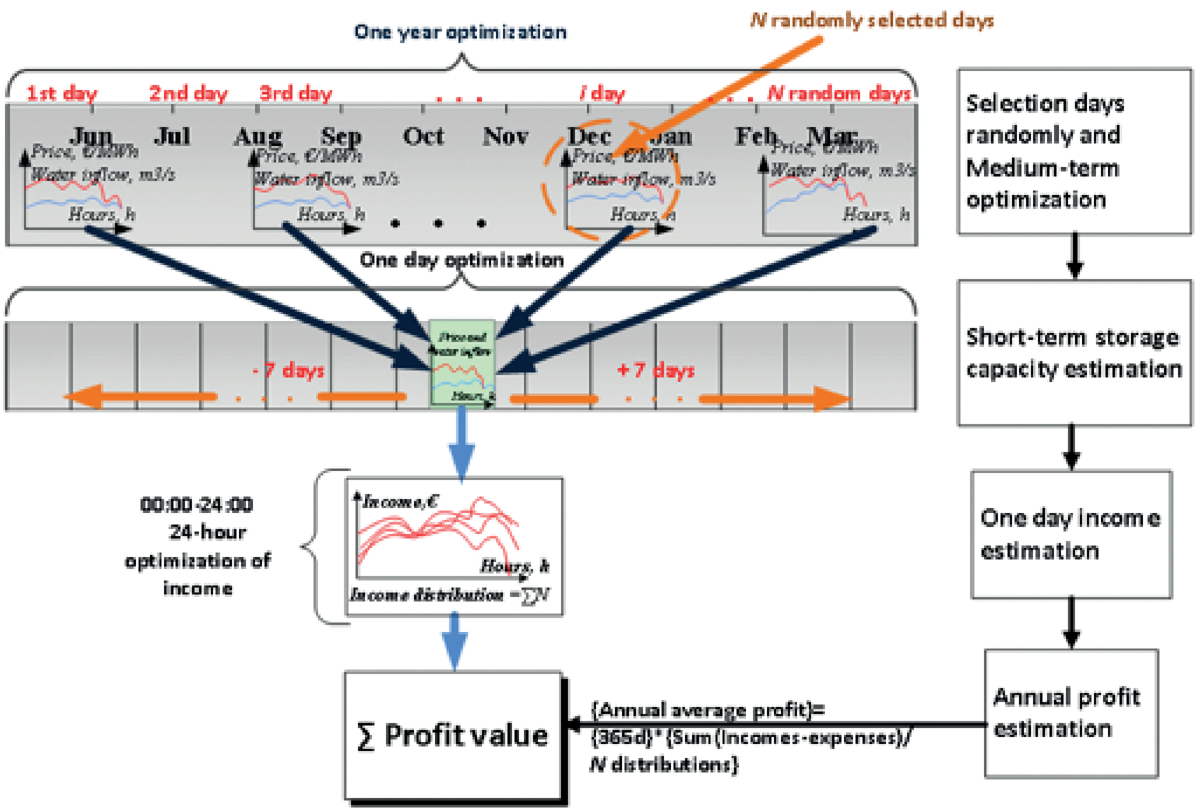

Figure 9. The main algorithm of optimization (Antans Sauhats et al., 2016)

The optimization steps are shown in Figure 10. A concrete day is chosen at random and the level of the reservoir is unknown. To make an accurately estimate of the reservoir level, 7 days before and 7 days after the selected day are selected. In the next step, only the previous reservoir levels are used. Profit maximization of the selected days is accomplished using a more accurate nonlinear model. Next, the short-term optimization results are generalized to the long-term using a time-averaged technique, thus combining long-, medium-, and short-term planning. The number of trials should be large enough to minimize the error rate.

3.5. Multiple probability simulation for profit forecasting

It is considered one day profit R_{ik}, which can be obtained on day *i* of year '*k*'. Due to influence of random and uncertain parameters R_{ik} is also random. The R_{ik} can be expressed as (3.26):

$$R_{ik} = M[R_k] + \underline{R_{ik}} \tag{3.26}$$

where; $M[R_k]$ is the mathematical expectation of average profit in year *'k'*;

R_{ik} is a centralized random variable. Also, it is assumed that M[R_{ik}] can be presented as the sum of two components:

$$M[R_{ik}] = d(k)M_1[R_k] + M_2\left[\underline{R_{ik}}\right]; \tag{3.27}$$

Where *d(k)* represents a multiplier that allows to take into account annual profit changes and is affected by price increases over the years. Expression (3.27) can be rewritten as follows:

$$M[R_{ik}] = M_1[R_k] + (1 + \mathrm{d(k)}) \tag{3.28}$$

Calculations using (3.28) allow to estimate the mathematical expectation of any day's profit in a year using a statistical model of first-year process. It is supposed that $R_{i1} = R_{i2} = \ldots = R_{iR}$. It means that probability distribution function of R_{ik} remains constant over the years. It is assumed that the processes observed in a day are stationary, which means it is possible to calculate the average profit as a time average value. This expression allows to calculate revenue using only a probabilistic representation of processes in the first year. This capability significantly reduces the number of tests in applying the Monte-Carlo method of profit estimation (Dong et al., 2019). If the power producer chooses to work in a market regime, for short-term SHPP optimization, firstly need to know the water flow rate and the electricity market prices which can be forecasted. Then we can decide how to use water resources by linear or non-linear programming. When we decide how much power we can produce on the next day by non-linear programming, then we can deal it with the market.

3.6. Long-term planning problem specifics

A mathematical statement of the problem is to be exhibited. In both cases (market conditions or fixed regime), we assume a nonlinear statement of the problem supposing that the shareholder's revenues R(t) can be described by any nonlinear function as (3.29):

$$R(t) = f(V(t), \rho(t)) \tag{3.29}$$

where *V (t)* stands for decision variables –the dimensions of the reservoir, the water head pond, the number of aggregates, the type and installed capacity of units, etc.;

ρ(t) stands for the random processes which influence income –the energy prices and the water flow rate to the reservoirs. The annual planning problem is formulated as follows:

$$\text{maximize} \Rightarrow R(T) = \int_0^{T=8760} R(t)\, dF \tag{3.30}$$

The planning process consists of several steps of alternatives and their evaluation according to the selected time strategy. For HPP feasibility, the planning process is divided into the five following steps for calculating NPV and IRR:

1st step − Identification of the problem: Definition of the problem.

2nd step − Determination of the goals: What goals are to be achieved? What is to be maximized and minimized?

3rd step – Identification of the alternatives: What options are available?

4th step − Evaluation of the alternatives: Evaluation of all the options on a sound basis.

5th step − The final decision: Selection of the best alternative based on the results.

There are so many methodological difficulties in making the final decisions. It is not easy to make a decision and choose the scenario which has information as to, for example, how big is the reservoir, how big is the net head, turbine types, capacities, etc., but only one option, the best one, should be chosen. The optimization procedure is applied to each scenario to reach the goal, which is to maximize the profit for each scenario and to choose the best alternative. Table 2 represents the profit matrix of the strategies and incomes.

The goals of HPP owners:

- profit maximization with reliability and sustainability;
- compliance with legislative, environmental, and technological restrictions;

Table 2

The matrix of income

Strategies	**Expected income by generated power**				
	P_1	P_2	P_3	…	P_n
S_1	T_{11}	T_{12}	T_{23}	…	T_{1m}
S_2	T_{21}	T_{22}	T_{23}	…	T_{2m}
…	…	…	…	…	…
S_n	T_{n1}	T_{n2}	T_{n3}	…	T_{nm}

The mathematical statement of accumulation of profit (3.31) can be considered as the sum of two processes depicting:

- income from produced energy that is sold to consumers;
- expenses that are necessary for energy production.

$$P_j(t) = I_n(t) - E_x(t) \tag{3.31}$$

We can declare that:

- income is a function of produced energy and market prices ;
- expenses are a function of capital investment and expenses for power plant running assessment.

