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OPTIMIZATION TECHNIQUES IN SHORT- AND LONG-TERM POWER PRODUCTION AT SMALL HYDROPOWER PLANTS

Summary of Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis will be publicly defended on 16 June 2016, at 14.00, Room 306, at the Faculty of Electrical Engineering, Riga Technical University, Azenes street 12/1, Riga.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Hasan H. COBAN .... (Signature)

Date: ………………………

The Doctoral Thesis is written in the English language and consists of an introduction, 5 chapters, conclusions, and a list of references. The total volume of the Thesis is 155 pages including appendixes. The Thesis contains 18 tables and 79 figures. The bibliography lists 148 sources of literature.

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1. A GENERAL DESCRIPTION OF THE WORK

Topicality of the subject of the Doctoral Thesis

Almost everything that we do in our lives from the time we are born, through every day of every year, depends on energy. Many specialized institutions, such as the International Energy Agency (IEA), make predictions about how the world energy demand will increase in the future (see Figure 1.1), which is predicted to rise by around 60 % within the next 30 years [1, 2]. The most critical question is how to meet this demand.

The energy was mostly known as fossil fuels since the Industrial Revolution. Nevertheless, the limited nature and the complexity make fossil-fuel-based energy run unsustainable. As a result of this, humanity has rediscovered nature-based renewable energy. Renewable energy is a key issue in today's world and may continue to play a globally important role in the future. The trend that started in the last quarter of the 20th century seems to be continuing in a more intense fashion. International organizations are also working in this area to produce a common policy for taking advantage of renewable energy on a multinational level. Renewable energy is important because of the benefits it provides. The major benefits are such as environmental ones; the environmental impact is much lower than with conventional energy technologies; this is energy for our children's children that will not run out for ever; also, it provides energy security, which is important in securing the future for ourselves.

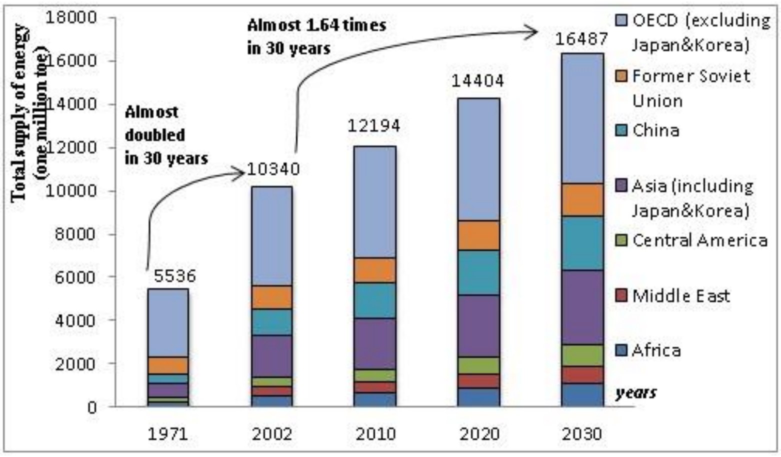

Fig. 1.1. Global energy demand in 1971–2030 [3, 4, 5].

In terms of diversity of renewable energy sources for countries that do not have fossil primary resources such as oil, natural gas, and coal, reduction of dependence on foreign sources and low-carbon economic development efforts of the decision-makers and countries which have a favourable geographical position like Turkey are becoming more important. Due to the fast reduction in the amount of conventional resources and increased demand, conventional primary resources in Turkey will be unable to satisfy the demand by 2020. Electricity consumption is on the rise because of the fast growing rate of the country's economy. The growing demand — driven by population and industrial growth — in emerging markets calls for an increase in the supply capacity as well as diversity in the generators. Diversification of primary energy supplies reduces dependency on a single source and contributes to supply security. The Turkish electricity market is among the fastest-growing ones in the world, with an average of approx. 9 % annual growth in 2010 and 2011, according to the Ministry of Energy and Resources [4]. This growing consumption calls for new investments.

The use of conventional energy sources is diminishing amid growing global concern for the environment. In this situation, the government should adopt two strategies: increase supply, and reduce demand. In this context, renewable energy and energy efficiency are particularly relevant. The use of renewable energy addresses the supply of energy and secures environment, and guarantees social and economic sustainability in the energy sector. There are different types of renewable energy, such as hydropower, solar, biomass, wind, and geothermal energy. Each type has its applications as well as advantages and disadvantages. A well-balanced mix of these can secure the energy supply in the country and even replace electricity, which is a typical source of energy. Moreover, renewable energy serves two key objectives: protection of the environment with zero-emission energy, and generation of energy to meet the demand. Energy efficiency addresses the need for a reduction in the electricity demand by achieving the maximum utilization of generated energy while diminishing waste.

The most obvious effect of energy generation is the human-induced climate change. As a result of the rapid increase in energy consumption and the global warming that are threatening the environment together with the unbalanced and unforeseen increases of the fossil fuel prices, interest in renewable energy sources has increased. These factors give emphasis to the importance of increasing the use of renewable energy sources. In this respect, small hydropower plants (SHPPs) have emerged as an energy source which is accepted as renewable, economical, harmless to the environment, easily developed, cheap, and with an average life span of 50–100 years. These reasons have increased small-scale hydropower development in value, giving rise to a new trend in renewable energy production.

Turkey has a huge hydropower potential. There is sufficient proof of the country's own potential for extracting energy from hydropower, especially power on-demand generation. Hydropower represents a secure and sustainable source of energy for the world with different beneficial side effects that can be used. In order to take advantage of it, the private sector needs to be involved.

One of the major problems faced by the world in the 21st century is secure energy supply. Hydropower has an especially important role in ensuring the security of supply. This can be explained by the possibility of hydropower to ensure energy storage in reservoirs and rapid start of generators in case of a need to increase power.

Small hydropower has long been developed in the world [6] and in Turkey; however, hundreds of small hydropower sites stay untapped. Many of them are environmentally and technically feasible but may not be returning the initial investment at the current level of technology, energy prices and support schemes. Massive effort is needed for developing efficient small hydropower plants.

Renewable energy in Turkey is still under development. Although there are the legal regulations and reforms to support the process, the system has not been completely established. The ratio of development is still below the expectations, and there is also a great level of non-utilized potential. In the renewable energy area, the incentives represent the main driving force as explained in detail. Renewable energy sources (RES) are promoted through different support schemes. There are also some support scheme structures for the attraction of RES financing and construction in Turkey. According to the results of the study on feed-in tariffs (FIT), the prices applicable to RES-oriented energy production are not functional in economical point of view, especially for SHPPs.

The potential of hydropower plants (HPPs) in Turkey is used partly, because HPP regime management considering the market price schedule is practically not performed. We can see that price schedule is very complicated for generation plan development. Appropriate algorithms and software tools are needed. These tasks are topical in many countries. Large numbers of papers [7, 8, 9, 10] are devoted to the solution of this problem.

It is important to notice that the HPP operation mode should be selected on the basis of future prediction. Therefore, it is necessary to take into account the inevitable influence of uncertain and random factors. The problem is further complicated by the presence of competitors whose decisions affect the energy system and the energy market conditions.

Summarizing the foregoing, the following can be noted:

1) the problem of promoting the use of water resources is relevant;

2) despite the efforts of researchers and governments, there remain many unsolved problems. In particular, it is very important to maximize the profit through optimal choice of HPP parameters and operation mode.

The objectives of the Thesis

The main objective of the present Doctoral Thesis is to develop short- and long-term planning models for the price-taker — the small hydropower producer — working in the electricity market regimes and striving for profit maximization considering the energy market conditions, uncertainties, and possibilities to co-operate with potential partners. To achieve the stated objective, the following tasks have to be solved:

- developing the stochastic optimization model and algorithm and proving its operation feasibility for the hydropower station;
- a forecast of natural water inflows for the reservoir in the short and long term;
- a forecast of electricity prices for the short and long term;
- a financial cost-benefit analysis estimating the potential returns on investment;
- presentation of the findings of a cost-benefit analysis of the total project costs for the generation capacity and the reservoir alternatives; creation of a long-time scenario for small hydropower plant (SHPP) feasibility to assess the specific features and to find the best alternative;
- use of the co-operative game theory approach to quantify an efficient distribution of the aggregated net economic advantage of the coalitions;
- synthesis of a model for the benefit of Turkish hydropower plant operators; definition of the volume of the necessary information and its resources; testing of the models during the solution of the optimization tasks; the opportunity of applying the models is proved jointly by the Quasi-Newton method and neural networks.

The methods and tools of the research

The results were obtained by applying the following methods and computer programs:

1. Prediction of the water flow and the electricity market prices by an artificial neural network (ANN);
2. The Quasi-Newton method for solving the task of optimization of the utilization of SHPP resources;
3. The game theory criteria with the coalitional game approach using the Shapley value in order to get additional income for the HPP operators;
4. The Monte-Carlo method for solving the profit estimation problem;
5. The Internal Rate of Return (IRR) and Net Present Value (NPV) calculation methods for the SHPP feasibility study;
6. Processing and graphical representation of the results by *MS Excel* and *Matlab*;
7. The economic part of the feasibility study of the example of the Saf SHPP is developed by using *RetScreen* software.

The novelty of the Doctoral Thesis and the basic results

The scientific innovation is characterized by the following aspects:

1. The operations of small-scale hydropower plants and reservoirs are studiedcarefully, they are identified, and the opportunity for their application for regime optimization is proved, also for the Turkish power system;

2. The hydropower plant working conditions optimization problem is solved by using the stochastic approach;
3. Water flow and market prices are predicted by using an artificial neural network;
4. The opportunity to apply the Quasi-Newton method for solving the task of income maximization (on the basis of a concrete SHPP example);
5. The opportunity to apply the Monte-Carlo method for the feasibility study;
6. Co-operative game methodology with the Shapley value is applied in the solution of the SHPP tasks; it gives the coalition participants the opportunity to get additional income. The support scheme (the feed-in tariff) for hydropower is overviewed and the requirement of operational regime regulation is proved by the changes in the market prices;
7. A methodology for determining a profitability analysis adapted to the market conditions has been substantiated.

The practical importance of the Doctoral Thesis

The results of the present Thesis can serve as a basis for further research in the field of special programming modules for the automated management of operational conditions of small hydropower plants, which encourages investors to maximum use of hydrological resources. The developed mathematical model allows maximizing the income effectiveness of active power by working at market conditions. It is so important for the power systems of developing countries such as Turkey, which has the largest hydropower potential in Europe. Also, it is very important to get the right answer in pre-feasibility studies of projects. Traditional cost-benefit analysis is not well adapted to hydropower plants, since it is based on a deterministic foundation and does not take into account the hourly variation of the electricity prices and the water flow rates. This Thesis provides a methodology by which we can get an accurate answer for the cost-benefit analysis of a SHPP.

The personal contribution of the author to the performed research

The selection of the hydropower generation optimization task and the economic part of the feasibility studies at free market conditions as the fundamentals of the work were under the supervision of Professor Antans Sauhats. The verification of the stochastic approach, the adaptation of co-operative game theory methodology and Shapley distribution have been carried out together with Professor Antans Sauhats. The simulation of the hydropower regime conditions and development of the models and necessary programming approaches for optimization and prediction applications have been worked out together with Doctor Roman Petricenko. All the calculations, collection and summarization of input data, verification of the results, and conclusions belong personally to the author.

The scope of the Thesis

Even though there are many hydropower schemes of every scale in the world, the hydropower potential is far behind being developed fully. Over the last decade, especially after the privatization in the energy market, many private companies have been engaged in the energy business in Turkey. The scope of the Doctoral Thesis refers to the parameters under hydropower plant operating conditions which are:

1) identifying optimal operating policies for small-scale hydropower plants; case studies of the Saf and Cobanli power plants;
2) exploring the capability of the stochastic method in finding solutions for optimal operation and comparing it with the solutions resulting from the classical deterministic method;
3) analyzing the efficiency of the elaborated optimization method;

4) constructing a simulation model for the above-mentioned reservoir system by using the Quasi-Newton method, which is provided by the *Matlab* software.

In the present Thesis, it is desired to give a general idea about the feasibility valuation of the operation regimes of small-scale hydropower plants. In this Thesis, two different working regimes, which are feed-in tariff and market condition operation, are examined and compared by using solvers. These studies contain the evaluation of two different alternatives, in which the location of the water intake structure and, therefore, the other components differ and in which operation takes place at market conditions or at a fixed price. The important parameters of the software are specified in the case study, and different alternatives for the feasibility study, which encompass the reservoir size and the capacity of the power plant for short term, middle term and long term, are compared in order to carry out a sensitivity analysis and to find the best alternative.

