DOI: 10.2478/jwld-2013-0004

JOURNAL OF WATER AND LAND DEVELOPMENT
J. Water Land Dev. 2013, No. 18 (I–VI): 29–35
PL ISSN 1429–7426

Available (PDF): www.itep.edu.pl/wydawnictwo; http://versita.com/jwld/

Received 27.09.2012
Reviewed 28.01.2013
Accepted 11.03.2013

A – study design
B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

The influence of hydrotechnical conditions on energy production in small-scale hydropower plants

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For citation: Bukowski M. 2013. The influence of hydrotechnical conditions on energy production in small-scale hydropower plants. Journal of Water and Land Development. No. 18 p. 29–35.

Abstract

Polish accession to the EU was followed by a need of adaptation of Polish legislation to the European requirements, also with regard to the energetic sector. The need of achieving 15% share of electric power from renewable sources in the total energy consumption till the year 2010 is a consequence of this decision. This target may be achieved in Polish conditions based on water and wind energy and from biomass combustion. The paper presents the influence of hydrologic conditions and technical parameters on the amount of produced energy. Factors affecting energy production in small hydropower plants were analysed. The formula was proposed to describe the effect of water flow in a river on energy production in small hydropower plants.

Key words: *energy policy, renewable energy sources, small-scale hydropower plants, water flow*

INTRODUCTION

One of the most important goals of energetic policy in Poland is to provide reliable supply of fuels and energy, to increase economic competitiveness and to decrease the negative environmental impact of energetic sector. The target may be accomplished through e.g. increasing the use of renewable energy sources which would contribute to the decrease of the country's dependence on imported energy carriers and would lead to a decreased emissions of harmful gases and dust to the atmosphere [Uchwała 202/2009 RM 2009].

Rapid development of renewable energy sources (RES) observed in Europe and in the U.S.A. since the end of the 1980s is a result of benefits brought by their use to local societies and national economy. Most important of these benefits are: increased energetic security, job creation and promotion of regional development, limiting the emission of greenhouse gases (especially CO_2), sulphur and nitrogen oxides [SADOWSKI *et al.* 2008]. Positive effects of energy production from renewable sources, including that from small hydropower plants, pertain mainly to non-urban areas, where such installations are usually localised. The effect of small hydropower plants on water relations in rural areas is one of the reasons why the Foundation for Rural Support elaborated the Programme for Reconstruction of Small Retention. Within this programme an investor (private owner, company or commune) could apply for financial support to reconstruct destroyed mills and hydropower plants. The value of preferential loans could reach up to 50% of capital outlay [LENART 1996].

Renewable energy sources in Poland may have substantial share in the energetic balance of particular communes or even provinces. They may contribute to the increase of energetic security of the region and specifically to the improvement of energy supply in areas of poorly developed energetic infrastructure.

Agriculture may potentially be the main consumer of energy from renewable sources, then residential buildings and communications. In regions of a high unemployment, the use of renewable energy sources offers a possibility of creating new jobs. Rural wetlands or areas of highly polluted soils unsuitable for growing edible plants may be intended for planting energetic plants [BUKOWSKI 2008].

The commune of Güssing in Austria with over 27 thousand inhabitants is an example of commune engagement in the development of energy production from own resources. Through consistently realised investment programmes the commune achieved energetic self-sufficiency and independence from energy derived from fossil fuels. Due to a large forest cover of the area and agricultural character of the commune, the main material in energy production is timber and agricultural products (maize and grass). Moreover, solar energy is also used [ISCMOiB 2012]. In the year 2010, a pilot programme „Energetic self-sufficiency in a commune" whose aim is to construct so many RES installations as needed to balance the energetic needs of the commune was also initiated in Poland. Energetic self-sufficiency of communes may be tested in the case of a failure in the power supply. Finally, the neighbouring communes should have power reserves they could share in case of urgent need. This does not mean, however, their disconnection with energetic networks. Three communes: Sokoły (Podlaskie Province), Gierałtowice (Śląskie Province) and Żukowice (Dolnośląskie Province) entered the programme in its preliminary stage of realisation.

Directive 2009/28/EU of the European Parliament and European Council on the promotion of energy use from renewable sources is a chance for the development of this sector. It estimates new goals for the whole European Union: 20% share of energy from renewable sources in the gross energy consumption till the year 2020 and 10% share of biofuels to achieve in every member state of the union. To reach this goal, every member state is obliged to prepare the country plan of activities which should determine the country targets of the share of energy from renewable sources in agreement with the obligatory general target. The latter for Poland is 15% share of energy from RES in the gross energy consumption in the year 2020. According to assumptions presented in the Energetic Policy of Poland till the year 2030, the target will be realised based on energy production from biomass (energetic crops, timber, forest and agricultural waste products, biogas) and on wind and water energy. Table 1 presents the achievable power of electric power plants that used renewable sources in Poland in the years 2000–2010.

