OPTIMAL EXPANSION STRATEGY FOR A DEVELOPING POWER SYSTEM
UNDER THE CONDITIONS OF MARKET ECONOMY AND ENVIRONMENTAL CONSTRAINT: CASE OF ARMENIA

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Misak G. Avetisyan
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OPTIMAL EXPANSION STRATEGY FOR A DEVELOPING POWER SYSTEM
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CONSTRAINT: CASE OF ARMENIA

by

MISAK G. AVETISYAN

has been approved for

the Program of Environmental Studies
and the College of Arts and Sciences by

David J. Bayless
Professor of Mechanical Engineering

Benjamin M. Ogles
Dean, College of Arts and Sciences
This research paper presents a mathematical model for the optimal development of the Armenian power system that will satisfy the electricity and capacity demands in conditions of the given reliability and given structure of the usage of energy resources providing minimum total expenses. It also accounts for optimal usage of hydro-resources and guarantees a certain level of energy independence and security of the country.

The relations between technical and economic criteria of the power system are non-linear, which makes the problem more complicated. In this model all non-linear relations are made linear. The considered model includes provisions for energy security, which is significant especially for countries that do not possess adequate energy resources. Furthermore, environmental constraint is placed on the model to formulate optimal expansion strategy for the developing power system.

During the considered period stochastic data are used because of uncertainty, which can produce not the optimal solution. For that reason the optimal solution is checked and verified by appropriate sensitivity analysis. Finally, some conclusions and recommendations are made based on the economic analysis of the model.

Approved:

David J. Bayless
Professor of Mechanical Engineering
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Introduction

For several years, after getting independence from the former Soviet Union, the Armenian economy was in recession. This was a result of collapsed regional trading relations and terminated payment contracts. From 1992 to 1993 the industrial output decreased by 60%, and the price level increased 110 times. Since 1994 the government has implemented strategic financial policies and programs with perspective structural improvements. The year 1994 can be characterized as a turning point. As a result, the budget deficit decreased and the GDP increased.

Though during the last several years significant results have been achieved, there are still many issues requiring urgent solution. If these problems are not solved in possible short terms they can make the macroeconomic development and economic transition in Armenia more complicated. One of those most important issues is the optimal development of the Armenian power system. The field of energy is one of the main sectors of the economy that guarantee the future development of the economy as a whole.

The structural properties of the country such as the deficit of local energy resources, and also the implied properties such as the current economic situation affected by future uncertainties, make the formulation of the energy development strategy very complex and important task. The decision making process for the development of the power system, especially finding the optimal set of power plants, depends on correctly specified economic and energy development scenarios. The latter being stochastic should be flexible enough to allow for calibration to match the changes of the uncertain environment.
The main objectives and the considered issues of this research are:

- Formulation of such a development plan (selection of optimal capacities) for a power system that will satisfy the energy demand in conditions of the given reliability and given structure of the usage of energy resources providing minimum total expenses
- Optimal usage of hydro-resources without threatening strategically important energy resources of the country
- Guaranteeing a certain level of energy independence and security of the country.

Considering partial stochastic nature of initial information it becomes unnecessary to use a precise model in formulating a strategy for the development of the power system. Consequently, a linear model and linear programming can be used to solve the considered problem providing a certain level of accuracy. In this case all non-linear relations are made linear by the linear approximation method of Griffith and Stewart. The linear model can simulate various scenarios of development, which later need to be calibrated by sensitivity analysis.

The optimal set of power plants in the system and their capacities depend on many factors such as the environmental issue. Along with the increase of the environmental impact of newly introduced hydro power plants (HPP) this factor will become more crucial for economic justification of the construction of those capacities. A new HPP removes a part of a natural river forever from the natural environment and converts it into a regular lake. It’s obvious that it will become one of the important factors if more and more rivers are converted into lakes to serve as reservoirs for HPP. Various projects were conducted for the development of the Armenian power system but none of them studied
the environmental impacts of newly introduced HPP’s. In this research project the environmental issues of a new HPP construction are considered by including an additional environmental constraint in the model.

The main innovative ideas of this research are:

- Both the demand of electricity and the internal demand of electrical capacity should be satisfied by maintaining a certain level of energy independence of the power system. Thus this level should be evaluated using both qualitative and quantitative methods of estimation.

- When the optimal capacities of hydro power plants are determined, some important factors should be considered. One of these important issues is the impact of environmental factor on the decision making process. The latter has a significant effect on capital investments necessary for the construction of hydro power plants. It makes investments less available and consequently more valuable.

- The continuous increase of expenses over time in employed thermal and nuclear power plants should also be taken into account. The parabolic increase of those expenditures can be used, which corresponds to the increasing accident probability curve of technical systems over time. This important issue has not been sufficiently considered in previous research of various authors. Thus the suggested model can considerably improve the results of previous research.
In market economy it becomes necessary to formulate such a strategy for optimal economic development of the power system that will allow discovering the risks, and preventing future negative results by appropriate policy analysis.

The thesis consists of introduction, 4 chapters, conclusions and references. The first chapter represents the review of research on formulation of power system development scenarios, as well as the analysis of various programs and scenarios designed for the development of the Armenian power system. The second chapter describes the economic effects of newly introduced power plants on a developing power system. The formulation of the computational model and the method of optimization for the development strategy for the power system are presented in the third chapter. Finally, in chapter four using the suggested model the development strategy for the Armenian power system is formulated, within the period of 2005-2020. To check the accuracy of the results of the model a sensitivity analysis is conducted.
1. Analysis of a Developing Power System and Selection of the Method of Optimization

1.1 Development Strategy for a Power System

Power system is one of the most important sectors of the economy which guarantees both the development of other economic sectors and the future social-economic development of a country.

The thesis is devoted to the formulation of a development strategy for the power system based on the analysis of optimal alternatives of introducing new capacities into possible macroeconomic development scenarios of a country.

To find the optimal expansion path of a developing power system long term planning and strategy formulation are usually used. The long term planning is implemented when the forecasts can be developed by the method of extrapolation. In this case the growth tendency is generally assumed. It is also implied that the expected estimates of forecasted variables will be much better than their past and current values. Having the required level of extrapolation accuracy it is possible to calculate the expected demand in advance. Therefore, the amount of necessary investments in different intervals of the considered period becomes the major tool for planning the long term development of a system. For that reason long term planning is more used for mass production and consumption.

The strategy formulation is applied when accurate prediction of the long term development path is not possible. Hence, when the external factors are both highly
fluctuating and uncertain over time the development strategy is used as a guide for decision making. One of the reasons of these uncertainties is the technical progress which leads to accelerated economic processes [13, 32].

Uncertainty is related to any forecast, and it is higher in those countries where the economic and energy policies are greatly affected by structural changes. Even a small change in demand-supply relation can cause a reconstruction of a power system.

This sector of the economy requires large capital investments. It can be characterized by long life of main assets, local factors, and by strong interrelation between energy production and its consumption in other economic sectors. The development of the power system is mainly determined by construction and operation of new power plants. In the energy sector construction involves the stages of economic projection, actual construction and operation of new power plants. At the stage of economic projection the possibility of power plant construction and technical-economic analysis of the project are considered.

In the energy sector the economic efficiency of capital investments depends on both economic and energy issues of a country. To determine the economic efficiency of power system development projects all the feasible scenarios are discussed.

The main issue of a perspective development of the energy sector is finding the optimal set of different types of power plants in the power system. The formulation of the optimal development scenario for the power system is a complex problem which is affected by various possible development scenarios of a system. It also depends on both the non-linear relationship among energy and economic factors of power plants and the stochastic character of initial information, as well as dynamic development of a system.
Currently, to solve this problem the mathematical modeling of the power system is used. These methods include linear and dynamic programming, probabilistic method, integer programming, etc.

The economic-mathematical model of a developing power system represents a set of equations and inequalities describing all internal and external relationships of a system. From the definition of the problem it becomes obvious that the mathematical model of the economic development of the power system should be non-linear, dynamic, as well as should have both stochastic and integer nature. Since initial information is partially stochastic, it is unnecessary to accurately consider all these factors in formulating a development strategy for the power system. The latter justifies the use of a linear model. For this reason in the power system development model all the non-linear relationships are made linear. This simplification allows solving the problem by the method of linear programming using linear approximation.

In fact the linear model predicts the development path of the power system, and later the forecasts are calibrated by sensitivity analysis. Though these models do not completely consider the non-linear and stochastic nature of both initial information and technical-economic criteria of power plants, they sufficiently illustrate the main energy and economic relationships among power plants, as well as the development dynamics of the system.

The final scenario of the power system expansion represents the development strategy of the system that considers stochastic character of initial information using sensitivity analysis.
In this research, considering existing international issues of the hydropower development, especially the environmental problems, the formulation of the development strategy of the Armenian power system is implemented.

Periodically, various programs were designed for the development of the Armenian energy sector, and all of them represented certain solutions to a limited number of issues. Though the predictions of those programs were not completely implemented, they still serve as strategic tools in selecting the optimal development path for the Armenian power system.

The model and expected results of this research also represent the development strategy of the Armenian power system and not the accurate planning of the future development.

1.2 Overview of the Development Programs Designed for the Armenian Power System

During the last decade, after getting independence from the former Soviet Union, various programs and policies were projected for the development of the Armenian energy sector. The brief overview of those programs is presented below:

a) The complex program “Energy” developed by the Ministry of Energy and Fuel of Armenia on April 10, 1993 [17]. The main objective of this program was to overcome the energy crisis and determine the development strategy.

c) Institute of Energy “Perspectives of the Development of the Armenian Power Sector, Including Nuclear Power Up to 2010, until 2020”, 1998 [10]. This long term development program projected introduction of additional nuclear power plants into the system.

d) State Engineering University of Armenia “The Quantitative Estimation of the Development Tendencies of the Armenian Power Sector until the Year of 2010”, Yerevan, 1999 [22]. This program represented the initial estimation of perspective development scenarios for the Armenian power sector.

e) USAID-Hagler Bailly “Least-Cost Generation Plan”, 2000, and USAID-PA Consulting Group “Least-Cost Generation Plan”, 2002 [27]. The main goal of these research projects was to evaluate the investments necessary for the expansion of the existing power plants.

f) Tacis-Sogin/DECON “Strategy Paper”, 2000 [25]. This policy paper by Sogin/DECON Consortium estimated the consequences of the shutdown of the Armenian nuclear power plant in 2004, and also discussed the technical-economic substantiation of the necessary capacity substitution.

g) USAID-Hagler Bailly “The Rehabilitation Plan of Operating Capacities”, 1999 [28]. Being a not perfect program it was the only complete report among other similar projects devoted to the long term rehabilitation of operating capacities.

h) WB-COWI/RAMBOL “Strategic Project of Heating for Residential Areas of Armenia”, 2002 [30]. This strategic project suggested gradual replacement of
existing heating companies with holdings to improve the management of this sector.

i) WB—“Yerevan-Project” CJSC “Investment Project for the Armenian Natural Gas Sector in Regard to the Heating Strategy of Residential Areas”, 2002 [31]. In this paper natural gas price forecasts were projected as well as the impact of investments on natural gas tariffs was estimated. This research suggested improvements in natural gas supply system at both institutional and judicial levels. It also supported the idea of creating a competitive market in this sector.

j) Tacis Project № Europe Aid/112135/C/SV/MultiFC/ib/AR014, 2003 [24]. In the framework of Tacis program SOFRECO consortium conducted a research project titled “Energy Supply Forecast”. This research was based on general macroeconomic and detailed microeconomic estimations of the member countries of Economic Cooperation and Development Organization. It also considered the elasticity of energy demand.

k) JEN Consult “Assistance to the Government of Armenia in Developing the Integrated Financial Rehabilitation for Public Utilities”, 2003 [12]. This project was devoted to the financial rehabilitation of public utilities. It included the sectors of energy, irrigation, drinking water, and public transportation. Though this research was important it had risky average term forecasts regarding the underestimation of the investments necessary for the energy sector. It also didn’t consider the energy independence and security issues.

l) International Agency of Nuclear Energy (IANE), ARM/0/004 “Study of Development Planning for the Energy Sector in Armenia, Including Nuclear
Energy, from 2000 to 2020” [11]. This project mainly studied the role of nuclear energy for electricity production in Armenia. It also considered the forecasted environmental impact of nuclear power plants corresponding to the projected development of the system.

The analysis of the aforementioned energy development programs shows that each of those projects suggested different strategies considering the uncertainty existing in the economic development scenarios of the country. It should be mentioned that none of the programs was fully completed. Hence any new research devoted to the prevention of uncertainties and the minimization of their impact on the decision making process should be considered as innovative and important.

1.3 Information Required to Determine the Optimal Structure of the Power System

Initial information is important in finding a solution. For the considered problem this information is:

1. The electricity consumption

2. The type of energy resources and their quantity

3. The technical criteria of power plants constructed over the considered period
4. The economic criteria of power plants, utilized energy resources, capital investments, annual operation and maintenance expenditures, and estimated expenses.

The accuracy of initial information depends on the duration of the considered time interval. In international practice 15-20 years is assumed to be the optimal planning period. And for this time interval the accuracy of initial information is usually being estimated. In this research the development scenarios are projected from 2005 to 2020. The duration of the time interval plays an important role in evaluating the dynamic loading curves of the system and their technical-economic criteria. For this considered period of time the following main objectives of the power system development are determined:

1. The industrial capacities of new power plants
2. The supply scheme of fuel resources.

The initial information is both stochastic and integer, which is the main reason that the model is different than the real system. The modeling consists of 4 stages:

a) Analytical description of the power system
b) Selection of the method of optimization
c) Analysis of the model
d) Final decision.

The accuracy of the mathematical modeling can be determined by sensitivity analysis. In modeling the optimal structure of the system several factors should be considered:

a) The uncertainty of initial information
b) The main internal relations of the system
c) The development of the power system  
d) The discrete character of introduction of new power plants  
e) The non-linear character of technical-economic criteria  
f) The accuracy of the model, which makes its properties much closer to those of the real system  
g) The accuracy of the results  
h) The convenience and simplicity of employing the model.