Approbation of the Doctoral Thesis

The results were reported and discussed at the following international conferences:

1. A. Sauhats, R. Varfolomejeva, I. Umbrasko, **H.H. Coban**. The Small Hydropower Plant Income Maximization Using Games Theory. Proceedings of the *International Conference on Environment, Energy, Ecosystems and Development* (*EUROPMENT 2013*). 28–30 September, 2013, Venice, Italy.
2. R. Varfolomejeva, M. Zima-Bočkarjova, A. Sauhats, I. Umbrasko, **H.H. Coban**. Reconsideration of Supporting Scheme for Renewable Energy Producer. *4th International Symposium on Environmental Biotechnology and Engineering*, September 9–12, 2014, Cinvestav, Mexico City, Mexico.
3. **H.H. Coban**, R. Varfolomejeva, A. Sauhats, I. Umbrasko. Hydropower Plant Regime Management According to the Market Conditions. *2nd International Congress on Energy Efficiency and Energy Related Materials* (*ENEFM*), 16–19 October, 2014, Oludeniz, Turkey.
4. **H.H. Coban**, R. Varfolomejeva, A. Sauhats, I. Umbrasko. Small Hydropower Plants Operations Optimization in the Market Conditions. IEEE *2nd Workshop on Advances in Information, Electronic and Electrical Engineering* (*AIEEE 2014*). 28–29 November, 2014, Vilnius, Lithuania.
5. **H.H. Coban,** R. Varfolomejeva, A. Sauhats. Comparing and Optimizing Hydroelectricity Power Production Models, *Ecres–3, European Conference on Renewable Energy Systems*, 07–10 October, 2015, Antalya, Turkey.
6. **H.H. Coban**, R. Varfolomejeva. Decision-Making in the Development of Small Hydropower Plants Considering Energy Storage Capacity. *International Renewable Energy Storage Conference* (*IRES*), 15–17 March, 2016, Düsseldorf, Germany.

Publications in internationally quotable scientific collections of the following articles:

1. A. Sauhats, R. Varfolomejeva, I. Umbrasko, **H.H. Coban**. The Small Hydropower Plant Income Maximization Using Games Theory. *Proceedings of the 2013 International Conference on Environment, Energy, Ecosystems and Development (EUROPMENT 2013)*. Venice, Italy, pp. 152–157. ISBN: 978-1-61804-211-8.
2. A. Sauhats, R. Varfolomejeva, I. Umbrasko, **H.H. Coban**. An Additional Income of Small Hydropower Plants and a Public Trader. *International Journal of Energy*, Vol. 8, 2014, pp. 29–35. ISSN: 1998-4316.
3. R. Varfolomejeva, M. Zima-Bočkarjova, A. Sauhats, I. Umbrasko, **H.H. Coban**. Reconsideration of Supporting Scheme for Renewable Energy Producer. *4th International Symposium on Environmental Biotechnology and Engineering*, September 9–12, 2014, Cinvestav, Mexico City, Mexico, pp. 62–63. ISBN: 978-607-9023-24-9.
4. **H.H. Coban**, R. Varfolomejeva, A. Sauhats, I. Umbrasko. Hydropower Plant Regime Management According to the Market Conditions. *2nd International Congress on Energy Efficiency and Energy Related Materials, Springer Proceedings in Energy*, pp. 141–152. ISBN: 978-3-319-16901-9.

5. **H.H. Coban**, R. Varfolomejeva, A. Sauhats, I. Umbrasko. Small Hydropower Plants Operations Optimization in the Market Conditions. *IEEE 2nd Workshop on Advances in Information, Electronic and Electrical Engineering*, Vilnius, Lithuania, 2014. ISBN: 978-1-4799-7123-7; DOI: 10.1109/AIEEE.2014.7020328.
6. **H.H. Coban,** R. Varfolomejeva, A. Sauhats. Comparing and Optimizing Hydroelectricity Power Production Models. Ecres–3 Proceedings. *European Conference on Renewable Energy Systems*, 7–10 October 2015. ISBN: 978-605-86911-3-1.
7. A. Sauhats, **H.H. Coban**, K. Baltputnis, Z. Broka, R. Petrichenko, R. Varfolomejeva. Optimal Investment and Operational Planning of a Storage Power Plant. *International Journal of Hydrogen Energy.* DOI: 10.1016/j.ijhydene.2016.03.0782016.

The structure and size of the Doctoral Thesis

The Doctoral Thesis is written in English, and it contains an introduction, 5 chapters, conclusions, 2 appendixes, and a bibliography with 148 reference sources. It is illustrated by 79 figures and 18 tables. The volume of the present Thesis is 157 pages.

2. THE BASICS OF SHPP DEVELOPMENT

The problem of hydropower plants development can be stated as related to the striving to achieve widely recognized main objectives — sustainability [11], effectiveness [12], reliability [13] — and to diminish the effects contributing to climate change [14, 15, 16, 17]. Let us profile the world's SHPP production, types, and development stages.

2.1. Hydropower in the world and in Turkey

According to recent data, hydropower supplies about 20 % of the world's electricity and 86 % of all electricity from renewable sources. Hydropower supplies more than 50 % of national electricity in about 65 countries, and more than 80 % in 32 countries [14, 18]. The European Commission has enacted the necessary legislation under the European Union strategy to increase the share of renewable energy in gross inland energy consumption up to 20 % by 2020 [19]. The objection is therefore clear: an unavoidable increase in energy consumption in the world, with climate change, global warming and the risk of an environmental impact, as a result of the combustion of fossil fuels [18].

Turkey is a high-altitude country located at the crossroads of Asia and Europe, with many river basins, including the transboundary Tigris and Euphrates rivers. Additionally, electricity demand is predicted to grow by more than 90 % within the next decade, which is why it is a must to take care of hydropower development [20]. Turkey's technical hydropower potential amounts to 1.5 % of the world's technical potential, while the European technical potential corresponds to 17.6 %, which amounts to 440 terawatt-hours. Figure 2.1 shows the distribution of the resources of the country's installed capacity as at the end of 2015.

Turkey has the highest hydropower potential in Europe with its 216 TWh/year technical hydropower energy, but was using only 18.3 % (39.6 TWh) of this technical hydropower potential as of the year 2005. However, different European countries such as Norway, Sweden and France are striving to bring their economically feasible hydropower potential within the range of 65–100 % [22].

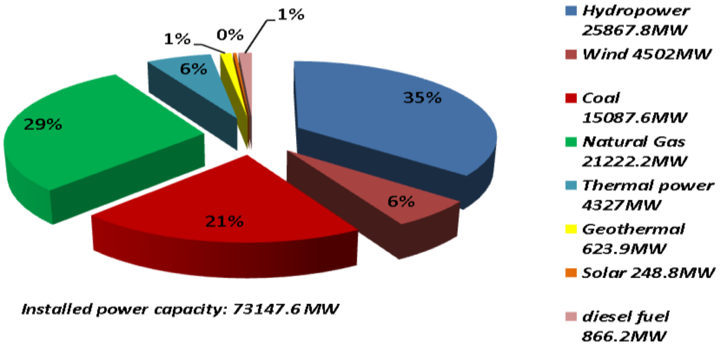

Fig. 2.1. Turkey's installed power as distributed among the types of resources [21].

The Turkish government guarantees to buy generated electricity for 10 years, offering a feed-in tariff of 7 $cent (6.2 €cent)/kWh. The law also includes additional bonus income for each component of the domestically manufactured electromechanical equipment used in plants.

2.2. A review of SHPP technologies

Hydropower electricity generation schemes commonly apply the technologies of discharge power plants, runoff power plants, and pumped storage power plants [23].

Run-of-river hydropower projects use only the water that is available in the natural flow of the river, meaning that there is no water storage and hence power fluctuates with the stream flow. This is a type of hydroelectric generation, whereby little or no water storage is provided. Some run-of-river power plants may have no storage at all, or a limited amount of storage; in that type the reservoir contains a relatively small amount of water behind a run-of-river dam, which is used for short-term (daily) regulation of the river flow rate [24].

Water storage (reservoir) developments as larger hydropower projects are attractive because they can provide "stored" power during peak demand periods. New dams for storage reservoirs for small hydropower plants are in most cases not economically feasible other than at isolated areas where the cost of electricity is possibly very expensive [25].

Pumped storage hydropower plants allow off-peak electricity to be used to pump water from a lower reservoir or river to a higher reservoir to generate power and discharge water during peak times. Pumped storage hydroelectric systems have two reservoirs, the lower reservoir. and the upper one. When the energy demand is high or the electricity prices are higher, electrical energy is produced by the water accumulated in the upper reservoir and tail water will be accumulated in the lower reservoir. At the times when the energy demand or the electricity prices are low, the water level is raised by pumping running water from the lower reservoir to the upper reservoir [26].

Developments using existing water networks built for irrigation, drinking water and even wastewater can be used. The advantage of using existing networks is that the initial cost is lower compared to other developments. Countries like Japan and Turkey may not have large fossil fuel reserves, but there are such alternatives to be considered [27].

2.3. SHPP development stages

Basically, SHPP development involves two main steps.

1. Project formulation and planning. This takes place before the application level, and a report has to be done which includes all investigations, data collection, project formulation, the feasibility study, the risks analysis, and the cost-benefit analysis.
2. Execution of the project. The decision to move ahead for project implementation by choosing the best alternative based on the feasibility report.

First, we have to start by planning and collecting data sources. Assessment of hydropower resources requires several types of data, including watershed boundaries, river geometry, topography, and water availability. These data enable the estimation of two critical variables for hydropower generation: the net hydraulic head, and the design flow. The steps of the feasibility study of a SHPP are listed below:

1) data collection and review. Provides documentation regarding the project's necessity (the water supply problem and its solution) and impacts (social and environmental);
2) definition of the power potential and estimation of the energy output;
3) development of alternatives: technical feasibility (the best project alternative);
4) assessment of the market potential;
5) a preliminary cost estimate;
6) economic analysis and selection of alternatives: economic, financial, and institutional feasibility. The financial program entailing the loan repayment capacity and security.

Design software can be used for developing real-life hydropower projects or in feasibility studies, after which a final design is made or construction is initiated. A number of software tools are available [28, 29], namely, ***Hydropower Evaluation, Smart Mini Hidro, HydroHelp, Bentley, RetScreen*** to assist in the assessment of SHPP projects.

2.4. The problems to be solved

The above overview of technologies, methods, and tools allows us to extract the problems that have to be solved.

One of the main reasons for **reconsidering SHPP development** methodologies are: the existence of an energy market, the revolution in the communication field, and the need for the development of rural areas. Also, it is necessary to propose a support mechanism that allows adapting the power plant's operation to the market situation. A coalition must be established between hydropower plants and the public trader. The creation of the coalition under consideration does not contradict the norms of the law. The power plant operation mode will be adjusted to the interests of all the actors and to the current market situation. For fair allocation of the additional gain, the approaches of the co-operative game theory can be applied, namely, the Shapley value.

Cost-benefit analysis (CBA) [30] is the heart of a feasibility study project. The costs and benefits to be provided for the entire life of an investment project are determined in monetary terms. Discounting is used to estimate the present values for future benefits and costs. The relevant decision rule in a CBA is therefore if the present value of the benefits is equal or greater than the present value of the costs — it is then considered acceptable to invest. Figure 2.2 represents an overview of the economic methodology for calculating the profit.

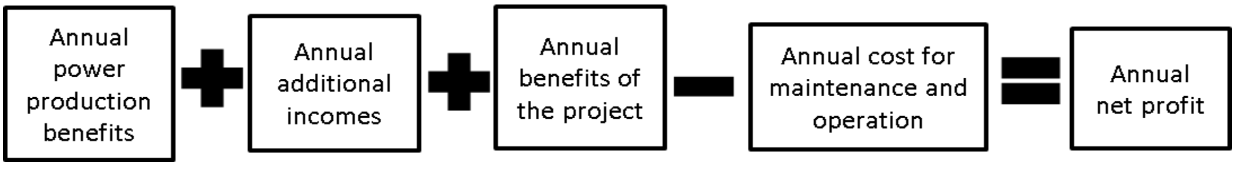

Fig. 2.2. An overview of the annual income calculation methodology of a SHPP.

To estimate annual net benefits, the costs of expenses, which are project operation and maintenance, are subtracted from the sum of income, which are gross power generation, additional benefits of the project, and additional incomes. Annual power production gains reflect the avoided cost of replacing a project's power generation and dependable capacity with power and equally reliable capacity from an alternative source. Additional annual benefits are related to being in coalition with other power producers, fishers, irrigation. Regarding annual benefits of the project services, some hydroelectric projects may offer benefits such as flood control, water supply, irrigation, and river navigability [31]. In many cases, in order to estimate costs and benefits, economic criteria are used, such as the **net present value (*NPV*)** and the **internal rate of return (*IRR*).**

2.5. The co-operation possibilities and additional profit distribution

The demand of electricity used by communities differs during the whole of the day and changes from season to season. For example, more power is used in the morning when people wake up and start using household appliances. Likewise, more power is needed on cold winter days and hot summer days when heaters and air conditioners are in peak use. Hydropower and solar resources generally complement each other seasonally and can often provide facility power with no back-up generator for local grids and small towns.

Combination of hydropower and wind energy makes some sense. According to the scheme of the most excellent condition, for example, when wind turbines are running, more water can be stored in the storage of the hydropower plant. Water from these reservoirs can be used to generate more electricity when the wind is blowing poorly [15, 32, 33].

For cascade HPPs, economical water usage will give a notable economic effect in corresponding circumstances. Although there is no possibility to forecast the water flow rate in the river, the power amount generated on a downstream HPP by managing upstream hydropower plant unit control optimization means that the economic effect can be notable.

