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Additional Income Distribution between Small Hydropower Plant and Public Trader Using Shapley Value

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Abstract. The small rivers energy usage and regime optimization is considered in the paper. Possibility of additional income reception in case of cooperative behavior of the power plant owners is demonstrated. Cooperative game theory approach is used for the additional income distribution and the small-scale hydro power plants (SHPP) regime planning and management. The obtained results demonstrate the possibility of the current supporting schemes revision, in case if SHPP regime optimization is made taking into account the market conditions.

Key words Hydroelectric power generation, power generation planning, smart grids, games theory.

1. Introduction

Aspiration to increase the efficiency of energy supply and to reduce an impact of the energy sector on the climate change has led to significant changes in the organization of the production of energy. Modern power system is divided into a number of legally independent parts that compete with one another. Competition is the main factor that can ensure rational development of power systems. At the competition conditions, it is inevitable that those companies that take weighed, technically and economically substantiated decisions are more likely to survive [19].

Regulation of the Cabinet of Ministers of the Republic of Latvia No 262 of 16 March 2010 "Regulations regarding the production of electricity using renewable energy resources and the procedures for the determination of the price" (hereinafter - Cabinet Regulation No 262) prescribes conditions for acquiring rights to sell electricity generated from renewable energy sources within the framework of mandatory procurement.

Support level for the production of electricity from renewable energy sources and high efficiency cogeneration depends on the type of energy source used, the installed capacity of the plant, number of working hours as well as natural gas and fuel sales price. Contrary to the forecasts in recent years natural gas prices have rapidly risen, contributing to the substantial growth of support intensity and respectively to the increase of number of supported electricity producers. Thus, support paid to the producers within the framework of mandatory procurement, which raises the overall electricity price, has also significantly increased. The analysis carried out by the Ministry of Economic revealed that volume of the mandatory procurement of electricity will continue to grow without changes in the historically applied support scheme.

Since availability of energy resources and their prices have always been one of the determinant factors of national and regional economic competitiveness Latvia like some other European Union countries by January 1, 2016 has suspended the granting the right to sell the produced electricity as the volume of electricity to be mandatory procured and the right to receive a guaranteed fee for the electric capacity installed in a power plant. Currently a support scheme is being revised to provide a stable, transparent and predictable investment environment for renewable energy and other industries, as well as reduce the burden of mandatory procurement on the Latvian electricity consumers. The purpose of the activity is to ensure the further development of competitiveness of the economy and prevent the deterioration of living standards. More clarity and predictability of the planned support scheme for subsidized energy production will give investors a clear long-term vision.

In the market conditions public trader, who is obligated to buy electrical energy from the power plants under mandatory procurement, sells and buys electrical energy also at the exchange stock and is interested in the harmonization of the operating regime of supported plants relative to the market price schedule. But a significant drawback of the support mechanism is independence of the producer revenues from the market price fluctuations. Producers that sell electricity under a mandatory procurement, are not interested in harmonizing of their power generation schedule to the market price schedule, as produced energy has the same price all the time (this price is significantly higher than market price). For example, price for SHPPs is shown in Table 1. That is why, in some hours the supported energy production could make troubles in system balancing, because the main issue of supported power plants is maximization of the production of electrical energy (it allows them to get maximal income).

Table I. - Feed-in Tariff for Small-Scale Hydropower Plants (Till 5 MW)

Year	Feed-in tariff , €ct/kWh
2008 (December)	16,7-21,5
2009 (March)	17,1-23,8
2009 (June)	12,3-19,7
2010 (April)	12,3-19,7
2011 (April)	12,3-19,7
2012 (November)	12,3-19,7

The necessity to review the support scheme for SHPPs in the market conditions is considered in the paper. This approach also can be used for biomass power plants, biogas power plants and other combined heat and power plants.

