RIGA TECHNICAL UNIVERSITY
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SOLVING POWER FACILITY DEVELOPMENT TASKS IN MARKET-ECONOMY AND UNCERTAINTY CONDITIONS

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on April 25, 2019 11:00 at the Faculty of Power and Electrical Engineering of Riga Technical University, Riga, Āzenes street 12/1, room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Igor Moshkin ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction; 6 chapters; Conclusions; 38 figures; 15 tables; the total number of pages is 126. The Bibliography contains 145 titles.

TABLE OF CONTENTS

1. GENERAL DESCRIPTION OF THE DOCTORAL THESIS

Topicality of the subject of the Doctoral Thesis

Human quality of life directly depends on energy consumption. During the course of historical development, the obtaining of new useful products of all types from natural systems is linked with increasing energy consumption.

Since the beginning of the current century, the consumption of electricity for the production of one agricultural product item in developed countries has increased 8–10 times, the power consumption for the production of one industrially produced item – 10–12 times [1], [2].

Saving energy by increasing the efficiency of consumption, actually results in an increase in consumption, not a decrease. Since the particular type of function requires less fuel, the released resources are diverted for other purposes. As a result, economic activity and consumption of energy resources grows.

The need for energy is obvious to people's normal life activity, industry and the continuation of global civilization development. The energy problem for the global community is very topical and it is not limited to the cost of coal, oil and gas reserves, and to the cost of their extraction, processing and use. Every year, environmental problems are becoming more pressing. In a modern world, it is imperative to review the policy in the field of energetics.

The growth of global population, limited access to energy resources and striving for the benefits offered by contemporary civilisation have resulted in the creation of huge scale energy systems [2].

They include thousands of generators, transformers, hundreds of thousands of kilometres of electricity transmission lines and millions of units of power consumption equipment. Maintenance and development of the energy system of any country requires significant investments. Several environmental factors greatly affect the operation of the energy system: temperature, wind speed, intensity of solar radiation. Changes in the conditions of operation create the necessity for changes in the operation mode of an energy object. Many factors cannot be precisely measured or described as probabilistic values, therefore many decisions must be made under the conditions of uncertainty.

This is one of the factors that raises the topicality of several energy-related problems, such as:

- efficiency and accessibility of energy supply;
- safety of energy supply;
- environmental impact;
- sustainability.

The significance of the aforementioned problems has become a causative factor for the adoption of international level decisions regarding the restructuring of energy systems and changes in control system. The energy system was divided into several legally independent, mutually competing parts. Competition has become one of the major factors that can ensure rational development of energy systems. Companies that make correct, technically and economically justified decisions will survive under the conditions of competition. **Energy markets** have been organised to stimulate competitiveness.

Division of the system into several parts reduces the size of the objects controlled, which simplifies the management, as well as decision making models and algorithms, while creating new problems that are primarily linked to mutual interaction of the actions taken by the competitors and market conditions.

Another significant process is occurring along with the division of systems into parts and reduction in their size – mass introduction of **renewable energy sources** into practice. In many cases, small capacity generators are developed and located close to consumers. It can be stated definitely that the number of dispersed generators within energy systems is increasing rapidly. Political decisions and various types of support, which are provided for by the decisions made on national level, stimulate the use of renewable energy sources.

The development of **electricity networks** is implemented to ensure competitiveness in wide regions and use the advantages provided by large energy systems. This process is especially important for Latvia and the Baltic States. New high voltage transmission lines have been built or are being built, the reconstruction of substations is implemented.

To sum up, we can say that significant changes are taking place in the energy sector. These changes require construction of new objects or reconstruction of the existing objects. In all cases, the changes are preceded by **respective projects**. Decisions that are made during the design phase determine the conformity of the scheduled object to all global targets of energy system development. Therefore, research dedicated to the substantiation of design decisions is highly topical and is capable of promoting the achievement of these electricity supply targets.

The hypothesis, the objective and the tasks of the Doctoral Thesis

Hypothesis of the Doctoral Thesis. Co-operation among the participants of the power system development process may increase the profitability of projects.

Objective of the Doctoral Thesis. The objective of the paper is to develop the operation of legally independent parts of the power system in the conditions of market economy and uncertainty with the purpose of improving the efficiency of power supply. In order to reach this objective, the following **tasks** are addressed:

- analysis of approaches and methodologies used in the operation of separately operating parts of power supply systems during their design and operation;
- analysis and development of approaches and methodologies of resolving technical and economic substantiation tasks in the projects of power facilities;
- substantiation of the efficiency of co-operative behaviour and synthesis of a problem resolution algorithm;
- substantiation of the use of methods of co-operative game theory in the designing of high-voltage power transmission lines;
- synthesis of an algorithm for solving the problem of increasing the profit and its efficient distribution for the project of a powerful solar power plant by using the new calculation and forecasting model and the methods of co-operative game theory;

- substantiation of the efficiency of co-operative behaviour in small hydropower plants and solar power plants and synthesis of an algorithm for solving development problems.

The scientific novelty of the Doctoral Thesis

The scientific results of the research performed within the Doctoral Thesis are as follows.

- An analysis of implementation methods of power system development and decision-making approaches that use game theory have been conducted.
- The usefulness and efficiency of co-operative approach in designing and implementing of designs of electrical power plants, electrical networks and prosumer installations have been substantiated. The corresponding algorithms and detailed models have been synthesised, input data have been identified and collected, and model verification has been performed.
- The objective functions of designing tasks have been substantiated and algorithms and software for performing calculations have been synthesised by using stochastic formulation of problems.

Methods and tools of the research

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

1. Cooperative game theory and Shapley Value.
2. “MatLab 2013a” interactive environment for intensive calculations, data analysis and visual representation of the data.
3. “Microsoft Excel 2013” software.
4. The stochastic approach and Monte-Carlo method for solving the problem of optimising entity structure and parameters.
5. A database of measurements of power production by a solar power plant and the power demand of several Latvian consumers.

Practical importance of the Doctoral Thesis

The practical significance of the algorithms and methodology offered in the Doctoral Thesis are as follows.

1. The use of the developed mathematical models in the development projects of power systems will allow increasing of the operation efficiency of the renewable energy generation sources of Latvia in the electricity market. The methodology can be used by many designing organisations as well as operators of transmission and distribution networks.
2. The recommendation to change the conditions for connecting producers can be implemented if a corresponding decision is adopted by the Ministry of Economy of the Republic of Latvia.

3. The algorithms and methodology were used for the implementation of projects funded by the European Communities (within the framework of the HORIZON 2020 programme) as well as the Latvian Council of Science and National Research Programmes for Energy.
4. The proposed and substantiated approach of co-operative construction of prosumer installations can be used for the construction of thousands of low-capacity solar power plants.
5. An example has been developed and the gain offered by the project has been calculated by using methods of co-operative game theory in a real-life Latvian 330 kV high-voltage transmission line project Kurzemes Loks (Kurzeme Ring).

Personal contribution of the author to the performed research

In 1953, American economist and mathematician Lloyd Stowell Shapley, who later (2012) became a winner of the Nobel prize in economics, offered his version for the resolution of coalition games, where each game is associated with a sole distribution of additional profit – the Shapley value. This discovery immediately became widely used in economics and mathematics. The doctoral theses of M. Bochkarjova, G. Vempers, N. Jankovskis, S. Berjozkina, R. Petrichenko, and H. H. Coban developed at the Institute of Power Engineering of Riga Technical University were dedicated to the use of the aforementioned approach to energy problems. This Doctoral Thesis serves as the continuation of the abovementioned Doctoral Thesis. Furthermore, the following new tasks were formulated and resolved in co-operation with the scientific supervisor.

1. A real-life project Kurzemes Loks (Kurzeme Ring) in Latvia within which the possibilities of applying game theory were reviewed. The potential gain from the project was calculated by using the methods of co-operative game theory, resolving the contradictions between the transmission and distribution networks.
2. Development of methodology for the technical and economic substantiation of the design for constructing a powerful solar power plant and connecting it to the grid.
3. Substantiation of possibilities of cooperation among prosumers and a resolution algorithm;
4. Assessment of collaboration possibilities between solar power plants and hydropower plants (jointly with H. H. Coban).
5. The database of Latvian consumers, collected by Dr. Nauris Jankovskis, was used.