All the processes used in (3.30) should be considered random processes. The numerical characteristics of such processes, particularly the average value, can be estimated based on the prediction of future processes.

The benefit of a supply of hydroelectricity is calculated by multiplying the quantity of electricity generated by the price of electricity. Ecological limitations, changes in the water flow rate, and changes in the electricity prices are also included in the equation. The data on the income from the sale of electricity collected and compared based on published data from the Nord Pool market prices (*Day-Ahead Prices, Nordpoolgroup*, 2022) and the feed-in tariff, which gives average values of 4.5 Eurocent/kWh.

Let us formulate the problem of investment optimization as maximization of the profit over the planning horizon. Annual profit estimation is calculated by the following formula:

$$AP = \sum_{t=1}^{8760} (AI - E_x) \rightarrow \max \tag{3.32}$$

Where;

AP – annual profit;

AI – annual income;

E_x – annual expenditure.

The objective of maximizing the expected profit $P_j(t)$ of the SHPP can be defined as follows:

$$P_j = \overbrace{\sum_{j=1}^{J.8760} p_j.c_j}^{Expected\ income} - \overbrace{(K_i.Inv + E_x)}^{Expenses} \Rightarrow \max \tag{3.33}$$

Where;

p_j – produced power;

c_j – market price;

K_i – the interest ratio;

Inv – investment amount;

E_x – expenses;

J – length of the planning horizon in years.

The subjects are:

- the highest and lowest level in the reservoir at hour j;
- the limitation on the water flow through the turbines;
- ecological limitations; which is according to Turkish law, the amount of water released downstream must be at least 10 % of the average flow of the last 10 years (Koç, 2018);
- electricity production at hour j, which is the maximum power level, and generators and turbines are used when the efficiency rate is best;
- the value of the reservoir at the end of the optimization time is taken into account.

The maximization problem (3.32) must be solved by considering various financial, environmental, technical, and legal constraints. The function (3.33) is usually non-linear and depends on uncertain or random variables such as discount rate, electricity price, etc. The solution of the maximization problem by function (3.33) which is generally nonlinear; can be performed by the Monte-Carlo presented in Figure 10.

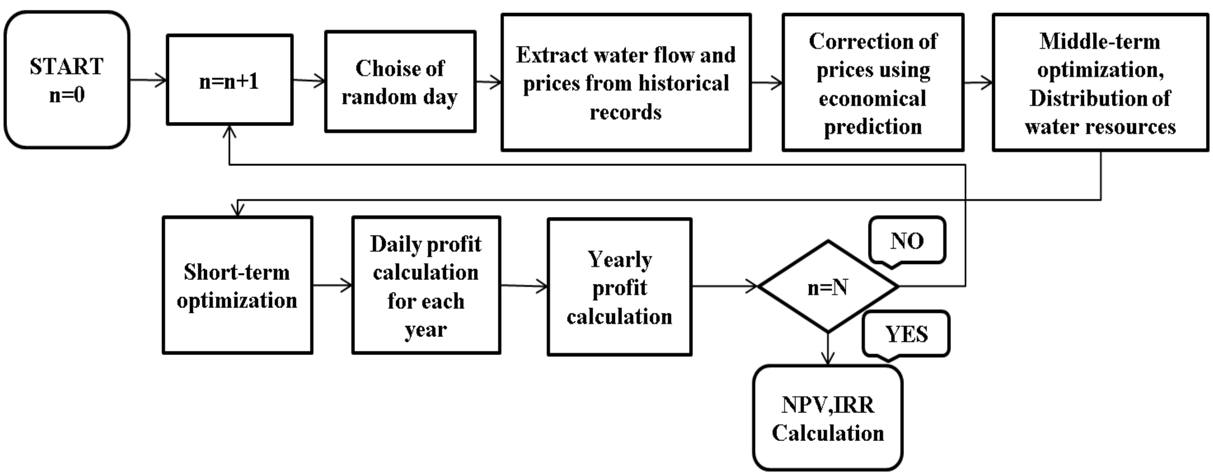

Figure 10. An algorithm based on the Monte-Carlo method to estimate the NPV of a HPP

Annual income must be calculated for HPP feasibility studies. Therefore, it is analyzed of the time period to have as small an error as possible. Firstly, the electricity market prices and water flow rate have to be known; then, it can be performed short and medium-term generation optimization, which allows to calculate annual profit. The Monte Carlo simulation serves to obtain a set of numerical results with a large number of repetitive randomly selected inputs (days). (Dong et al., 2019). When the Monte-Carlo simulation runs are performed by random values, we can analyze the percentage of error each duration outcome between 1 and 365 days. This will be shown graphically in Figure 21.

3.7. The model of the reservoirs

Let us consider water storage models which have to describe H as a function of and , (see Figure 11) namely;

$$H\left[\left(W_{in}-W_{fl}\right),T\right] \tag{3.34}$$

Where;

W_{in} – water flow in the river;

W_{fl} – water discharge.

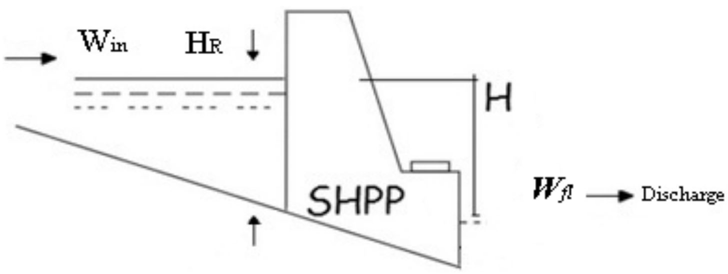

Figure 11. A model of the water reservoir

It is obvious that function (3.34) is non-linear in the common case. Only in the case of a reservoir with strongly vertical borders can this function be described by a linear function. Let us assume that such a reservoir is modelled. Two parameters are needed for model identification –the surface of the reservoirs (S) and the head of the reservoir (H_R). In this case an expression can be written as follows:

$$H=H_0+\left(W_{in}-W_{fl}\right)\cdot\frac{T}{S} \tag{3.35}$$

where is the initial level of water (t=0)

Expression (3.35) can be used as the basis for the modelling of real-life reservoirs. For that, it is necessary to divide the real reservoir into a sufficient number of parts (sub-reservoirs), which allows to use (3.35) with acceptable accuracy. Let us assume that the length of the reservoir head is divided into n selections but T is short enough for making an additional assumption as follows: during time T, the reservoir level does not exceed the boundaries of the initial sub-reservoir. In this case, the algorithm shown below is obtained. (see Figure 12)

Let us note that the water flow includes two components, water discharge through the turbine(s) and water consumed by the partners.