The performed outlook lets us conclude that in the common case SHPPs can generate electricity not only for the electricity market. Electricity can be consumed by local small town consumers or any local utility. The operation mode of the SHPP can influence the profit of utilities which use water from reservoirs (fisheries, agriculture companies, cascade SHPPs). Taking into account the interests of these related companies, it is possible to obtain additional revenues. However, a new problem appears: in most cases, companies and SHPPs have different owners, but in accordance with the operation of SHPPs, the interests of companies mostly create additional revenues and diminish the expenses of SHPPs. The income has to be distributed fairly.

3. THE BASICS OF SHPP DESIGN AND OPERATION

Hydropower applications are governed by different conditions and limitations, the interconnection of which defines the space of feasible solutions, which meet all the criteria and concepts. The conditions can be divided into three areas: economic, legal, and technical. Legal conditions basically explain the regulations that have to be considered in the case of investing. It is the largest issue because it involves all the various environmental, social and other aspects and conditions, the objectives of which are guaranteed by government laws. In one respect, the legal setting cases also define the other two conditions, since technology and economy are also managed to prohibit wrong usage or risk to stakeholders comprised in resource management, the process of decision-making, procurements, etc. [35]. Technical and economic conditions are important to design schemes with built-in flexibility to accommodate changes in socioeconomic and environmental demands, market conditions and changing technologies.

3.1. Statement of the optimization problem and the structure of the solution algorithm

This subchapter aims at identifying the cost drivers for small hydropower generation through cost analyses. In order to solve the working conditions optimization problem, we formulate a mathematical model to represent the situation. Let us observe the SHPP working regimes in terms of optimization tasks, both in short-term and long-term planning. Both tasks contain similar and different features:

- the main goal in both tasks can be formulated as profit maximization;

- solutions have to be made on process prediction basis;
- optimization procedures in both cases can be non-linear and capable of taking into account a large number of decision and state variables;
- the objective function may contain random and uncertain variables.

At the same time, we can observe significant differences:

- the planning time horizon in feasibility studies is much larger;
- the number of decision variables during feasibility studies is much bigger because they involve variables describing parameters of power plant construction.

Despite the existing differences, both tasks can be presented by an algorithm with one common structure. Figure 3.1 shows the basic structure of generalized optimization tasks.

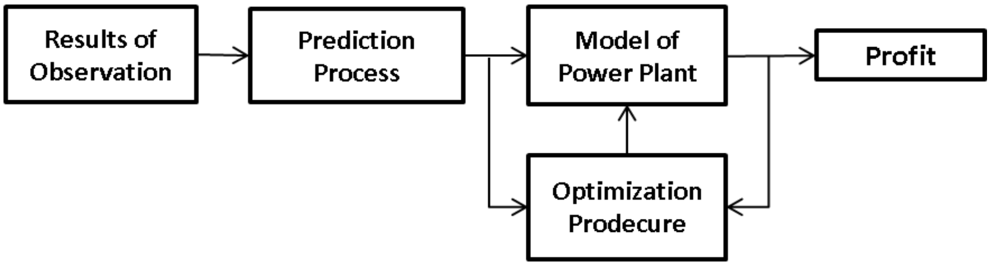

Fig. 3.1. The structure of generalized SHPP optimization tasks.

With this structure, the task of calculating the profit of the SHPP under study can be resolved. This thesis examines and compares two approaches. The first one is the classical method, based on a deterministic approach; in this case, it is impossible to obtain an exact answer for the optimizing procedure and the feasibility studies by neglecting uncertainties. The second method is more complicated but more accurate, that is, the stochastic approach, which can be used for income calculations considering the volatility of variables. The structure of Figure 3.2 contains three main blocks that should be analyzed, namely, the forecasting process, the optimization of the SHPP working conditions, and the estimation of the profit of the power plant.

3.2. The model of the power plant

Let us analyze the power plant model; the structure of the model is depicted in Figure 3.2 and contains three main blocks. The first block represents the model of the reservoir, symbolizing the type and storage capacity of the reservoir, which will be explained in Chapter 4. Selecting the appropriate type of turbine and generator depends primarily on available head-pond and water flow rate. The second block represents the model of turbine(s) and generator(s) that typically make use of mathematical optimization techniques, which take into account limitations and restrictions. The last block represents calculation of the profit that assumes competition for the market-based electricity price and the expenses, which will be explained in Chapter 4.

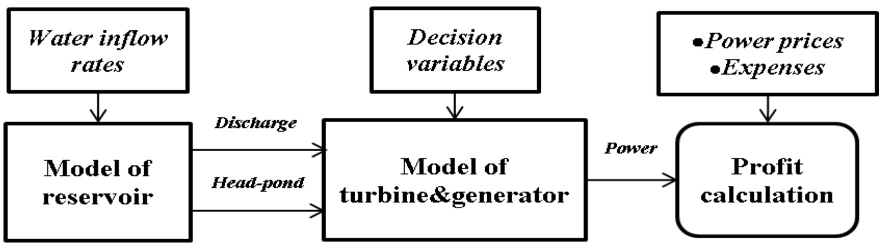

Fig. 3.2. The structure of a power plant model.

In real life, the model of a power plant can be synthesised when concrete equipment is chosen. For details on the calculation of the produced power, see Chapter 5.

3.3. General mathematical programming problem

Let us assume that the profit of the power plant owner is any function of prices, water flow rate, power of generators, etc., and can be described as follows:

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

where: $R_{i\Delta}$ — the power plant's profits. We assume that power plants are trying to maximize it; t — the time interval, t (years); P_{it} — the installed capacity; U_{it} — the number of units; H_{it} — the head pond, m; C_t — electricity market prices, Eur/MWh; A_{it} — capacity of reservoir, m^3; ρ_{it} — efficiency of turbine and generators; OM_{it} — operations and maintenance costs in year "t"; D_t — risks ratio for year "t"; K_t — the discount factor for year "t"; CH_t — the catchment area, km^2; i — the number of the option (alternative) for power plant construction; Inv_t — the construction cost, which is tightly related to construction design and parameters.

In the deterministic case, all the input parameters are known. However, in the stochastic case, some of these parameters are probabilistic and (or) uncertain. In this case, $R_{i\Delta}$ is also random. The optimization problem can be formulated as an average profit maximization task in the following form:

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

where *F* is a multidimensional probability distribution function [10, 36]. Presented in the form (3.2), the objective function is not only difficult for maximization, but even the calculation is very complicated.

3.4. Constraints of SHPP operation

Let us analyze and formulate the constraints that should be considered in the general optimization model for multiple-period hydropower reservoir and generation operations. The main constraints of HPP operation can be classified into four groups.

1. The reservoir storage volume limits:

The height of the head pond, which means the difference in elevation between water levels upstream and downstream of a dam. We assume that *H* can be any value lying within the domain $[H_{\min}, H_{\max}]$, where $H_{\min}, H_{\max}$ are positive constants specified in the operation plan [37]:

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

where *H* is the water level; the min and max are the allowable lowest and highest levels during time *t* respectively. H_i is the reservoir storage at the beginning of period t;

$$H_i^t + A_i^t - Q_i^t = H_i^{t+1} \quad (3.4)$$

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

$$H_{i,\max}^t \ge H_i + \textstyle\sum_{t=1}^{T} A_i^t - \sum_{t=1}^{T} Q_i^t \ge H_{i,\min}^t \quad \forall i \in I,\ \forall t \in T, \quad (3.6)$$

where: I, i — the set and index of the reservoir; T, t — the set and index of hours in the time horizon; H_i^t — the water level at hour t; A_i^t — the water flow rate into the reservoir at hour t; Q_i^t — the water discharge at hour t.

The rate of the water flowing into the dam *A* is a positive variable. The water level relationship can be reformulated as the sum of beginning level storage and the difference between incoming flow and discharge from periods 1 to T as follows:

2. The water discharge of the reservoir:

Water discharge is the rate of the water flowing through the turbine. We assume Q can be any value residing within the domain $[Q_{min}, Q_{max}]$, where Q_{min} is 0, and Q_{max} is determined by the turbine's head. The lower limit of the water discharge from a reservoir is to satisfy the downstream needs, such as navigation and ecology, while the upper limit of the discharge is set as the maximum allowable discharge of the reservoir, as shown in equation:

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

where: $Q_{\min}$ and $Q_{\max}$ are the lower and the upper limits of the water discharge, respectively. The minimum water discharge is considered negligible in our case study.

3. The power generation:

P is a function of reservoir release Q and water head ΔH:

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

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

where: n_i^t — the power efficiency at hour t; ΔH_i^t — the vertical distance of the waterfalls; the height of the head pond at hour t; $P_{i,max}^t$ — the maximum power generation at hour t.

4. Minimum unit production:

The minimum production must be set to some percentage of the maximum production on each unit, taking into account the cavitation and efficiency of the turbine and generator:

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

where R denotes the minimum electricity production of each unit.

3.5. Objective functions

The deterministic approach. To maximize power generation as one of the operational objectives, one way of accomplishing it is to utilize the water head to increase the power generation while reducing the wasted water. In this method, the electricity prices are constant; so the only way to maximize income is by maximizing power generation.

The optimization task can be formulated as follows:

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

where: E is the amount of annual power produced by the power generator c at a constant electricity price in EUR/kWh; Ex stands for the expenses, namely, operation and maintenance costs and interest payments. According to equation (3.11), the decision variable is hydropower output, which depends on reservoir release, which is determined to be the decision variable Pi.

The stochastic approach. Profit maximization; at market conditions, the optimization problem can be formulated as follows:

$$M\left[R(P_1, P_2, ..., P_j)\right] = M\left[\sum_{j=1}^{J} R_j(c_j, P_{SHPP\,j})\right] \to \max \tag{3.12}$$

where M is the mathematical expectation of the value; P_{SHPP} — SHPP generated power, kWh; P_j — power generated at j-time; c_j — random market price at time period j, EUR/kWh; Q_j — random water inflow through the turbine, m^3/s; $R_j(c_j, P_j)$ — the profit from the sales of electricity.

It is required to determine the SHPP operating schedule by providing maximum income for the regulation cycle.

The objective function for cascade of SHPP optimization. The main objective function for the optimization of cascade hydropower plants is to increase the profit and to provide operation with the best efficiency rate. Figure 3.3 represents a cascade of two SHPPs.

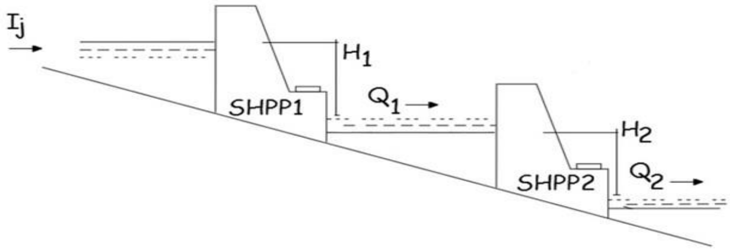

Fig. 3.3. A cascade of two small hydropower plants [38]

The optimization issue becomes more complex in the case when the power plants in the cascade are the property of different owners. It is natural to suppose that each owner strives to increase their own profit. The upstream power plant in the cascade is independent and is able to choose the best running condition. On the other hand, the power plants located downstream the river need to work taking into account the water inflow rates from the previous plants. Each owner strives to maximize their own profit. The profit of the last power plant in the cascade is influenced by the previous power plants. Here are the possibilities of stating the optimization task:

1) each power plant runs independently. In this case, the task can be described as follows:

$$R_1 \rightarrow \max,\ R_2 \rightarrow \max,\ \dots \tag{3.13}$$

2) all the power plant owners have agreed to establish a coalition. The optimization task can be described as follows:

$$\sum_{i=1}^{I} R_{\mathrm{i}} \rightarrow \max \tag{3.14}$$

Such agreement is possible only if the following inequality is fulfilled:

$$\left(\sum_{i=1}^{I} R_i\right)_{max} > R_{1\max} + \cdots + R_{I\max} \tag{3.15}$$

In this situation, there is not only additional profit but also a new issue is created. This issue is very significant in real life and can be expressed by the question how to fairly distribute additional profit. This problem will be explained in the next subchapter.

3.6. Cooperation, model of cascade Shapley distribution

As described in Chapter 2.5, many cases can be defined which involve cooperation and therefore may use the game theory for fair income distribution, namely, Shapley distrubition [29, 44]. A game includes a set of players, each of which has a number of strategies that they can employ based on their choices. The game theory is a mathematical method, which is used for analyzing the strategies of each player, to maximize each player's chance of winning (in our case, to maximize income), and to predict the possible consequences of the game. Let us assume the project of energy supply progress planning in the form of a static game with complete information [39]:

$$\left\{I,\ S = \prod_i \left\{S_i\right\} i \in I,\ R = \left\{R_1, R_2, \dots R_n\right\}\right\} \tag{3.16}$$

where I is a list of players, $\{S = \prod_i \{S_i\}\} i \in I$ reflects all the combinations of situations and revenues R of each player at all his strategies and at each combination of the competitors' strategies.