Result analysis of all calculations, programming and checking of calculation procedure, presentation of results, conclusions and summaries are the personal property of the author.

Approbation of the Doctoral Thesis

Publications

1. I. Moshkin, S. Berjozkina, A. Sauhats. Transmission Network Development Planning by Using a Cooperative Game Theory Approach. Conference proceedings. The 7th

International Conference on Electrical and Control Technologies, Kaunas, Lithuania, 2012.

2. I. Moshkin, S. Berjozkina, A. Sauhats. Solving of Power Systems Development Tasks in Market and Uncertainty Conditions. Conference Proceedings. EEM 2012: 9th International Conference on the European Energy Market, Florence, Italy.
3. A. Sauhats, A. Utans, M. Silarajs, J. Kucajevs, D. Antonovs, E. Biela and I. Moshkin. Power System Dynamical Simulation Application for Out-of-Step Relay Testing. Journal of Energy and Power Engineering, ISSN1934-8975, USA, 2012.
4. I. Moshkin, A. Sauhats. Transmission and Optical Networks Creating By Using a Cooperative Game Theory Approach. 53rd International Scientific Conference of Riga Technical University, Riga, Latvia, 2012.
5. I. Moshkin, A. Sauhats. Solving District Heating Problems by Using Cooperative Game Theory Methods. 2016 IEEE International Conference on Environment and Electrical Engineering (EEEIC 2016), Florence, Italy, June 6–9, 2017.
6. I. Moshkin, A. Sauhats. Solving District Heating Optimization Problems in the Market Conditions. 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga-Cesis, Latvia, October 13–14, 2016.
7. Hasan H. Coban, Igors Moskins, Antans Sauhats. The Optimization Capabilities of Combined Solar/Hydropower Plant Operation. The 4th Workshop on AIEEE'16, Vilnius, Lithuania, November 10–12, 2016.
8. I. Moshkin, J. Kucajevs. Solving Company Cooperation Tasks in the Construction of Power Transmission Lines. 17th IEEE International Conference on Environment and Electrical Engineering, Milan, Italy, June 6–9, 2017.
9. V. Oboskalov, R. Valiev, S. Gusev A. Mahnitko, I. Moshkin. An Analytical Approach for Calculations of Power System Generation Adequacy Indices (accepted for publication). 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, October 12–13, 2017.
10. Antans Sauhats, Laila Zemite, Lubov Petrichenko, Igor Moshkin and Aivo Jasevics. Estimating the Economic Impacts of Net Metering Schemes for Residential PV Systems with Profiling of Power Demand, Generation, and Market Prices. Energies (ISSN 1996-1073; CODEN: ENERGA), 2018.
11. Lubov Petrichenko, Laila Zemite, Galina Bockarjova, Igor Moshkin, Aivo Jasevics. *Shapley value-based distribution of the costs of solar photovoltaic plant grid connection.*

The results were reported and discussed in the following international conferences

1. The 7th International Conference on Electrical and Control Technologies, Kaunas, Lithuania, 3–4 May 2012.
2. EEM 2012: 9th International Conference on the European Energy Market, Florence, Italy, 10–12 May 2012.

3. 53rd International Scientific Conference of Riga Technical University, Riga, Latvia, 11–12 October 2012.
4. IEEE International Conference on Environment and Electrical Engineering (EEEIC 2016), Florence, Italy, June 6–9, 2017.
5. 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga-Cesis, Latvia, October 13–14, 2016.
6. The 4th Workshop on AIEEE'16, Vilnius, Lithuania, November 10–12, 2016.
7. 17th IEEE International Conference on Environment and Electrical Engineering, Milan, Italy, June 6–9, 2017

Sructure and contents of the Doctoral Thesis

The Doctoral Thesis is written in English, and it contains an introduction, 6 chapters, Conclusions, the bibliography containing 145 reference sources. It is illustrated by 38 figures and 15 tables. The volume of the present Thesis is 118 pages.

2. PROBLEMS AND SOLUTIONS IN THE DEVELOPMENT AND PLANNING OF POWER SYSTEMS AND THEIR ENTITIES

In keeping with the requirements, planning problems were formulated, which comprised the following steps: definition of the planning goals, selection of criteria and search for the best course of development. Along with the increase in the energy demand, the discussed task becomes more complex due to several main reasons.

1. The increase in the dimensions of power systems and in the number of their elements. Even a small power system comprises hundreds of thousands of elements (generators, lines of various voltage, electrical utilisation equipment, substations).
2. Requirements regarding reliability are becoming more stringent, especially in the power supply of large cities.
3. The amount of available technologies has increased, leading to the need to consider new development alternatives.
4. Energy production has started to have a most powerful impact on climate.

Projects can be extremely different. It is possible to design power plants with capacities of a matter of gigawatts and with required investments in the amount of billions of euros. An alternative solution is designing microgeneration with capacities of a matter of kilowatts, with required investments in the amount of hundreds of euros. In the first case, the designing involves hundreds of specialists; in the second one, one certified specialist is enough. At the same time, the designing steps that can be singled out for both borderline cases are similar:

1) estimation of the amount of energy and the power demand;
2) selection of technologies;
3) evaluation of the amount of investment;
4) evaluation of profitability;
5) obtaining approval from government authorities for the setting up of the planned facility;
6) coordination of the operation with the whole power system;
7) coordination of operation with other utility systems (transportation, communications, possibly gas utilities etc.);
8) assessment of the environmental impact.

Public efforts to improve efficiency and safety of energy supply and mitigate the impact on climate change have led to significant changes in energy production [3], such as:

1) rapidly growing number of renewable energy sources (RES), power and proportion of them in the amount of energy production [3].
2) the role of cogeneration plants has increased [4], [5].

In many countries, the power system is divided into several independent parts, which, on the one hand, compete with each other, and on the other hand, provide for the exchange of reserves, assisting partners in case of need. In order to ensure the coordination of independent energy producers, different types of energy markets have been created, through which certain procedures are introduced for joint activities. At the same time, variable energy prices are formed in the market conditions. Thus, manufacturers are forced to adjust energy production to variable prices [6].

Summarizing the peculiarities of the functioning of modern power system, it is claimed that the activities of the energy companies and the factors characterizing them, such as: the amount of produced energy, the amount of used fuel, profit, production costs, etc. are variable and dependent on natural factors. A lot of influencing factors and processes must be taken into account when planning the future power system modes. In order to carry out the analysis of energy objects, the mathematical models of influencing processes and objects to be viewed are necessary. An important part of this paper is devoted to synthesis of such models.

To understand the complexity of the planning task, the main sources of difficulties are considered; it is noted that serious difficulties emerge, such as:

- estimating cash flow by setting many goals and calculating a large number of criteria;
- considering the impact of stochastic processes;
- choosing and realizing the optimization procedure.

The Shapley approach [7] and distribution of the gain between the members of the coalition – Shapley value is considered separately. In case of cooperative behaviour, there is a problem of revenue distribution between the members of coalitions. The simple approach would be to give to each player its contribution c_i:

$$c_i = R(S \cup \{i\}) - R(S), \qquad (2.1)$$

where

$R(S)$ – the revenue of coalition S;

$R(S \cup \{i\})$ – the revenue of coalition S with participation of actor i.

However, such an approach is not anonymous, i.e. ordering of the players makes difference in the amount they are rewarded.

In game theory, the Shapley value (2.2) describes one approach for fair allocation of gains avoiding the mentioned drawback. Fair allocation is ensured by selecting uniformly a random ordering and rewarding each player with its expected marginal cost in ordering. Since players can form $n!$ possible random orderings, the probability of set S being ranked exactly before player i, is $|S|!\,(n-1-|S|)!/n!$. Thus the additional amount that the player i gets is

$$\varphi_i = \sum_{i \notin S \subseteq N} \frac{|S|!(n-1-|S|)!}{n!} (R(S \cup \{i\}) - R(S)), \qquad (2.2)$$

where

n – the total number of players;

$|S|$ – size of set, S the sum extends over all subsets S of N not containing player i.