Table 1. Achievable capacity of power plants that used renewable sources for electric power generation in the years 2000–2010, MW

Technology	Years										
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Hydropower	817	868	841	867	876	915	925	922	929	932	936
Wind power	4	19	32	35	40	121	172	306	526	709	1 108
Biomass	n.d.	n.d.	n.d.	24	24	25	25	33	40	42	53
Biogas	9	12	14	17	24	30	33	40	52	68	81
Total	830	899	887	943	964	1 091	1 155	1 301	1 547	1 750	2 178

Explanation: n.d. – no data.
Source: own elaboration based on the Central Statistical Office information [GUS 2007 and 2011].

A constant increase of the total power of electric power installations that used RES was observed between the years 2000 and 2008. The biggest annual increments were observed in 2005 (13.2%) and in 2008 (19.1%). Only in 2002 a slight decrease of achievable power (by 1.3%) caused by the decrease of the total power of hydropower plants (by 3.1%) was noted. The increase is particularly visible since 2005 when the renewable energy sector has been supported by a mechanism of certificates of origin and property rights. In the year 2004 the total achievable power of electric power plants based on renewable carriers was by only 16% larger than in 2000. Comparison of the year 2010 (2178 MW) with the year 2004 shows more than twofold increase of achievable power.

METHODS

Data presented in this study were obtained from a survey performed among the owners of small hydropower plants (SHP). The power of turbines installed in analysed objects did not exceed 5 MW, which is a maximum adopted in our country for small hydropower plants. Random selection of studied objects was adopted in this study. From among all SHP localised in northern Poland (zachodniopomorskie, pomorskie, kujawsko-pomorskie and warmińsko-mazurskie provinces) 50 plants were selected and their owners were asked to answer the questionnaire. This group constitutes 7% of all SHP in Poland (from the total of 724 in the year 2010) and over 16% of all SHP in northern provinces [URE 2010]. Analysed objects were situated on lowland rivers whose flow characteristics differed from that in mountain rivers.

Information useful for further analyses were obtained from 44 owners of SHP. In 6 cases there was no response or the obtained information was not sufficient to be used in further analyses. Analysed group was dominated by through-flow power plants of low river gradient. The latter feature is typical of all SHP [URE 2010]. Care was taken to select objects in a way that each group of installed power was represented by similar number of objects.

Professional power plants that belonged to energetic concerns prevailed (2/3) among analysed objects. The number of objects from outside professional energy sector was distinctly lower. This is because the objects are a property of private investors who often do not carry regular hydrological measurements and do not keep detailed accountancy. Therefore, it is impossible to obtain from them complete data that would enable proper analysis of the economic effect of particular hydro-technical parameters.

Primary data used in the analysis were obtained in a steered survey with the use of questionnaires. They were supplemented with data from an analysis of the accounts obtained from those owners who kept the accountancy.

The following information was the basis for performed study:
– monthly mean water flows,
– the amount of produced energy,
– the amount of energy used for own needs,
– time of operation of the hydropower plant.

Information acquired from the owners from non-professional energy sector were not always complete. Therefore, the number of samples was given when presenting the relationships between analysed variables.

RESULTS

Hydropower plants, apart from wind power facilities, are the most important renewable sources of electric energy. Out of all hydropower sources, 30% is obtained from small hydropower plants [Obwieszczenie MG… 2010]. An increment of power in this group of hydropower plants is expected in the years to come. Construction of large hydropower plants is not planned due to a lack of appropriate localization, high investment costs and environmental issues. Table 2 presents the development of small hydropower sector in the years 1998–2007 with the division into professional sector (firms operating within energetic companies) and non-professional sector (power plants being the property of private owners).

Table 2. Small hydropower plants in Poland in the years 1998–2007

Type of power plant	Parameter	Year									
		1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Professional energetics	number	110	110	111	112	112	110	110	112	113	114
	power, MW	131.5	131.7	132.4	134	132.7	134.2	137	137.1	139.8	140.2
	production, GWh	494.2	499.3	470	457	497	363.2	410.8	454.1	414.9	491.8
No-professional energetics	numer	325	259	399	456	492	515	531	551	557	560
	power, MW	31.9	36.1	39.6	47.7	52.2	53.9	62.2	71.8	76.1	73.3
	production, GWh	120.3	136.7	145.4	174.2	200.6	166.4	207.1	248.5	246.4	294.4

Source: GUS [2009].

A great variability of production and installed power was observed in this period, chiefly in non-professional energetic sector. The number of objects within this group increased by 235 (by 72% in relation to the year 1998) at parallel increase of installed power by 41.4 MW (130%). The greatest increase in the number of SHP was observed at the break of 1999 and 2000 while the greatest increment of installed power was in 2000/2001. Both factors resulted in the increase of electric energy production by 175% in the years 1998–2007 in non-professional SHP.