The Shapley value is the reference rule for paying participants according to their contribution in coalitional games with transferable utility. Between the power producers or between the power producers and the public trader, coalitions are possible because the players are assumed to negotiate effectively with each other [40].

The result of formulating a coalitional game can be defined mathematically in the following form. The marginal contribution of player i ∈ N towards coalition S, i /∈ S

$$v(S \cup \{i\}) - v(S). \tag{3.17}$$

The simple approach would be to give each player his contribution c_i :

$$c_i = R(S \cup \{i\}) - R(S) \tag{3.18}$$

where: $R(S)$ is the revenue of the coalition S, $R(S \cup \{i\})$ is the revenue of the coalition S with the participation of the actor i. Since the players can form n! possible random orderings, the additional income/profit that the *i*-th player receives is as follows:

$$\phi_i = \sum_{i \notin S \subseteq N} \frac{|S|!(n-1-|S|)!}{n!} \left(R(S \cup \{i\}) - R(S)\right) \tag{3.19}$$

where *n* is the total number of players, $|S|$ is the size of the set S, the sum extends over all subsets S of N not containing player *i*.

By Shapley value, the fairly distributed profit of cooperation when two participants participate in the game obtains the simplest possible form as follows:

$$\phi 1 = \phi 2 = \left(R(S \cup \{i\}) - R(S)\right)/\,2 \tag{3.20}$$

There are possibilities to get additional income from the creation of a coalition between SHPPs or with a public trader. Two of them are summarized below:

1) the public trader motivates SHPPs to work according to the market price schedule under the feed-in tariff and shares this additional income with the SHPPs. Such an approach can lead to additional income for the power producers and the public trader;
2) for cascade power plants, the operator of a downstream station cannot understand the generating plan of an upstream station and cannot have a possibility of prediction of water flow rate. The cascade power plants can create a coalition and work cooperatively in order to increase their income.

4. SYNTHESIS OF AN ALGORITHM FOR SHPP OPTIMIZATION AND FEASIBILITY STUDY

This chapter is devoted to describe problem revision striving for accuracy and effectiveness. Let us assume that the power system involves generation companies *Gcom*, power network *Pnet*, and consumers *Conc*:

$$Own(G_{com}, P_{net}, C_{ons}). \tag{4.1}$$

In general, each of them includes many objects which are managed by different owners:

$$\begin{gathered} G_{com}(g_{com1}, \dots, g_{comn1}) \\ P_{net}(p_{net1}, \dots, p_{netn1}) \\ C_{ons}(c_{ons1}, \dots, c_{onsn1}). \end{gathered} \tag{4.2}$$

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

$$R(Own_j) \Rightarrow max. \tag{4.3}$$

In the common case, we can suppose that the profit of the owner is any nonlinear function from:

configuration *Σ* and parameters *Π* of the owned objects;

configuration and parameters of objects owned by the remaining owners

$$\Sigma_{i\_};\ \ \Pi_{i\_}. \tag{4.4}$$

The part configuration and parameters may chang over time:

$$\Gamma(t) = \Sigma_{i\_}(t);\ \ \Pi(t). \tag{4.5}$$

The configurations and parameters depend on random and uncertain events and processes (ambient temperature, wind speed, solar radiation, etc.). The part configuration and parameters must be selected before the start of the experiment (at the design stage). The selection of configuration *Σ* and *Π* is subject to many legislative, technical and environmental restrictions δ. $\delta \ni \Omega$,

where *Ω* is the boundary of the space where all the restrictions are fulfilled.

Taking into account all of the above, we can start to formulate the optimization task objectives of the owners, which can be presented in the following form:

$$\begin{gathered} R(Own_1) = F_1(\Sigma, \Pi, \Sigma_{i-}, \Pi_{i-}, t, \Gamma(t)) \Rightarrow \max \\ \vdots \\ R(Own_n) = F_{n\Sigma}(\Sigma, \Pi, \Sigma, \Pi\ , t, \Gamma(t)) \Rightarrow \max \end{gathered} \tag{4.6}$$

subject to: $\delta(\Sigma, \Pi, \Sigma_{i-1}, \Pi_{i-1}\ , t, \Gamma(t)) \ni \Omega.$

Optimization in the form (4.6) cannot be solved because: each function *F* contains random time-dependent processes $\Gamma(t)$; profit *R* depends on time.

To take into account the above, it is necessary to create appropriate statistical models of random processes $\Gamma(t)$, to choose the planning period length, and to select indicators which allow describing profit by one number. Performance of the above steps allows us to express the owner's profits in form (3.6). Using (3.6), we can rewrite (4.6):

$$\begin{gathered} M[R(Own_1)] \Rightarrow max \\ \vdots \qquad\qquad \vdots \\ M[R(Own_n)] \Rightarrow max \qquad\qquad \textit{subject to: } \delta \ni \Omega. \end{gathered} \tag{4.7}$$

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

Expressions (4.7) describe an extremely complicated problem because:

1) the equation (3.2) contains an integral and an extremely complicated probability distribution function which should describe a multidimensional random process $\Gamma(t)$;
2) solution of (4.7) is related to the decisions of all owners. Each owner mostly makes his own decisions in a situation of incomplete information about the behaviour of the competitors;
3) objective functions of (4.7) are in the common case nonlinear and contain discrete variables that describe configurations of power system objects under the optimization. The number of configuration variants can be enormous;
4) planning period T has to be equal to 20–40 years; at the same time, the running conditions change each hour;
5) the influence of random processes should describe the future.

4.1. Simplification of the SHPP optimization task

The following simplifications should be based on SHPP optimization tasks peculiarities which are described below.

1. The limited capacity of each SHPP and even the capacity of the sum of SHPPs allow us to suppose that on the power market, electricity prices can be considered exogenous, which means that prices do not depend on the running regime of SHPP owners. This hypothesis leads to a significant simplification of the objective function because consideration of the decisions of the majority of competitors becomes unnecessary.

2. The existing methodologies, approaches and software tools allow diminishing the number of possible configurations of SHPPs under study.
3. According to the description in Subchapter 3.8, in many cases SHPP running regime can be selected taking into account the needs of the neighbouring companies. In this situation, we can suppose that the interests of all the companies can be subjected to consortium profit maximization.

Analyzing expressions (3.2) and (4.7), we can conclude that the stochastic approach leads us to the formulation of an extremely complicated objective function in terms of the required computational effort and the vast scope of input data. To estimate the expected profit according to (4.7), we need to calculate the multidimensional integral. It should be added that the dimension of the integral for the considered problem can be huge, since the typical planning horizon is thousands of hours leading to a corresponding dimension of the integral. Moreover, it is necessary to operate with several correlated random processes in the specific problem. In this case, autocorrelation and correlation functions should be taken into account, which shapes an extremely complicated and computation-intensive distribution function, making it unsuitable for practical application.

The difficulties of computing the integral (3.2) can be considered as the main reason for applying the scenario approach. However, the theory of random processes addresses a particular type, the so-called ergodic processes, which have the same behaviour averaged over time as averaged over the state space [41]. In other words, the ergodic property implies that the time-averaged value is equal to the value averaged over the state space. This property allows us to avoid computing the multi-dimensional integral.

Now, let us assume that the process under consideration (the time-varying profit) is ergodic. In such case, as seen Figure 4.1, we can replace the expected ensemble average value by the time average:

$$M\left[R_{ri}\right] \approx \overline{R}_{ri} = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} R_{ri}\, dt \tag{4.8}$$

Transition to the time average allows us to compute the expected average profit without explicit knowledge of the conditional probability [42] distribution function (3.1). However, the resulting simplification causes new difficulties since the time average value approaches the ensemble average only when the integration time and duration of processes tend to infinity [36].

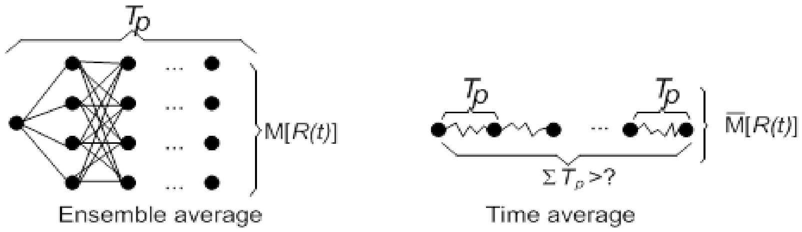

Fig. 4.1. Transformation of the stochastic optimization problem [10].

As a result, a forecasting procedure of the random processes needs to be implemented. Practically, the length of time is defined by the requirements regarding the accuracy, computational expense and complexity of the problem represented by the integrand.

4.2. Decomposition and restriction of the optimization problem

Let us assume that the SHPP owner is a player in the day-ahead electricity market. A long-term planning problem is being studied. In this situation we can declare that:

1) profit is accumulated during N years or $N_t \cdot 8760$ hours;

2) profit is influenced by electricity market prices, water flow rate into the reservoir, and other possible random processes;
3) all processes can be predicted with one-hour resolution;
4) prediction results change every day and every hour;
5) profit value calculation requires choice of SHPP power for the day-ahead and intraday markets separately.

We will formulate the yearly profit $M[R(Own_i)]$ maximization problem. The planning period profit can be calculated as the sum of annual profit. Each annual profit R_i can be depicted as a sum of daily profits:

$$R_i = \sum_{K=1}^{365} \sum_{J=1}^{24} M[R(Own_i)]_j \qquad (4.9)$$

Analyzing (4.9), we can conclude that one-day profit is linked with the other day's water amount in the reservoirs at the start and at the end of the day under study. If these variables are fixed (such a possibility will be proved below), the estimation of the profit becomes much simpler, especially when taking into account the rationality of applying the Monte-Carlo method for long-period profit estimation. In this case, using the peculiarities of the named method and a limited number of randomly chosen days, we can estimate long-term profit. This approach becomes useful when the water amount in the reservoir is known. Unfortunately, these variables cannot be selected on one-day problem statement basis. Water amount at the beginning of the day is depending on the previous process, and the amount at the end of the day is influencing the following day's profit.

That brings us back to the long-term problem and, as a result, to the necessity to solve a task with a large number of decision variables. However, exhibition of the one-day optimization problem allows us to resolve the water amount fixation issue using a relatively simple and effective tool. This tool is based on specific features of SHPPs:

- water reservoirs of SHPPs are obviously relatively small;
- linearized models of SHPPs do not lead us to critical errors in profit estimation.

Additionally, observations of optimization procedure results allow us to conclude that taking into account a limited number of days, it is possible to solve the one-day problem and that the solution outputs weakly depend on the reservoir water amount at the end of the period under study.

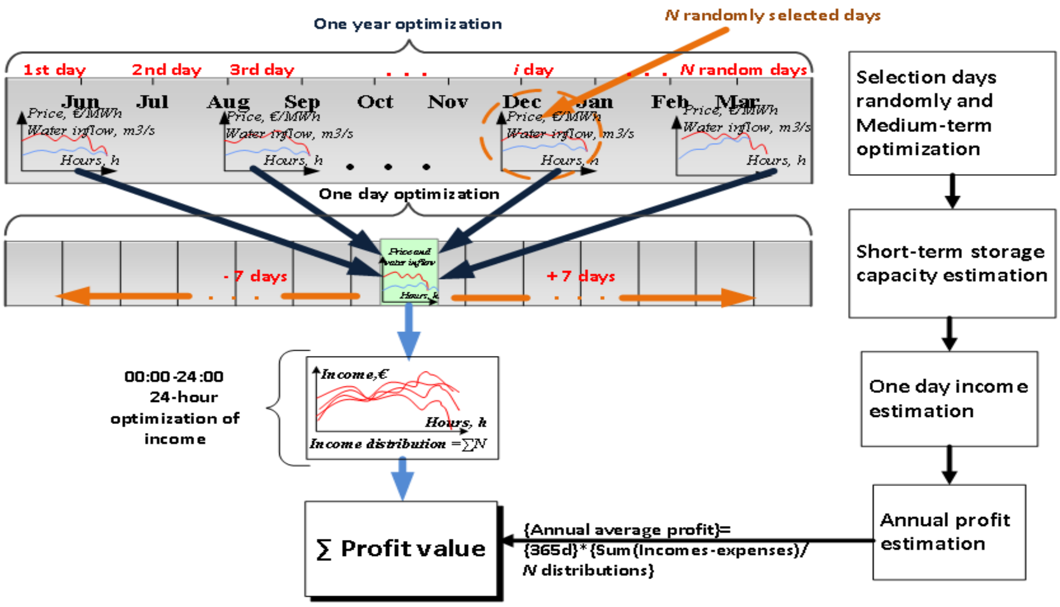

Fig. 4.2. The main algorithm of optimization combining the long, medium and short term [36].

As a result, a simplified optimization algorithm can be presented by the structure in Figure 4.2. The depicted structure performs steps as follows:

1) a concrete day is randomly selected. The level of the reservoir is unknown. In order to estimate the reservoir level, we select additional 7 days before and 7 days after the selected day and solve an optimization task using a linear model of the SHPP. Only the reservoir levels are used in the following step (the motivation of this choice can be seen in [36]);
2) profit maximization of the selected days is performed by using a non-linear model;
3) the named steps are prepared. The number of trials has to be large enough to achieve the required accuracy.