In the simplest case, when only two players participate in the game, the expression (2.2. is simplified and obtains the following form:

$$\varphi_1 = \varphi_2 = \frac{(R(S \cup \{i\}) - R(S))}{2}. \qquad (2.3)$$

The Shapley value describes the fair (in a sense determined by the accepted axioms) [8], [2] distribution of additional gains in case of formation of the coalition. In particular, the definition is based on the assumption that possible combinations of the players who form the coalition are equally probable. In real life, this assumption may fail because of the differences in initiative and competence of the management of companies that participate in the market. A case of this type is discussed further, and the corresponding gain allocation algorithm is derived. With this, the following assumption is made.

Among n companies, candidate members of the coalition, there is an initiator, e.g. the j-th company that has suggested the idea to create this coalition. In this case, the coalition may be formed gradually, when the rest of the companies are one by one joining the j-th company. Doing this, the initiator can choose the following strategie: gaining maximum total profit for the initiator in the moment of forming a complete coalition from N participants. Such a strategy is based on the conviction that the set goal, i.e. to form a complete coalition from N players, will be achieved. The procedure of looking for maximum profit can be based on searching through all the possible alternatives of formation of the final coalition.

Every time when a new player joins the coalition, the following two new tasks appear.

- Distribution of gains between the members of already existing coalition and its new member. It is supposed that this task can be solved by using the Shapley value according to formula (2.2).
- Distribution of the additional gains that appears due to a new member joining the existing coalition between its old members. It is supposed that such distribution will be in proportion to the guaranteed (and probably legally approved) revenues.

Publications featuring the Shapley approach [20]–[22], [24], [26] have been reviewed, a drawback common for the reviewed articles has been noted – setting the cooperative tasks, in which coalitions have already been created. In fact, the question is only about redistributing benefits. This redistribution requires not only calculations, but also additional measurements, the costs of which may not justify the benefits of using a new approach. The statement of such a task does not use the first, perhaps the main advantage of the cooperative game approach; this approach allows to transform competitors into partners and reach a new, beneficial situation for all of them.

The tasks nearest to a real power system design practice have been considered, which are formulated in the promotion paper by G. Vempers (2012) [2], where the cooperative game approach has been used to solve the tasks regarding the distribution network development and the district heating in Riga. It is noted that the variable conditions of electricity market are not taken into account in these papers.

3. SUBSTANTIATION OF THE SCHEME FOR CONNECTING PROSUMERS TO ELECTRICAL NETWORK

Development of electrical transmission and distribution networks, appearance and need for connection of new prosumers (production units with diffused generation sources and renewable energy sources) raises a topical issue regarding the choice of the electric scheme for connecting new consumers and the rational and equitable distribution of capital investments among the project participants. The appearance of new energy users results in changes in the electrical networks.

The essence of the project. It is assumed that a production unit (PR) with the maximum consumed power of 5 MW and generation using solar panels for auxiliary power supply have been proposed. An autonomous power system cannot be created due to a mismatch between generation and consumption schedules. Power exchange with the electrical network, which would receive the excess power, should be provided during periods when the applicant generates more energy than consumed and, on the contrary, returns energy when generation is lower than consumption. There is a known PR placement near the 110 kV high-voltage line. The following basic connection options are possible:

1) H-type substation;
2) simplified substation;
3) 20 kV line to the nearest 110/20 kV substation.

Each option can be implemented in different ways, meaning the existence of many suboptions.

The following should be substantiated and selected:

1) a capacity of the solar power plant;
2) a connection option;
3) a billing system between the PR owners and the electrical network operators.

Expenses and benefits of the players. When comparing the options, the criteria for assessing their effectiveness should be selected. Let us assume that each player tries to maximize its annual profit. Therefore, it must be calculated. The most advantageous for each player is the option that provides the lowest cost of project implementation and maintenance, which can be calculated differently. Let us assume that some additional profit has been calculated for the networks, which can be received in the event of implementation of the project in question. A virtual profit similar to the benefits of using solar energy will be calculated for the project applicant. Namely, we will evaluate the reduction of energy costs by using a solar power plant compared to the option when the production unit were built without its own energy source.

When determining the total annual benefits of the selected alternative solutions, the size of the connection capacity, the load distances from the substations and the high-voltage line, the value of the land used, and the equipment costs should be taken into account. Output data for cost calculations and constraint verification are strongly dependent on a particular situation, so the main results of the selected examples will be reflected further, evaluating the efficiency of the project construction in different calculation conditions and taking into account the technical constraints.

Methodology and data to be used

In order to calculate the efficiency criteria, it is necessary to describe the process changes for many years to come. This task causes uncertainty and the need to use the methods of theory of random processes.

The task is simplified by adopting the hypothesis about the stationary nature of the stochastic processes [30]. In this case, we will be able to use the historical data of the input process calculations or measurement results: generation W_{GH}, consumption W_{CH}, and price C_H. In such a case, the statistical models are not needed [31].

Process predictions are used, based on measurement of the respective processes and using the so-called *Naivo* or modified forecasting approach for generation W_{GF}, consumption W_{CF} and price C_F [33], on the basis of the assumption that the past processes will be repeated in the future, which allows taking into account the annual average price change [33]. The algorithm block scheme is presented in Fig. 3.1.

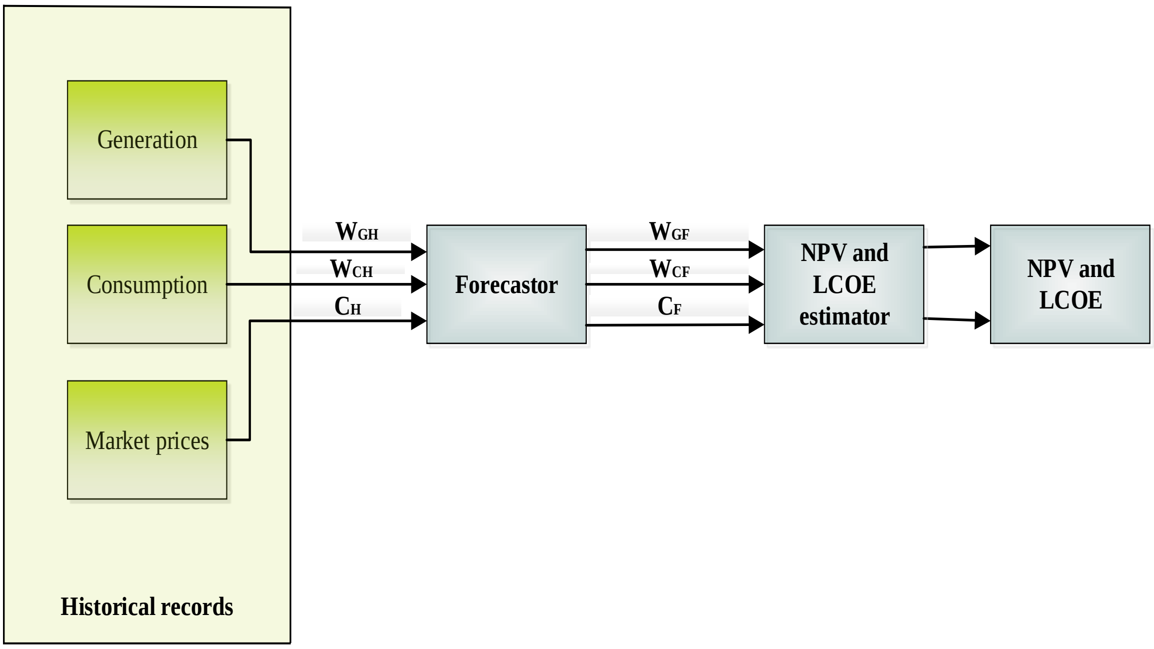

Fig. 3.1. Sheme of process prediction structure.

In the case of analyzing the benefits of the players, only the historical measurement results of one process are available, namely – the energy market price. In order to predict generation and consumption, the generation and consumer measurement records of other solar power plants can be used as an example. This opportunity will be used in this paper.

The scheme of algorithm structure for solving the prosumer efficiency evaluation task is presented in Fig. 3.2.