2. Coalition Establishment And Shapley Value

The main idea of the paper is based getting the additional income from the coalition creation between SHPPs and public trader [19].
This problem can be solved by using the methods of co-operative games theory (Shapley value).
The Shapley value use are considered by authors in [19] (at those example where were two stations and public trader), but at the given paper authors are considering mostly complicated question there are distributed the additional income among four players.
There are considered two optimization approaches:
1) in optimization is considered feed-in tariff;
2) in optimization is considered market price.
A coalition does not require the repeal of the existing legislation on support of renewable energy sources. At the same time the results of this work can be considered as an argument for amendments of legislation in the future.
To formalize this situation, we use the notion of a coalitional game: we start out with a set N (of n players) and a function $v: 2^N \to \mathbb{R}$ with $v(\varnothing) = 0$, where $\varnothing$ denotes the empty set. The function v that maps subsets of players to reals is called a characteristic function.
The function v has the following meaning: if S is a coalition of players, then $v(S)$, called the worth of coalition S, describes the total expected sum of payoffs the members of S can obtain by cooperation.
The Shapley value is one way to distribute the total gains to the players, assuming that they all collaborate. According to the Shapley value, the amount that player i gets given a coalitional game (v, N) is

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n-|S|-1)!}{n!}\left(v(S \cup \{i\}) - v(S)\right) \qquad (1)$$

where n is the total number of players and the sum extends over all subsets S of N not containing player i. The formula can be interpreted as follows: imagine the coalition being formed one actor at a time, with each actor demanding their contribution $v(S \cup \{i\}) - v(S)$ as a fair compensation, and then for each actor take the average of this contribution over the possible different permutations in which the coalition can be formed.
In case if coalition is formed by all participants and coalition is known, it is not necessary to determine mathematical expectation of different coalition's variants and the expression (1) can be written as [18]:

$$\phi_i(v) = \frac{1}{|N|!}\sum_R \left[v\left(P_i^R \cup \{i\}\right) - v\left(P_i^R\right)\right] \qquad (2)$$

where the sum ranges over all $|N|!$ orders R of the players and P_i^R is the set of players in N which precede i in the order R.
Shapley allocation is inherent significant drawback because the volume of calculations in determining the Shapley value, in common case, catastrophically increases with increasing number of players [11]. Discussed below task really is formulated for a large number of players, but the specific features of their unification into a coalition lead to the ultimate simplification of distribution calculations Shapley [19].

3. SHPP Regime Optimization

The small capacity of water reservoir before the dam at upstream does not allow the regular changes use in seasonal water inflow. The regulation of SHPP work is made in this way; first of all, in some period of time it works out the water inflow by consuming water from the reservoir before dam, and secondly, SHPP uses less water amount to fill up the water level in reservoir. In Latvia mostly are not specially built water reservoirs there are dams at the river and the water level increases or decreases in whole river area (but water level change availability with taking into account is less than 30 cm at each SHPP).
The change of water pressure on SHPP is caused by the change of water level in upstream and downstream. This is due to the water use through the turbines of SHPP. Hence, the change of the water level before the dam should be restricted by $H_{\max}$ from the top and by $H_{\min}$ from the bottom.
The main expression of the electric energy determination at hydropower unit, is determined:

$$P_{SHPP\,j} = 9{,}81 \cdot \eta_{HA} \cdot Q_j \cdot H_j \qquad (3)$$

where P_{SHPP} - SHPP capacity, *kW*; Q - water flow through the turbine, $m^3/sec.$; H - difference between water levels at the SHPP, *m*; η_{HA} - efficiency factor of hydro unit in relative units: $\eta_{HA} = \eta_{turb} \cdot \eta_G$, where η_{turb} - turbine efficiency factor in relative units; η_G -

generator efficiency factor in relative units [4],[5],[6],[7],[17].

The income maximization criteria is used for the SHPP optimization task solution It is required to determine the SHPP operating schedule by providing maximum income for the regulation cycle *T*.

$$I(P_1,P_2,...,P_j)=\sum_{j=1}^{J} I_j(c_j,P_j)\rightarrow \max \qquad (4)$$

under the condition of water usage restriction and condition of use of the set amount of water in water reservoir.

$$\sum_{j=1}^{J} Q_j \cdot \Delta t_j = W_J \qquad (5)$$

where $I_j(c_j, P_j)$ - income from sale of electricity, that is produced on SHPP during the time interval Δt_j by known market price c_j, €; T – the regulation cycle duration: $T=\sum_{j=1}^{J}\Delta t_j$ ($\Delta t_j = 1$ hour).

In SHPP optimization should be taken into account the natural inflow of the river Q_{flow}, due to which increases the water level before the dam at the river. But the used water flow in each time interval of regulation is determined by value Q_j that depends of the usage of water reservoir capacity (m3) [5], [6].