4.3. Reducing the number of trials using the Monte-Carlo method for profit estimation

Let us consider one-day profit R_{ik}, which can be obtained on day *i* of year *k*.

Due to the influence of random and uncertain parameters, R_{ik} is also random. Let us assume that R_{ik} can be expressed as follows:

$$R_{ik} = M[R_k] + \underline{R_{ik}}, \tag{4.10}$$

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

$\underline{R_{ik}}$ is a centralized random variable. Let us assume additionally that $M[R_{ik}]$ can be presented as the sum of two components:

$$M[R_{ik}] = d(k)M_1[R_k] + M_2\left[\underline{R_{ik}}\right], \tag{4.11}$$

where: *d(k)* is a multiplier which allows taking into account the annual changes in profit influenced by price augmentation during the years. Expression (4.10) can be rewritten as follows:

$$M[R_{ik}] = M_1[R_{ik}]\big(1 + d(k)\big). \tag{4.12}$$

Calculations using (4.12) allow us to estimate the mathematical expectation of any day's profit in a year using a statistical model of the first year's process. We suppose that $R_{i1} = R_{i2} = \cdots = R_{iR}$. It means that the probability distribution function of R_{ik} remains constant over the years. We suppose that within one day, the processes under observation are stationary, which means that we can calculate the average profit as a time average value. The expression allows us to calculate the income of any year using a probabilistic representation of processes of only the first year. This capability dramatically reduces the number of tests in the implementation of the Monte-Carlo method performing the profit estimation.

4.4. Models of SHPP running in a coalition and profit formation

The model of the partner's behavior is as follows.

The possible partners are: the owners of the remaining part of the cascade power plants, local electricity consumers, fishers, water consumers, etc. Here, we have two kinds of working behavior:

1) independently; each partner strives for the maximization of its own profit or benefit;
2) cooperation.

Without losses of generality, let us further consider a coalition consisting of two SHPPs operating in a cascade and two local consumers (the limitation of this number is not essential and can be extended). Our initial conditions are as follows:

1) there are not existing partners or clients who use water (not for generation);
2) the owners of the SHPPs are different;
3) there exist local power consumers.

The structure of the system under consideration is depicted in Figure 4.3. When the first SHPP and the second SHPP are running independently of each other, the first power plant can resolve the optimization task in an egoistical manner, without taking into account the interests of the second SHPP and local consumers.

At the same time, the owner of the second power plant has to make a decision in accordance with the working condition of the first SHPP while striving to the profit maximum, because the water inflow in the reservoir is caused not only by nature but is also in direct dependence on the operation mode of the first SHPP.

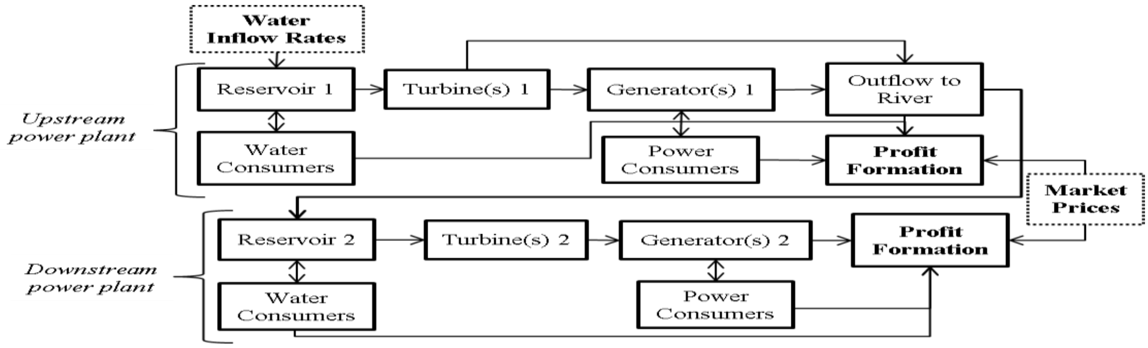

Fig. 4.3. The structure of cascade SHPP profit calculation.

The model of Figure 4.3 describes the profit of the actors of the system as a function of water inflow, the parameters of all the blocks, the parameters of the SHPP, and the consumers' running regime.

4.5. Forecasting processes

Figure 4.4 shows a block diagram of the processes required for designing a forecast model that predicts future electricity market price and water flow using artificial neural networks (ANNs).

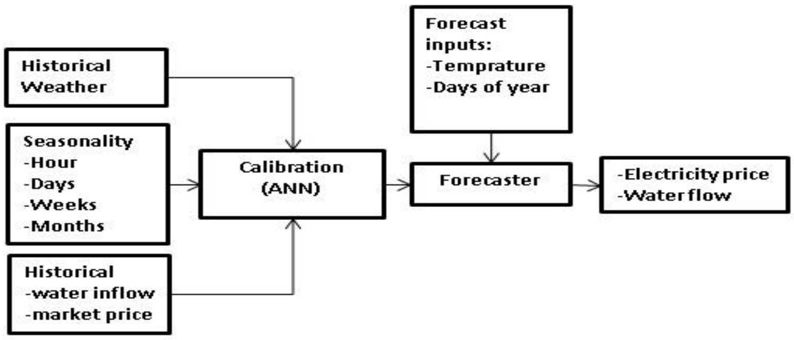

Fig. 4.4. A block diagram of model design procedures.

Let us assume that all the predictions can be performed by forecasting the mean value. Historical forecast data and prediction errors have been logged and are available. The statistical properties of prediction errors are constant in time allowing us to generate the realizations of stochastic processes. The duration of those processes is limited only by the available historical data and the rate of their aging.

Based on the above assumptions, we estimate the prediction errors. As a result, when the day-ahead prediction of the mean values is made, it is adjusted by adding the historical forecast errors, thus allowing to simulate long realizations of the future processes which are necessary for calculating the time-average profit. It is beneficial to use stochastic optimization when solving the 24-hour planning sub-problem [36].

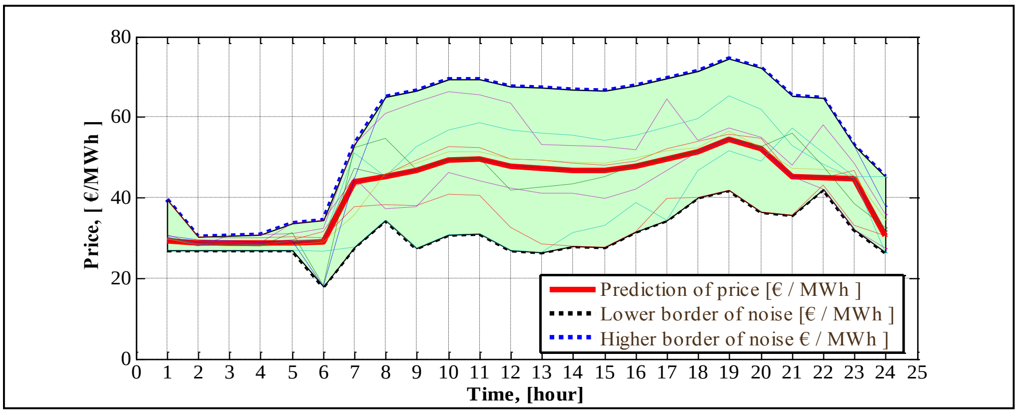

Fig. 4.5. Electricity market price forecasts [36].

It should be noted that for this test, we used a total of 11 realizations. Predictions for January 21, 2014 (Figure 4.5), were implemented in the short-term optimization algorithm and when all the 11 of them were taken into account, the expected profit for the day increased from 1727.2 to 1905.8 Euros. That is a 10.34 % improvement in the expected profit when the uncertainty of price predictions is accounted for. It can be concluded that it is beneficial to use the stochastic approach when optimizing the short-term operation of a storage plant. This will also be reflected in the long-term planning when estimating the potential profit [36].

4.6. Long-term planning problem specifics

The maximization problem (4.11) should be solved taking into account a number of technical, environmental, legal, and financial limitations. The function (4.11) is generally nonlinear, and it is dependent on random or uncertain variables, such as electricity market price, discount rate, etc. The solution of the task (4.11) can be performed by the Monte-Carlo-algoritm-based NPV and IRR calculation presented in Figure 4.6. For HPP feasibility studies, a calculation of yearly income will be needed. Therefore, we will make an analysis as to how many days would be needed to have as small an error as possible. Firstly, we have to know (predict) the water flow rate and the electricity market prices; then, we can perform short- and medium-term power plant working optimization, at the end of which we will have a result of short- and medium-term profit, which will be the way for us to calculate yearly profit. The Monte-Carlo simulation randomly selects the input numbers of days for the different tasks to generate the possible outcomes.

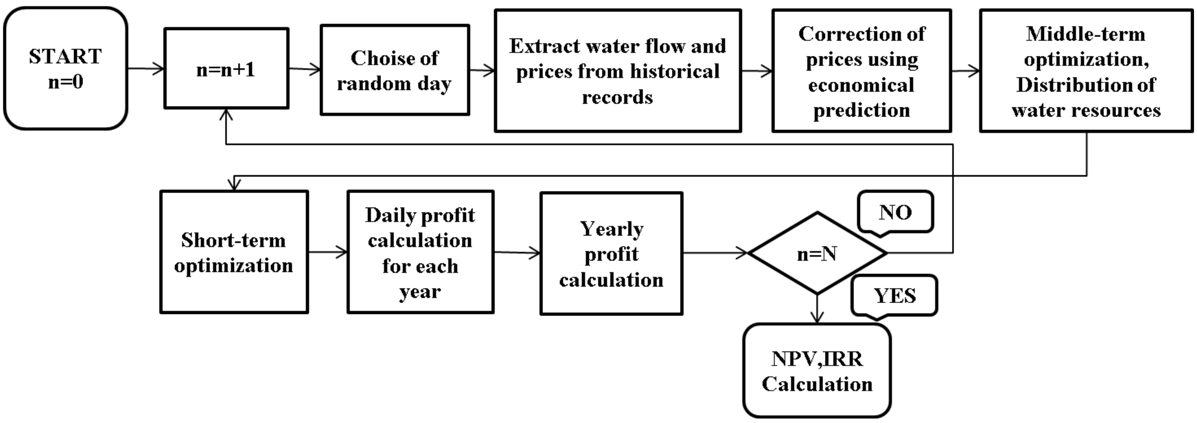

Fig. 4.6. An algorithm for estimating the NPV of a HPP, based on the Monte-Carlo method.

5. EXAMPLES AND THE CASE STUDY

Let us describe and analyze the main features of the real-life SHPP selected for the case study. The powerhouse and the reservoir have been built on the Goynuk River in the city of Bingol, Eastern Turkey. The height of the head pond is 130 meters; the nominal capacity is 21 MW; the yearly average inflow into the water reservoir is 5.48 m^3/s, the maximum water level before the dam is 3 m; the efficiency factor of the hydropower set is 90 %, and the surface of the reservoir is 40 000 m^2. The total cost of the power plant is 15 000 000 €.

The constraints for Saf HPP:

a) the reservoir storage volume limit:

$$1\ \mathrm{m} \leq h_i^t \leq 3\ \mathrm{m}, \tag{5.1}$$

where *h* is the water level; min and max are the allowable lowest and highest levels of *t* and *i*, which are the indices of the time and the reservoir, respectively;

b) the water discharge of the reservoir:

$$Q_{i,\min}^t \leq Q_i^t \leq 17.03\ \mathrm{m}^3/\mathrm{s}\,, \tag{5.2}$$

where Q_{min} and Q_{max} are the lower and upper limits of the water discharge, respectively;

c) the characteristic curve of power plant generation:

$$0 \leq P_i^t \leq 21\ \mathrm{MWh}, \tag{5.3}$$

where the power output *P* is the generated power;

d) the water balance equation:
the rate of the water flow through the turbine (Q) is a negative variable:

$$V_i^{t+1} = V_i^t + (I_i^t - Q_i^t) \cdot \Delta t \tag{5.4}$$

where *V* denotes the storage and *I* is the inflow in meters;

e) the initial and terminal reservoir storage volumes:

$$H_{i,1} = H_{i,begin} \tag{5.5}$$

$$H_{i,25} = H_{i,end} \geq 1\ \mathrm{m}\,, \tag{5.6}$$

where *i* is the index of the reservoir; $H_{i,1}$ is the initial (1st hour) storage level of the reservoir; $H_{i,end}$ is the final (25th hour) storage level of the reservoir, and it cannot be less than 1 m because of the ecological factors and fish gates;

f) the water use rights in Turkey; the amount of water released downstream must be at least 10 % the average flow of the last decade. If the current flow is less than 10 % the average flow in the river over the last ten years, all the water has to be released downstream to let the natural life continue [44]:

$$I_i^t \cdot 10\ \% \leq Q_i^t. \tag{5.7}$$

The FDC shows flow distribution during a year, which is useful for calculating the water available for a hydropower scheme. The duration curve of the multiannual mean daily discharges at the design section of the river Goynuk is shown in Figure 5.1.