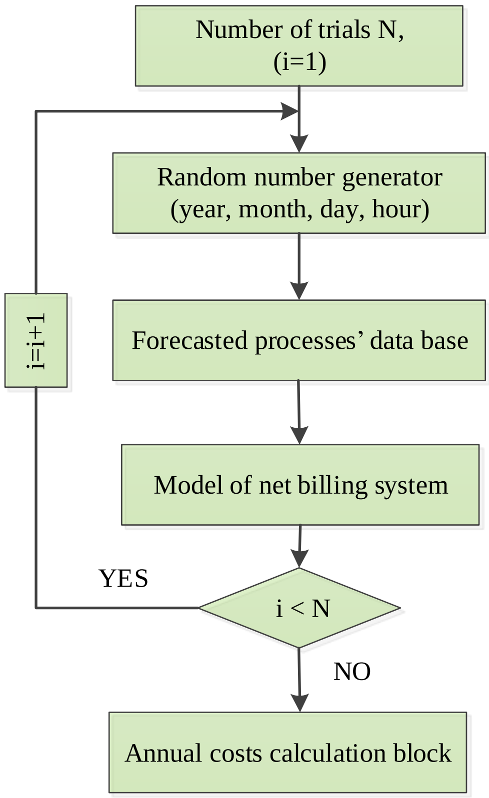

Fig. 3.2. The algorithm structure.

The algorithm uses the hourly (*i*) measurements of energy submitted to the grid, W_{G+}, and received from the grid, W_{G-}, the hourly electricity price C and the hourly electricity consumption W_C (Block 1). For every prosumer, the grid forms an individual bill, which accounts for the amounts of electricity submitted to the grid or received from the grid, Exp_{store}, (Block 2) and the hourly MC payments are accumulated. If, during a given hour, the generation amount exceeds consumption and the prosumer submits to the grid more electricity than it receives, it needs to additionally pay only for the FV component, E_{FV} (Block 3). The annual expenses *Exp* increase by this amount. Otherwise, Exp_{store} is checked. If Exp_{store} exceeds the Exp_{store} of the current month (in our case, the Exp_{store} of the preceding hours), then, in some countries, the prosumer does not have to pay the VP component E_{VP-} at this hour; however, the prosumer always has to pay for the FV component and the MC for the electricity received, C_{c+} (Block 4). Otherwise, the prosumer pays in the same way as in Block 4 or only pays for the total difference, E_{VP}, of the VP component for the current hour, Exp_{store} (Block 5). In the calculation, we assume that the prosumer pays the VP component E_{VP-}. If Exp_{store} is negative or equal to zero, the prosumer pays in full for the electricity received from the grid (as an ordinary consumer) (Block 6). Once a year, the process is started over again.

Consumers' bills contain components paid to finance the operating costs of the power system:

1) the fixed volume of (FV) component is based on the connection capacity (kVA);
2) the variable progressive (VP) component – in this component, the tariff per kWh increases along with an increasing measured consumption level;

3) the market component (MC) is equal to the day-ahead hourly price in the electricity market (for example, *NORDPOOL*) [35], [33].

This tariff is only possible with smart meters [35]. If the prosumer generates a smaller amount of electricity than it consumes (over a month), then, according to the NS, the prosumer's bill contains the FV and the VP, which include only payment for the difference between the amount of energy received from the grid and the amount of energy submitted to the grid. In the opposite case, when the prosumer consumes less than it has generated and has submitted more energy to the grid than it has received, the resulting difference is regarded as a debt of the power system, which is included in the bills of the following months. The structural diagram of the algorithm for evaluating the annual expenses *Exp* is provided in Fig. 3.4.

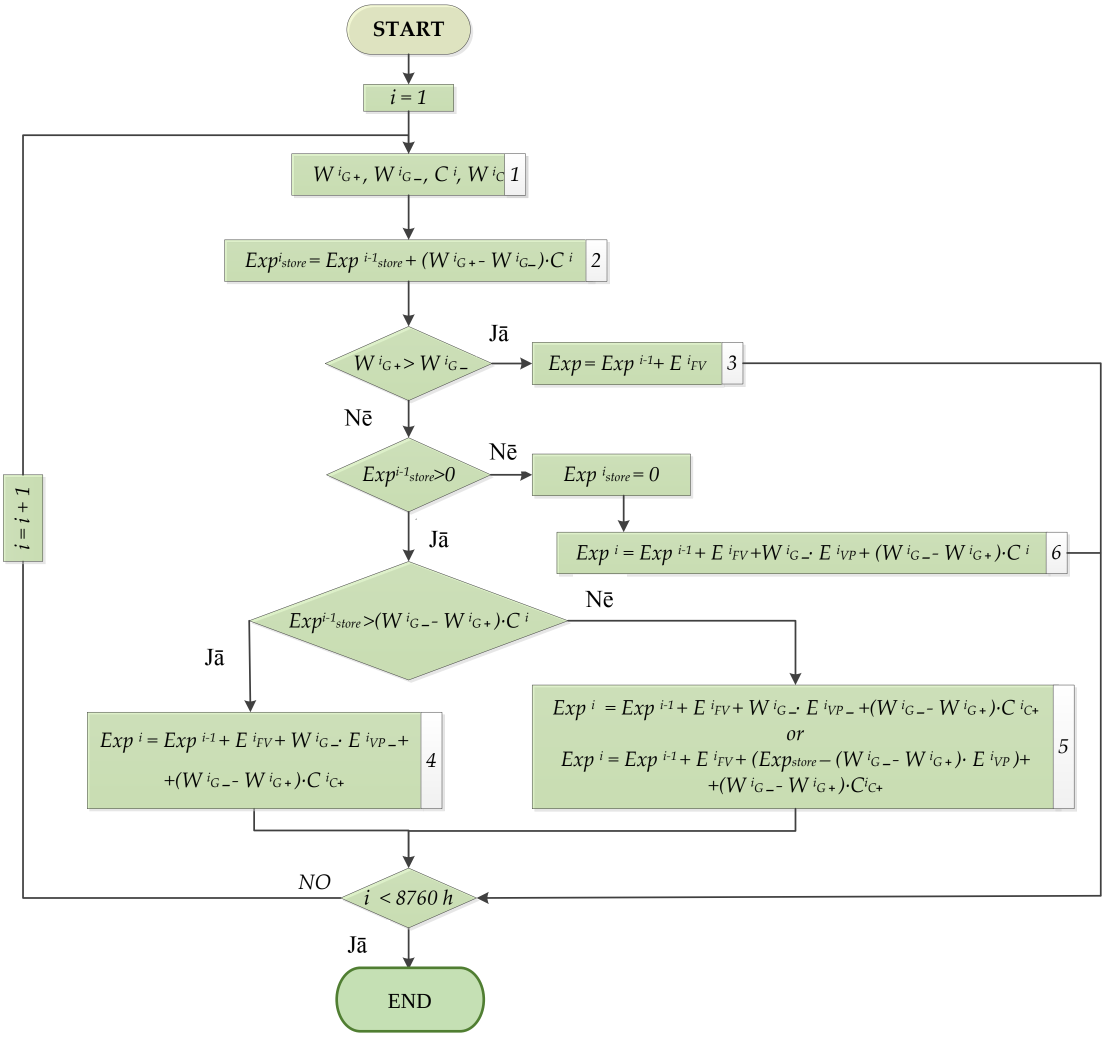

Fig. 3.4. The structure of the algorithm for evaluating annual expenses.

To analyse the feasibility of the system which is described in Fig. 3.4, prediction and simulation of random correlated processes of generation, electricity production, consumption and market electricity pricing are required.

Input information and assumptions. For case study we identify two cases:

- base case, when a householder does not have NS;
- when householder has NBS.

As already mentioned, solving the task in question requires the change in time of three input processes with one-hour step modeling.

1. Power demand: information about the power demand profiles of many prosumers is needed. We use the annual records of smart meters of 100 different randomly selected consumers [35].
2. Power generation: the records of the new generator installed in 2017 are used for simulation of the generation of 100 potential prosumers. These records are transformed by changing the capacity of the equipment for each of 100 prosumers so that the annual power generation and consumption balance is reached;
3. Electricity market prices: the *Nord Pool* market prices are used. Using the Fourier transformation [36], we distinguish the constant component for which we set the variable depending on the number of the planning year. The changes of the average price are set, using the published results and the selected scenarios.