4. Examples and the Case Study

Goynuk Stream comes from a height of 2000 m in the mountains and is carried from 1700 m down to the Karliova district of Turkey. In this mountainous region, both the treated water source itself and the raw water source are under significant pressure that must be discharged at intervals, providing an opportunity to generate energy. The powerhouse and the reservoir have been built on the Goynuk River

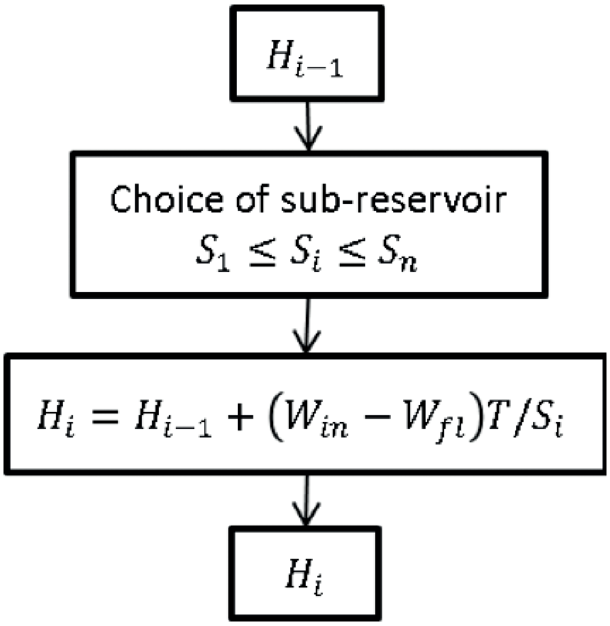

Figure 12. The algorithm of the water reservoir

in the city of Bingol, Eastern Turkey. The powerhouse started to produce electricity in September 2013. The Francis-type turbines at the Saf powerhouse with 2 units of 8.4MW and a unit of 4.2MW power capacity (50Hz). The length of the penstock is 810m. The capacity of the pool is 4605. The main data for Saf HPP is given the yearly average inflow rate is $5.48m^3/s$; the nominal capacity is 21MW; the head pond is 130m; the maximum water level before the reservoir is 3m; the total efficiency factor of the system set is 90% and the surface of the water in the reservoir is 40000 m^2. Table 3 represents the technical specifications of Saf HPP.

Table 3

Optimization limitations for Saf HPP

Restrictions	**Range**
Power	0≤ P ≤21 MW
Water through the turbine	0≤ W ≤17.03
The water level in the reservoir	1 m≤ H ≤3 m
Ecological water use limitation	Max 90%
Reservoir level at the end of day	Min 1 m

Within the feasibility phase, an economically and technically viable reservoir-type hydropower scheme is developed. In the framework of the analysis, the potential schemes were technically evaluated, the construction costs (Table 4) were estimated and the economic attractiveness was defined. The estimation of the construction costs includes both non-contract costs and field costs. Non-contract costs are related to engineering, environmental studies, site investigations, design, construction management, etc. Replacement, maintenance, and operation costs are not taken into account in construction cost estimates.

Given 21MWh of installed power capacity and 40ha of water storage surface, the total real investment is nearly 15000000€ for the Saf power plant. When the actual cost of the plant is known, it can be compared using the methodology described in the literature (Fen et al., 2012; Kotchen et al., 2006; Tayefeh Hashemi et al., 2020; Yildiz & Vrugt, 2019). Due to the different economic levels of North America and Turkey; the price of expenses differs and calculation of the total cost of the power plant by (3.35) we received almost three times bigger amount.

Table 4

Estimation of the construction costs of Saf HPP

Type of work	Cost Estimation
Civil works	35%
Penstock	20%
Turbine, generator, switchgear field	20%
Power transmission line	5%
Electromechanical installations	10%
Study, project, consultancy	3%
Expropriation	3%
Insurance expenses	2%
Unknown	2%
Total Cost	15.000.000€

The constraints for Saf HPP:

a) the volume of reservoir (4.1):

$$1\ \text{m} \leq h_i^t \leq 3\ \text{m} \tag{4.1}$$

where *h* donates the water level; *t* is the time and *i* is the reservoir.

b) the discharge (4.2) of water from the reservoir:

$$Q_{i,\min}^t \leq Q_i^t \leq 17.03 m^3/s \tag{4.2}$$

Where Q_{min} and Q_{max} are the lowest and highest amount of the water discharge, respectively.

c) the capacity of energy generation (4.3) of the power plant:

$$0 \leq P_i^t \leq 21\ \text{MWh} \tag{4.3}$$

where *P* donates the produced power.

d) the water balance equation (4.4) of the catchment:

The water flow rate (*Q*) through the turbine is a positive variable.

$$V_i^{t+1} = V_i^t + \left(I_i^t - Q_i^t\right) \cdot \Delta t \tag{4.4}$$

where *I* donates the naturel inflow and *V* represents the storage.

e) The limits of the reservoir (4.5, 4.6):

$$H_{i,1} = H_{i,begin} \tag{4.5}$$

$$H_{i,25} = H_{i,end} \geq 1\ \text{m} \tag{4.6}$$

where i represents the index of the reservoir, $H_{i,1}$ is the initial (starting point) level of the reservoir; $H_{i,end}$ is the final (ending point) level of the reservoir; it is mandatory that it be minimum 1m because of the fish gate and ecological factors.

f) privatisation of water use rights in Turkey; the amount of water to be released downstream for the continuation of the natural life will be at least 10% of the last ten-year average flow based on the project (4.7). If it is determined that this amount will not be sufficient considering the ecological needs, the amount is increased. If there is less than 10% of the average flow of the last ten years in the river, all of the water is left to the downstream for the continuation of the natural life. The type and properties of the fish gates are assessed at a certain construction phase. (Koç, 2018)

$$I_i^t \cdot 10\% \leq Q_i^t \tag{4.7}$$

The flow duration curve (FDC) represents an important element of hydrology study, which is useful to define different parameters of the hydropower scheme. This curve shows the proportion of time during which the discharge equals or exceeds certain values for a design section of the river. The FDC characterizes the relationship between the amount and frequency of daily, weekly, monthly (or other time interval) flows at a particular station in any stream. All values of a series of flow records from a river determining station (preferably no fewer than 15 years) are ordered from highest to lowest value the curves answer the question: What amount of energy can be generated annually? Regularly, design discharges corresponding to 20% of the time are proper as the design discharge (Kuriqi et al., 2020). The FDC of the multi-year average daily discharges of the Goynuk River is depicted in Figure 13. Following this data, exceeding the multi-year average annual flow for 12% of the time during one year in the design segment equals 17.03 m³/s, this discharge provides full power generation for 44 days throughout the year (see Figure 14). Based on this flow duration curve, different discharges with different exceedance can be selected from a given hydrological series.