The aforementioned information leads to the conclusion that it is difficult to formulate a precise model because the power system is non-linear, discrete, dynamic, and it has enormous elements and relations as well as many imperceptible characteristics. And also in contrast to fully automatic systems the power system is dealing with human factor, which is not possible to describe by mathematical equations. Consequently the mathematical model of the power system will always be inaccurate. Thus the optimal expansion of the developing power system is determined by minimizing the objective function (total expenses) and finding the types and industrial capacities of power plants, and the time of their introduction into the power system, satisfying the given capacity and electricity demands [1, 16].
1.4 Analysis of Planning Models and Methods for Prospective Development of a Power System

**Planning models**

In different countries various models were used to solve the optimal planning problem of the developing power system. The prospective development of the power system in the former Soviet Union countries was implemented by formulating so called GOELRO plans. Because of the complexity of the problem only simplified models and methods were used. These models were mostly statistical, and considered fuel-energy balances for a particular period of time. The main criteria of finding the optimal development scenario represented capital investments, operation and maintenance expenses, total costs, and the payback period of investments. Policy makers were also considering other economic criteria such as productivity, economic characteristics of equipment, fuel consumption, electricity consumption for plant’s own needs, “freezing” of capital because of long construction time, etc. The planning period was estimated to be 10 years, and scenarios considered only uniform production. And the optimal development plan was the scenario with minimum total expenses described by the following equation:

\[
TE_t = K + E_t \sum_{t=2}^{T} (1 + \rho_t)^{t-t} \quad (1.1)
\]

where,

- \(K\) represents total investments;
- \(E_t\) is the amount of annual operating and maintenance expenditures;

---

\( \rho_t \) is a coefficient of discounting.

Then the types and capacities of power plants were selected. Generally the type of a plant was determined by existing energy resources, fuel balance, consumption of thermal and electrical energy, etc. Decisions about hydro power plant construction depended on several factors such as efficient utilization of the complex, including fisheries and navigation. The capacities were selected based on estimated electrical and thermal loadings.

To compare the development scenarios some other criteria were used such as capital investments for 1 kW installed capacity, the operation costs of unit capacity, as well as the amount of investments necessary for 1 kWh electricity production [16]. Because of the lack of efficient models and methods and complexity of the problem the solution process required long and complicated calculations until it became possible to create economic-mathematical models using linear and dynamic programming.

Since early 90’s in the countries of the former Soviet Union the experts concluded that the discounted value of total expenses can no longer serve as optimality criteria for finding the optimal development strategy of the power system. Based on international experience they applied another approach using profit maximization as the main factor for decision making. They started using new criteria such as money and profit flows, internal rate of return, etc. As a result there was a smooth transition from old plan-based economy to a market system.

In most countries the privatization of electrical industry and the creation of competitive electricity markets significantly affect both the price of industrial capacities and the operations and maintenance expenses. The electric companies in the developed
countries are more concerned about decreasing the cost of equipment over the entire period of operation. There has been a significant trend in moving from “technical” to “financial” approach.

In European countries, especially in Germany, Italy, France, Switzerland, and Sweden experts are using the minimum Life Cycle Cost (LLC) during the considered period of operation as the main criteria for formulation of a long-term development strategy for the power system:

\[
LLC = CI + (CF + CV) \left[ \frac{(1 + E)^n - 1}{E(1 + E)^n} \right] \quad (1.2)
\]

where,

- \( CI \) is the investment cost;
- \( CF \) is the fixed cost;
- \( CV \) is the variable cost;
- \( E \) represents the interest rate,
- \( n \) is the estimated work time of the industrial capacity, which starts from the moment of introducing it into the system.

It is worth to mention that \( E \approx \rho \) because \( \rho \) is adjusted by a credit interest rate. The latter is about 5-12% for short-term deposits in world markets depending on the currency. According to specific reports its value is 0.083 for the U.S. [14] and 0.07 for France [21].

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2 Misrikhanov M. Sh., Mozgalev K. V., Neklepaev B. N., Shuntov A. V. Technical-economic comparison of scenarios for power capacities in projection, Power Plants, 2004
In their paper on economic-technical comparison of capacity projections Misrikhanov et al. show that at the stage of projection the equations (1.1) and (1.2) are equivalent [19]. Particularly by substituting $1+E=q$ in (1.2) they show that:

$$\frac{(1+E)^n-1}{E(1+E)^n} = \frac{q^n-1}{(q-1)q^n}$$

(1.3)

After several simplifications:

$$\frac{q^n-1}{(q-1)q^n} = \frac{(q^n-1) + q^{n-2} + ... + 1}{(q-1)q^n} = q^{-1} + q^{-2} + ... + q^{-n} = \sum_{j=1}^{n} q^{-j} = \sum_{j=1}^{n} (1+E)^{-j}$$

(1.4)

If $j=t-1$ and $T=n$, which means that the construction is completed in the first year and the operation starts from the second year, and by assuming that $E \approx \rho_t$ we will have:

$$\sum_{j=1}^{n} (1+E)^{-j} = \sum_{t=2}^{T} (1+\rho_t)^{-t}$$

(1.5)

Consequently when the operation and maintenance costs are fixed there is no difference between (1.1) and (1.2).

The successful experience of power system planning in the U.S. and Europe will help the countries of the former Soviet Union to efficiently develop their power sectors. Being designed for private companies these models will serve a good basis for the development of the Armenian power system, which is currently in the period of transition when the state property is privatized.

**Planning methods**

Currently there are various *mathematical modeling methods* used for the economic analysis of power system development models. These methods are:
• Classical analysis
• Linear programming
• Non-linear programming
• Game theory
• Comparison of power system expansion alternatives.

**Classical analysis** represents the method of Lagrangian multipliers used to find solutions minimizing the objective function:

\[
F = \sum_{i=1}^{n} f_i(x_i) \rightarrow \min \quad (1.6)
\]

\[
\sum_{i=1}^{n} x_i = X \quad (1.7)
\]

Then the multiplier \( \lambda \) is introduced to formulate supporting function:

\[
L = F - \lambda x \quad (1.8)
\]

By making the partial differential of function \( L \) equal to zero we get the following system of equations:

\[
L' - \lambda = 0 \text{ or } f_i'(x_i) - \lambda = 0 \quad (1.9)
\]

\[i=1, 2, \ldots, n\]

From this system of equations we can find the optimal values of all variables. It should be noted that the method of classical analysis is not possible to use in linear models because the critical values of these functions are located at marginal points.

**Linear programming** can be used when the objective function and constraints are linear, and the decision variables are non-negative [33]:


\[ Z = \sum_{i=1}^{n} c_i x_i \quad (1.10) \]

subject to:

\[ \sum_{i=1}^{n} a_{ij} x_i \leq b_j \quad (1.11) \]

\[ j=1, 2, \ldots, m \]

In prospective planning of the power system development researchers used mostly linear models. And one of the applications of linear programming is determination of the optimal capacities and the optimal set of power plants in the system.

The initial data necessary for solving this problem can be described as technical and economic. Technical data are the main characteristics of loading, allocation of power plants, annual electricity consumption, environmental impact of power plants, types of capacities, allocation of fuel resources, estimated loss of electricity in the network, reserve and accident capacities, etc. Economic data represent capital investments and operation expenses, rate of discounting, depreciation, price of fuel including extraction and transportation costs, electricity supply expenses, monetary value of environmental damage, etc.

The main disadvantage of the linear models is that they do not sufficiently consider existing non-linear relationships, particularly the interrelation between fuel consumption and industrial capacity of a power plant. It is possible to use this method also for non-linear functions. In this case the objective function and all existing non-linear relationships are made linear, which makes the model larger and leads to inaccurate solution of the problem. Therefore the large system is divided into small subsystems, and
then the solutions from these systems are coordinated with each other to form the optimal solution of the whole system.

Based on the description of linear models we can conclude that they can sufficiently describe the dynamic development of the power system, and by linear approximation can take into account the non-linearity of economic characteristics. These models also consider the discrete nature of introducing power plants into the system, the initial stochastic data, and can serve as a reliable guide in defining the optimal development strategy of the power system.

There are many algorithms to solve non-linear problems, but none of them has significant advantages. The methods used for non-linear programming are classified by [9]:

1. The nature of the problem:
   - Objective function:
     a) Without constraints
     b) Constraints presented by equalities
     c) Constraints presented by inequalities
     d) Constraints presented by both equalities and inequalities
   - Discrete variables (integer)
   - Square programming, etc.

2. The methods of solution:
   - Methods using differentials
   - Analytical and numerical determination of derivatives
   - Methods using first and second order derivatives
• Gradient method
• Simultaneous iteration of all variables
• Methods of internal and external points
• Deterministic and stochastic search.

3. The type of a computer: Digital, analog or hybrid

4. The programming language.

The non-linear problem is also possible to solve using the method of linear approximation suggested by Griffith and Stewart in 1961 [8]. This method assumes multiple simulations of subsequent linear programming problems. After several iterations it provides solutions more likely to those resulting from the non-linear programming problem. This algorithm is sometimes defined as gradient method. After linear approximation the problem can be described as:

\[ f(x) - f(x^{(k)}) = \sum_{j=1}^{n} \frac{\partial f(x^{(k)})}{\partial x_j} \Delta x_j^{(k)} \rightarrow \min \quad (1.12) \]

Subject to the following constraints:

\[ \sum_{j=1}^{n} \frac{\partial h_i(x^{(k)})}{\partial x_j} \Delta x_j^{(k)} = -h_i(x^{(k)}) , \ i=1, \ldots, m \quad (1.13) \]

\[ \sum_{j=1}^{n} \frac{\partial g_i(x^{(k)})}{\partial x_j} \Delta x_j^{(k)} \geq -g_i(x^{(k)}) , \ i=m+1, \ldots, p \quad (1.14) \]

where \( \Delta x_j^{(k)} = (x_j - x_j^{(k)}) \)

In contrast to other mathematical methods, which consider only the equality restrictions the method of linear approximation allows for accounting both equality and inequality constraints. One of the approximation methods was suggested by Glass and
Cooper [7]. They show that if after linear approximation of initial constraint the decision variable appears to be out of feasible region it can still go back by changing the search direction through adding a constant to the right hand side of the linearized inequality.

Another method used for optimization problems is gradient method described by Crocket and Chernoff [5]. Using this method the most efficient power plants are selected to enter the power system. The gradient method uses only the first order derivatives of the objective function. In searching the optimal point at period \( k \) we move from point \( x^{(k)} \) to \( x^{(k+1)} \), which can be described by:

\[
\begin{align*}
    x^{(k+1)} &= x^{(k)} + Ax^{(k)} = x^{(k)} + \lambda^{(k)} s^{(k)} = x^{(k)} + \lambda^* s^{(k)} \\
    \end{align*}
\]

(1.15)

where,

\( Ax^k \) is a vector moving from from point \( x^{(k)} \) to \( x^{(k+1)} \);

\( \hat{s}^{(k)} \) is a unit vector at \( Ax^k \) direction;

\( s^{(k)} \) is any vector at \( Ax^k \) direction;

\( \lambda^{(k)}, \lambda^*^{(k)} \) are scalars determined by the following equation:

\[
\begin{align*}
    Ax^{(k)} &= \lambda^{(k)} s^{(k)} = \lambda^*^{(k)} s^{(k)} \\
    \end{align*}
\]

The method of dynamic programming enables solving non-linear problems of different complexity using functional equalities and the optimality principle. It allows substituting the single state algorithms by multiple state methods, and searching the optimal solution based on given functional equalities. The mathematical model can be presented as:
In case of uncertainty it is recommended to use the \textbf{game theory}, which assumes different strategies with corresponding probabilities for players [29]. The probability that the player will select strategy $i$ can be described by the following vector:

$$x_i=\left(x_1, x_2, \ldots, x_n\right)$$

The following system should be solved:

$$\sum_{i=1}^{n} a_{ij} x_i \geq P$$ \hspace{1cm} (1.19)$$

$$\sum_{i=1}^{n} x_i = 1$$ \hspace{1cm} (1.20)$$

$$x_i \geq 0$$ \hspace{1cm} (1.21)$$

$$j=1, 2, \ldots, m$$

Using the same approach we find the probability of selecting strategy $j$ by the opposite player, which is described by the following vector:

$$y_i=\left(y_1, y_2, \ldots, y_m\right)$$

The following system needs to be solved for the opposite side:

$$\sum_{j=1}^{m} a_{ji} y_i \geq P$$ \hspace{1cm} (1.22)$$

$$\sum_{j=1}^{m} y_j = 1$$ \hspace{1cm} (1.23)$$

$$y_j \geq 0$$ \hspace{1cm} (1.24)$$
After solving above mentioned systems by linear programming we find \((x_1, x_2, \ldots, x_n)\) and \((y_1, y_2, \ldots, y_m)\) strategy solutions.

Finally, the **method of comparison of power system expansion alternatives** considers various scenarios of development [33]. In each scenario different types of power plants are introduced that satisfy the capacity and electricity balances of the system. After comparing the results of economic analysis the optimal development scenario is selected.

It can be concluded that the optimal development strategy of the power system can be formulated using any of the considered methods. In this research project, considering the stochastic nature of initial information, the method of linear programming with sensitivity analysis is used. In this case all non-linear relationships are made linear by the method of linear approximation, and later the results are checked for accuracy using sensitivity analysis.
2. Economic Effects of New Capacities on a Developing Power System

2.1 Optimal Capacity Expansion of a Developing Power System under the Condition of Environmental Constraint

The power system consists of different types of power plants. During the simultaneous and cooperative work of these plants their various properties and characteristics can have a positive impact on the economic-technical criteria of the system\(^3\) [4]. The process of determining the optimal capacity of the power plant depends on many factors such as the environmental constraint. Along with the increase of the environmental impact of newly introduced power plants this factor will become more crucial for economic justification of the construction of those capacities.

Currently the construction of hydro power plants (HPP) faces severe environmental opposition, particularly in developed and developing countries. This factor meets considerable contradiction by traditional approaches for the decision making and substantiation of HPP construction, which consider both the expected profits from HPP and significantly low operation and maintenance costs. Hence, the conventional benefit-cost analysis does not in general justify the expansion of capacity although it may be a sufficiently accurate proxy for particular circumstances. However, the failure to meet the

conventional economic profitability criterion is considered a sufficient condition to reject a construction of new HPP.