The following limiting conditions were taken into account in the simulation.

NPV is calculated for two options: option 1 – a loan is taken; option 2 – a loan is not taken and prosumer's money savings Exp_{store} are used.

NPV is calculated, taking into account prosumer's income Exp_{store} received from PV generated electricity.

Results. The classical approach – networks and prosumer act independently. The prosumer changes in time NPV_{RL} are shown in Fig. 3. The initial investments (4 500 000 EUR) excluding the connection costs (1 200 000 EUR) are used in this calculation.

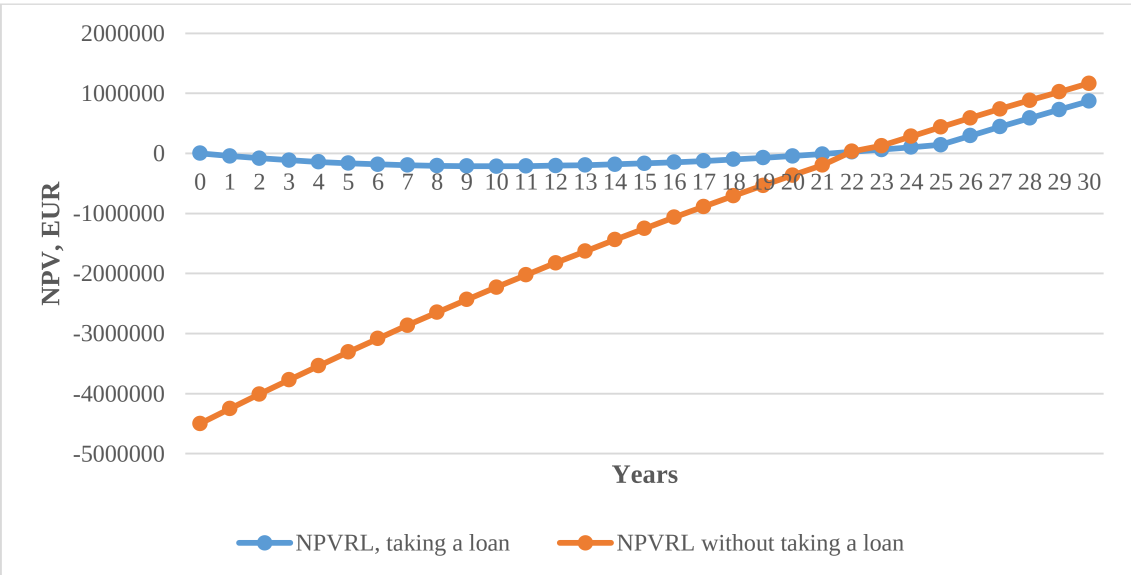

Fig. 3.5. NPV_{RL} for the NET case (excluding the connection investments).

Since the expenses of the prosumers exceed their income in the first eleven years of the planning period, the NPV_{RL} characteristic (marked blue) shows a negative tendency. Still, in the twelfth year, the prosumers' income exceeds their expenses and the NPV characteristic starts growing steadily. Only in the twenty-second year do the prosumers start gaining net income. The same situation is observed when no loan has been taken since the prosumers' investment payback period is 23 years.

A calculation is made of the gains of the high-voltage and distribution network operators from the net system, which are 158 713.53 EUR. This is almost half of the total costs (Scenario 2).

The next step is to calculate the NPV and the payback period if the connecting investments are taken into account. The results are shown in Fig. 3.6.

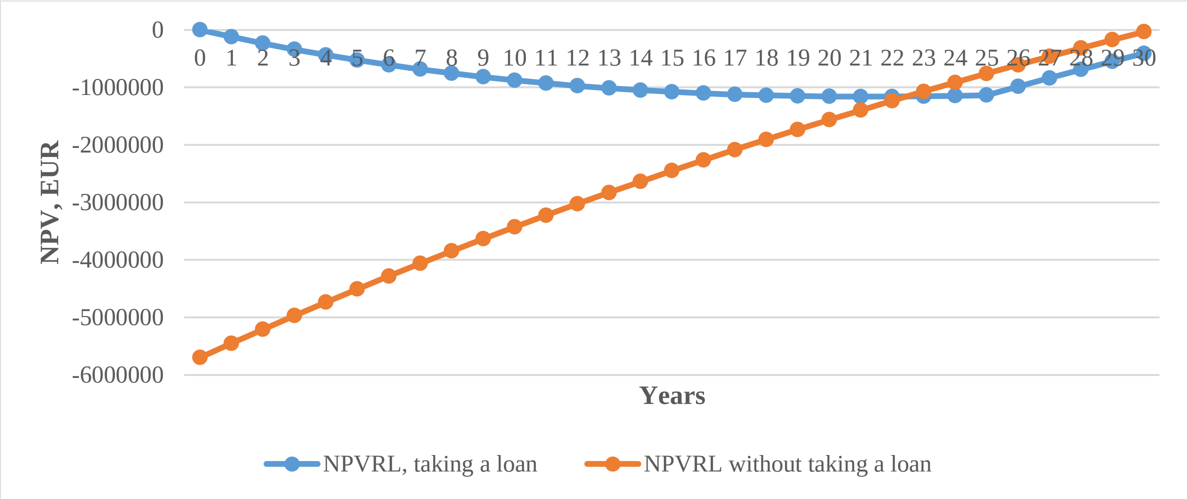

Fig. 3.6. NPV_{RL} for the NET case (including the connection investments).

When the prosumers invest their money in the purchase of solar panels and compensation of the connection costs, the payback period is more than thirty years (i.e. 31 years), which is considerably more than in the case discussed previously. This cannot stimulate the attraction of new prosumers. The situation is even worse when a loan has been taken. In the first twenty years of the planning period, the prosumers' expenses considerably exceed their income and the NPV_{RL} characteristic (marked blue) shows a negative tendency. Only in the twenty-sixth year does the prosumers' income exceed their expenses and the NPV characteristic starts growing steadily. However, the service life of a RES equipment unit is 25 years, which means that this alternative is not attractive for the prosumer.

In this alternative, when all the investments are taken into account, the conditions of the existing net system are not adapted to using smart technologies, i.e. the prosumers are not stimulated to install energy production/consumption management devices and perform management, which might give advantages both for the prosumers and the power system as a whole. At the same time, let us point out that if the project was implemented, the grid operators would receive considerable income

A coalition between the grid operators and the prosumer. Let us assume that the above reasons, if the connection costs are to be borne by the applicant, lead to the project not being implemented. In this case, investments are not needed. However, also the profit will be zero (the total profit as well as that of each player individually). Further, we will overview the project implementation conditions, assuming that the prosumer and the grid operators form a coalition. We have consciously (to improve the clarity) used a slightly simplified algorithm (without taking into account the rate of discount). The result is as follows.

The profit of the prosumers equals 252 957 EUR (avoided costs) – 180 000 EUR (paying back the investments over 25 years) = 73 000 EUR.

1. The profit of the distribution grid + the high-voltage grid equals 158 713 EUR.
2. The profit of the coalition equals approx. 230 000 EUR.

If the Shapley distribution is applied (see Chapter 2), it can be said that it is fair to distribute the coalition's profit equally among the players, i.e. 115 000 EUR – 73 000 EUR = 42 000 EUR should be additionally paid to the prosumers.

The additional payment can be implemented in different ways:

1) by increasing the tariffs, which would cause discontent among the public in Latvia;
2) by diminishing the payment for connection, which means that the prosumers in the example under consideration should be completely exempted from the connection payment;
3) by announcing a tender for receiving connection licences.

In the second case, the connection costs have to be borne by the grids. However, it can easily be seen that the payback period of these investments can be considered acceptable since it would not exceed ten years.

The third case is very attractive since it allows selecting a cautious strategy for regulating the number of new prosumers.