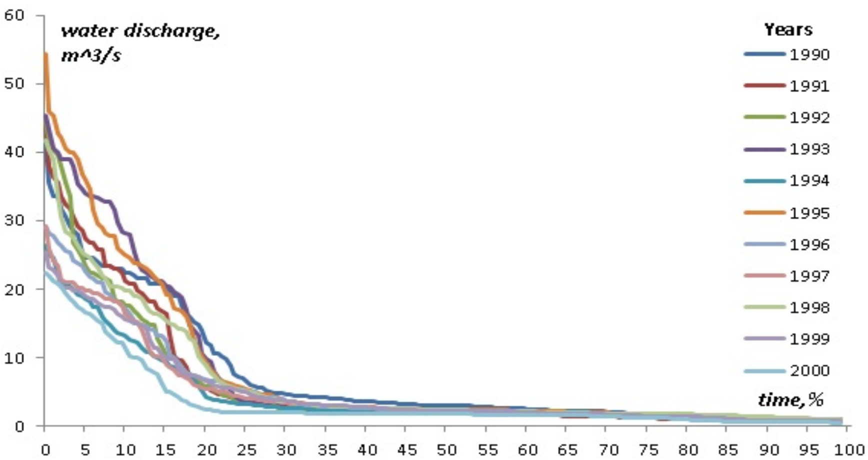

Figure 13. FDC of multi-annual mean daily discharge

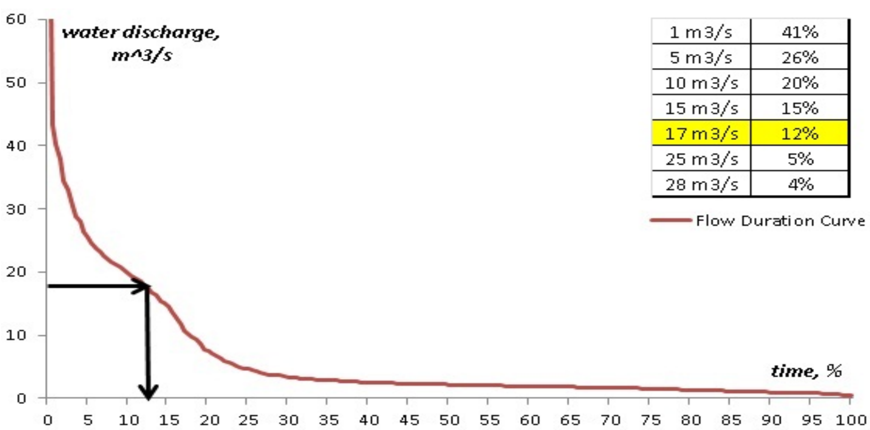

Figure 14. The average FDC for the years 1990–2000

The daily water flow rate of the observed discharge data is recorded by the Hydrology Department of the National Environmental Agency of Turkey (DSG). The initial data contain 35-year of observations which allow us to make reliable statistical analyses. Generally, minimal discharges are observed in the winter and summer periods but overflow appears in springtimes. This data is used for a feasibility study which will be explained in the next subchapter. According to the feasibility report of Saf HPP, the expected annual average electricity production is 42.17 GWh (see Figure 15). The provided 40 years of data taken between the years of 1965 – 2004 is used in the calculations.

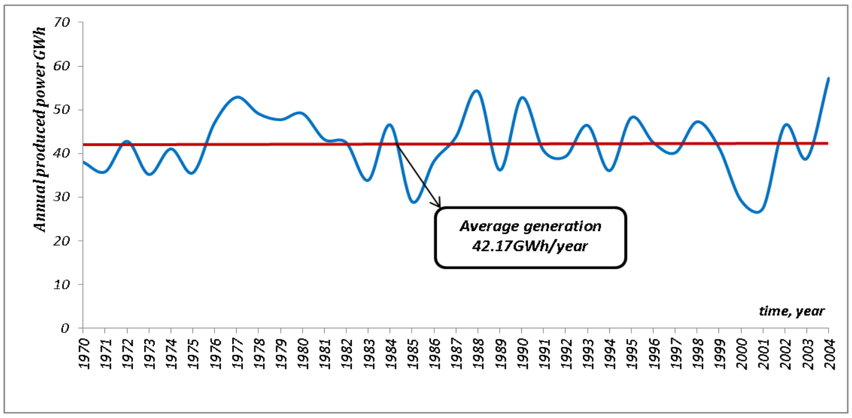

Figure 15. The Saf HPP annual average electricity production estimation

4.1. Application results and comparison of optimization methods

Deterministic models are systems in which there is no randomness in determining the future states of the system. That is, for a well-modeled deterministic system, the system will always give the same result under the same conditions and for the same initial states. On the other hand, Stochastic models contain randomness. This randomness can be in system parameters, dynamics, inputs. Therefore, the output of the system will have similar randomness. In such systems, the same results may not be obtained even if the same experiment is repeated under the same conditions. Let's compare the methods and generating tasks for SHPP feasibility studies. The stochastic and deterministic tasks have common features:

- the main objective function can be formulated as profit maximization in both tasks;
- solutions must be made based on process estimation;
- in both cases, optimization procedures should be non-linear and capable of taking into account a large number of decisions.

a) The result of deterministic method:

The operating method for Saf HPP, which takes into account the constant water flow and electricity price, is shown in Figure 16. With the fixed-price operation, since it is not used in the optimization procedure and the electricity price is fixed, the electricity producer can maximize the income by only increasing the amount of energy produced.

Interpretations of the result obtained will be presented along with an analysis of the stochastic optimization results in the upcoming sub-chapter.

b) The stochastic method:

For decision-making problems under uncertainty, stochastic programming provides a comprehensive framework with the knowledge of stochastic processes that define uncertain parameters such as demand growth. When the parameters of electricity prices with uncertainty and water inflow to reservoirs are defined by stochastic processes, it is possible to formulate the uncertainty of these parameters as a mathematical programming problem. In the stochastic programming model, if the values of the parameters contain

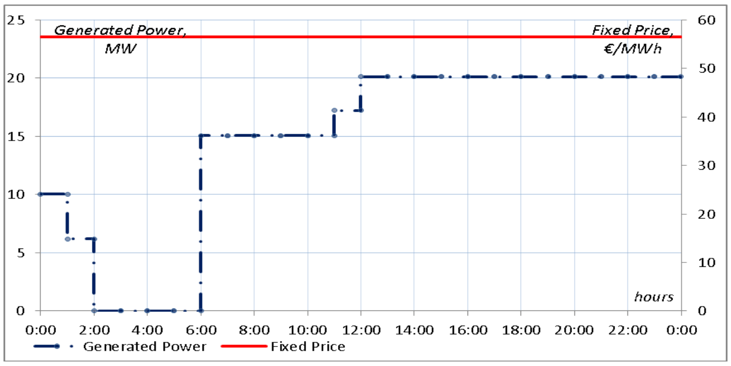

Figure 16. The generation by a fixed price schedule

uncertainty, these parameters can be defined as distributions or multivariate stochastic processes. Thus, the problem turns into an optimization problem in function spaces, and the decisions depend on the observed values of these processes. Figure 17 shows the actual power produced for four consecutive days at Cobanli HPP, where the production results are not optimal.

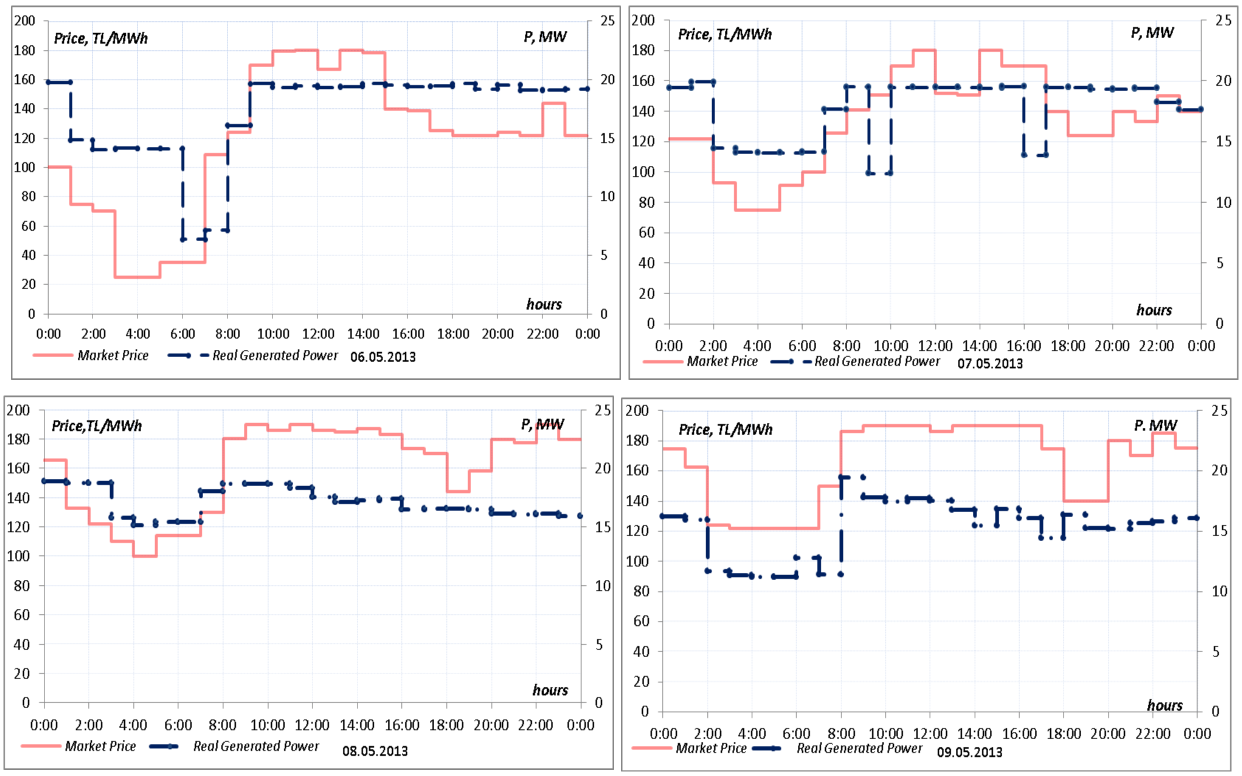

Figure 17. Actual generation in the market conditions from 6 to 9 May (Coban et al., 2015)

The results obtained when electricity generation is optimized according to the market price chart are presented in Figure 18. The SHPPs collect water from the reservoir when market prices are low and use water when market prices are high. The results of the optimization show the similarity of 24-hour power generation with more accurate regime planning to generate maximum revenue. The optimization model has been implemented taking into account the current situation and can be applied to future storage capabilities, which will be explained when discussing the feasibility study of Saf HPP in the next subsection.