Two different factors lead to this conclusion, which can be defined as external and internal. With external factors we mean externalities, which arise when a new HPP removes a part of a natural river forever from the natural environment and converts it into a regular lake. During the decision making process for the HPP construction the role of this factor was traditionally underestimated. It’s obvious that it will become one of the important factors if more and more rivers are converted into regular lakes to serve as reservoirs for HPP. In this case the investments for HPP construction become more scarce and valuable. Hence, the economic advantages of HPP construction will overcome environmental obstacles as long the environmental impact is ignored.

The internal factor illustrates that the current expenditures and requirements for conventional profitability criteria will affect the cost of future HPP. Therefore, the costs of additional HPP capacity will have increasing tendency if following the optimality condition the most efficient HPP be constructed first. In other words, the construction of HPP today will increase the costs of future new HPP.

**The model of optimal HPP capacity expansion**

Social welfare $U$ is an increasing function, although at a diminishing rate, from the possible capacity of HPP $N(t)$. As the resource, technical and the country specific geographic conditions limit the capacity expansion for HPP, then the $N(t) \leq N^{max}$, which represents the technically available capacity. Besides, the larger HPP that has a great impact on the environment will decrease the utility from hydro-energy for the society.
According to Wirn (1989) this can be presented by increasing and convex disutility function $V$ \[6\]. Finally, the introduction of additional HPP with the capacity $n$ into the power system will require $C(n, N)$ investments. The cost of additional capacity will tend to increase if the most efficient HPP is built first.

Above mentioned definitions can be described by mathematical expressions:

$$U' > 0, \ U'' > 0 \quad (2.1)$$

$$V' > 0, \ V'' > 0 \quad (2.2)$$

$$\lim_{N \to \max} C(n, N) = \infty \quad (2.3)$$

$$C_n > 0, \ C_{nn} > 0, \ C_N > 0, \ C_{NN} > 0, \ C_{nN} > 0 \quad (2.4)$$

where

$U'$ and $U''$ are the first and second derivatives of utility function or social welfare by dN and dN$^2$, respectively;

$V'$ and $V''$ are the first and second derivatives of disutility function by dN and dN$^2$, respectively;

$C_n$ and $C_N$ are the first derivatives of $C(n, N)$ by dq and dN, respectively;

$C_{nn}, \ C_{NN}$ and $C_{nN}$ are the second derivatives of $C(n, N)$ by d$n^2$, d$N^2$ and dqdN respectively.

(2.3) illustrates that additional HPP capacities become unacceptably expensive if all the rivers are used as a source of hydro-energy. From (2.3) follows that the economically efficient capacity expansion, based on conventional but not right profitability condition, will decrease the physically available amount of capacity. Hence, the expression $N(t) \leq N_{\text{max}}$ is sufficient and not necessary economic condition. A similar effect may rise if
maintaining the ecosystem all rivers are not used for electricity production, which will result in the increase of disutility function $V$.

The last condition (2.4) illustrates that along with the increase of capacity the cost of additional HPP will tend to rise. The impact of installed capacity on the amount of expenditures is similar - increasing and convex, because the process of HPP expansion will finally result in the situation when additional expenditures will not decrease along with the capacity expansion. The conventional criterion for estimation of power plants’ construction and maintenance costs enables to find a relation between the present value of social surplus and expenses for additional power plant. By simplifying, and not making basic assumption, we can assume that each plant is eternal and require that the marginal utility at each moment be not less than the discount rate of additional HPP, which can be expressed as:

$$U' \geq rC_n$$ where $r$ is the discount rate \hspace{1cm} (2.5)

As Wiril (1989) stated the optimal economic development of hydro energy can be presented as optimal control problem [6]. The optimality criterion can be described as:

$$
\max_{\{n(t) \geq 0\}} \int_0^\infty e^{-rt}[U(n(t))-V(n(t))-C(n(t),N(t)))]dt \hspace{1cm} (2.6)
$$

$$
\dot{N}(t)=n(t), \hspace{0.2cm} N(0)=N_0, \hspace{0.2cm} N(t) \leq N^{max} \hspace{1cm} (2.7)
$$

The Hamiltonian is: $H = U - V - C + \lambda n$  \hspace{1cm} (2.8)

The necessary and sufficient conditions are:

$$H_n = -C_n + \lambda = 0 \hspace{0.2cm} \Rightarrow \hspace{0.2cm} C_n = \lambda \hspace{1cm} (2.9)$$

---

\[ \dot{\lambda} = r\lambda - U' + V' + C_N \]  \hspace{1cm} (2.10)

In equations (2.8)-(2.10) as well as in sequel calculations the time and other arguments are dropped out as a matter of convenience. \( H \) is current value Hamiltonian, and \( \lambda \) is dependent variable or shadow price of capacity. The shadow price \( \lambda \) accounts the impact of hydro energy on both expected revenues from HPP and social surplus. In other words, it accounts the increase in the cost of additional HPP as well as the social losses because of the damage caused to ecosystem. Therefore, the conventional cost-benefit analysis, which compares \( C_n \) with the value of additional benefit \( U'/r \) is misleading. To prove this proposition consider first the equilibrium condition derived from equations (2.9) and (2.10):

\[ \frac{U'}{r} = \frac{(V'C_N)}{r} + C_n \Rightarrow U' \geq rC_n \]  \hspace{1cm} (2.11)

where \( \frac{(V'C_N)}{r} + C_n \) represents “true” marginal costs in equilibrium.

To analyze the economic intuition of “true” marginal costs consider the Figure 2.1.
The construction of additional HPP will be economically efficient as long as the curves of marginal benefit $U'/r$ and marginal cost $C_n$, illustrated in Figure 2.1, don’t intersect. In this case the condition $U' >> rC_n$ derived from the equilibrium condition (2.11) becomes significant justifying the construction of additional HPP.

In equilibrium the true marginal cost is considering the following factors:

- Impact on the environment
- Increase in costs because of the construction of new HPP

While the first factor, the damage to the environment, will be disputed, and probably, may be objected to by many people, the second factor $C_n$ should be considered by decision makers. In Figure 2.1 we compare the equilibrium condition (2.11) with the hydro energy development condition (2.5), derived from the conventional profitability criterion. The optimal solution corresponds to $N^*$. The condition (2.5) justifies termination of additional HPP construction when the current value of social surplus $U'/r$
intersects with the cost of additional HPP. Therefore, in optimal expansion of HPP their
construction should be terminated prior to the intersection of marginal benefits with
marginal costs of capacity expansion.

\[ \text{Increase in cost because of the damage caused to environment} \]
\[ \text{Decrease in cost because of the introduction of new technologies} \]

**Figure 2.2. Cost components of HPP construction**

Figure 2.2 illustrates the dynamics of two cost components: introduction of new
technologies and the damage to environment from HPP. It’s obvious that the HPP with
new technologies considerably decreases the cost of the future power plants. Hence, the
positive effect of additional HPP can be more significant then the negative impact
considered in this model. This positive effect will be considerable at the first stage of
hydro energy development which will create incentives to satisfy the increasing demand
of electricity by HPP, and as was already mentioned, application of new technologies will
decrease the amount of necessary capital investments for future HPP.

On the other hand, an increasing social contradiction to the environmental impact of
HPP will lead to a decreasing utility of additional HPP construction which results from
the optimal level of social surplus [2, 3, 18, 26]. In this research the environmental issues
of a new HPP construction are considered by including an additional constraint in the model.

Finally, one of the most important features of HPP is the ability to develop variable capacity in the power system illustrated by the following equation:

$$N_{HPP} = f(Q, H, \eta_{HPP})$$  \hspace{1cm} (2.12)

where,

$$Q$$ is water consumption;

$$H$$ is the projected height;

$$\eta_{HPP} = f(Q, H)$$ is the efficiency of electricity production.

Because of fluctuations in per second water consumption the annual water supply of HPP is relatively small. This disadvantage can be completely eliminated by utilizing HPP with adjustable water flow. Moreover, HPP can start working and taking electrical loadings very quickly as well as stop their operation almost instantly. Besides, these plants require very small amount of energy for their own needs. Therefore HPP are often used as both accident and frequency reserves, and also to cover the daily or seasonal peak loading of the system.

2.2 Energy Independence Issues of a Developing Power System

Any country in the world needs a certain level of energy independence and security, which is primarily important for the countries that have limited energy resources. The
introduction of new capacities into the power system for satisfying the electrical capacity and the electricity demands should consider a necessary level of the energy independence. This independence level is determined based on existing energy resources of a country.

In the countries with limited energy resources the condition of energy independence can only be satisfied by nuclear power plants (NPP) because nuclear fuel can be considered as a local resource even if a country has no nuclear resources. This assumption is based on the fact that even though nuclear fuel is imported it has long storage and operation periods. Armenia is one of the world countries that do not possess sufficient energy resources, and the further development of its power system assumes introduction of nuclear power plants that will maintain a certain level of energy independence.

To model the possible emergency situation in the power system after the shutdown of the Armenian nuclear power plant the following assumptions are made:

1. The amount of electricity produced by power plants in the system is:
   - Armenian nuclear power plant (NPP) – 2400 million kWh (considering a one month shutdown for testing and possible repairs)
   - All thermal power plants (TPP) - 0 million kWh (in case of full termination of the gas supply)
   - All hydro power plants (HPP) - 1100 million kWh (based on the assumption that the water from Lake Sevan is used only for irrigation purposes, and the total water balance has declined by 25%).
2. The termination of gas supply resulting to heating suspension, and also strict decline in import of oil resources:

- Will not change the electricity demand (the best case scenario)
- Will increase the electricity demand at residential and industrial levels by 1.5 and 1.2 times, respectively.

3. The import and export of electricity is not implemented.

4. The technological losses of energy are constant.

5. The demand of electricity for different sectors is estimated based on consumption losses of 2002. The latter occur mainly in 0.4 kV networks and are proportionally added to residential and industrial electricity demands.

The analysis of satisfying electricity demand under emergency conditions is summarized in Table 2.1.

<table>
<thead>
<tr>
<th>Consumption sectors</th>
<th>The best case scenario</th>
<th>The worst case scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Demand, million kWh</td>
<td>Demand satisfied</td>
</tr>
<tr>
<td>Residential</td>
<td>1554.0</td>
<td>1098.4</td>
</tr>
<tr>
<td>Industrial</td>
<td>772.0</td>
<td>599.7</td>
</tr>
<tr>
<td>State agencies</td>
<td>232.0</td>
<td>186.2</td>
</tr>
<tr>
<td>Drinking and</td>
<td>647.0</td>
<td>543.5</td>
</tr>
<tr>
<td>Transportation</td>
<td>118.0</td>
<td>61.8</td>
</tr>
<tr>
<td>Other consumers</td>
<td>695.0</td>
<td>378.6</td>
</tr>
<tr>
<td>Total</td>
<td><strong>4018.0</strong></td>
<td><strong>2868.2</strong></td>
</tr>
</tbody>
</table>

It follows from Table 2.1 that in case of emergency it will be possible to satisfy the total annual electricity demand by 71.4% and 52.0% under the best and worst case
scenarios, respectively. Under these conditions the most affected sectors of the economy will be transportation and other consumers, and for the worst case scenario also the residential sector. The latter is resulting from using the electricity for heating purposes in residential buildings.

The maximum deficit in satisfying the electricity demand will occur in the winter months, and also during the NPP testing and repair work periods, shown in Table 2.2.

<table>
<thead>
<tr>
<th>Consumption sectors</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>W</td>
<td>B</td>
<td>W</td>
</tr>
<tr>
<td>Residential</td>
<td>62.7</td>
<td>41.8</td>
<td>91.8</td>
<td>61.2</td>
</tr>
<tr>
<td>Industrial</td>
<td>71.6</td>
<td>59.6</td>
<td>93.8</td>
<td>78.2</td>
</tr>
<tr>
<td>State agencies</td>
<td>76.6</td>
<td>63.9</td>
<td>91.9</td>
<td>76.6</td>
</tr>
<tr>
<td>Drinking and irrigation water</td>
<td>66.6</td>
<td>55.5</td>
<td>95.5</td>
<td>79.6</td>
</tr>
<tr>
<td>Transportation</td>
<td>58.1</td>
<td>48.4</td>
<td>77.5</td>
<td>64.6</td>
</tr>
<tr>
<td>Other consumers</td>
<td>54.3</td>
<td>36.2</td>
<td>76.2</td>
<td>50.8</td>
</tr>
<tr>
<td>Total</td>
<td>63.6</td>
<td>45.5</td>
<td>89.9</td>
<td>66.3</td>
</tr>
</tbody>
</table>

Note: The estimates are for the best B and the worst W case scenarios

During the winter season the electricity production by HPP is declining along with the increase of electricity demand, which results in increase of deficit. We will have a better situation in summer because the electricity demand is declining, and also the water resources of Lake Sevan are used for electricity production. The deficit of electricity will increase again in the fall during the testing and repair works of the Armenian NPP.

It is also important to analyze the capacity demand coverage. According to 2002 data of daily system loadings in the system the capacity demand was 1200MW. Under both
emergency conditions and declined winter water regimes this demand could be possibly satisfied by existing power plants with the total capacity of 930MW. Hence, the capacity demand will be covered by 77.5% creating additional constraints for electricity supply.

Finally, in case of emergency the electricity demand can be covered only by HPP production if the operation of the existing NPP is terminated. The results of the analysis are illustrated in Table 2.3.

<table>
<thead>
<tr>
<th>Consumption sectors</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>12.2</td>
<td>20.9</td>
<td>20.0</td>
<td>20.1</td>
<td>17.3</td>
</tr>
<tr>
<td>Industrial</td>
<td>18.5</td>
<td>28.7</td>
<td>27.3</td>
<td>27.0</td>
<td>25.3</td>
</tr>
<tr>
<td>State agencies</td>
<td>21.4</td>
<td>37.4</td>
<td>38.4</td>
<td>38.9</td>
<td>31.3</td>
</tr>
<tr>
<td>Drinking and irrigation water</td>
<td>9.0</td>
<td>25.0</td>
<td>30.0</td>
<td>21.7</td>
<td>24.1</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.0</td>
<td>4.3</td>
<td>7.4</td>
<td>4.1</td>
<td>3.6</td>
</tr>
<tr>
<td>Other consumers</td>
<td>6.9</td>
<td>14.5</td>
<td>11.4</td>
<td>9.4</td>
<td>9.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12.2</strong></td>
<td><strong>22.7</strong></td>
<td><strong>23.6</strong></td>
<td><strong>20.3</strong></td>
<td><strong>19.1</strong></td>
</tr>
</tbody>
</table>

Note: The priority of satisfying the electricity demand is given to the strategically important agencies and buildings of the country

Based on the considered estimates we can expect that:

- The demands of electricity and capacity will increase because of gas supply termination and declined import of oil resources.
- The electricity and capacity demands can be covered by 71.4% and 52.0% for the best and worst case scenarios, respectively.
- The electricity supply will decline during the winter and fall months when the demand is satisfied by 60% and 40% under the best and worst case scenarios, respectively.
• The possible shutdown of the Armenian NPP will reduce the electricity demand coverage up to 19.1%, and will decrease further up to 12.2% in winter period.