4. COOPERATIVE APPROACH IN NETWORK PROJECTS

The Chapter looks at the following new tasks:

1) distribution of investments in the construction of a two-circuit high-voltage line, provided that the circuits are different and belong to different companies;
2) distribution of investments under the first task conditions and in case the line route and supports are used for the construction of the optical communication channel;
3) allocation of costs if there are objects in the high-voltage line route that require reconstruction (lower voltage lines, roads);
4) attraction of investments by planning the reconstruction of medium-voltage networks.

The real data collected in the course of designing the Kurzeme Ring lines are used in the tasks.

The Kurzeme Ring (KR) is an energy infrastructure project involving the construction of a 330 kV overhead line and reconstruction of existing 110 kV transmission line in the western part of Latvia with a main purpose of increasing the throughput capacity in Kurzeme region, which was impossible up to now. It is a part of the larger NordBalt project, the implementation of which includes the interconnection installation Latvia-Estonia-Sweden with a view to improve power supply reliability in the Baltic countries [41]. Besides, this solution will provide reducing bottlenecks in the Kurzeme network, increasing the limited possibilities of the development of generating capacities in Latvia like renewable energy (new wind power plants) as well as ensure the potential of connecting new electrical installations of consumers.

Layout of a future cooperative circuit consisting of 110 kV and 330 kV systems is presented in Fig. 4.1.

Based on the accepted limits, the examined part of the Kurzeme Ring project (Action 1) was evaluated as three main alternatives:

1) there is a double-circuit 110 kV overhead line with a steel aluminium conductor; the phase is divided into two conductors (2 × AS-240/32); as a result, such an alternative provides 1210 A;
2) there is a single-circuit 330 kV overhead line with a steel aluminium conductor; the phase is divided into three conductors (3 × AS-400/51) with an installed ampacity of 2475 A;
3) there is a cooperative circuit, which consists of a single-circuit 110 kV overhead line with a steel aluminium conductor; the phase is divided into three conductors (3 × AS-400/51) with an installed ampacity of 2475 A; there is a 330 kV overhead line with a steel aluminium conductor; the phase is divided into two conductors (2 × AS-240/32) with an installed ampacity of 1210 A.

The power line construction costs as an economic aspect were calculated for each variant.

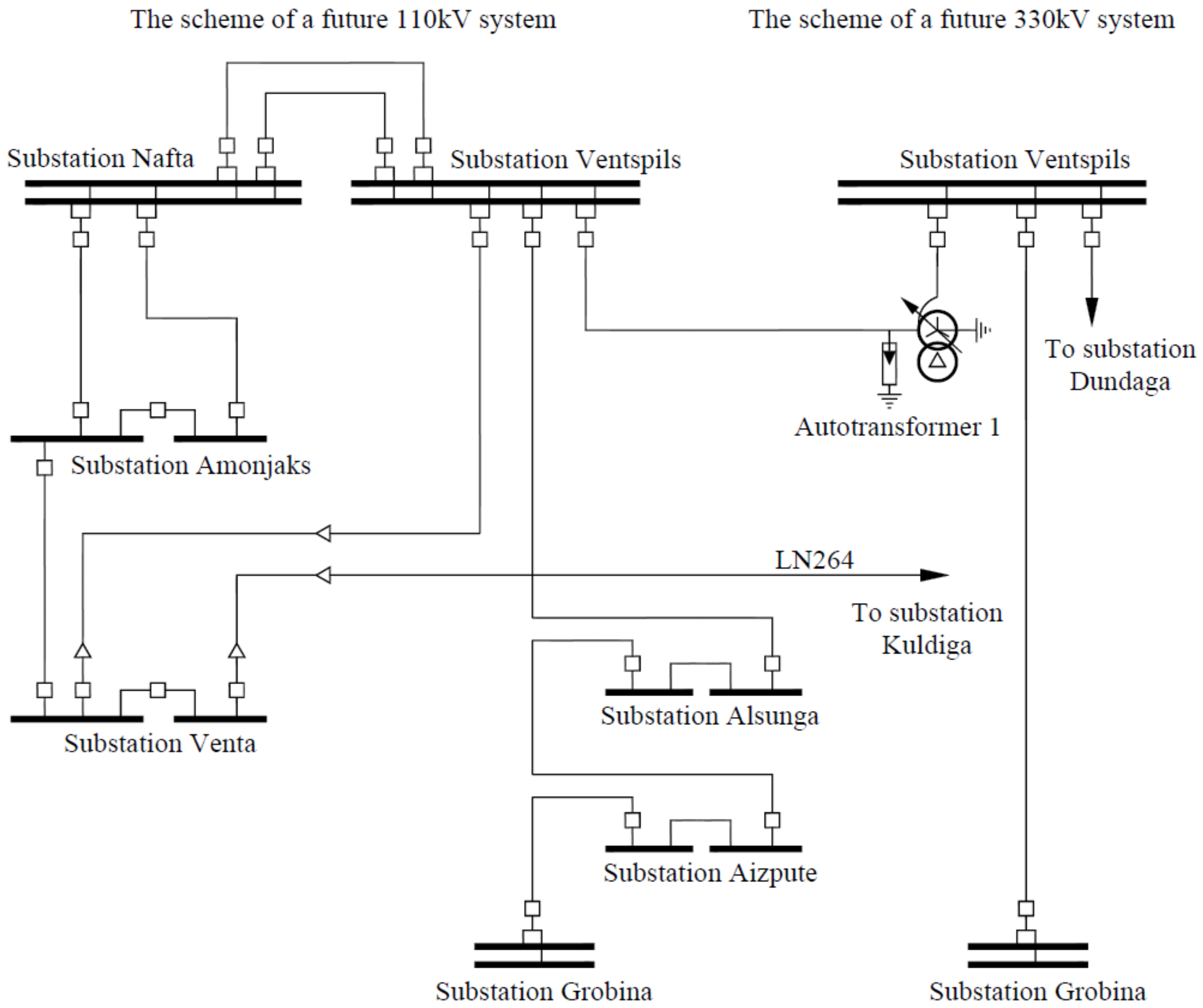

Fig. 4.1. Layout of a future cooperative circuit consisting of 110 kV and 330 kV systems.

Table 4.1

Overhead Line Construction Costs in The Case of Cooperative Behaviour

	Investments, r. v.
Coalition of companies A and B	29 952 795
Additional profit for each company	7 946 641
Total additional profit for companies A and B	**15 893 282**

It is obvious that in case of cooperative behaviour, the investments of the project are considerably reduced. This means that the formation of such a coalition is rational and possible in terms of economy of investments. Be it noted that in the real-life project, the profit is a matter of tens of millions EUR.

In the second example, it is assumed that there are three independent companies, two of them are engaged in the creation of power transmission lines and the third company is interested in implementing optical communication line. One of the power transmission companies is engaged in the creation of a 110 kV transmission line and the other in the creation of a 330 kV transmission line. The alternatives that are advantageous for each company have to be chosen as the decision. It is also necessary to show the costs of the project and the potential benefit for each company in the case of an individual approach, implementing the whole project separately, and check if it is possible to form different variants of coalition. Then there is the task of analyzing the outlook for forming coalitions with other companies.

In the third example, it is assumed that the high-voltage PTL company agrees to meet the expenses of the designing works, assembly and materials for replacing the 20 kV PTL section in the land plot directly affected by their 330/110 kV project. However, at a distance of three spans after the examined place, there is a transformer substation. Due to this, laying a small portion of the 20 kV PTL as a cable line is not rational. Hence, it can be assumed that in one of the possible alternatives, the company that owns the distribution networks may decline to approve such a reconstruction project, since that would increase the operating costs and diminish the reliability of the line as a whole. In this situation, the company that owns the distribution networks approves the laying of part of the 20 kV line as a cable only on the condition that also the part up to the transformer substation will be replaced.