As seen from the results, in Figure 18 that water is stored when the market prices are low and starts production when the market price increases. If Cobanli HPP could operate at a fixed price during these four days (06.-09.05.2013), the income was 2094690 Turkish Lira (TL). The real income of the power plant, which is operated at market prices, was 236809 TL. However, according to the optimization model with

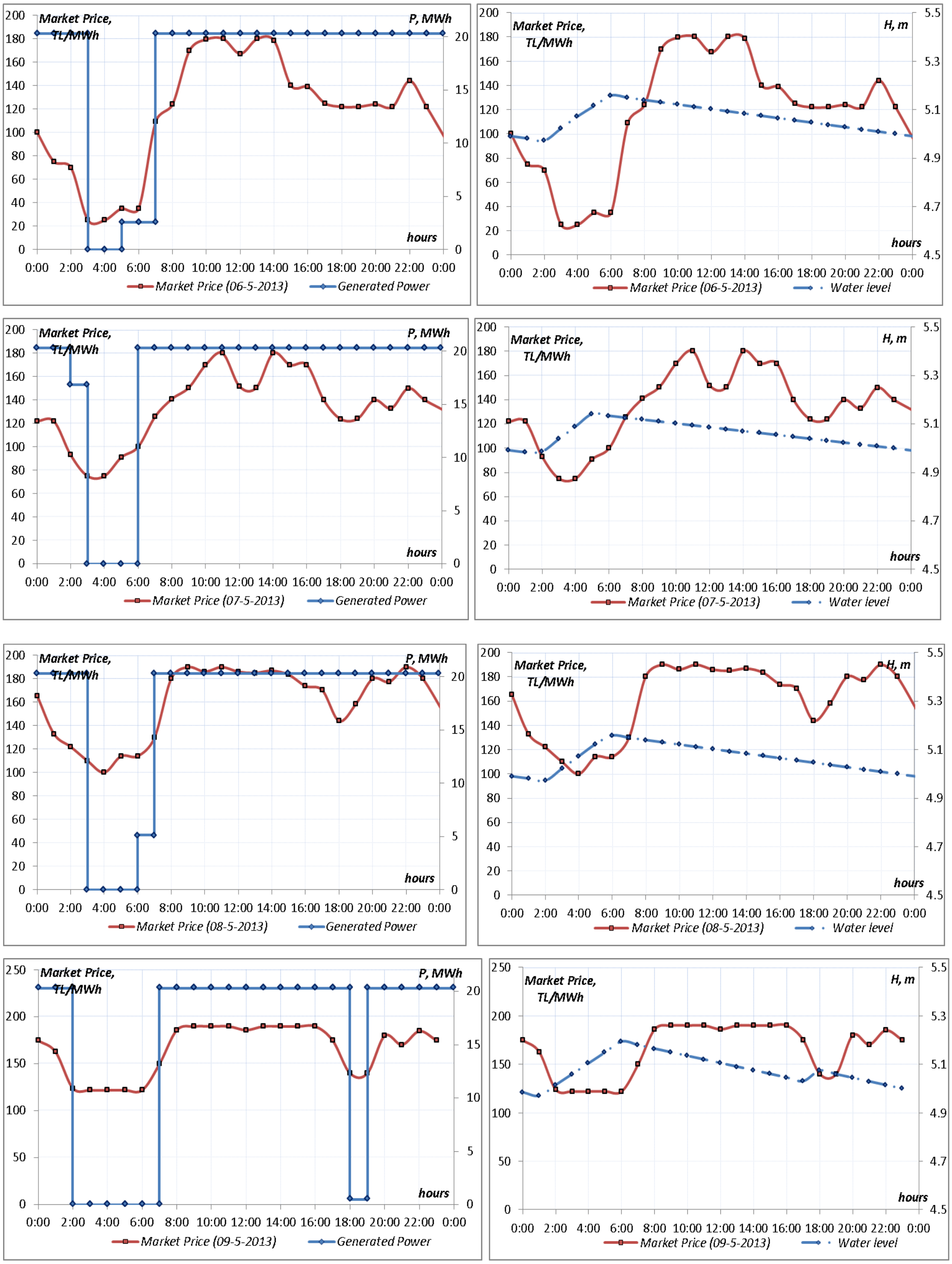

Figure 18. Optimized electricity generation for Cobanlı HPP (6-9 May)

market price, the income reaches 246448 TL. The results allow it to be concluded that in the stochastic case, the power generator provides an opportunity to maximize the amount of income under conditions of limited resources. At the same time, the optimization procedure applied, namely the Quasi-Newton method, succeeded in obtaining the global maximum of the objective function in all cases.

4.2. Cost-benefit analysis for Saf HPP

Estimated costs and input parameters are depicted in Table 4, which summarizes the cost estimate of various reservoir capacities for 21 MW, 35 MW, and 50 MW power capacities. The investigations have been carried out based on the 17, 28 and 35 discharges and the head of the pond is constant 130 m (see Table 5). By calculating the profitability for each alternative, there is an opportunity to see if the current design discharge of 17.03 and the capacity of 21 MW are an optimal choice.

Table 5

Cost estimation (M.Euro) for various design flows, including contingencies

Reservoir Capacity			Power Capacity
200 ha	100 ha	40 ha	
21,16	21,06	21,0	50 MW
18,16	18,06	18,0	35 MW
15,16	15,06	15,0	21 MW

Optimization was carried out at a pre-selected time for three different situations, taking into account the initial and final conditions of the 360-hour period. In the reference case, the initial and final degree of reservoir filling is equal (75%); in the second case, the reservoir level drops from 100% to 33%, and in the third case the level increase from 33% to 100%. The second and third case cause 0.89% and 0.88% respectively income change in 24-hour income. Therefore, it can be concluded that the initial and final state of the reservoir in the medium-term horizon do not have a significant effect on profit. Consequently, all other calculations have been made assuming the degree of reservoir level is 75% at both the beginning and end of any 360-hour period. Figure 19 shows the advanced stochastic optimization method for Saf HPP, which takes into account hourly water flow rates and market prices over 360 hours.