• The partially covered capacity demand will impose additional constraints on the electricity supply.

It should be noted that the considered estimates are approximated.

There are several important conclusions made based on the aforementioned analysis:

1. The possible shutdown of the Armenian NPP will have a negative impact on energy independence of the Armenian power system.

2. In short-run it will be possible to temporarily increase the energy independence of the country affected by the shutdown of the Armenian NPP by utilizing local renewable energy resources. But this can not serve as a long-run solution because the local reserves of energy resources are limited, and also the social-economic development of the country will eventually increase the demand for resources.

3. The possible shutdown of the Armenian NPP will have a negative impact also on the reliability of electricity supply by reducing the reserve capacity of the system. This can be overcome only by constructing new generating capacities.

Taking into account the results of the analysis we conclude that the types and capacities of the new power plants in the Armenian power system should be selected based on maintaining the required level of energy independence by emphasizing the role of nuclear power plants. Therefore the energy independence level is evaluated by both qualitative and quantitative estimators.

In this research project the energy independence and security condition is included in the model as an additional constraint, and can be described as follows:
\[
\begin{align*}
&\left(\sum_{i=1}^{k-1} \sum_{i=1}^{n} N_{HPPi}(t) * h_{HPPi}(t) + \sum_{i=1}^{n} \Delta N_{HPPi} * h_{HPPi} + \sum_{i=1}^{k-1} \sum_{i=p+1}^{m} N_{TPPi}(t) * h_{TPPi} + \sum_{i=p+1}^{n} \Delta N_{TPPi} * h_{TPPi}\right) \\
&\quad * h_{TPPi} + \sum_{i=1}^{k-1} \sum_{i=m+1}^{q} N_{Obhi}(t) * h_{Obhi} + \sum_{i=m+1}^{n} \Delta N_{Obhi} * h_{Obhi} + \sum_{i=i}^{m+1} \Delta N_{Obhi} * h_{Obhi}(t) + \\
&\quad + \sum_{i=m+1}^{q} \Delta N_{Obhi} * h_{Obhi} * a_{\min} % \leq \sum_{i=1}^{k-1} \sum_{i=p+1}^{m} N_{NPPi}(t) * h_{NPPi}(t) + \sum_{i=p+1}^{n} \Delta N_{NPPi} * h_{NPPi} \\
&\quad (2.12)
\end{align*}
\]

and

\[
\begin{align*}
&\left(\sum_{i=1}^{k-1} \sum_{i=1}^{n} N_{HPPi}(t) * h_{HPPi}(t) + \sum_{i=1}^{n} \Delta N_{HPPi} * h_{HPPi} + \sum_{i=1}^{k-1} \sum_{i=p+1}^{m} N_{TPPi}(t) * h_{TPPi} + \sum_{i=p+1}^{n} \Delta N_{TPPi} * h_{TPPi}\right) \\
&\quad * h_{TPPi} + \sum_{i=1}^{k-1} \sum_{i=m+1}^{q} N_{Obhi}(t) * h_{Obhi} + \sum_{i=m+1}^{n} \Delta N_{Obhi} * h_{Obhi} + \sum_{i=m+1}^{q} \Delta N_{Obhi} * h_{Obhi} + \\
&\quad + \sum_{i=m+1}^{q} \Delta N_{Obhi} * h_{Obhi} * a_{\max} % \geq \sum_{i=1}^{k-1} \sum_{i=p+1}^{m} N_{NPPi}(t) * h_{NPPi}(t) + \sum_{i=p+1}^{n} \Delta N_{NPPi} * h_{NPPi} \\
&\quad (2.13)
\end{align*}
\]

where,

\[N_{HPPi}(t), N_{TPPi}(t), N_{NPPi}(t)\] and \[N_{Obhi}(t)\] are the capacities of hydro (HPP), thermal (TPP), nuclear (NPP), and other power plants, respectively, at the beginning of \(k\) interval of time;

\[\Delta N_{HPPi}, \Delta N_{TPPi}, \Delta N_{NPPi}\] and \[\Delta N_{Obhi}\] are the required capacities of HPP, TPP, NPP, and other power plants, respectively, at the beginning of \(k\) interval of time;

\[h_{HPPi}(t), h_{TPPi}(t), h_{NPPi}(t)\] and \[h_{Obhi}(t)\] are annual work-hours of HPP, TPP, NPP, and other power plants, respectively, operating at the beginning of \(k\) interval of time;

\[h_{HPPi}, h_{TPPi}, h_{NPPi}\] and \[h_{Obhi}\] are annual work-hours of newly introduced HPP, TPP, NPP, and other power plants at \(k\) interval of time, respectively;
$a_{\text{min}}$ is a coefficient representing the minimum required total capacity of NPP in the system;

$a_{\text{max}}$ is a coefficient representing the maximum required total capacity of NPP in the system.

According to this condition the total amount of electricity produced by nuclear power plants should be at least $a_{\text{min}}\%$ (independence) of total electricity produced in the country and not more than $a_{\text{max}}\%$ (security) of the same total electricity production in each $k$ interval of time. The value of $a_{\text{min}}$, representing the independence component of the condition, is defined by the total minimum electricity required for the reliable non-stop operation of the strategically important facilities of the country, which are government buildings, airports, hospitals, etc. The value of $a_{\text{max}}$, representing the security component of the condition, is defined by the maximum permissible capacity for the specific country, which is limited by country-specific climate and geographic conditions as well as by the management flexibility of the system. In this research the values of $a_{\text{min}}$ and $a_{\text{max}}$ for the Armenian power system are assumed to be 20% and 40%, respectively.

Consequently, 40% of the total electricity demand in the Armenian power system will be satisfied by the production of nuclear power plants, and 20% by hydro power plants. The aggregate share of these two types of power plants in total electricity production will allow satisfying the emergency demand by providing sufficient level of energy independence. Particularly, in case of termination of gas supply it will allow providing reliable electricity supply for strategically important agencies and buildings and also for residential sector.
3. Formulation of the Computational Model

3.1 Investigations of Power System Development Perspectives and Long-Term Development Forecasts

The sustainable development of a power system requires periodical calibration of long-term development projections of both economic relationships and introduction of industrial capacities in the power sector. The most important condition for the power system development is the existence of a competitive energy market, which will create incentives for potential investors.

Taking into account the large investments required for the construction of power plants and the long process of negotiations, the implementation of rehabilitation programs in the energy sector will require a long period of time. Thus the economic analysis of renovation or construction of different types of power plants should consider a projection time period of 15-30 years.

Various projects and programs are designed to make transition from the old methods of planning, management and control of power systems to the mechanisms able to operate in the market economy. As a result energy development forecasts and energy and fuel demand projections are formulated, which correspond to the economic development scenarios of a country. Based on this forecasts the optimization of technical-economic criteria of the system is implemented [20].
The long-term development forecasts of the power system are conducted at both macro- and microeconomic levels. At first the socio-economic development scenarios of a country are considered, which illustrate the best and the worst macroeconomic expectations: the growth rate of GDP, development of the sectors of the economy, the income and final consumption of households, etc. Then the most important criteria of the economic development and living standards are determined which are necessary for forecasting the capacity and electricity demands.

After analyzing the power supply alternatives corresponding to each economic development scenario, the electricity demand is forecasted. Then the initial version of the electricity balance of a country is formulated, which considers the relationship between projected demand of energy resources and their import. The potential environmental impact and energy savings are also estimated, which are impossible to ignore in case of a developing power system.

The main characteristics of the electricity balance of a country are presented as objective criteria, and based on this assumption the new capacities are forecasted. The latter allows determining the optimal construction of the power system and the fuel supply alternatives, which depend on the projected electricity prices and financial stability of energy companies.

To forecast the development of the power system the following problems should be consecutively solved:

a) For different types of power plants a comparative analysis of innovative technologies is conducted.
b) The acceptable scenarios of power system development are formulated, which satisfy the forecasted demand for capacity and electricity.

c) For each scenario the total expenses are evaluated, and based on these estimates the optimal scenario with minimum expenses is selected. The optimal version should also satisfy both the reliable power supply and the energy independence and security conditions.

d) After selecting the optimal scenario it should be checked to determine whether its development is realistic. This final estimation is mainly based on the forecasts of electricity prices and financial future of energy companies considering the expected economic trends.

The economic criteria of the power system development previously analyzed at the microeconomic environment are later evaluated at the macro level. These criteria are the price dynamics of energy resources, the tax inputs into the budget of a country, estimated capital investments, etc. Based on this information and import-export relationships the resource and financial balances of the power system are determined.

Finally the scenarios of the economic development are calibrated considering energy savings, efficiency of importing the energy resources, investments, pricing and taxation policies in the power sector, etc. Using this forecasting method with one or two iterations the energy development scenarios of a country can be formulated, which will provide more efficient utilization of the energy potential of the country and maintain the economic growth.
3.2 The Monetary Criterion of the Power System Optimization

The objective of the considered model is to find the most efficient way of production, distribution and utilization of electrical energy. From this concept the main optimization criterion of a developing power system can be derived, which represents the discounted value of total expenses over the considered period of time. Sometimes even with perfect cost information and calculations it is not possible to find a certain solution because it may appear that a group of solutions is optimal. And each of these solutions has the same minimum total cost. To narrow the range of possible equivalent results of optimization it is recommended to use additional optimization criteria that do not contradict the main objective.

All large manufacturing systems, particularly the power systems, are dynamic and always develop. Thus the main monetary criterion representing the power system development can not be static, and should consider the dynamic development.

The dynamic development of the power system consists of three stages:

1. Construction of a power plant until the beginning of operation of its first energy blocks.

2. Temporary operation, characterized by both continuing capital investments and energy production. The latter creates annual operation and maintenance expenses.

3. Normal operation, characterized only by operation and maintenance expenses corresponding to actual energy production. It is also assumed that the expenses occurred in early intervals of time of the considered period are
not equivalent and should be discounted to the same year. This can be included in the cost function using the discounting factor.

The dynamics of power plant construction can be expressed by the following equation:

$$TE_t = \sum_{t=1}^{T} (E_{ht} K_t + \Delta E_t)(1 + \rho_t)^{t-1}$$  \hspace{1cm} (3.1)

where,

- $T$ is the last year of temporary operation, after which follows normal operation of the plant;
- $\Delta E_t = E_t - E_{t-1}$ is the expected increase of annual expenses during temporary operation of the plant.

The economic intuition behind (3.1) is more obvious from the following expression:

$$TE_t = E_{ht} \sum_{t=1}^{T} (K_t + E_t)(1 + \rho_t)^{t-1} + E_{t+1}$$  \hspace{1cm} (3.2)

where,

- $E_{t+1}$ represents annual operation expenses during normal operation of the plant.

This expression states that the development of generating capacities consists of the following time periods:

---

1. From the beginning of construction until normal operation, when capital investments and annual operating expenses are discounted.

2. Normal operation, when only operation and maintenance expenditures are considered, and are also discounted.

This expression is correct only when beginning the year \( T+1 \) the operation and maintenance costs are constant. In comparing the real-life development scenarios of large power systems we need to consider the continuous development of its elements, which practically do not have normal operation period. This occurs mostly because of annual capital investments and exploitation of new power plants.

The comparison of power system development scenarios is implemented through the following steps. The considered time period \( T \) consists of the following components:

1. Optimization period \( T_0 \), which considers introduction of new power plants. It is usually equal to 15 years.

2. Calibration period \( T_n=T-T_0 \), which generally accounts for operation and maintenance costs of power plants that were introduced into the system during \( T_0 \). It can consider also the capital investments necessary for normal operation of the plants.

Therefore the optimality criteria of a developing power system can be expressed as:

\[
TE = \sum_{t=1}^{T_0} (K_i + E_i)(1 + \rho_t)^t + \sum_{t=T_0+1}^{T} E_i(1 + \rho_t)^t
\]

(3.3)

The second right hand side component of (3.3) describes the total annual expenses of the plants introduced during \( T_0 \) [1, 16].
3.3 The Economic-mathematical Model of a Developing Power System

The economic-mathematical model of a developing power system should determine the optimal capacities and electricity production of newly introduced power plants, and also their types based on the given capacity and electricity demands. Since the initial information is partially stochastic, particularly the forecasted scenarios for economic and energy development, the use of precise methods becomes not necessary. Hence, the power system can be described by a linear mathematical model, and then solved using the method of linear programming. Later the formulated development scenarios should be checked for accuracy by sensitivity analysis. Using the same approach the economic-technical characteristics of the considered power plants can also be presented in linear form by appropriate linear approximation [7, 8].

To determine the optimal structure of the developing power system the following data should be given in each interval of time:

1. The electricity consumption and demand corresponding to the maximum loading of the power system in the considered period of time.
2. The technical-economic criteria, necessary capital investments, and operation and maintenance expenses for all power plants that exist or are in the process of construction at the beginning of the considered period.
3. The set of power plants that exist or are in the process of construction at the beginning of the considered period.
4. The reserve and accident capacities required for the power system.
5. The types of potential power plants and different energy blocks, their marginal capacities, maximum available electricity production, and the starting time of the first energy block of each potential plant.

6. The available energy resources and the maximum possible import of required additional resources and their supply scheme over the planning period.

7. The estimated environmental impact of different types of power plants.

The main variables of the model will be:

1. The capacities of newly introduced power plants in the developing power system over the considered period.

2. The types of newly introduced power plants in the developing power system over the considered period.

3. The electricity production of newly introduced power plants in the developing power system over the considered period.