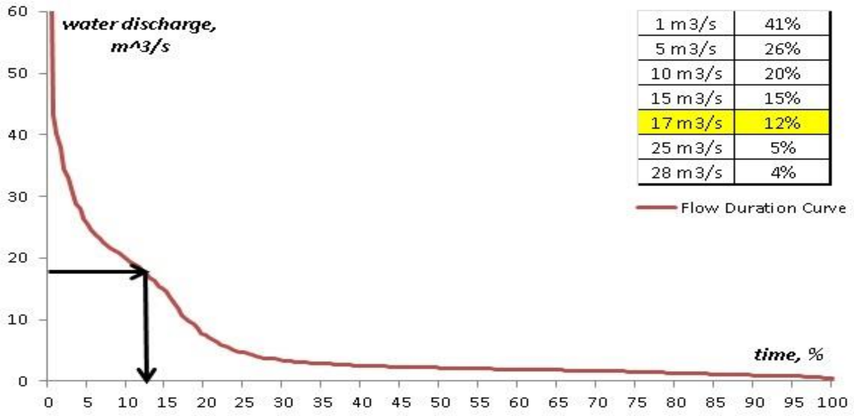

Fig. 5.1. The flow duration average curve for the years 1990–2000.

Following these data, the exceedence of the multiannual mean annual flow is equal to 17.03 m^3/s at the design section for 12 % of the time over a year; it means that this discharge provides generation of full power for 44 days during the year.

5.1. The forecasting process

The tools and process of obtaining the prediction were described in Chapter 4.5. Training of the ANN is performed in a supervised manner using historical data (the statistics of 2013 and 2014) of the market prices and water inflow rates in the river Goynuk. We underline that since Turkish electricity market prices are accessible only for market participants, the author takes the hourly electricity market price from the Nord Pool Spot [45].

5.1.1. Forecasting of water flow and electricity market prices

Figure 5.2 shows the prediction of water flow. The maximal error is about 6 %. It is very useful data for a feasibility study in order to have an accurate answer.

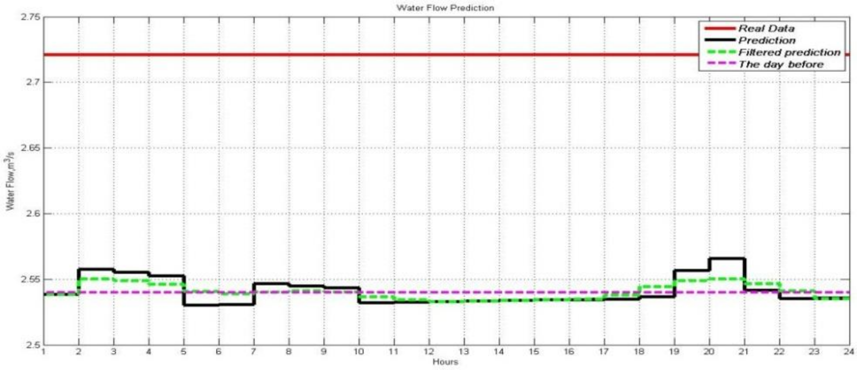

Fig. 5.2. Water flow prediction for 24 hours.

The time-series forecast analysis has been conducted using a neural network by means of the *Matlab* software. For each prediction study, the obtained forecast results have been validated against actual measured data. We can conclude that the artificial neural networks forecast technique has proven to give accurate results for the case under discussion.

The relationship between the forecast and actual electricity market prices and the forecasting error are presented in Figure 5.3. The prediction error was about 15 %; however, it can be concluded that it is beneficial to employ the stochastic approach to consider the uncertainty of the electricity price forecast for short-term operation optimization of the SHPP. This will also be reflected in the long-term planning when estimating the potential profit.

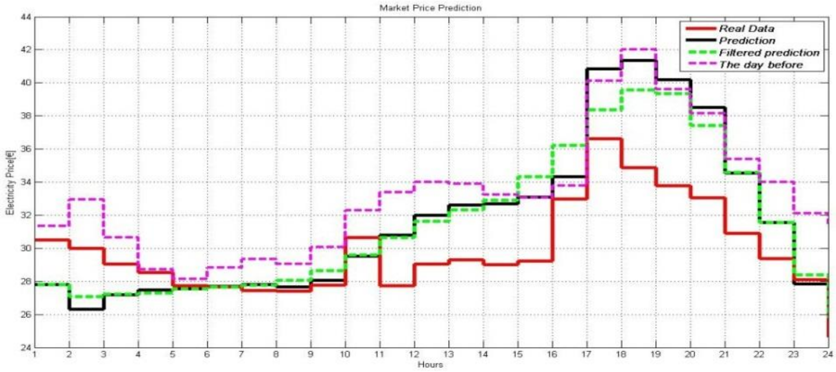

Fig. 5.3. Market price prediction for 24 hours.

For long-term prediction, we can use annual electricity prices. The electricity prices in the long-term horizon show high volatility, making it difficult to predict their future value, but as a reference case by the results of the articles [46, 47], the prediction has been conducted (see Figure 5.4) [47].

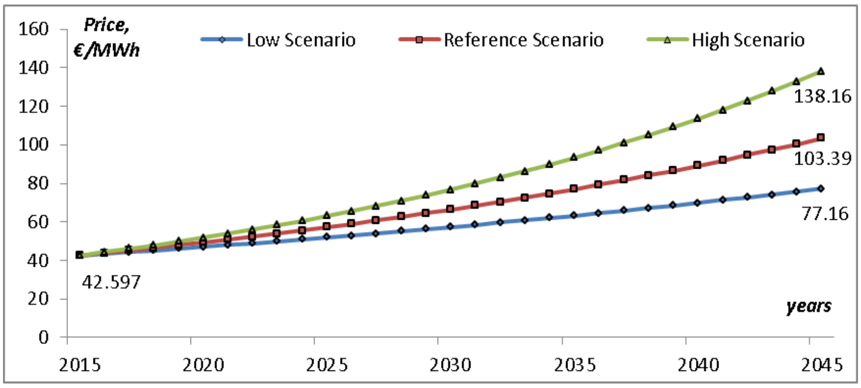

Fig. 5.4. Electricity price projections, 2015–2045.

Three price scenarios are implemented with different assumptions, namely, a low, reference, and high case. In the low, reference, and high scenario, it is assumed that the electricity prices will increase by 2 %, 3 %, and 4 % respectively annually from 2015 onwards.

5.2. Results of application and comparison of the optimization methods for Saf SHPP

Applying two models, let us compare the results of SHPP optimization. The first model is deterministic, which means that it disregards the uncertainties related to water inflow and electricity price forecasts. The second model is stochastic. Let us compare the methods for performing the SHPP feasibility studies and for the regime operation tasks. Both tasks, the deterministic one and the stochastic one, have common features, which are that the main objective function in both tasks can be formulated as profit maximization, solutions have to be made on process prediction basis, and optimization procedures in both cases must be non-linear and capable of taking into account a large number of decision and stochastic variables.

a) The deterministic method (fixed price)

The fixed electricity price working regime for the Saf HPP is represented in Figure 5.5, which takes into account a constant electricity price and water flow. With fixed-price operation, the power producer can maximize the income by increasing the amount of produced energy because the electricity price is constant and is not used in the optimization procedure.

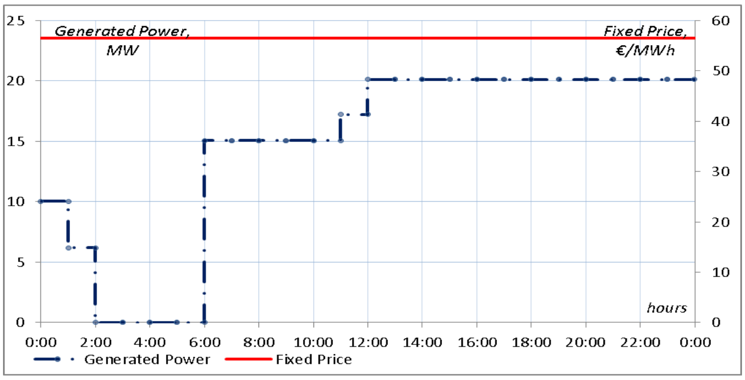

Fig. 5.5. HPP power generated according to a fixed price schedule.

Comments of the obtained result will be presented together with an analysis of the stochastic optimization results.

b) The stochastic method

The stochastic methodology and the formulas described in Chapters 3 and 4 are used. We are striving to answer a question which is as follows: how does a developed model take advantage of additional information regarding uncertain electricity prices and water inflow to the reservoirs, and how does profit change when market prices are used?

This stochastic model takes into account the variations in water flow rate and prices to obtain the maximum profit on the following day. One of the goals of this thesis is to test the Quasi-Newton method that operates in the stochastic optimization of the SHPP. Figure 5.6 shows the real generated power at the Cobanli HPP for two consecutive days.

However, unfortunately, in this case, as we see, the power generation results are not optimal. In order to maximize income, water scheduling from the reservoir should be designed to obtain an optimal operation pattern through the turbine(s). Water storage levels were not maintained to maximize the income by power generation.

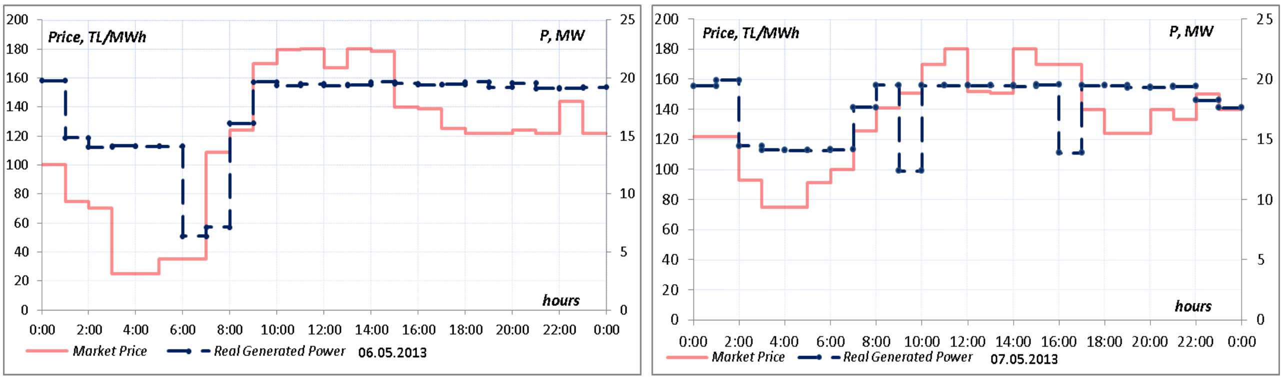

Fig. 5.6. Real generated power according to the market price schedule (06–07.05.2013) [48].

When power generation is optimized according to the market price schedule, the obtained results are presented in Figure 5.7. It lets us conclude that SHPPs collect the water in the reservoir in the case when the prices at the market are lower and utilize the water when the market price is high. The results of the optimization show the similarity of power production for 24 hours, with more accurate regime planning to get maximum income. The optimization model has been applied considering the current and can be applied to future, which will be described in the next sub-chapter when discussing the feasibility study of the Saf HPP.

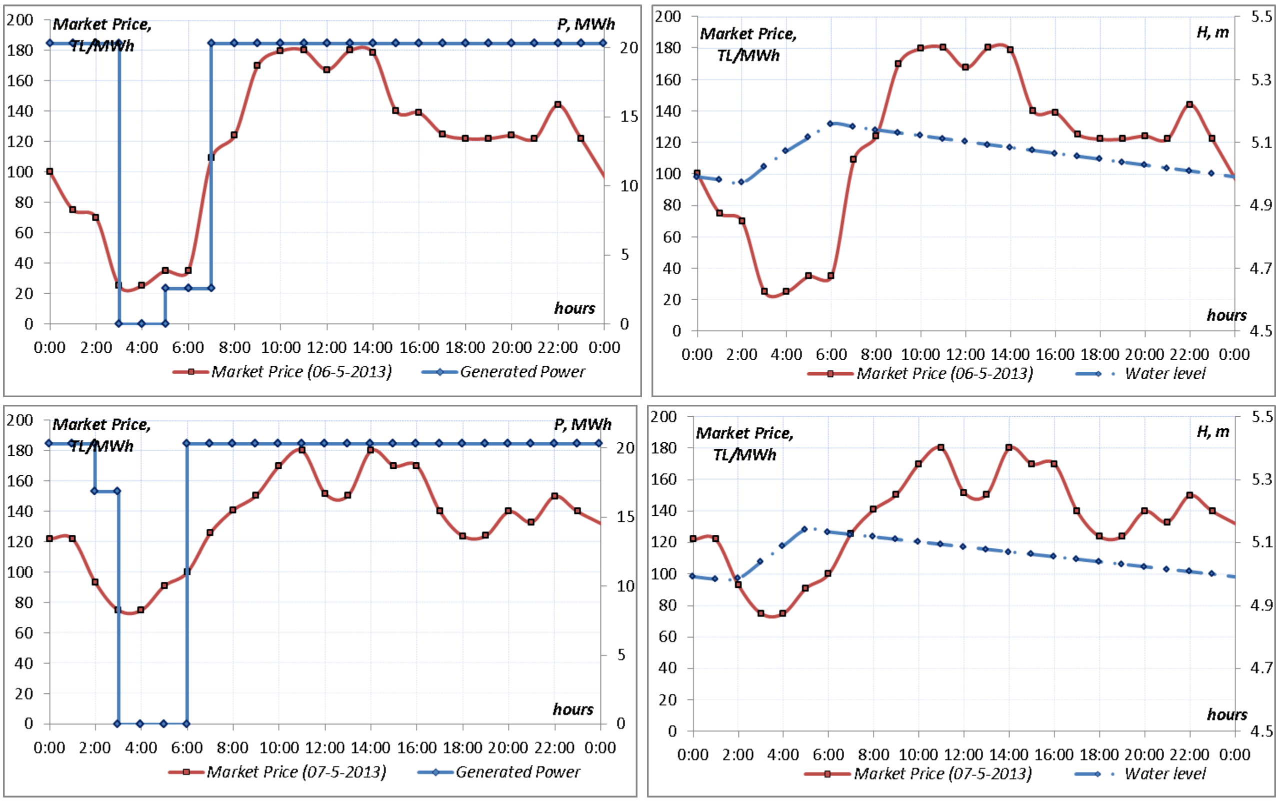

Fig. 5.7. Cobanli HPP optimized power generation according to the market price schedule and the water level of the reservoir (06–07.05.2013).