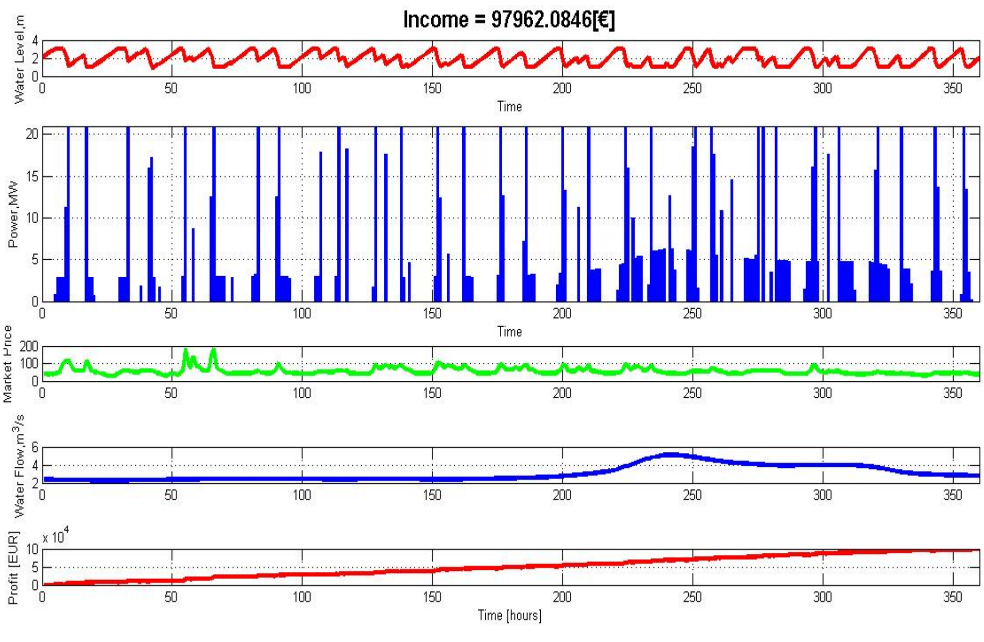

Figure 19. The results obtained from the developed optimization program

The optimization results of the developed algorithm allowed us to choose the best possible alternative for Saf HPP. Finally, the NPV estimate is obtained by summing the discounted total annual revenue estimates. If the NPV of the project is positive, the execution of the project is estimated to be efficient and the CBA method suggests that the project is viable. It is assumed that the production period is 30 years, the total efficiency of the hydroelectric power plant is 90%, the construction plant will last for 2 years, and the annual standstill losses are 2 days, and various interest rates are applied.

Following the existing regulations in Turkey to ensure environmental protection conditions downstream of the intake site of Saf HPP, 10% of the mean annual water discharges shall be selected as the minimum ecological discharges at the design section. The annual escalation rate of the energy price is assumed as 3%. Annual operation and maintenance costs are usually quoted as a percentage of the current year's income or the investment cost per kW per year. Typical values range between 1% and 4%. The IEA assumes 2.2% for large-scale hydropower and 2.2% to 3% for small-scale projects, with around 2.5% a global average (Irena, 2012; WorldBankGroup, 2015). In this study, it is assumed that annual fixed operating and maintenance costs constitute 3% of the total income.

The optimization model is implemented in MATLAB R2013a with solvers by the Quasi-Newton method in a non-linear optimization procedure. Since the objective function is a non-linear constrained-bounded and multivariable function employed "fmincon" (multidimensional constrained nonlinear minimization) (Singh & Singal, 2018) to find the optimal solution. In optimization, the technical limitation of the turbine as well water reservoir constraints are taken into account. Also, the Monte-Carlo method can be used to avoid difficulties. A large number of trials leads to higher accuracy of calculations, while also increasing the computation time. We ran several simulations per year using a different number of trials to find an appropriate number of Monte-Carlo trials that did not significantly reduce the accuracy and also increase the computational load too much. The reference case is 365 trials (days), and various simulations which are compared with the baseline to determine the error. Figure 20 represents randomly chosen days in a year for Monte-Carlo trials.

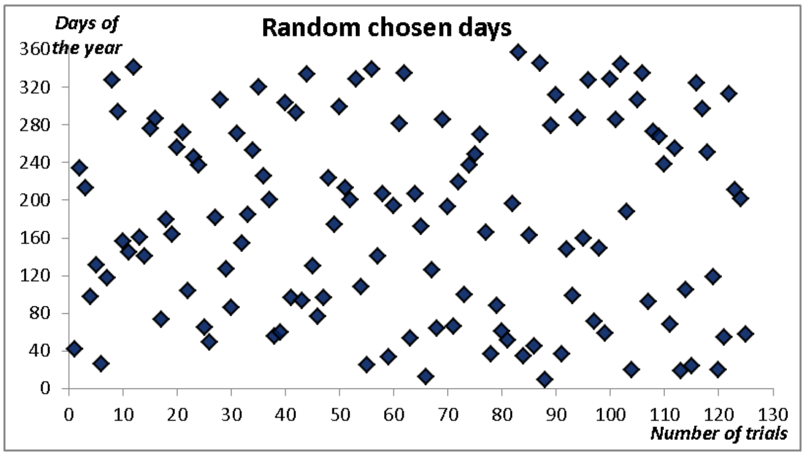

Figure 20. Randomly chosen days in a year for Monte-Carlo trials

The program is run for a single dam operation. All calculations were performed using 2 cores on a Windows PC with Intel I3 CPU processors, 2.53 GHz, 4 GB RAM, and Windows 7 operating system. As seen in Figure 21 it is determined that 120 trials (days) were a sufficient number because it neither introduced a very high estimation error (4.6%) nor required excessive computation time (computation time was 105 minutes). According to the results summarized in Figure 19; a possible improvement can be made by introducing a more efficient algorithm with better performance for a large number of decision variables.

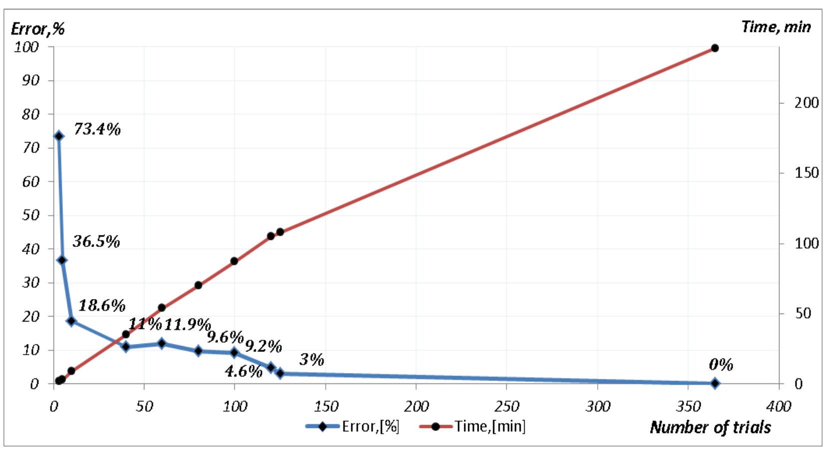

Figure 21. The number of Monte-Carlo trials and calculation error

The results of the IRR and NPV calculations for the 4%, 6%, and 8% interest rates (IR), as well as the cost estimates for the various design flow values, including contingencies, are summarized in Table 6. It is concluded that the best alternative is to choose the 6th one (A6) with a power capacity of 35 MW and a reservoir capacity of 200 ha; The IRR is 15.5% and it takes 12 years to reach the breakeven point.

Table 6

Types of alternatives and the results of IRR and NPV for 30 years

Alternative	Deterministic approach, 8% IR		Stochastic approach, 4% IR		Stochastic approach, 6% IR		Stochastic approach, 8% IR	
	NPV, €	IRR, %	NPV, €	IRR, %	NPV, €	IRR, %	NPV, €	IRR, %
A1	19684434	15.8	21825628	16.2	20587278	15.5	19291375	14.8
A2	19628359	15.8	23429968	16.7	22186664	16.0	20885577	15.3
A3	19534901	15.7	23434537	16.7	22182978	16.0	20873252	15.3
A4	21954523	15.4	25782054	16.2	24296034	15.5	22740950	14.8
A5	21898448	15.4	28024941	16.9	26533967	16.2	24973700	15.4
A6	21804990	15.3	28486431	17.0	26987201	16.3	25418295	15.5
A7	19150785	13.6	24057220	14.6	22323529	13.9	20509265	13.2
A8	19094710	13.6	25972403	15.2	24233758	14.5	22414310	13.7
A9	19001252	13.5	28075139	15.7	26328239	15.0	24500152	14.3

It is difficult to obtain precise results using the deterministic technique because it does not take into account the uncertain and random variables. Figure 22 compares the highest incomes obtained by the stochastic and the deterministic approach for a 30-year horizon.