Since the development of the power system is dynamic, there will always be incomplete power plants in each interval of time. Thus, during the process of optimization these incomplete plants will artificially be replaced by other types of power plants.

In the model the dynamic development of the system is considered by solving single problems for each interval of time. In determining the optimal structure of the power system the n year projection period is selected. This considered period highly depends on the set of potential power plants and the increase of electricity demand. And for these
power plants the capacity and electricity balances and their introduction into the system are formulated.

Later, the $m$ year calculation period is selected, which is $l$ years longer than $n$. $l$ is the time period during which the power plants that are included in capacity and electricity balances will achieve their projected operation parameters. To prevent the existence of incomplete power plants at the end of the considered period $n$, new power plants will not be constructed during the time interval $l$, at which the structure of the power system should not be considered as optimal.

Since the power system is described by a linear mathematical model, the technical and economic characteristics of power plants should also be linear.

In the considered model the main variables are the capacities and produced electricity of newly introduced power plants. The objective function or the optimality criteria of the linear model for the power system’s economic development represents total expenses in a given period of time:

$$TE(R)=\sum_{t=1}^{T_p} \sum_{i=1}^{n} \left[ E_H K_i(R_t)+\Delta E_H(R_t)\right] \rho_t \rightarrow \min \quad (3.4)$$

$$R=(R_1, R_2, \ldots, R_{T_p}), \rho_t=(1+p)^{T_{p-t}}$$

where,

$R_t$ is a vector, representing the parameters of power plants (type of turbine, steam pressure, type of generator, type of fuel used etc., which are already defined by technical standards for each kind of power plant) at time $t$;
Kit(Rt) is an amount of total investments at time t, which are in functional relation with Rt;

ΔEit(Rt) is an amount of annual operating and maintenance expenditures of newly introduced power plants, which are in functional relation with Rt. This is the change of total annual operation and maintenance expenditures compared with the previous year;

E_H is a coefficient representing the efficiency of investments, which can be defined as:

\[ E_H = \frac{1}{T_H} \]  \hspace{1cm} (3.5)

where \( T_H \) is the payback period of capital investments.

\( T_p \) is a considered period of time, \( p \) is a norm considering the time factor, and \( \rho_t \) is a coefficient of discounting.

This objective function looks similar to ones already well known from the theory of “Optimization of Development and Management of Large Power Systems” by Russian scientist L. A. Melentiev [16].

To simplify model simulations the value of objective function and the variables of the model are determined for unit capacity.

The following main constraints are included in the model of the power system:

1. **Balance of Capacity**

The balance of capacity is calculated for each time interval and is described by the capacity constraints, which enable the model to accurately consider operation of the
hydropower plants in the linear model. These plants can work both as base and as peak loading units.

The peak loading duration curve is considered in this model so the power system will be able to satisfy any capacity and electrical demand with excess. In this model we consider different types of power plants:

- Thermal power plants
- Hydropower plants with daily, seasonal and multi-year arranged reservoirs
- Nuclear power plants.

At each \(k\) interval of time the total capacity is defined as a sum of the capacities that are introduced at \(k\) interval of time, and the capacities that were already operating at the beginning of that time interval:

\[
N_{ik} = \sum_{t=1}^{k-1} \sum_{i=1}^{n} N_i(t) + \sum_{i=1}^{n} \Delta N_{ik} \quad (3.6)
\]

where,

- \(N_i(t)\) is the capacity at the beginning of \(k\) interval of time;
- \(\Delta N_{ik}\) is the total capacity of newly introduced power plants in each \(k\) interval of time.

It follows that the total capacity of operating and newly introduced power plants should satisfy the demand in maximum capacity of the power system, including accident and repair capacities as well as plants’ own needs in each \(k\) interval of time:
\[
\sum_{i=1}^{n} \sum_{t=1}^{k} N_{\text{HPP}}(t) + \sum_{i=1}^{n} \sum_{t=1}^{k} \Delta N_{\text{HPP}} + \sum_{i=n+1}^{p} \sum_{t=1}^{k} N_{\text{TPP}}(t) + \sum_{i=n+1}^{p} \Delta N_{\text{TPP}} + \sum_{i=p+1}^{m} N_{\text{NPP}}(t) + \\
+ \sum_{i=p+1}^{m} \sum_{t=1}^{k} \sum_{i=m+1}^{q} \Delta N_{\text{NPP}} + \sum_{i=m+1}^{q} \Delta N_{\text{Obh}}(t) + \sum_{i=m+1}^{q} \sum_{t=1}^{k} \Delta N_{\text{Obh}}(t) \geq P_k \omega \tag{3.7}
\]

where,

\( N_{\text{HPP}}(t) \), \( N_{\text{TPP}}(t) \), \( N_{\text{NPP}}(t) \) and \( N_{\text{Obh}}(t) \) are the capacities of hydro (HPP), thermal (TPP), nuclear (NPP), and other power plants, respectively, at the beginning of \( k \) interval of time;

\( \Delta N_{\text{HPP}} \), \( \Delta N_{\text{TPP}} \), \( \Delta N_{\text{NPP}} \) and \( \Delta N_{\text{Obh}} \) are the required capacities of HPP, TPP, NPP, and other power plants, respectively, at the beginning of \( k \) interval of time;

\( P_k \) is a total maximum capacity necessary for power system;

\( w \) is a coefficient representing accident and repair capacities as well as plants’ own needs. This coefficient takes into account the probability of failure of a power plant’s normal operation because of possible accidents \( (w_a) \) and repair works \( (w_r) \). Power plants need part of their capacity for their own needs \( (w_p) \), which are proportional to the plant’s capacity and are also included in coefficient \( w \). The coefficient \( w \) is always \( w > 1 \) and can be defined as:

\[
w=(1+w_a)*(1+w_r)*(1+w_p)>1 \tag{3.8}
\]

Using the same approach we can easily determine the coefficient \( w_{EL} \) in the balance of electricity. Further, the balance of capacity is defined by the capacities of newly introduced power plants.

2. **Balance of Electricity**

The total amount of electricity produced by operating and newly introduced power plants should satisfy the electrical demand during each \( k \) interval of time:
\[
\sum_{i=1}^{k-1} \sum_{t=1}^{n} N_{HPPi}(t) * h_{HPPi}(t) + \sum_{i=1}^{n} \Delta N_{HPPi} * h_{HPPi} + \sum_{i=n+1}^{k-1} \sum_{t=1}^{p} N_{TPPi}(t) * h_{TPPi}(t) + \sum_{t=1}^{p} \Delta N_{TPPi} * h_{TPPi} + \sum_{i=m+1}^{q} N_{Othi}(t) * h_{Othi}(t) + \sum_{i=m+1}^{q} \Delta N_{Othi} * h_{Othi} \geq EL_k w_{EL}
\]

where,

\( EL_k \) is a demand for electricity during \( k \) interval of time;

\( h_{HPPi}(t), h_{TPPi}(t), h_{NPPi}(t) \) and \( h_{Othi}(t) \) are annual work-hours of HPP, TPP, NPP, and other power plants, respectively, operating at the beginning of \( k \) interval of time;

\( h_{HPPi}, h_{TPPi}, h_{NPPi} \) and \( h_{Othi} \) are annual work-hours of newly introduced HPP, TPP, NPP, and other power plants at \( k \) interval of time, respectively.

In the balance of electricity the coefficient \( w_{EL} \) has the same meaning as the coefficient \( w \) in the balance of capacity, and is determined using the same approach.

Since the problem is solved by linear programming, the work-hours of power plants are calculated artificially and are considered as known values. Otherwise it will be impossible to solve this problem by linear programming.

### 3. Capacity Constraints for Different Types of Power Plants

For each type of newly introduced power plants we consider capacity constraints in each \( k \) interval of time:

\[
\sum_{i=1}^{n} \Delta N_{HPPi} \leq N_{marginal}^{HPPi}
\]

\( (3.10) \)

\[
\sum_{i=n+1}^{p} \Delta N_{TPPi} \leq N_{marginal}^{TPPi}
\]

\( (3.11) \)
\[
\sum_{i=p+1}^{m} \Delta N_{NPP_i} \leq N_{NPP_{ik}}^{\text{marginal}} \tag{3.12}
\]

\[
\sum_{i=m+1}^{q} \Delta N_{Oth_i} \leq N_{Oth_{ik}}^{\text{marginal}} \tag{3.13}
\]

where,

\[N_{HPP_{ik}}^{\text{marginal}}, \ N_{TPP_{ik}}^{\text{marginal}}, \ N_{NPP_{ik}}^{\text{marginal}} \text{ and } N_{Oth_{ik}}^{\text{marginal}}\] are the marginal possible capacities of HPP, TPP, NPP, and other power plants in \( k \) interval of time, respectively.

In the considered model of the developing power system additional constraints are included. The detailed description of these conditions is given in Chapter 2, which is summarized below:

- The environmental impact is one of the most important factors in determining the optimal capacities of hydro power plants. And its role has always been underestimated in the decision making process regarding the construction of power plants. In Chapter 2 we have analyzed the environmental issues regarding HPP construction, which shows that the costs of additional HPP capacity will have an increasing tendency if following the optimality condition the most efficient HPP be constructed first. In this research project the environmental impact of the construction of power plants, particularly HPP, is considered by a specially designed economic-mathematical model. It works as sub-program helping to determine the optimal HPP capacities by generating additional constraints for the main model. Particularly, the equation (2.11) is used as additional constraint.
The types and capacities of new power plants in the power system should be selected based on maintaining the required level of energy independence, which is evaluated by both qualitative and quantitative estimators. The results of the analysis of energy independence issues described in Chapter 2 are incorporated in the power system development model as energy independence and security condition. Particularly, the equations (2.12) and (2.13) represent the additional constraints used in the main model.

Summarizing the linear model of the optimal development of the power system we can describe it by the objective function representing the total costs subject to the following constraints:

1. Balance of capacity
2. Balance of electricity
3. Capacity constraints for different types of power plants
4. Environmental constraint for HPP (described in Chapter 2)
5. Energy independence and security condition (described in Chapter 2).
4. The Development Strategy for the Armenian Power System

4.1 Description of the Problem

The future development of the Armenian economy and the power system is uncertain regarding the maintenance and development of industrial capacities and infrastructure. This is a result of independence from the former Soviet Union, the economic crisis, and the transition period. Uncertainty is related to any forecast, and it is higher in countries where the economic and energy development is subject to rapid structural changes. Even a small change in supply-demand relation can result in reconstruction of the power system.

In this chapter the economic-mathematical model of the power system is used to determine the development strategy of the Armenian power system within the period of 2006-2020. The main objective of the problem is the selection of such a development scenario with minimum expenses, which will satisfy the capacity and electricity demands under the conditions of given reliability and supply of the existing energy resources.

In order to solve the problem we need the following initial data:

1. The composition of electricity consumers, their industrial capacities and projected electrical consumption for the next 15-20 years.

2. The available amount of fuel resources, and the economic criteria of their transportation. The main fuel resource used in Armenian thermal power plants is the natural gas imported from Russia.
3. The capacities of operating power plants at the beginning of the considered period.

4. The main technical and economic criteria of operating and newly introduced power plants.

5. The capacity balance of the power system, including accident and repair capacities.

6. The electricity balance of the power system, including accident and repair capacities.

7. The feasible development alternatives of power plants in the power system and their marginal capacities.

8. The estimated environmental impact of power plants, which in this study is applied to hydro power plant construction.

Currently Armenia has full electrification and the total existing capacity of the Armenian power system is 3040 MW. The total capacity of operating **thermal power plants** (TPP) is about 1754 MW. These plants are mainly burning natural gas. The Hrazdan TPP, which has a capacity of 1110 MW, started its operation within the period of 1966-1974. The next large TPP located in Yerevan, has a capacity of 550 MW, and began its operation within the period of 1963-1968.

Armenia has one **nuclear power plant** (NPP) located in Medzamor. This power plant started its operation in 1976-1980. It has 2 reactors with the total capacity of 815 MW. After its temporary shutdown from 1989 to 1995, the operation of the second energy block of the plant was restarted with the capacity of 407.5 MW.
The total existing capacity of the hydro power plants (HPP) is 1000MW. The Sevan-Hrazdan complex includes 7 HPP, which started their operation within the period of 1949-1959. It covers over 55% of the total hydro capacity of the country. The Vorotan HPP complex consists of 3 plants, which began their operation within the period of 1970-1984. This system provides about 40% of hydro capacities. The other 5% of hydro capacity is covered by small HPP.

The following figure shows the shares in total electricity production of Armenian power plants\textsuperscript{6}.

\textbf{Figure 4.1. Share of electricity production of power plants in Armenia}

\textsuperscript{6} Armenian Research Institute of Energy
It can be clearly seen from Figure 4.1 that the electricity production in 1988 was about 15 billion kWh, which exceeds the 2000-2001 production levels by 2.5 times. This is a result of declined number of external and internal electricity markets:

- The Armenian energy sector was developing within Caucasus United Power System to satisfy its base loading, and was exporting 20-25% of its total electricity production. But from 1993 to 1997 it was isolated because of regional complicated political and economic situation.

- Armenia was one of the most developed industrial republics of the former Soviet Union manufacturing a wide variety of chemicals, mechanisms, and electrical equipment. The economic crisis of 1992-1995 followed by the collapse of the Soviet Union negatively affected Armenian economy. In 1994 the output of the manufacturing sector represented only 37% of that in 1991, resulting to decreased electricity demand and significant changes in energy consumption structure.

The Armenian Research Institute of Energy estimated the current state of existing power plants in the Armenian power system, which is summarized below:

- 38% of the installed generating capacities have already been employed more than 30 years.

- The working hours of the generating capacities in thermal power plants have reached their marginal value of 200,000 hours, and also their technical-economic as well as environmental impact criteria do not correspond to international standards.
• 70% of the installed capacities in hydro power plants have operated more than 30 years, and 50% about 40 years.