Results: Judging by the results, Figure 5.7 provides a conclusion that this HPP collects the water before the dam in the case when the prices at the market are lower and takes advantage of the water when the market price becomes higher.

During these two days (06.–07.05.2013) we can conclude that if the Cobanli HPP could work with a fixed price, the income would be 1 047 345 Turkish Lira (TL). The power plant worked by market prices and the real income was 108 953 TL. However, according to our optimization model with the market price, the income reaches 115 038 TL. The results allow us to conclude that in the stochastic case, it provides the opportunity to the power producer to maximize the income amount at conditions of limited resources. Such results prove not only the validity of the models used but also the skill of the operator.

Additionally, we can conclude that the applied optimization procedure, namely, the Quasi-Newton method, was able to achieve a global maximum of the objective function in all cases.

5.3. Additional income distribution using the Shapley value

The operability of the developed optimization algorithm is illustrated on the example of the Saf HPP (the first player) and the Cobanli HPP (the second player) regime optimizations. The technical specifications for both HPPs are summarized in Table 5.1.

Table 5.1

Technical data of HPPs

Power plant	Capacity	Number of units	Flow through the turbine	Head
Saf HPP	21 MW	3	17.03 m^3/s.	130 m
Cobanli HPP	19 MW	3	18.0 m^3/s.	125,81 m

Let us assume that both power plants work according to a fixed price regime. The power generated under mandatory procurement is presented in Figure 5.8 during a selected day. The income for the Saf HPP is 25066.9 €, for the Cobanli HPP — 24344.96 € [49].

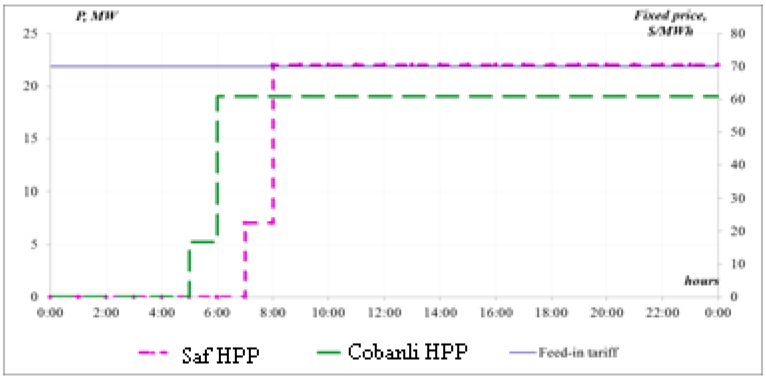

Fig. 5.8. The power produced by the HPPs according to the fixed price schedule [49].

The power producers can have additional income by creating a coalition with the electric power trader. We suppose that the public trader represents the society and must organize the operation of the HPPs according to the market conditions. The generated power charts for the Saf HPP and for the Cobanli HPP are presented in Figure 5.9.

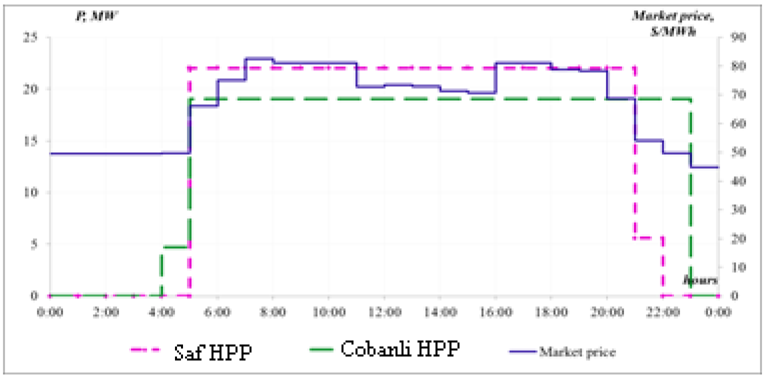

Fig. 5.9. The power generated by the HPPs according to the market price schedule [49].

The income from the participation of the Saf HPP in the electricity market equals 27 093.18 €. If the HPP sells all the generated energy (which is generated according to the market price schedule) under mandatory procurement at the feed-in tariff, it receives 25 066.9 €. So, in that case, we can conclude that for the Saf HPP it is worth to work considering the fixed price schedule. If it works to maximize the generated active power, the income equals 25 166.7 €. Additional income is calculated according to the market price and amounts to 1378.22 €. Additional income, if the HPP works according to the market price schedule, equals 1378.22/2 = 689.11 € [49].

The Cobanli HPP gets 25 349.26 € if it works at the electricity market conditions; however, if it works under mandatory procurement, it receives 24 344.96 €. Additional income, if the HPP works according to the market price schedule, equals 293.74/2 = 146.87 € [49].

Table 5.2

Income matrix for the HPPs

Power producer	Feed-in tariff	Market tariff	Additional income
Saf HPP	25066.9 €	27093.18 €	689.11 €
Cobanli HPP	24344.96 €	25349.26 €	146.87 €

These results provide a conclusion that the participants could obtain additional income from cooperation in the game and it can be distributed fairly by Shapley value.

5.4. Cost-benefit analysis for Saf HPP

For the Saf HPP, the reservoirs and the capacities are investigated by the model presented in Chapter 4.2 to compare the economic potential of the alternatives of the power plant. For these technologies to be comparable, the potential hypothetical projects were assumed to have different installed power and water storage capacity. The input parameters and estimated costs are summarized in Table 5.3, which shows cost estimation of small, medium and large reservoir capacity for the capacities of 21 MW, 35 MW, and 50 MW respectively. The head of the pond is constant — 130 m. The profitability is calculated for each alternative; therefore, there is an opportunity for us to see whether the current design discharge of 17.03 m^3/s and the installed power capacity of 21 MW is an optimal choice or not.

Table 5.3

Cost estimation for various design flows including contingencies (millions of EUR)

Power	Reservoir Capacity		
	40 ha	100 ha	200 ha
21 MW	15,00	15,06	15,16
35 MW	18,00	18,06	18,16
50 MW	21,00	21,06	21,16

For the hydropower business strategy, the design flow of a project is the most important characteristic because according to the selected design discharge rate, all the other components of the projects have to be designed. Subject to this chosen design discharge, the transmission water tunnel dimensions from the reservoir to the head-pond, the diameter of the penstock and the power capacity are selected; based on these data, the net heads have been established with calculations. A logical cost-benefit analysis also has to deal with the uncertainties associated with a project, for example, technological problems that may occur in the future, possible environmental impacts, or delays in the construction period.

Figure 5.10 represents the developed stochastic optimization method, which takes into account hourly market prices and water flow rates over 360 hours (15 days) for the Saf HPP. The first chart represents the water level in the reservoir, the second shows the generated power in megawatts, the third is the electricity market prices, the fourth is the natural hourly water flow in the river, and the fifth is the benefit. The peculiarity of the medium-term planning to be considered is the effect of the initial and final state of the 360-hour period on the short-term period. The optimization has been performed for three different cases at a previously selected time. In the first (reference) case, the initial and final reservoir filling degree is equal (75 %); in the next case, storage filling degree decreases from 100 % to 33 % (according to the ecological limitation, the level must be at least 1 m, which corresponds to 33 %); and, finally, it is set to increase from 33 % to 100 %. The second case results in changes in the short-term (24-hour) profit by 0.89 %, and the third case — by 0.88 %. Thus, it can be concluded that the initial and final state of water storage in the medium-term horizon has no sizable effect on the short-term profit calculation. Consequently, all the further calculations are performed assuming a water reservoir filling degree of 75 % both at the beginning and at the end of any 360-hour period.

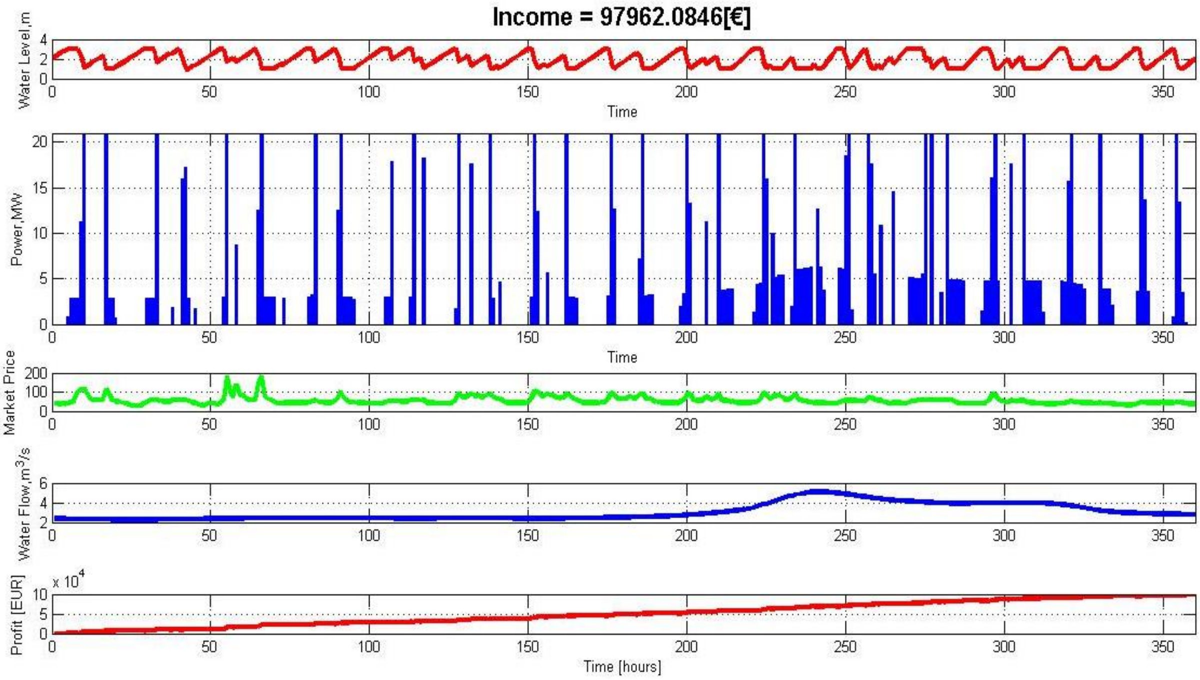

Fig. 5.10. A view of the results from the developed optimization program for 360 hours.

These optimization results of the developed algorithm lead us to choose the best feasible alternative for the Saf HPP. It is assumed that the construction of the power plant takes two years, the generation period is 30 years, the discount rate is set at 7 %, and various interest rates have been applied. The overall efficiency of the hydropower plant is taken as 90 % constant. Transformer losses have not been taken into account, and parasitic energy losses and annual downtime losses are assumed as 0.5 % in order to take into account the outages due to grid failure and unplanned maintenance. It corresponds to 2 days per year. Still, the results may overestimate the project's benefit and underestimate its costs. We assumed that annual fixed operation and maintenance costs represent 3 % of the current year's income. The full CBA could be done if taking into account all of the above.

As mentioned in Chapter 4.2 and Figure 4.2, we underline once more that the model is estimating the problem of annual expenses and revenue of the project during its lifetime and can be divided into four steps according to the developed algorithm.

1. Firstly, input data have to be gathered, which include the technical and financial parameters of the project as well as price statistics and predictions. Then, a certain number of days are selected randomly.
2. For each of the selected days, medium-term optimization is performed by considering a week before and after this day to allow for the possibility of weekly planning and diminish the effect of initial water level in the reservoir.
3. Afterwards, short-term (24-hour) optimization is done for each of the selected days to obtain the expected daily profit.
4. The results are then generalized for the whole year to find the annual profit.

Before the model could be used for feasibility studies, some of its main parameters were adjusted to ensure reliable results. First of all, it was necessary to decide on the length of the medium-term planning horizon and the state of the water resevoir at the beginning and at the end of the planning period. Secondly, the number of Monte-Carlo simulations in a year had to be chosen. Unfortunately, the number of days and hours in the whole plannning period is too large for practical implementation. To avoid the difficulties, the Monte-Carlo method can be used [50, 51, 52, 53]. A larger number of trials leads to a higher accuracy of calculations, while it also increases the computational time.