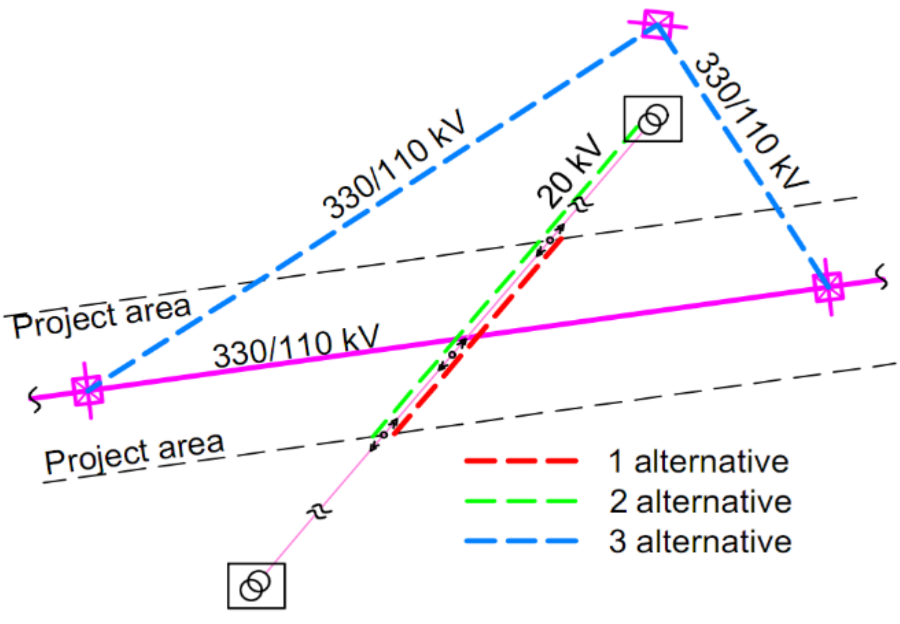

Fig. 4.2. Layout of PTL reconstruction design with solution alternatives.

In such a case, the high-voltage network company obtains two other solution alternatives: either to accept the conditions and lay as a cable line a larger portion than planned or to design a bypass of the 20 kV PTL to be crossed.

Figure 4.2. provides a basic layout of all the three solution alternatives for the examined PTL reconstruction project:

- Alternative 1 entails replacement of a portion of the 20 kV PTL only in the project area;
- Alternative 2 entails replacement of the portion of the 20 kV PTL in the project area and additionally up to the transformer substation;
- Alternative 3 entails by passing the 20 kV PTL to be crossed.

In all of the four examples examined, the behaviour of the cooperative members allows to reduce capital investment and increase project profitability.

5. THE POSSIBILITIES OF OPTIMISING THE OPERATION OF COMBINED SOLAR/HYDROPOWER PLANTS USING THE COOPERATIVE APPROACH

Two tasks are considered in this section.

The first task uses an example and data collected in Turkey (together with Doctor Hasan Coban) [26]. There is a situation, when the solar energy is supplied to the local consumers in order to meet the electricity demand. When there is a sufficient amount of sunlight, this is diverted to the local substation, and during that time the HPP accumulates water in order to work when the electricity price is higher. When the solar power does not meet the local consumers' electricity demands sufficiently, the hydro system produces energy utilizing the water stored in the reservoir. This arrangement of power supply makes it possible to get an additional benefit, both for the producers and for the consumers. For equitable distribution of profits, it is proposed to use the Shapley value.

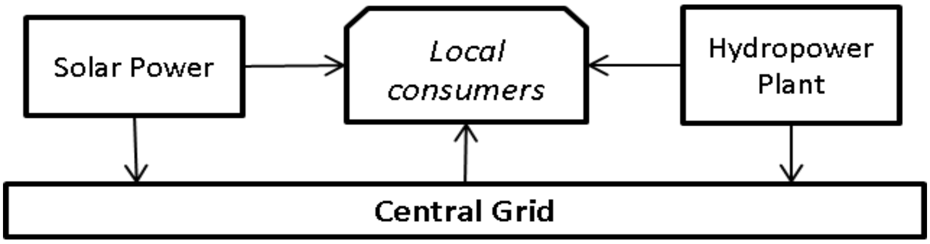

Fig. 5.1. Schematic diagram of the combined system and energy flow.

The efficiency of cooperation is clearly visible in Fig 5.2. The duration of the repurchase period is reduced by about five years, creating a cooperation.

Let us note that the considered situation can also emerge in Latvia by developing the solar energy and using the possibilities of the existing small hydropower plants.

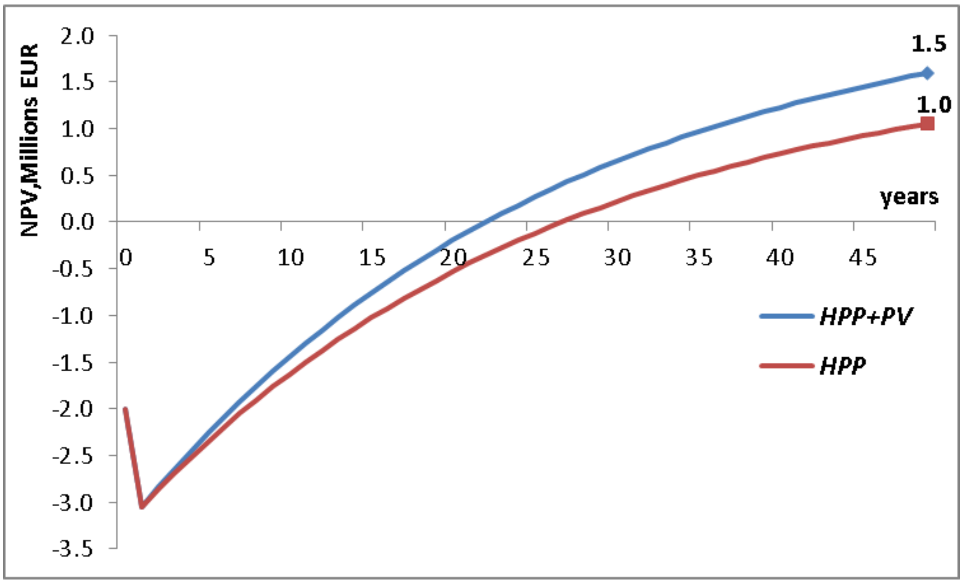

Fig. 5.2. The NPV estimation results for 49 years.

The second task deals with the situation that may emerge in Latvia in the nearest future by installing low-power solar generation in individual houses. Opportunities for cooperation between neighbours are being explored, one of which is installing solar panels, while the other is to be ready to partially use it. Three scenarios have been developed.

- **Base Scenario.** We assume that the user is a passive energy user who does not produce energy and does not use a net settlement system.
- **Net System Scenario 1.** We assume that prosumer provides an annual electricity balance. The prosumer supplies to the network and receives from the network the same amount of electricity over the year.
- **Net System Scenario 2.** We assume that the excess electricity generated by prosumer is firstly returned to the next-door neighbour and only then to the network. If there is a lack of electricity, then the power is taken from the network.

Figure 3 shows how much a next-door neighbour (randomly selected from the consumer database) usually pays per year for electricity consumed from the network, as well as Scenario 2, when prosumer sells the amount of produced electricity to the next-door neighbour at the price of the *Nord Pool* stock exchange.

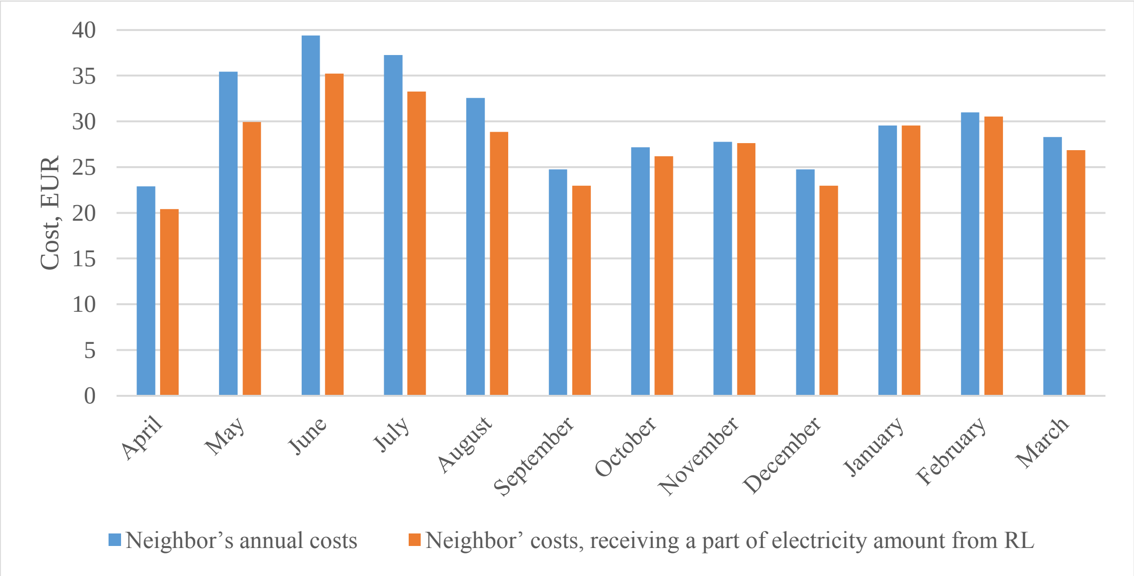

Fig. 5.3. Neighbour's monthly payments in different scenarios.