The brief description of the status of installed generating capacities in the existing power plants is given in the following tables:

### Table 4.1. Armenian NPP

<table>
<thead>
<tr>
<th>Equipment type</th>
<th>Starting year of operation</th>
<th>Working hours as of 01/06/02, hours</th>
<th>Number of starting as of 01/06/02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor N 2</td>
<td>1980/1995</td>
<td>107,382</td>
<td>103</td>
</tr>
<tr>
<td>Turbine N 4 K-220-44</td>
<td></td>
<td>96,633</td>
<td>140</td>
</tr>
<tr>
<td>Generator N 3</td>
<td></td>
<td>100,115</td>
<td>142</td>
</tr>
<tr>
<td>Generator N 4</td>
<td></td>
<td>96,437</td>
<td>135</td>
</tr>
<tr>
<td>Block N 2</td>
<td></td>
<td>105,526</td>
<td>103</td>
</tr>
</tbody>
</table>

**Note:**
1. According to the producer standards the normal operation period of Reactor N 2 is 30 years.
2. According to the producer standards the number of annual work hours for Block N2 is 7358.

### Table 4.2. Sevan-Hrazdan HPP complex (continued on the following page)

<table>
<thead>
<tr>
<th>Generating capacity</th>
<th>Starting year of operation</th>
<th>Installed capacity, MW</th>
<th>Working hours as of 01/06/02, hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Sevan HPP</td>
<td>1949</td>
<td>34.2</td>
<td>295 305 285 397 7 866</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S.K.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hrazdan HPP</td>
<td>1959</td>
<td>81.6</td>
<td>216 664 207 078</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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7 Armenian Research Institute of Energy
### Continuation of Table 4.2

<table>
<thead>
<tr>
<th></th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argel HPP</td>
<td>1953 Attachments</td>
<td>224 Attachments</td>
<td>210 237 Attachments</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td>266 602 Attachments</td>
<td></td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 3</td>
<td></td>
<td>260 686 Attachments</td>
<td></td>
</tr>
<tr>
<td>N 4</td>
<td></td>
<td>238 233 Attachments</td>
<td></td>
</tr>
<tr>
<td>Arzni HPP</td>
<td>1956 Attachments</td>
<td>70.6 Attachments</td>
<td>248 567 Attachments</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td>247 720 Attachments</td>
<td></td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 3</td>
<td></td>
<td>235 353 Attachments</td>
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<tr>
<td>Kanaker HPP</td>
<td>1936 Attachments</td>
<td>102 Attachments</td>
<td>267 313 Attachments</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td>349 726 Attachments</td>
<td></td>
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<td>N 2</td>
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<td>373 843 Attachments</td>
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</tr>
<tr>
<td>N 3</td>
<td></td>
<td>368 474 Attachments</td>
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<td>N 4</td>
<td></td>
<td>229 142 Attachments</td>
<td></td>
</tr>
<tr>
<td>N 5</td>
<td></td>
<td>210 738 Attachments</td>
<td></td>
</tr>
<tr>
<td>N 6</td>
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<td></td>
</tr>
<tr>
<td>Yerevan HPP-1</td>
<td>1962 Attachments</td>
<td>44 Attachments</td>
<td>212 620 Attachments</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td>194 664 Attachments</td>
<td></td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yerevan HPP-3</td>
<td>1960 Attachments</td>
<td>5 Attachments</td>
<td>79 875 Attachments</td>
</tr>
</tbody>
</table>

### Table 4.3. Vorotan HPP complex

<table>
<thead>
<tr>
<th>Generating capacity</th>
<th>Starting year of operation</th>
<th>Installed capacity, MW</th>
<th>Working hours as of 01/06/02, hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatev HPP</td>
<td>1970</td>
<td>157</td>
<td>189 192</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td></td>
<td>136 653</td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td>170 503</td>
</tr>
<tr>
<td>N 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shamb HPP</td>
<td>1978</td>
<td>168</td>
<td>47 733</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td></td>
<td>38 416</td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spandaryan HPP</td>
<td>1989</td>
<td>75</td>
<td>26 279</td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td></td>
<td>27 758</td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.4. Hrazdan TPP

<table>
<thead>
<tr>
<th>Equipment type</th>
<th>Starting year of operation</th>
<th>Installed capacity, MW</th>
<th>Working hours as of 01/06/02, hours</th>
<th>Number of starting as of 01/06/02</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Block section</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>N 1</td>
<td>1971-1974</td>
<td>200</td>
<td>166 666</td>
<td>475</td>
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<tr>
<td>N 2</td>
<td></td>
<td>200</td>
<td>156 642</td>
<td>402</td>
</tr>
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<td>N 3</td>
<td></td>
<td>200</td>
<td>158 713</td>
<td>376</td>
</tr>
<tr>
<td>N 4</td>
<td></td>
<td>210</td>
<td>168 972</td>
<td>368</td>
</tr>
<tr>
<td>Non-block section</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boilers</td>
<td>1966-1969</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 1</td>
<td></td>
<td></td>
<td>151 726</td>
<td>271</td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td></td>
<td>145 161</td>
<td>327</td>
</tr>
<tr>
<td>N 3</td>
<td></td>
<td></td>
<td>125 386</td>
<td>313</td>
</tr>
<tr>
<td>N 4</td>
<td></td>
<td></td>
<td>130 392</td>
<td>281</td>
</tr>
<tr>
<td>N 5</td>
<td></td>
<td></td>
<td>114 124</td>
<td>295</td>
</tr>
<tr>
<td>Turbines</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 1</td>
<td>1966-1967</td>
<td>50</td>
<td>208 534</td>
<td>198</td>
</tr>
<tr>
<td>N 2</td>
<td></td>
<td>50</td>
<td>180 602</td>
<td>182</td>
</tr>
<tr>
<td>N 3</td>
<td>1969</td>
<td>100</td>
<td>127 758</td>
<td>312</td>
</tr>
<tr>
<td>N 4</td>
<td></td>
<td>100</td>
<td>126 292</td>
<td>305</td>
</tr>
</tbody>
</table>

Note:
1. According to the producer standards the normative work hours of turbines is 220,000 hours.
2. The work hours of boilers is not defined.
3. Some of the non-block devices almost reached their projected total work hour level.

Table 4.5. Yerevan TPP (continued on the following page)

<table>
<thead>
<tr>
<th>Equipment type</th>
<th>Starting year of operation</th>
<th>Installed capacity, MW</th>
<th>Working hours as of 01/06/02, hours</th>
<th>Number of starting as of 01/06/02</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Non-block section</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boilers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 1</td>
<td>1963</td>
<td></td>
<td>173 177</td>
<td></td>
</tr>
<tr>
<td>N 2</td>
<td>1964</td>
<td></td>
<td>177 331</td>
<td></td>
</tr>
<tr>
<td>N 3</td>
<td>1966</td>
<td></td>
<td>201 866</td>
<td></td>
</tr>
<tr>
<td>N 4</td>
<td>1967</td>
<td></td>
<td>196 806</td>
<td></td>
</tr>
<tr>
<td>N 5</td>
<td>1965</td>
<td></td>
<td>168 016</td>
<td></td>
</tr>
<tr>
<td>Turbines</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 1</td>
<td>1963</td>
<td>60</td>
<td>190 149</td>
<td>373</td>
</tr>
</tbody>
</table>
Continuation of Table 4.5

<table>
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<tr>
<th>Block section</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boilers</td>
<td>N 2</td>
<td>1963</td>
<td>60</td>
<td>191 966</td>
<td>297</td>
</tr>
<tr>
<td></td>
<td>N 3 (N 3 CVD)</td>
<td>1963 (1992)</td>
<td>60</td>
<td>198 004 (4 525)</td>
<td>181 (8)</td>
</tr>
<tr>
<td></td>
<td>N 4</td>
<td>1964</td>
<td>60</td>
<td>152 345</td>
<td>328</td>
</tr>
<tr>
<td></td>
<td>N 5</td>
<td>1966</td>
<td>50</td>
<td>198 986</td>
<td>318</td>
</tr>
<tr>
<td>Turbines</td>
<td>N 6</td>
<td>1965</td>
<td></td>
<td>150 950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N 7</td>
<td>1966</td>
<td></td>
<td>148 560</td>
<td></td>
</tr>
</tbody>
</table>

Note:
1. According to the producer standards the normative work hours of turbines N1-N5 is 220,000 hours.
2. The number of starting for turbines is 600.
3. According to the producer standards the normative work hours of boilers is 300,000 hours.
4. Some of the devices almost reached their projected total work hour level.

4.2 Expected Increase in both Electricity Demand and Maximum Loading in the Armenian Power System from 2005 to 2020

From various development forecasts formulated for the Armenian power system the results of the “Strategy Paper” by TACIS will be used as initial data for this research [25]. In this paper 2 scenarios of capacity and electricity demand are forecasted based on the economic development predictions of Armenia. Scenario A and Scenario B described in Table 4.6 represent the best and the worst possible economic and energy development of the country, respectively8:

---

Table 4.6. Forecast Scenarios A and B

<table>
<thead>
<tr>
<th></th>
<th>1988</th>
<th>1998</th>
<th>1999</th>
<th>Scenario A</th>
<th></th>
<th></th>
<th>Scenario B</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total consumption of final energy (10^6 tons of oil equiv.)</td>
<td>6.402</td>
<td>1.158</td>
<td>0.960</td>
<td>2.86</td>
<td>4.60</td>
<td>6.69</td>
<td>2.49</td>
<td>3.57</td>
<td>4.75</td>
</tr>
<tr>
<td>Electricity consumption (TWh)</td>
<td>9.3</td>
<td>4.3</td>
<td>3.6</td>
<td>5.8</td>
<td>8.0</td>
<td>10.9</td>
<td>4.9</td>
<td>5.7</td>
<td>6.9</td>
</tr>
<tr>
<td>Electricity demand in the system (TWh)</td>
<td>11.1</td>
<td>5.4</td>
<td>5.1</td>
<td>6.9</td>
<td>9.3</td>
<td>12.4</td>
<td>5.8</td>
<td>6.6</td>
<td>7.9</td>
</tr>
<tr>
<td>Energy intensity: total final energy (kg oil equiv./US$)</td>
<td>1.88</td>
<td>0.63</td>
<td>0.50</td>
<td>1.06</td>
<td>1.27</td>
<td>1.38</td>
<td>1.06</td>
<td>1.31</td>
<td>1.43</td>
</tr>
<tr>
<td>-electricity consumption (kWh/US$)</td>
<td>2.73</td>
<td>2.32</td>
<td>1.90</td>
<td>2.14</td>
<td>2.22</td>
<td>2.24</td>
<td>2.08</td>
<td>2.09</td>
<td>2.09</td>
</tr>
<tr>
<td>Per capita energy consumption: total final energy (kg oil equiv./ab)</td>
<td>1854</td>
<td>371</td>
<td>310</td>
<td>884</td>
<td>1343</td>
<td>1804</td>
<td>830</td>
<td>1227</td>
<td>1641</td>
</tr>
<tr>
<td>-electricity consumption (kWh/ab)</td>
<td>2696</td>
<td>1377</td>
<td>1171</td>
<td>1789</td>
<td>2345</td>
<td>2936</td>
<td>1627</td>
<td>1953</td>
<td>2397</td>
</tr>
<tr>
<td>Percentage changes</td>
<td></td>
<td>'88 / '99</td>
<td>'99 / '05</td>
<td>'05 / '10</td>
<td>'10 / '20</td>
<td>'99 / '05</td>
<td>'05 / '10</td>
<td>'10 / '20</td>
<td></td>
</tr>
<tr>
<td>Total consumption of final energy</td>
<td>-15.8</td>
<td>20.0</td>
<td>9.9</td>
<td>3.8</td>
<td>17.2</td>
<td>7.5</td>
<td>2.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>-8.2</td>
<td>8.1</td>
<td>6.7</td>
<td>3.1</td>
<td>5.0</td>
<td>3.1</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity demand in the system</td>
<td>-6.9</td>
<td>5.3</td>
<td>6.2</td>
<td>2.9</td>
<td>2.3</td>
<td>2.6</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy intensity: total final energy</td>
<td>-11.3</td>
<td>13.2</td>
<td>3.7</td>
<td>0.8</td>
<td>13.3</td>
<td>4.4</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-electricity consumption</td>
<td>-3.3</td>
<td>2.1</td>
<td>0.7</td>
<td>0.1</td>
<td>1.5</td>
<td>0.1</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Per capita energy consumption: total final energy</td>
<td>-15.0</td>
<td>19.1</td>
<td>8.7</td>
<td>3.0</td>
<td>17.8</td>
<td>8.1</td>
<td>2.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-electricity consumption</td>
<td>-7.3</td>
<td>7.3</td>
<td>5.6</td>
<td>2.3</td>
<td>5.6</td>
<td>3.7</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In spite of the fact that over the previous decade the energy consumption was decreased almost by 16%, both scenarios predict an increasing total energy demand within the next 15 years. It is expected that the electricity demand will also grow at an
increasing rate, which will be slower than that of the total energy demand. This is a result of decreased demand in different types of energy over the previous decade. In 1999 the consumption is 10 times less compared to 1998 levels.

According to Scenario A, the total energy consumption will increase annually by 9.9% within the period of 2005-2010, and by 3.8% from 2010 to 2020. Scenario B assumes annual increase in energy consumption by 7.5% and 2.9% for the same periods, respectively.

Per capita consumption of both total energy and electricity is also increasing over the considered period. It should be noted the expected per capita consumption will be lower than that of 80’s excluding the consumption levels of 2020 in Scenario A.

To forecast the energy demand for Armenia several economic development scenarios have been simulated by TACIS, and two of them Scenario A and B have been analyzed in detail [23, 25]. These two scenarios illustrate the possible development strategy of the Armenian economy within the period of 2000-2020. According to both scenarios we expect an increase in both GDP (Million USS ’98) and corresponding electricity demand, which is shown in Figure 4.2.
Scenario A represents an annual increase in GDP by 6% in 2003-2010, and by 3% within the next decade. It assumes full realization of the government’s new economic reforms creating incentives for manufacturing sector development, which in its turn will contribute to the economic growth of the country. Scenario A is also projecting appropriate development of infrastructure.

Scenario B assumes half realization of the government’s new economic reforms in short-run. Under this scenario the foreign investment levels are lower than expected; the economic crisis of Russia is negatively affecting regional trade, etc. Hence, Scenario B assumes an annual increase in GDP by 3% in 2003-2010, and by 2% within the next decade.