The distribution of additional income of SHPP is illustrated on the example of three SHPP regime optimizations [2], [3]. The optimization was made to maximize the summary income (objective function) for whole day period (24 hours) of SHPP work.

1. The first SHPP main data which allows its regulation is given: the maximal level of the water reservoir – 8,2 *m*; nominal capacity – 300 *kW*; the year average inflow at the river – 2,4 m^3/sec. Due to the regulations of the environmental protection in Latvia the minimal level of the water in the SHPP dam should not be less than 7,9 *m*.

2. The second SHPP main data which allows its regulation is given: the maximal level of the water reservoir – 6,4 *m*; nominal capacity – 400 *kW*; the year average inflow at the river – 5,35 m^3/sec. Due to the regulations of the environmental protection in Latvia the minimal level of the water in the SHPP dam should not be less than 6,2 *m*.

3. The third SHPP main data which allows its regulation is given: the maximal level of the water reservoir – 8,0 *m*; nominal capacity – 600 *kW*; the year average inflow at the river – 3,53 m^3/sec. Due to the regulations of the environmental protection in Latvia the minimal level of the water in the SHPP dam should not be less than 7,7 *m*.

The results have been found by using nonlinear programming – generalized reduced gradient method (GRG) [9]. Genetic algorithms (evolutionary method) and dynamic programming (DP) also can be used in that task. The GRG method usage can provide more accurate result than DP, because GRG method does not depend from the discretization, i.e. water level step value. Superiority of GRG method over DP method in such task is considered in [14]. Use of genetic algorithm is discussed in [15], [16].

In respect that first 20 years from the date of taking of the decision to grant the SHPP the right to sell the produced electricity within the scope of mandatory procurement, SHPP sells electricity at feed-in tariff, so it is actual to optimize the power station operation regime at a constant price value (0,18 *€/kWh*.) [8]. In this case, SHPP increases its income by maximizing its power production (Fig.1).

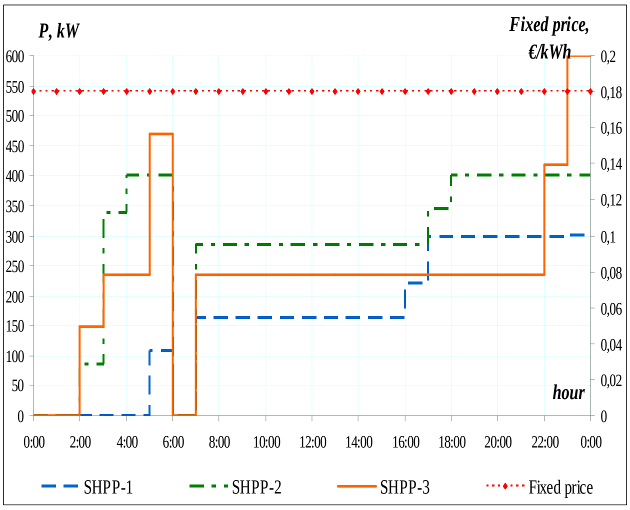

Fig. 1. The price and generated power graphs for three SHPP, in optimization is used fixed price

The income at feed in tariff (from optimization considering the natural inflow and the ability to store up water) for the first SHPP is about 703,24 €, but for the second SHPP is 1228,42 € and for the third SHPP is 1015,14 €.

The public trader (AS “Latvenergo”) buys and sells electricity in the Nord Pool Spot [1] exchange stock and should buy all electricity produced under mandatory procurement. As previously mentioned, SHPPs are not interested in harmonizing of their power generation schedule to the market price schedule, as produced energy has the same price at all time. They produce electricity at their own discretion and can work at full capacity in the hours with minimal load that adversely affect public trader. That is why it is important to optimize regime of SHPP considering price changes in the market (for example Nord Pool Spot) [19].

The additional income from the participation at different types of coalitions is got from the difference of produced electric energy in two optimization cases (at first case of feed-n tariff the SHPP increases their income by producing the maximal electric energy at all 24 hour optimization period, but in second case of market condition the SHPP produce power only in hours of maximal market price).

Such approach can lead to additional income for the public trader. To motivate SHPPs to work according to the market price schedule public trader share this additional income with SHPPs. Surely, SHPPs sell produced electricity to system operator at the feed-in tariff.