Cost estimations for various design flow values including contingencies as well as the results of IRR and NPV calculations for 8 %, 6 % and 4 % interest rates are summarized in Table 5.4. We can conclude that the best alternative is to choose 35-MW power capacity and 200-ha reservoir capacity, that is, the 6th alternative (A6); the IRR is 15.5 %, and 12 years are required to reach the break-even point.

Table 5.4

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

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

To find an appropriate number of Monte-Carlo trials that does not considerably decrease the accuracy and, at the same time, does not increase the computational burden too much, we performed several simulations using different numbers of trials per year. The reference case is 365 trials (days) and the rest of the simulations, which include 2, 10, 40, 60, 80, 100, 120 and 125 trials, are compared to the reference case to determine the error.

All the calculations were performed with *Intel i3 CPU* processors, 2.53 GHz, 4 GB of RAM and *Windows 7* operating system. We established that 120 trials (days) is a sufficient number as it neither introduced a too high estimation error (4.6 %) nor required excessive computation time (the computation time was 105 minutes). A possible improvement could be made by introducing a more efficient algorithm that has a better performance for large numbers of decision variables. The results are summarized in Figure 5.11.

Figure 5.11.a summarizes the calculation error and the time of computation of Monte-Carlo trials. Figure 5.11.b shows the comparison of NPV calculations for 40 ha of water storage area. As can be seen in the Figure, the curve starts from negative benefit values because of the costs for building the HPP; then, it reaches the break-even point, which is the first major step towards profitability. Then, the HPP owner starts to gain profit.

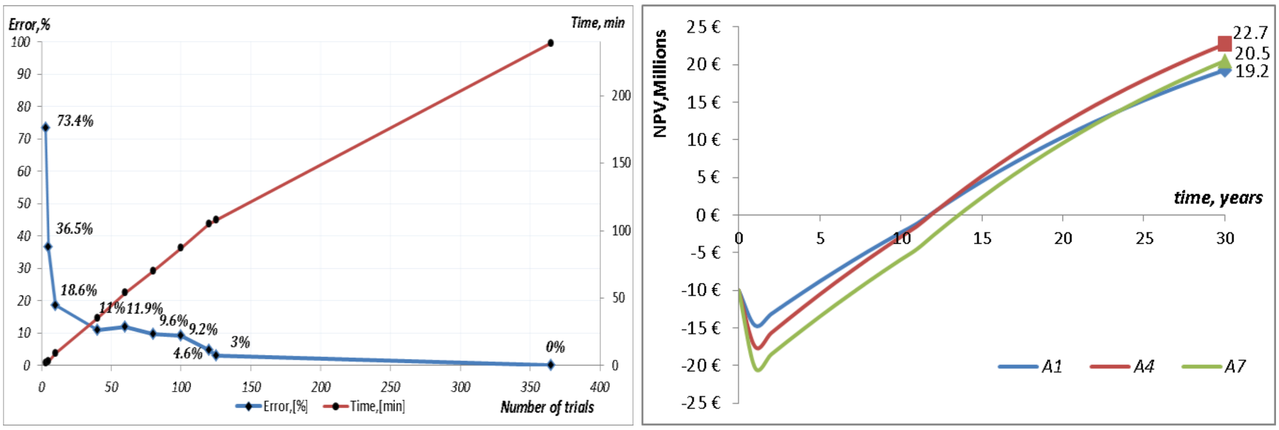

Fig. 5.11: a — The calculation error and computation time depending on the number of Monte-Carlo trials; b — NPV comparison for a 40-ha reservoir by stochastic approaches.

By the deterministic method, it is impossible to get the right answers because it does not take into account the random and uncertain variables.

5.5. The influence of reservoir capacity and discount rate on the profit of Saf HPP

Let us investigate the water reservoir types for the Saf HPP. How big should the water storage of the HPP be? The capacity of the reservoir is determined by the degree of seasonal changes in the water amount, the amount of water available, the distribution line capacity, and specific geological conditions that allow reservoir construction. Figure 5.12 verifies that water is stored in the reservoir and is then released through the turbine and generates electricity when demand and price are higher (during peak hours). The income for a 40-ha reservoir is 6518 €, and the income for a 200-ha reservoir is 6699 €; it means that this storage can accumulate a larger amount of water and generates power during peak hours. This maximizes the income and increases the flexibility of power generation.

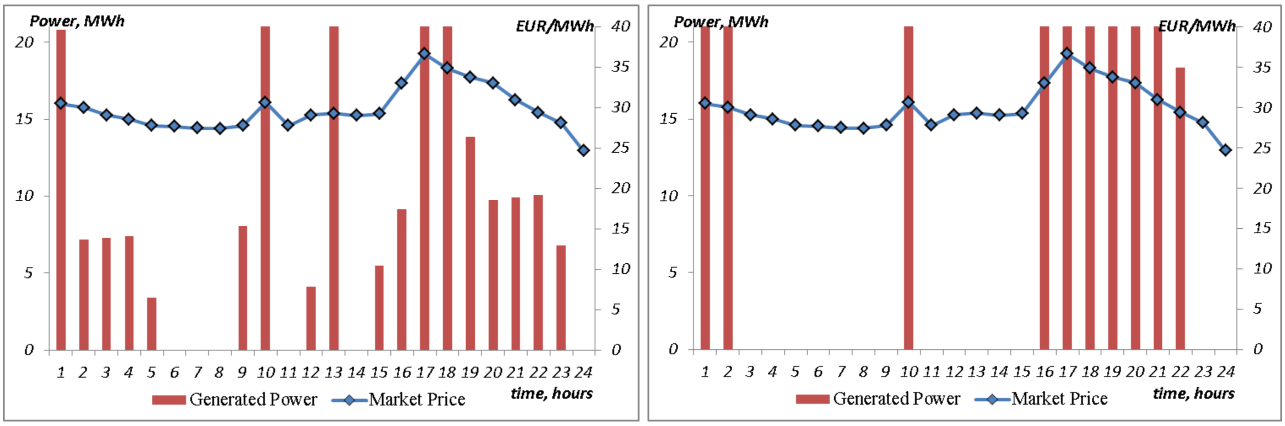

Fig. 5.12: a — The market price and generated power for a reservoir of 40 ha; b — the market price and generated power for a reservoir of 200 ha

The existing reservoir for the Saf HPP is 3 m deep and has a surface area of 40 ha. For the feasibility studies, we assumed four different alternatives; each of them has various designs (see Table 5.5). Let us imagine a dam-type water storage for the Saf HPP, which is 110 m in length and 20 m deep and has a water storage area of 200 ha. It is assumed that the power producer is a market player and can export electricity into grid; energy market operation is based on day-ahead rules. A dam is a barrier that impounds water streams. Dam-type reservoirs are constructed in a valley and rely on the natural topography to provide most of the basin of the reservoir. It is typically located at a narrow part of a valley downstream of a natural basin. The valley sides act as natural walls, with the dam located at the narrowest practical point to provide as low a construction cost as possible and as high effectiveness as possible.

Table 5.5

Technical and economic parameters of the power plants under study

Alternatives		Cost estimation, €
A1	21 MW – 40 ha	15000000
A2	21 MW – 100 ha	15060000
A3	21 MW – 200 ha	15160000
A4	21 MW – 200 ha – **Dam**	15660000

In Turkey private, companies get a license for 49 years from the government and the feasibility study is done for a period of 49 years. The economic feasibility results for the Saf HPP are shown in Table 5.6: the annual interest rate is constant — 6 % — for 10-year payback time for each alternative, the deterministic approach consists of 7 % of discount rate yearly, and the stochastic approach consists of three cases — (1), (2), (3) —, taking into account 3 %, 5 %, and 7 % discount rates respectively.

Table 5.6

NPV and IRR results for Saf HPP

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

It is clear that the discount rate has a reasonable influence on the level of NPV. For instance, NPVs of profit calculated with an interest rate of 3 % are almost 3 times higher than the discount rate of 7 %. However, the variation in NPVs also increased for lower rates of interest. Figure 5.13 summarizes NPV results for each reservoir model and compares NPV calculations for various discount rates in the 4th alternative.

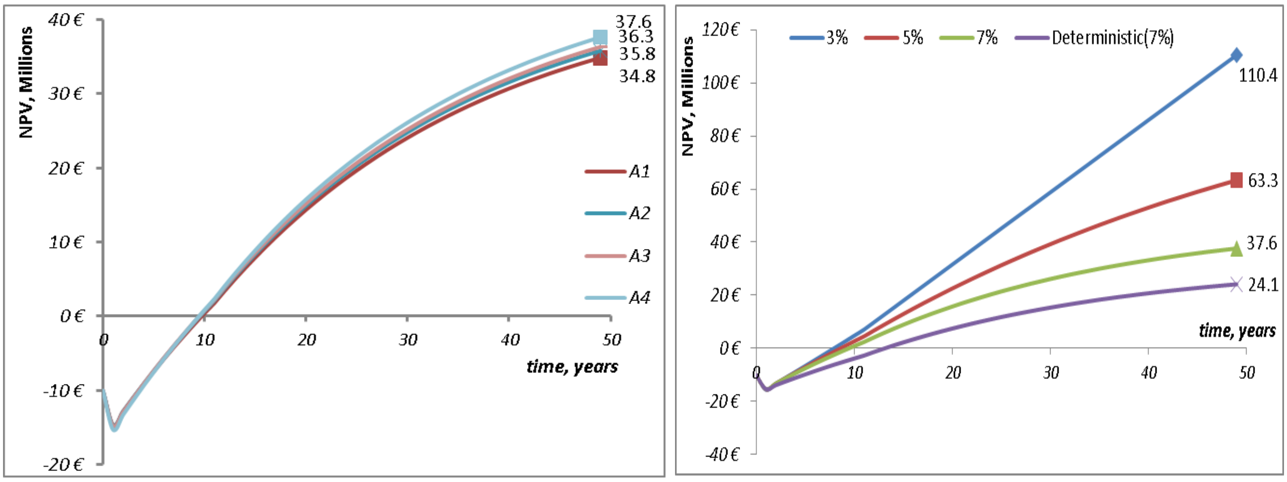

Fig. 5.13: a — NPV of different reservoirs and varying capital costs; b — NPV for various scenarios of the discount rate for the 4th alternative.

As a conclusion, the results prove that for the Saf HPP, which is located in a hilly region, it would be effective to build a dam-type reservoir in order to store as much water to achieve an objective function which maximizing of income. The biggest water storage could provide a bigger amount of profit using the stochastic approach than the deterministic one. The discount rates also significantly influence the amount of profit gained.

CONLUSIONS AND RECOMMENDATIONS

1. Human activities are overloading the atmosphere with greenhouse gas and carbon dioxide (CO_2) emissions, which increase the planet's temperature and create catastrophic and significant influence on our climate, our health, and our environment. Renewable energy faciltites have a much lower environmental impact than conventional energy technologies, namely, they are clean, green and will not run out ever. Fossil fuel sources are finite and will be depleted one day.
2. Hydroelectric power is an excellent source of green energy because it diminishes the effects of global warming and decreases the energy dependence on foreign countries.
3. Turkey is an energy importing country, which is why the development of its hydropower potential represents a secure domestic source of energy. Therefore, the Turkish government and the policy-makers should support and encourage especially small hydropower projects, which have low cost and are easy to build; the country has 14 % of the European potential.
4. The SHPP regime optimization problem is extremely complex and cannot be solved without taking appropriate simplifications. It should provide the ability to select the operating mode including two alternatives: work according to the guaranteed power purchase price or according to the market conditions.
5. Uncertainty and randomness play a significant role in the CBA and the optimization problem. Consequently, models and tools to solve the problems should be stochastic.
6. Optimization task statement with the approach based on the calculation of the time- average profit simplifies modelling of random processes, as the need of the knowledge of the probability of their realization disappears.
7. The applied optimization procedure, namely, the Quasi-Newton method, was able to achieve a global maximum of the objective function in all cases.
8. The prediction of realizations of random processes can be carried out with the help of a trained ANN and adopting the hypothesis of the stationary nature of predicting errors.
9. A comparison of the CBA results showed that the stochastic methods are significantly more accurate than the deterministic model. The impacts of timing, discount rate and interest rate can significantly affect the results.
10. The economic part of the feasibility study determines a project's viability, with suggestions as to how to manage the various stages of the project. The results allow us to conclude that the power producer has to choose the best efficiency; for the Saf HPP, it corresponded to 35 MWh of installed capacity and 200-ha surface of the water reservoir.
11. Methods based on the game theory can provide making the right decision about the coalition between the market players, the public trader, and local consumers. The Shapley value can be used to distribute the income fairly.
12. The stochastic statement, which has found application in the world and has been a successfully tested scientific and practical model in the Turkish SHPP and in terms of the country's electricity sector, involves analysis of the potential benefits of the wholesale, investors, and production companies. The testing and implementation of this scientific model according to the conditions of the countries will make an important contribution to the developing electricity industry.

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