The increase of electricity demand highly depends on the continuous growth of population and consumption of other goods. The power system is required to supply more electrical energy (electricity demand) than it is actually consumed (electricity consumption) by consumers.
The difference between electricity demand and consumption is usually referred to distribution and transmission system losses. Usually these two should be equivalent but in some cases there exist other factors affecting demand-consumption relationship. Such factors are the difference between documented consumption (based on the meter readings) and billed amount of money, and electricity thieving. Figure 4.3 shows the electricity demand and consumption balance fluctuations in Armenia.

![Electricity losses as a percentage of demand](plot)

*Figure 4.3. Historical and projected balance of electricity demand and consumption in Armenia*

Differences show instability tendency where some peak values have similar behavior with electricity tariff growth. This tendency can result from the complexity of acquiring historical data from different sources. However, these variances didn’t affect the technical loss forecasts. The latter are partially responsible for differences between

---

demand and consumption beginning from 1990’s. The rest can be considered as “unreported” consumption, which are incorporated in electricity demand projections. In the future forecasts the demand-consumption differences are referred only to technical losses, because “unreported” losses are distributed over final consumption sectors.

Electricity is a specific product that should be produced and consumed simultaneously. For each electricity demand forecast it is recommended to have appropriate capacity demand prediction, which allows having complete information about the expected demand for total energy. The important feature of the capacity demand is that it should be satisfied at any time. Therefore the accurate forecasting of the expected peak loading of capacity and the maximum demand of electricity is very important. These forecasts were predicted by TACIS for the Armenian power system from 2005 to 2020, based on the assumption of the peak demand usage factor.¹⁰

<table>
<thead>
<tr>
<th></th>
<th>1998</th>
<th>1990</th>
<th>Scenario A</th>
<th>Scenario B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity demand in the system (TWh)</td>
<td>5.4</td>
<td>6.9</td>
<td>9.3</td>
<td>12.4</td>
</tr>
<tr>
<td>Peak demand usage factor (%)</td>
<td>50.4</td>
<td>57.0</td>
<td>60.0</td>
<td>63.0</td>
</tr>
<tr>
<td>Peak capacity demand (MW)</td>
<td>1213</td>
<td>1382</td>
<td>1776</td>
<td>2241</td>
</tr>
</tbody>
</table>

In this research project the peak loading of capacity and the maximum demand of electricity will be used as maximum values for the capacity and electricity constraints.

To maintain reliable operation of the power system the considered economic-mathematical model should also account for reserve generating capacities. The total manageable capacity of the power system is mainly determined by the sum of maximum loading, repair and possible accident reserve capacities in the system.

The projected electricity demand and other basic technical-economic criteria for Scenario A and B are summarized in Table 4.8 and 4.9, respectively. In these tables the manageable capacity of the system is determined based on the operated work hours and manufacturer’s standards for different types of power plants, as well as the reliability of electricity supply.
### Table 4.8. Scenario A – Projected electricity demand and other technical-economic criteria

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GDP, $10^6$ USD '98</td>
<td>2020</td>
<td>2141</td>
<td>2270</td>
<td>2406</td>
<td>2550</td>
<td>2703</td>
<td>2865</td>
<td>3037</td>
<td>3220</td>
<td>3413</td>
<td>3618</td>
<td>3838</td>
<td>3953</td>
<td>4072</td>
<td>4194</td>
<td>4319</td>
<td>4449</td>
<td>4583</td>
<td>4720</td>
<td>4862</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Maximum loading of the system, MW</td>
<td>1123</td>
<td>1175</td>
<td>1227</td>
<td>1278</td>
<td>1330</td>
<td>1382</td>
<td>1461</td>
<td>1540</td>
<td>1618</td>
<td>1697</td>
<td>1776</td>
<td>1822</td>
<td>1869</td>
<td>1915</td>
<td>1962</td>
<td>2008</td>
<td>2055</td>
<td>2101</td>
<td>2148</td>
<td>2194</td>
<td>2241</td>
</tr>
<tr>
<td>5</td>
<td>Reserve capacity of the system, MW</td>
<td>336.9</td>
<td>352.4</td>
<td>368</td>
<td>383.5</td>
<td>399.1</td>
<td>414.6</td>
<td>438.2</td>
<td>461.9</td>
<td>485.5</td>
<td>509.2</td>
<td>532.8</td>
<td>546.7</td>
<td>560.6</td>
<td>574.6</td>
<td>588.5</td>
<td>602.4</td>
<td>616.4</td>
<td>630.4</td>
<td>644.3</td>
<td>658.3</td>
<td>672.3</td>
</tr>
<tr>
<td>6</td>
<td>Total capacity of existing power plants in the system, MW</td>
<td>3090</td>
<td>3087</td>
<td>3083</td>
<td>3072</td>
<td>3054</td>
<td>3028</td>
<td>2995</td>
<td>2955</td>
<td>2907</td>
<td>2852</td>
<td>2790</td>
<td>2720</td>
<td>2643</td>
<td>2558</td>
<td>2412</td>
<td>2036</td>
<td>1945</td>
<td>1847</td>
<td>1743</td>
<td>1632</td>
<td>1515</td>
</tr>
<tr>
<td>7</td>
<td>Total manageable capacity of the power system, MW</td>
<td>Deficit</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Surplus</td>
<td>+1630</td>
<td>+1560</td>
<td>+1489</td>
<td>+1410</td>
<td>+1325</td>
<td>+1232</td>
<td>+1096</td>
<td>+953</td>
<td>+803</td>
<td>+646</td>
<td>+481</td>
<td>+351</td>
<td>+213</td>
<td>+69</td>
<td>-</td>
<td>-</td>
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<tr>
<td>No</td>
<td>Technical and economic criteria</td>
<td>The worst case Scenario B</td>
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<tr>
<td>1</td>
<td>GDP, $10^6$ US$ 98</td>
<td>2020 2081 2143 2207 2274 2342 2412 2484 2559 2636 2715 2769 2824 2881 2938 2979 3057 3118 3181 3244 3309</td>
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<tr>
<td>2</td>
<td>Electricity demand, TWh</td>
<td>5.27 5.376 5.482 5.588 5.694 5.8 5.96 6.12 6.28 6.44 6.6 6.728 6.856 6.984 7.112 7.24 7.368 7.496 7.624 7.752 7.88</td>
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<tr>
<td>4</td>
<td>Maximum loading of the system, MW</td>
<td>1093 1115 1137 1160 1182 1204 1223 1242 1261 1280 1299 1314 1329 1344 1359 1374 1389 1405 1420 1435 1450</td>
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<tr>
<td>5</td>
<td>Reserve capacity of the system, MW</td>
<td>327.9 334.6 341.2 347.9 354.5 361.2 366.9 372.6 378.3 384 389.7 394.2 398.7 403.2 407.8 412.3 416.8 421.4 425.9 430.4 435</td>
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<tr>
<td>6</td>
<td>Total capacity of existing power plants in the system, MW</td>
<td>3090 3087 3083 3072 3054 3028 2995 2955 2907 2852 2790 2720 2643 2558 2121 2036 1945 1847 1743 1632 1515</td>
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</tr>
<tr>
<td>7</td>
<td>Total manageable capacity of the power system, MW</td>
<td>Deficit - - - - - - - - - - - - 103 233 370</td>
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<tr>
<td></td>
<td>Surplus +1669 +1637 +1605 +1565 +1518 +1463 +1406 +1340 +1268 +1188 +1101 +1012 +915 +811 +354 +249 +138 +21 - - -</td>
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</tbody>
</table>
**Additional data used in model simulations**

In our calculations we use different electricity tariffs for each type of existing and newly introduced power plants based on the recent reports of the Public Service Regulatory Commission of Armenia. Taking into account the most recent advancements in turbine manufacturing we assume that the conditional fuel consumption for gas turbines is 220-250 gram/kWh.

As previously mentioned there are various models and programs formulated for the development of the Armenian power system but none of them considers the environmental impact on power plant construction decisions.

In Chapter 2 we have discussed the impact of environmental issues on the optimal capacity selection for hydro power plants, which shows that the costs of additional HPP capacity will have an increasing tendency if following the optimality condition the most efficient HPP be constructed first. These costs have two components: introduction of new technologies and the damage to environment from HPP. It’s obvious that the HPP with new technologies considerably decreases the cost of the future power plants.

On the other hand, an increasing social contradiction to the environmental impact of HPP and also geographical conditions of the region will lead to a decreasing utility of additional HPP construction which results from the optimal level of social surplus.

In this research the environmental impact of the construction of power plants, particularly HPP, is considered by a specially designed economic-mathematical model. It works as sub-program helping to determine the optimal HPP capacities by generating additional constraints for the main model. Using this model and assuming zero profits
(profits are zero, because this sector is government regulated) we conduct cost-benefit analysis for the Armenian hydropower development opportunities, and find that the optimal total HPP capacity in Armenia is about 250MW. After this point the cost of additional 1MW of installed capacity will be greater than the benefit from that unit being affected by both technological and environmental cost components. The results of this sub-model serve as additional constraints in the main model of economic development of the Armenian power system.

The minimum of the average cost of capacity expansion for HPP in Armenia is illustrated in Figure 4.4.

![Average cost curve of HPP construction in Armenia](image)

**Figure 4.4. Average cost curve of HPP construction in Armenia**

Armenia has the least water resources in the region and uses them for electricity production only because of the lack of other energy reserves. The use of scarce water
resources should be limited not to threaten strategically important water reserves of the country.

In this project the unit capital investments for different types of power plants are estimated to have the following values:\(^{11}\):

- **Hydro power plants:**
  
  \(k_{\text{HPP}} = \$1600/\text{kW, if the capacity } N_{\text{HPP}} < 10 \text{MW}\)
  \(k_{\text{HPP}} = \$900/\text{kW, if the capacity } 10 \text{MW} < N_{\text{HPP}} < 100 \text{MW}\)
  \(k_{\text{HPP}} = \$600/\text{kW, if the capacity } N_{\text{HPP}} > 100 \text{MW}.\)

- **Thermal power plants:**
  
  \(k_{\text{TPP}} = \$900/\text{kW, if the capacity } N_{\text{TPP}} < 300 \text{MW}\)
  \(k_{\text{TPP}} = \$600/\text{kW, if the capacity } N_{\text{TPP}} > 300 \text{MW}.\)

- **Nuclear power plants:**
  
  \(k_{\text{NPP}} = \$1800/\text{kW, with existing infrastructure}\)
  \(k_{\text{NPP}} = \$2400/\text{kW, without infrastructure with capacity } 400 \text{MW} < N_{\text{NPP}} < 600 \text{MW}.\)

Annual work hours for different types of power plants are\(^{11}\):

- **Existing hydro power plants:**
  
  \(h_{\text{Vorotan}} = 1800 \text{hours}, h_{\text{Sevan}} = 1000 \text{hours}\)

- **Newly introduced hydro power plants:**
  
  \(h_{\text{Small}} = 3000 \div 3500 \text{hours}, h_{\text{Average}} = 4000 \text{hours}, h_{\text{Large}} = 3000 \div 4000 \text{hours}\)

- **Thermal and nuclear power plants:**
  
  \(h_{\text{TPP}} = 6600 \text{hours}, h_{\text{NPP}} = 6600 \div 7400 \text{hours}\)

\(^{11}\) Armenian Research Institute of Energy
It is assumed that in existing nuclear and thermal power plants the operation and maintenance expenses are growing along with increasing operation hours, decreasing installed capacity and declining reliability of plants in the system. These expenses have parabolic growth tendency, which is similar to the behavior of accident curve of technical systems over time. This assumption is justified by basics of substitution theory.

The dynamic change of operation and maintenance expenditures in existing power plants haven’t been sufficiently studied by other researchers. Hence, by incorporating this idea in the model simulations we can suggest new and more accurate approach to this issue.

Finally, the price of natural gas, which is the main fuel used in thermal power plants, and is the dominating component in the price of electricity, is assumed to rise from $80.1/1000m^3 to $95.7/1000m^3 over the considered period\textsuperscript{11}.

4.3 Results of the Development Strategy Formulation for the Armenian Power System and Sensitivity Analysis

In this research the formulation of the optimal development strategy for the Armenian power system is based on Scenario A, which describes the best economic and energy development of the country. Such an approach is justified because the worst case development Scenario B assumes maximum required capacity deficit only at the end of the considered period. Moreover, Scenario A is more likely to match the economic
development policy of the Armenian government, and it also seems to be the most realistic one.

The model simulations are also taking into account the insufficient level of local energy resources in Armenia, which always depends on imported energy resources. The negative impact of such dependence was significant especially in 1993-1994, prior to the restart of Medzamor NPP. Therefore, any energy diversification and security program designed for Armenia should always consider this issue as critical and very important.

It has been previously mentioned that the electricity produced by NPP in the countries with insufficient energy resources is considered to be a local energy production. This conclusion is based on two assumptions. First, the cost of nuclear fuel is significantly lower compared to the amount of investments. And second, though this fuel is imported it can be stored for a long period of time. This assumption is included in the model as energy independence and security condition.

The use of hydro energy resources in Armenia should be limited because of increasing environmental impact, and maintaining the strategically important water resources of the country. This idea is incorporated in the model as environmental constraint.

The results of modeling the optimal development strategy of the Armenian power system are illustrated in Table 4.10. It shows the optimal capacities, their types and optimal introduction time into the power system:

Under Scenario A we find that if the Medzamor NPP continues to operate until 2014, then according to the modeling results it should immediately be replaced by new NPP with the installed capacity of 480 MW to maintain the necessary level of energy
independence and security of the country. Then in 2015 and 2016 the model introduces two hydro power plants with the total installed capacity of 250 MW. Finally, at the end of the considered period in 2017-2020 thermal power plants with total capacity of 668 MW should be introduced into the power system.

The amount of capital investments necessary for the optimal development of the Armenian power system is about 1.38 billion US dollars.