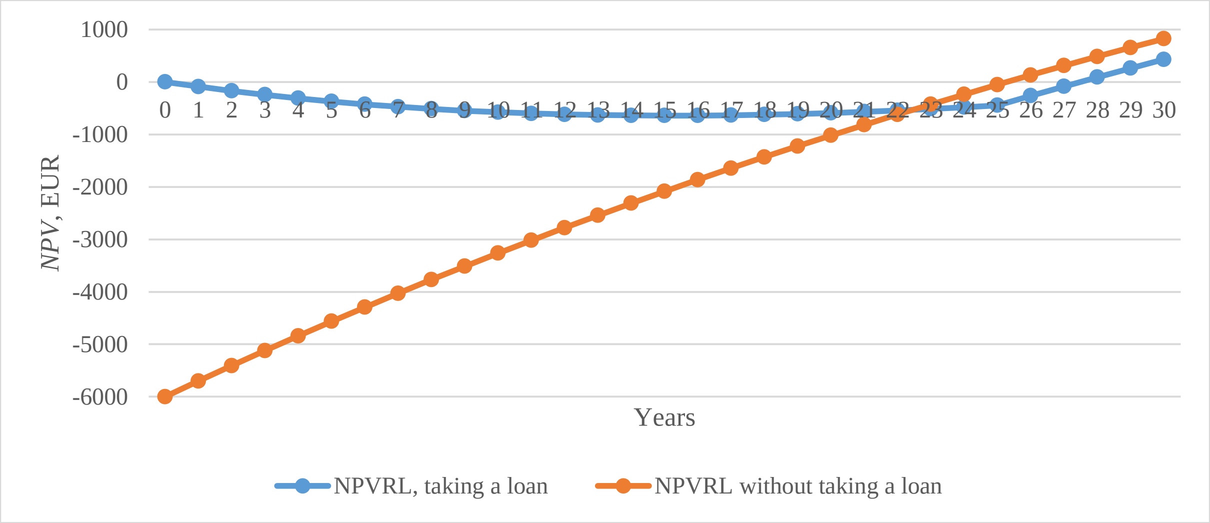

Fig. 5.4. NPV_{RL} for the net case (Scenario 2).

The results allow for the conclusion that cooperation is possible and beneficial for all players involved. Let us note that neighbours' cooperation requires additional intelligent metering for energy exchange between households.

CONCLUSIONS

1. Along with the increase in energy demand, the problem of planning energy facilities becomes much more complex due to the following main reasons.
   - The increase in the dimensions of power systems and the number of their elements. Even a small power system comprises hundreds of thousands of elements.
   - The requirements regarding reliability are becoming more stringent, especially in the power supply of large cities.
   - The number of available technologies has increased, which has made it necessary to look at many new development alternatives.
   - Energy production has started to have a most powerful impact on climate.
2. Within all planning problems, the cost minimisation goal is set. Most often, the criterion is used, which characterises the net present value of the cash flow (NPV).
3. Very significant difficulties arise in the calculations due to the following reasons:
   - the number of alternatives may be very large;
   - the cash flow is influenced by random quantities, for example outdoor air temperature, loads, water inflow in rivers etc.;
   - the cash flow depends on many selectable technical parameters of equipment.

   When compiling estimations of the payback period and afterwards formulating the minimisation or maximisation problem, many technical, legal and environmental limitations need to be taken into account.
4. The number of project selection criteria may be very large. The problem of selecting the best alternative, which is difficult to solve, arises.
5. In designing tasks, the enumeration method is often used, which is applied for solving combinatorial optimisation problems, in cases when it is not possible to calculate and use gradients of objective functions.
6. The criteria evaluation problem can be simplified, by assuming the hypothesis that input processes are stationary and ergodic, since it is possible to use one sufficiently long realisation of the set of stochastic processes in the calculations.
7. The Nash equilibrium approach, which is widely used in economics, disregards the possibility of forming coalitions and may lead to irrational decisions.
8. The techniques of the cooperative game approach may provide considerable gains to all the players, in cases when coalitions between them are possible.
9. The problem regarding the connection of new prosumers to the electrical grid can be solved by means of the techniques of cooperative game theory. In this case, solutions emerge that are capable of increasing the gains of all the players and stimulating the use of renewable energy sources in Latvia at the same time.
10. Construction of simplified substations can ensure a considerable economy of capital investments and is widely applied in many countries (Germany, the USA, Finland, Sweden etc.).

11. The decision regarding the choice of the prosumer connection layout and of the distribution of the costs simultaneously affects the interests of the transmission grid, the distribution grid, the state and the connection applicant, the discrepancy of which may lead to incorrect solutions.
12. The usefulness of constructing simplified substations depends on many factors (the size of load; the locations of loads; the distance to existing substations; the configuration of the medium-voltage network; the electricity price). Depending on the exact situation, construction of simplified substations or development of the medium-voltage network can each become the most advantageous solution.
13. Consideration of market conditions and changes in load, when making decisions about connecting the new prosumers to the grid and about the selection of the connection layout, requires labour-intensive calculations, which can be automated by means of specialised software, which can be synthesised with relatively little financial means, applying the methodology laid out in this Thesis.
14. Distribution of the connection costs among the grids and the users can be done by organising a tender for receiving connection licences.
15. Methods based on game theory can contribute to making the right decision about the development of power transmission lines. In particular, the cooperative game taking into consideration the possibility of building the coalition should be used.
16. The suggested method was applied to the example based on a real project with planned

    330 kV and 110 kV high voltage transmission lines construction. It shows a great result and high level of profit. The method is applicable in a variety of other tasks where independent companies can gain by forming the coalition with other market participants.
17. In the designing of PTLs, it is necessary to address the tasks related to the crossing of utilities, medium and low voltage distribution networks and roads as well as issues related to the crossing of private land plots. Here, several possible courses of action emerge for various market participants, from which the optimum solutions have to be chosen. Upon analyzing the obtained results, a conclusion can be made, namely, the development of technologies, the improvement of infrastructure as well as the market conditions bring about uncertainty and create basis for the emergence of conditions in which part of companies may benefit at the expense of the development of other companies. In this way, a number of power companies arrive at avoided costs, which can often become a perceptible contribution as a percentage of current and new projects. To ensure fair distribution of the profit gained, it is proposed to use the Shapley value. Such an approach helps to take account of the costs and the interests of several companies participating in the project.
18. The combined solar and hydropower system in rural places is suggested as an absolutely profitable investment. A general optimization model for finding an optimal combination of community-based combined energy systems is developed for Turkish

conditions. This compatible model is applicable to renewable power generation in any rural village.

19. The plants are located in close proximity to the local consumers and have to adapt to their needs and schedules of consumption. The ability of a hydropower plant to accumulate energy should be used.
20. Slar energy is supplied to local consumers in order to meet the electricity demand. When there is a sufficient amount of sunlight, this is diverted to the local substation, and during that time the HPP accumulates water in order to work when the electricity price is higher. When the solar power does not meet the local consumers' electricity demands sufficiently, the hydro system produces energy utilizing the water stored in the reservoir.
21. This arrangement of power supply makes it possible to get an additional benefit, for both the prosumers and the consumers. For equitable distribution of profits, the Shapley value can be used.

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