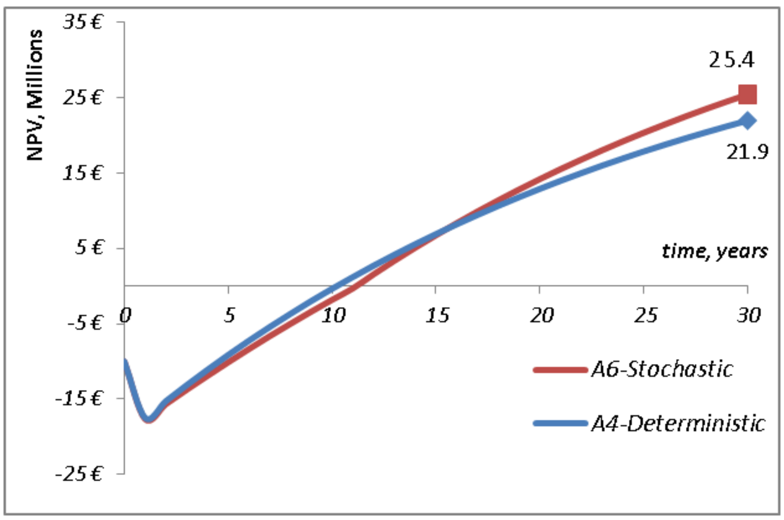

Figure 22. A comparison of deterministic and stochastic approaches

4.3. The influence of reservoir capacity and discount rate on the profit

The construction of hydroelectric plants is a large-scale project that requires a long lead time for site studies, environmental impact assessments, and hydrological studies. Generally, reservoirs are used for water supply, irrigation, electricity generation, flood control, recreation. In order to maximize a reservoir's usage of a river namely store as much as water, it is essential to prepare the plan that considers all aspects as well as long-term prospects. It is natural that the way of building about the selection of dam sites differs according to the purpose of the project. Figure 23 and Figure 24 verify that stored water in the reservoir is released through the turbine and generates electricity during peak hours in other words when demand is higher. The difference lies in installed power capacity and water storage capacity; Figure 23 represents a reservoir of 40ha and at the end of the day the income is 6518€. Figure 24 represents a reservoir of 200ha and the income is 6699 €; it means that this storage can accumulate a larger amount of water and transform its potential energy into electrical energy during peak hours that increases flexible power generation and maximizes the income.

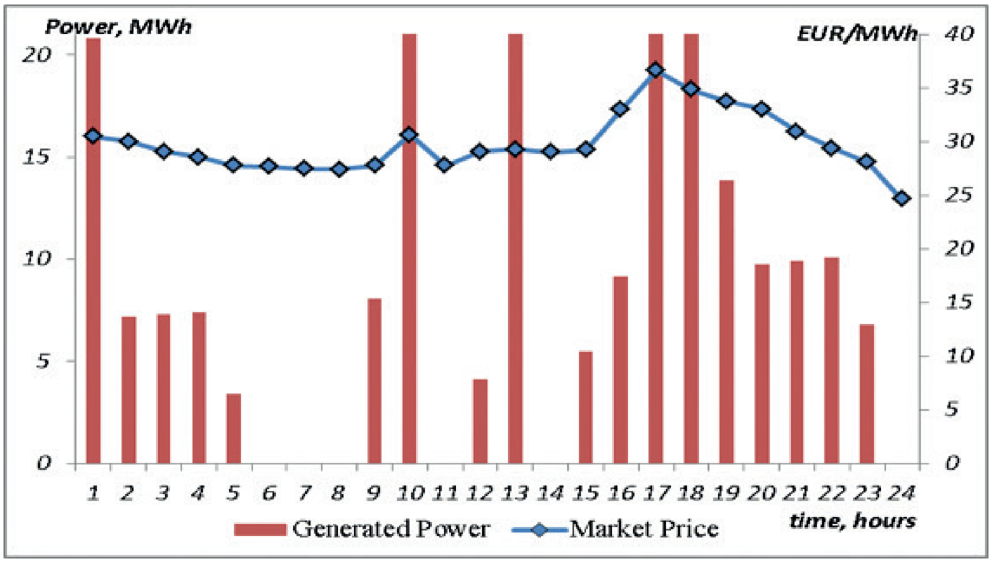

Figure 23. Generation for a 40-ha reservoir capacity

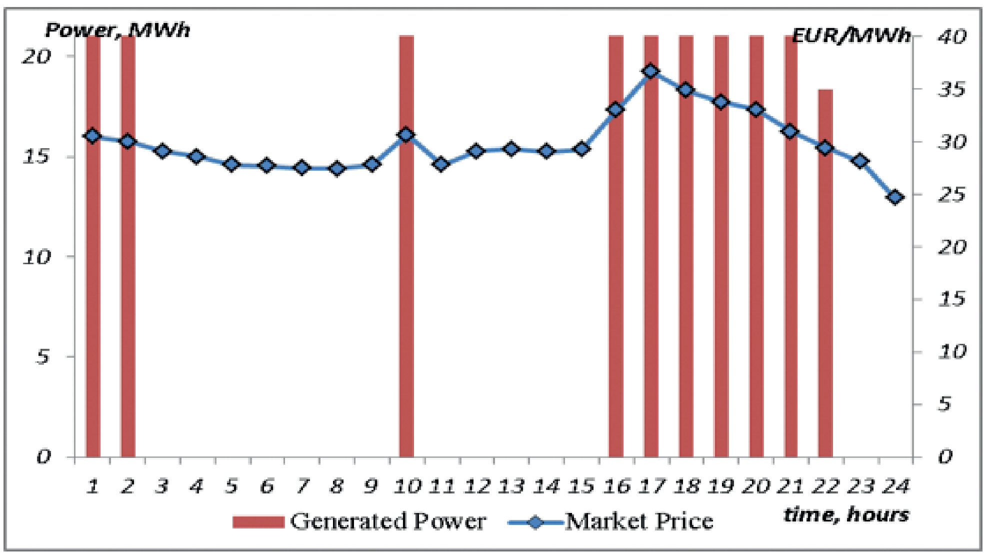

Figure 24. Generation for a 200-ha reservoir capacity

It is assumed four different alternatives for the feasibility study; each of them has various designs which correspond to small, medium, large, and dam-type reservoir capacity. Figure 25 represents the existing reservoir for Saf HPP which has 3 m deep and 40 ha.

Let us consider a dam-type reservoir (see Figure 26) for Saf HPP with a length of 110 m and a depth of 20 m and a water storage area of 200 ha. It is assumed that the electricity producer is a market player and can export electricity to the grid, the operation of the energy market is based on day-ahead rules, electricity

Figure 25. Existing reservoir for Saf HPP (3 m deep-40 ha)

market prices are exogenous for the power producer, each day, the power producer participates in the day-ahead market. For building, an optimization procedure is performed beforehand to maximize the profit, the behaviour of other market players is neglected.

Figure 26. Dam-type reservoir for Saf HPP

A dam is an obstacle that holds back water; Dams are mainly used to divert, manage and/or prevent excess water flow to certain areas. Dam-type reservoirs are built in a valley based on the natural topography to provide most of the reservoir basin. Dams are often built downstream of a natural basin in a limited part of a valley. The valley sides act as natural walls with the dam located at the narrowest practical point to ensure as low construction cost as possible and as high efficiency as possible. The economic and technical parameters for each alternative are summarized in Table 7.