The income at market price (from optimization considering that the SHPP produces power in dependence of the market price, but sell produced electricity at fixed tariff Fig.2.) for the first SHPP is about 692,94 €, but for the second SHPP is 1212,5 € and for the third SHPP is 991,94 €.

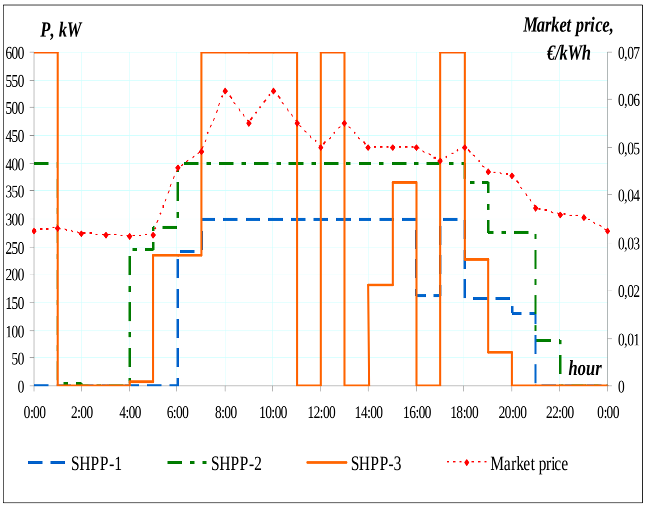

Fig. 2. The price and generated power graphs for three SHPP, in optimization is used market price

Co-operative game (v, N) is called relevant if

$$\sum_{i \in N} v(i) < v(N) \qquad (6)$$

The division of game (v, N) is a vector $x = (x_1, x_2, x_3, x_4)^T$, which meets following conditions:

- $\sum_{i \in N} x_i = v(N)$ (condition of co-operative expediency),
- $x_i \geq v(i)$, $i \in N$ (condition of individual expediency).

The public trader (player 4) buys electricity from SHPPs, and if it is not in coalition with them $v(3) = 0$ €. If SHPPs are not in coalition with public trader, they get the income from selling electricity by feed in tariff: the first SHPP (player 1) – $v(1) = 703.24$ €, the second SHPP (player 2) - $v(2) = 1228{,}42$ € and the third SHPP (player 3) - $v(3) = 1015{,}14$ €. If there is the coalition of two SHPPs, the summary income is $v(1,2) = 1931{,}652$ €. The coalition of the first SHPP with the public trader brings an income $v(1,4) = 713{,}43$ €, accordingly, the coalition of the second SHPP with the public trader brings an income $v(2,4) = 1235{,}99$ €. The coalition of all three SHPP would provide the income $v(1,2,3) = 2946{,}79$ €. The coalition of all three SHPP and public trader would provide the income $v(1,2,3,4) = 2975{,}74$ €. In that way the gain of all coalitions can be determined as:

$$v(S) = \begin{cases} 703{,}24, & S = \{1\} \\ 1228{,}42, & S = \{2\} \\ 1015{,}14, & S = \{3\} \\ 0, & S = \{4\} \\ 1931{,}65, & S = \{1;2\} \\ 1718{,}38, & S = \{1;3\} \\ 713{,}43, & S = \{1;4\} \\ 1931{,}65, & S = \{2;1\} \\ 2243{,}56, & S = \{2;3\} \\ 1235{,}99, & S = \{2;4\} \\ 1718{,}38, & S = \{3;1\} \\ 2243{,}56, & S = \{3;2\} \\ 1026{,}33, & S = \{3;4\} \\ 2946{,}79 & S = \{1;2;3\} \\ 1949{,}41 & S = \{1;2;4\} \\ 1739{,}76 & S = \{1;3;4\} \\ 2262{,}32 & S = \{2;3;4\} \\ 2975{,}74 & S = \{1;2;3;4\} \end{cases}.$$

The result (Shapley vector) is given:

$$x = (x_1, x_2, x_3)^T = (708.33, 1232{,}20, 1020{,}73, 14.64)^T.$$

4. Conclusion

The maximal effect for power system from the operation of the SHPPs can be obtained in the conduct of their regime relative to the schedule of the electricity market price change.

In terms of operation a SHPP in a period of low prices, it can be shut down to accumulate water. It is required to consider restrictions on the natural water flow on small rivers and possible amount of water that may be consumed by a SHPP during the day.

The example of this paper shows that participants could get the additional income from cooperation in the game.

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