<table>
<thead>
<tr>
<th>Projection period, year</th>
<th>Minimum total expenses, US dollars</th>
<th>Capacity of new thermal power plants, MW</th>
<th>Capacity of new hydro power plants, MW</th>
<th>Capacity of new nuclear power plants, MW</th>
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<tbody>
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<td>2000</td>
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<tr>
<td>2014</td>
<td>$600,525,674.58</td>
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<td>480</td>
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<tr>
<td>2015</td>
<td>$33,789,800.88</td>
<td>-</td>
<td>95</td>
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<tr>
<td>2016</td>
<td>$61,746,415.08</td>
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<td>155</td>
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<tr>
<td>2017</td>
<td>$133,040,236.51</td>
<td>155.3</td>
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<tr>
<td>2018</td>
<td>$157,928,098.39</td>
<td>164.6</td>
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<tr>
<td>2019</td>
<td>$183,649,462.07</td>
<td>170.9</td>
<td>-</td>
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<tr>
<td>2020</td>
<td>$213,390,143.83</td>
<td>177.3</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>$1,384,069,831.35</strong></td>
<td><strong>668.1</strong></td>
<td><strong>250</strong></td>
<td><strong>480</strong></td>
</tr>
</tbody>
</table>

Under Scenario B we also see that if the Medzamor NPP continues to operate until 2014, then according to the modeling results it should immediately be replaced by new
NPP with the installed capacity of 380 MW to maintain the necessary level of energy independence and security of the country.

It has been previously mentioned that in this project the formulation of the optimal development strategy for the Armenian power system is based on Scenario A, because under Scenario B the deficit of maximum capacity in the system exists only at the end of the considered period. And it is satisfied by introducing a new NPP with the installed capacity of 380 MW.

The graphical view of the optimal development of the Armenian power system based on Scenario A is shown in Figure 4.5.
Sensitivity analysis of the results

Since the initial information used in this model is partially stochastic it is useful to see how sensitive the original optimal solution is to the various parameters of the model. This is usually implemented by changing the value of the parameter from its initial estimate to other possibilities in the range of likely values. The optimal solution can be reliable only when it is justified by the results of sensitivity analysis. Moreover, sometimes the constraints of a problem are resulting from management policy decisions, which need to be reviewed after estimating their potential impact. Thus, it is very important to check the optimal strategy solution of the linear model by sensitivity analysis. As a result there may be parameters that do not affect the optimal solution, as well as other factors that can significantly change the optimal values.

In our optimal development strategy formulation problem the sensitivity analysis is conducted by studying the possible changes of work hours of the maximum capacity of the system. We analyze the development strategy of the Armenian power system under Scenario A.

The work hours of the maximum capacity operation can increase because of the developing central heating system and increasing use of natural gas. In this analysis we assume that this parameter will increase by 150 hours in 2010, 200 hours in 2015, and 250 hours in 2020. As a result the maximum capacity demand of the system and some other energy parameters are changed, which are illustrated in Table 4.11 – 4.12.
Table 4.11. Sensitivity analysis – The change in the maximum capacity demand of the Armenian power system

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<tr>
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</thead>
<tbody>
<tr>
<td>Maximum capacity demand of the system, MW</td>
<td>1123</td>
<td>1382</td>
<td>1776</td>
<td>2008</td>
<td>2241</td>
</tr>
<tr>
<td>Work hours of maximum capacity operation in the system, hour</td>
<td>4693</td>
<td>5000</td>
<td>5250</td>
<td>5404</td>
<td>5520</td>
</tr>
<tr>
<td>Electricity demand, TWh</td>
<td>5.27</td>
<td>6.91</td>
<td>9.32</td>
<td>10.85</td>
<td>12.37</td>
</tr>
<tr>
<td>Increase of work hours of the maximum capacity operation in the system, hour</td>
<td>0</td>
<td>+100</td>
<td>+150</td>
<td>+200</td>
<td>+250</td>
</tr>
<tr>
<td>Decrease of maximum capacity demand of the system, MW</td>
<td>1123</td>
<td>1355</td>
<td>1727</td>
<td>1936</td>
<td>2144</td>
</tr>
</tbody>
</table>
Table 4.12. Scenario A – The change of projected energy parameters resulting from increased work hours of the maximum capacity in the Armenian power system

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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GDP, 10^6 US$ 98</td>
<td>2020</td>
<td>2141</td>
<td>2270</td>
<td>2406</td>
<td>2550</td>
<td>2703</td>
<td>2865</td>
<td>3037</td>
<td>3220</td>
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<td>4319</td>
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<td>4583</td>
<td>4720</td>
<td>4862</td>
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</tr>
<tr>
<td>4</td>
<td>Maximum loading of the system, MW</td>
<td>1123</td>
<td>1169</td>
<td>1216</td>
<td>1262</td>
<td>1309</td>
<td>1355</td>
<td>1429</td>
<td>1504</td>
<td>1578</td>
<td>1653</td>
<td>1727</td>
<td>1769</td>
<td>1811</td>
<td>1852</td>
<td>1894</td>
<td>1936</td>
<td>1978</td>
<td>2019</td>
<td>2061</td>
<td>2102</td>
<td>2144</td>
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</tr>
<tr>
<td>5</td>
<td>Reserve capacity of the system, MW</td>
<td>336.9</td>
<td>350.8</td>
<td>364.7</td>
<td>378.7</td>
<td>392.6</td>
<td>406.5</td>
<td>428.8</td>
<td>451.1</td>
<td>473.5</td>
<td>495.8</td>
<td>518.1</td>
<td>530.6</td>
<td>543.2</td>
<td>555.7</td>
<td>568.3</td>
<td>580.8</td>
<td>593.3</td>
<td>605.8</td>
<td>618.2</td>
<td>630.7</td>
<td>643.2</td>
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</tr>
<tr>
<td>6</td>
<td>Total capacity of existing power plants in the system, MW</td>
<td>3090</td>
<td>3087</td>
<td>3083</td>
<td>3072</td>
<td>3054</td>
<td>3028</td>
<td>2995</td>
<td>2955</td>
<td>2907</td>
<td>2852</td>
<td>2790</td>
<td>2720</td>
<td>2645</td>
<td>2558</td>
<td>2121</td>
<td>2036</td>
<td>1945</td>
<td>1847</td>
<td>1743</td>
<td>1632</td>
<td>1515</td>
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</tr>
<tr>
<td>7</td>
<td>Total manageable capacity of the power system, MW</td>
<td>Deficit</td>
<td>-</td>
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<tr>
<td></td>
<td>Surplus</td>
<td>+1630</td>
<td>+1567</td>
<td>+1503</td>
<td>+1431</td>
<td>+1353</td>
<td>+1267</td>
<td>+1137</td>
<td>+1000</td>
<td>+855</td>
<td>+704</td>
<td>+545</td>
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<td>+289</td>
<td>+150</td>
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</tbody>
</table>
Taking into account the results of the sensitivity analysis we make additional model simulations for the optimal development strategy problem of the Armenian power system, which is summarized in Table 4.13.

<table>
<thead>
<tr>
<th>Projection period, year</th>
<th>Minimum total expenses, US dollars</th>
<th>Capacity of new thermal power plants, MW</th>
<th>Capacity of new hydro power plants, MW</th>
<th>Capacity of new nuclear power plants, MW</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
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<td>2002</td>
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<td>2014</td>
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<td>2016</td>
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<td>2017</td>
<td>$99,959,506.58</td>
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<td>2020</td>
<td>$205,687,397.52</td>
<td>170.9</td>
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<tr>
<td>Total</td>
<td>$1,266,227,945.12</td>
<td>572</td>
<td>250</td>
<td>450</td>
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</table>

We find that after conducting the sensitivity analysis the optimal solution has slightly changed. It follows that if the Medzamor NPP continues to operate until 2014, then according to the new modeling results it should immediately be replaced by new NPP with the installed capacity of 450 MW to maintain the necessary level of energy independence and security of the country. Then, from 2015 to 2017 the model introduces
three hydro power plants with the total installed capacity of 250 MW. Finally, the model simulations suggest introducing four thermal power plants with the total installed capacity of 572 MW within the period of 2017-2020. The percentage change of optimal results after the sensitivity analysis is illustrated in Table 4.14.

<table>
<thead>
<tr>
<th>Projection period, year</th>
<th>Results of the optimal solution</th>
<th>Results of the optimal solution after conducting the sensitivity analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>TPP, MW</strong></td>
<td><strong>HPP, MW</strong></td>
</tr>
<tr>
<td>2014</td>
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<tr>
<td>2015</td>
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<td>2018</td>
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<td>2019</td>
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<td>-</td>
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<tr>
<td>2020</td>
<td>177.3</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>668.1</td>
<td>250</td>
</tr>
<tr>
<td>Percentage change of the optimal solution after the sensitivity analysis, %</td>
<td>-14.38%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

The quantity and introduction years of the hydro power plants have changed but their aggregate installed capacity is the same as before. The capacity of the projected nuclear power plant has declined by 6.25%, which can be accepted as limited change. The most significant changes occur for thermal power plants resulting in the reduction of the total installed capacity by 14.38%. Therefore, the latter are the most sensitive parameters of the model, which can be explained by their late introduction into the system when the forecasted maximum capacity has higher level of uncertainty. Finally, the amount of
investments declines to 1.27 billion US dollars, which is less from the optimal value by 0.11 billion US dollars.

From aforementioned analysis we conclude that to overcome the uncertainties that have a negative effect on both the economy and the energy sector, as well as to keep the considered risks at an acceptable level, we need to carefully consider the current change of the factors that negatively affect the forecasted demand in energy and maximum capacities. It is recommended that the average and long-term scenarios for the economy and energy field development be checked year by year to either verify the initially created data or, if necessary, to change investment programs of development.

Finally, the solution of the optimal development strategy formulation for the Armenian power system is compared with the results of “Strategy Paper” prepared by TACIS, which is shown in Table 4.15.

<table>
<thead>
<tr>
<th>Projection period, year</th>
<th>Capacities of newly introduced thermal power plants, MW</th>
<th>Capacities of newly introduced hydro power plants, MW</th>
<th>Capacities of newly introduced nuclear power plants, MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thesis research results (optimal solution)</td>
<td>TACIS</td>
<td>Thesis research results (optimal solution)</td>
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<tr>
<td>2000</td>
<td>-</td>
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<td>-</td>
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<td>2012</td>
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</table>
From the comparison of the results we can clearly see that there are significant differences between our optimal strategy and TACIS projections regarding the capacities and introduction times of large power plants. Particularly, our optimal solution introduces thermal power plants within the period of 2017-2020 with the total installed capacity of 668 MW, while TACIS paper projected gradual introduction of such power plants with the total installed capacity of 860 MW beginning from 2003. Moreover, TACIS is not projecting the construction of another nuclear power plant, which will definitely affect the energy independence of the country. In contrast to TACIS paper, this issue is one of the most important constraints in our model, and it is satisfied by introducing a new nuclear power plant in 2014 with the installed capacity of 480 MW.

There is also significant difference in hydropower development projections between our optimal solution and TACIS results. It should be mentioned that TACIS paper projected introduction of alternative sources of electricity from 2008 to 2011 with the total installed capacity of 75 MW. Since these energy sources are still in the process of development in Armenia, we do not consider them as main sources of electricity production in our research.

<table>
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<tr>
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<td>2019</td>
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<td>195.5</td>
<td>480</td>
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</tbody>
</table>

Continuation of Table 4.15
Conclusions

Based on the results of this research project several conclusions are made, which are summarized below:

1. The formulation of optimal expansion strategy for the power system is the main problem in perspective planning the energy sector of the country.

2. During the considered period stochastic data are used because of uncertainty, which can produce not the optimal solution. For that reason the optimal solution needs to be checked and verified by appropriate sensitivity analysis.

3. For this type of the problem it is recommended to use linear programming, and always check the results by sensitivity analysis.

4. The environmental impact is one of the most important factors in determining the optimal capacities of hydro power plants. During the decision making process for the HPP construction the role of environmental impact was traditionally underestimated. Each new HPP removes a part of a natural river forever from the natural environment and converts it into a regular lake. An increasing social contradiction to the environmental impact of HPP and also geographical conditions of the region will lead to a decreasing utility of additional HPP construction, which results from the optimal level of social surplus. Thus, we use additional model for cost-benefit analysis of hydropower development, and find that for any country the marginal cost of installed hydro power capacity will increase, and water resources will become scarcer because of growing environmental impact.
5. For countries with limited energy resources like Armenia, the certain level of energy independence and security can be provided by nuclear power plants. This is incorporated in our results by introducing a nuclear power plant in 2014 with the installed capacity of 480 MW. This solution is based on the fact that nuclear power plants can be considered as local energy sources because of their long operation period regardless the proximity of fuel resources.

6. Considering the geography and environmental issues in Armenia, we recommend studying the optimal use of local water resources for electricity production not to threaten the strategically important water reserves of the country.

7. Expansion of hydropower plants in Armenia should be terminated prior to the intersection of its marginal costs with marginal benefits of HPP capacity expansion. After a certain level of installed capacity, the marginal cost of HPP will increase if the decision makers follow the optimality condition of building the most efficient HPP first.

8. The optimal development strategy of the power system is the main element that enables the estimation of the vitality of specific energy policy problems and the formulation of investment programs in the energy sector. The country-specific infrastructure and geography as well as uncertain economic forecasts for Armenia, make the formulation of the optimal development strategy for the power system more complicated and more necessary. The optimal development strategy of the power system will serve as a basis for the optimal expansion of the power sector.

There are two risks related to the optimal expansion strategy:
• Underestimation of energy infrastructures, which has great social influence. If the deficit continues for a long time and demand is not satisfied, then the economic development of the country will be in danger.

• Overestimation of energy infrastructures, which can lead to inappropriate distribution or waste of financial resources.

It has to be mentioned that this dual risk has an asymmetric character. In fact, the power system damaged from underestimation can not be restored in a short period, therefore causing a significant damage to the country. Temporary and average overestimation has a limited effect and in many cases it can be decreased or even prevented by appropriate regulations. In order to overcome the uncertainties that have a negative effect on both the economy and the energy sector in Armenia, as well as to keep the considered risks at an acceptable level, we need to carefully consider the current change of the factors that negatively affect the forecasted demand in energy and maximum capacities. It is recommended that the average and long-term scenarios for the economy and energy field development be checked year by year to either verify the initially created data or, if necessary, to change investment programs of development.

9. The considered optimal expansion model of the power system and the method of solution could be applied for the formulation of the optimal development strategy of the power system for any country, especially for the countries that have insufficient energy resources and are in a transition period.
References