The feasibility study is related to different numbers of alternatives, and each alternative is based on the expected scenarios. It is underlined ones more that these extensive calculations can be simplified using the Monte-Carlo method which offers average profit. In Turkey private companies get a license for 49 years from the government and the feasibility study is done for 49 years (Üçüncü, 2018). Table 8 summarizes the

Table 7

Economic and technical parameters of the power plants under the study

Alternative		**Cost estimation, €**
A1	200 ha-21 MW - Dam	15.660.000
A2	200 ha - 21 MW	15.160.000
A3	100 ha - 21 MW	15.060.000
A4	40 ha - 21 MW	15.000.000

economic feasibility results for Saf HPP; the deterministic approach uses a discount rate of 7%, with an annual interest rate of 6% for a 10-year payback time for each alternative, and the stochastic approach uses three cases with discount rates of 3%, 5%, and 7%, respectively.

Table 8

IRR and NPV results for Saf HPP

Alternative	Deterministic approach, 7% discount rate		Stochastic approach (1), 3% discount rate	Stochastic approach (2), 5% discount rate	Stochastic approach (3), 7% discount rate	Stochastic approach (1, 2, 3) IRR, %
	NPV, €	IRR, %	NPV, €			
A1	24147161	13.91	110484765	63344684	37647625	17.42
A2	24732171	14.26	106767761	61192738	36346641	17.36
A3	24849173	14.33	105420216	60379112	35824568	17.28
A4	24919374	14.38	103154375	58966493	34879630	17.06

The discount rate has a reasonable effect on the NPV level. The NPVs of profit calculated at the 3% interest rate is almost 3 times higher than the 7% discount rate. Figure 27 shows the NPV results for each reservoir model.

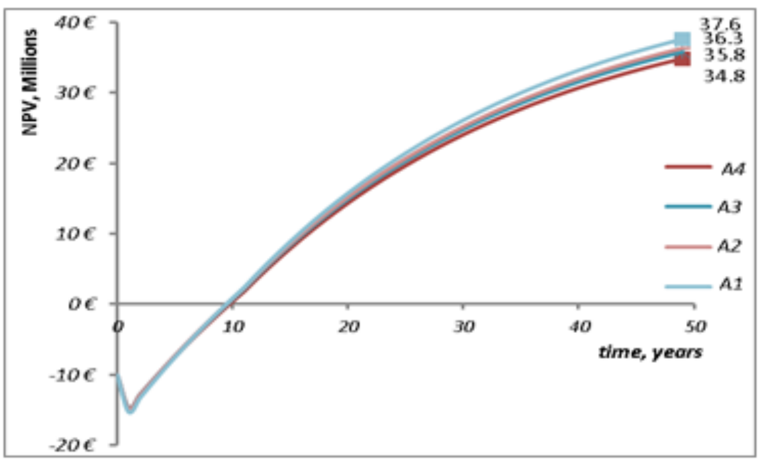

Figure 27. NPV of different reservoirs and varying capital costs

As a conclusion, hydropower plant reservoirs can be created by controlling a water stream that drains an existing body of water. In addition, a dam can be used in river valleys or a reservoir can be constructed by building retaining walls and embankments, or by digging the ground. The results proved that for Saf HPP located in a hilly area, it would be effective to construct a dam type reservoir to store more water to achieve an income maximizing objective function. The discount rates also significantly influence the amount of profit gained. Figure 28 represents the comparison of NPV calculations for various discount rates in the 4th alternative.

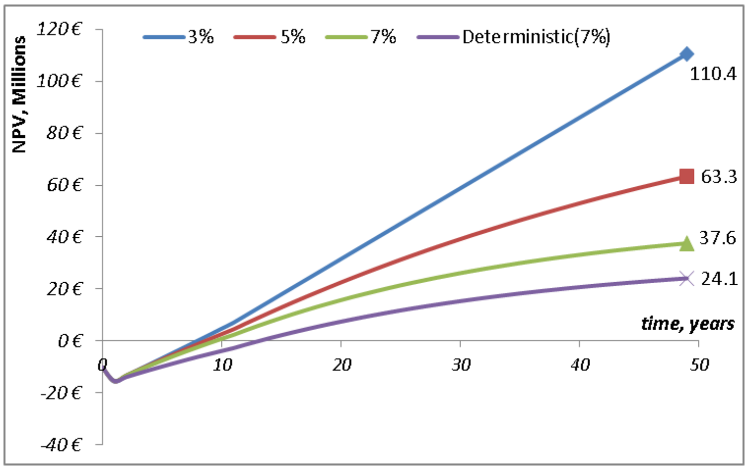

Figure 28. The effect of the interest rate on the investment

Discounted cash-flow analyses are instrumental in investment decision-making during the pre-feasibility stages of the investment and since it is reasonable to formulate an investment strategy that should have an application to the cash flow towards the risk management of the economic part of the investment. The described approach can be easily extended to the more complicated case study, where maybe chosen number and type of turbines, the head-ponds, the deepness of reservoir, and its capability.

To be able to solve the SHPP optimization task, it is necessary to take into account the specific structures and parameters of the power plant and market price. The most widely used methodology (deterministic) of feasibility studies is not useable in market conditions because it does not take into account hourly energy prices and the flexibility of the power plants. The Monte-Carlo method is useful while analyzing income and schedule. With the help of the Monte-Carlo analysis, the calculation of the long-term HPP income planning can be solved. A cost-benefit analysis model has been expanded to cope with social, economic, and environmental factors under uncertainty in order to appraise hydropower projects. In the application to Saf HPP, various discount and interest rates of long-time preference, a positive NPV will likely be obtained. The elaborated algorithm of the problem solution is based on the Quasi-Newton method. A solver program in Matlab R2013a has been developed. The considered numerical examples show its efficiency. Our experience shows that the program works well, and the received results are approved by the requester. A discount and interest rate causes a considerable influence on the number of future benefits and costs.

5. Conclusions

The study discussed the application of the algorithm techniques to find the optimum operating policy for reservoirs and the power plant. The stochastic approach results were compared with the traditional deterministic programming. The optimization problem is formulated in a way that maximizes the total energy income. However, there may be situations where the goal is the maximization of the energy generation or achievement of multiple purposes such as supplying irrigation, flood mitigation, creating a coalition with potential partners, or domestic water together with energy generation. The selection of the optimization procedure is a complicated task. From many of the eventual algorithms, the Quasi-Newton method is selected for further verification and applied for the solution of maximizing obtained profit at Saf and Cobanli HPP. The developed models are tested by Nord-Pool electricity market prices and satisfactory results are achieved. Comparing the NPV results from the deterministic and stochastic methods, results with the stochastic methods are significantly more accurate than with the deterministic model. The optimization results show that the proposed models perform very well in the absence of volatility. The direction of this economic feasibility assessment is to analyze and determine opportunities for new small hydropower development in Turkey and the developed model can be universally applied to other countries. A CBA is a systematic evaluation of the disadvantages (costs) and economic advantages (benefits) of a set of investment alternatives. The impacts of timing, discount, and interest rate represent a feature of CBA that can significantly affect results. The output of the analysis consists of the NPV and the IRR.

These parameters are used to assess the viability of the investment. Design, hydrology, and alternative solutions have been analyzed and the results from the financial due diligence study indicate that the Saf HPP project is financially viable given a 30-year concession period in an open market perspective. The stochastic statement, which is a scientific and practical model that can be applied around the world and has been successfully tested in the Turkish SHPP in terms of the country's electricity sector, includes an analysis of the potential benefits of generation companies, wholesalers, and investors.

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Author Contributions

Hasan Huseyin Coban: Methodology, Data curation, Writing-original draft, Visualization, Investigation, Validation, Conceptualization.

Antans Sauhats: Supervision, Conceptualization.

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