The effect of water flow on the amount of produced energy was calculated. At temporally variable parameters, the amount of energy E (kWh)[1)] may be calculated from the equation:

$$E = \rho g \sum\nolimits_i Q_{ti} h_i d_{ti} \qquad (1)$$

where:
ρ – water density, kg·m^{-3};
g – gravitational acceleration, m·s^{-2};
h_i – standard water head in the i-th time period, m;
Q_{ti} – unit flow in the i-th time period, m^3·s^{-1};
dt_i – the length of the i-th time period, s,
i – index of the time period in which water flow Q_{ti} occurred at water head h_i.

[1)] Joule is the energy unit in SI (J = kg·m^2·s^{-2}). Energy in eq. 1 was calculated in these units. Due to the fact that the produced and consumed energy is expressed in kWh – such unit was adopted in this paper. One joule is equivalent to 1/3600000 kWh ≈ 0.278 · 10^{-6} kWh.

The amount of energy production in hydropower plants at a constant head depends on the amount of water flowing through a turbine. The latter is in turn determined by the total water flow through a cross-section area of the river upstream. That is why the amount of produced energy largely varies annually, monthly and daily. To illustrate this variability, Fig. 1 presents the total annual production of energy in 8 study objects localized along the same river. Mean ($\pm SD$) annual production for 20 years in the analysed objects was 30 643 thousand $\pm$4 305 $MWh \cdot y^{-1}$. The ratio of maximum to mean production was 1.28 and the ratio of minimum to mean production was 0.76. Such a large fluctuation of annual production resulted from variable hydro-meteorological conditions. Fluctuations were random and resulted from alternating dry and wet periods.

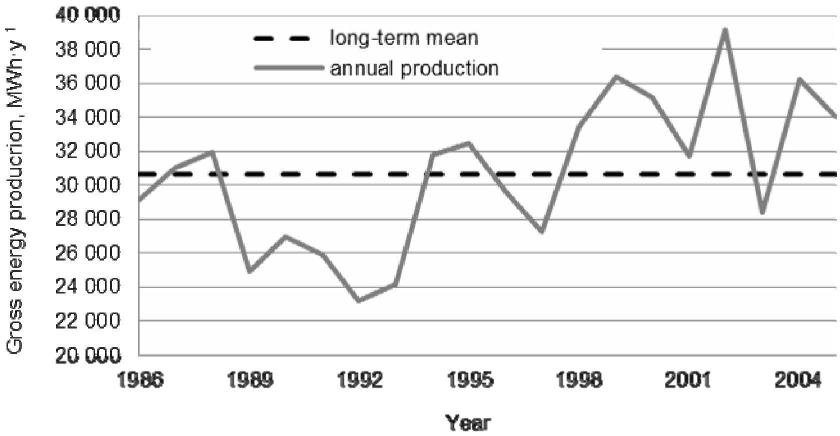

Fig. 1. Total annual energy production in 8 small hydropower plants in the years 1985–2005; source: own study

The ratio of net energy production (E_{net}, kWh), i.e. the energy actually sold and generating incomes, to the energy likely to be produced at a given total flow (E_{st}, kWh) may be estimated as:

$$\alpha(t) = \frac{E_{net}(i)}{E_{st}(i)} \tag{2}$$

where:

- t – the number of unit time period;
- $\alpha(t)$ – empirical parameter, variable in time;
- $E_{net}(i)$ – net energy (kWh) in the i-th time period;
- $E_{st}(i)$ – barrage energy, i.e. the total amount of potential energy (kWh) of water that flew through the barrage in the i-th time period.

Parameter α depends on:

– the index of flow utilization (w_{wp}),
– the efficiency of conversion (η_{pe}),
– the ratio of net energy delivered to the energetic network to the gross energy produced (p_{we}).

The index of flow utilization is estimated as a proportion of converted energy (E_p) to potential energy of water flowing through the barrage (E_{st}).

$$w_{wp} = \frac{E_p}{E_{st}} \tag{3}$$

Potential energy of water flowing through the barrage is determined from the total amount of water flowing to the barrage. In periods when total flow is larger than the amount of water able to flow through the turbine, the excess is directed to spillways such as permanent weirs, barriers or overflows. Converted energy is the potential energy of water that flew through turbines. It is part of the barrage energy resulting from the existence of unused (lost) flow.

Both total and lost flows are calculated indirectly based on the amount of water used by turbines per unit of produced energy and tabulated characteristics of weirs and overflows. These values are burden by a hard to assess error dependent on the accuracy of indices adopted for calculations. The indices vary more or less during exploitation (exploitation of facilities, change in the efficiency). Momentary values may also be subject to large fluctuations (variable load of turbines, changes in water head, pollutants that may accumulate in the inflow canals etc.).

The index of flow utilization is a variable parameter that depends on many factors, the main of which is the ratio of the total flow to the turbine's gullet. Moreover, the index is affected by random factors like e.g. the damage of turbines. In power plants on dam reservoirs, low index of flow utilization may result from the need of discharging large amounts of water through weirs to prepare the reservoir for flood wave. Monthly means of the index in studied objects are presented in Fig. 2. The index assumed lowest values from February till April because of larger water flow in rivers during spring snow melting. In the autumn period, however, no marked decrease of the index due to long-lasting rainfalls was noted.

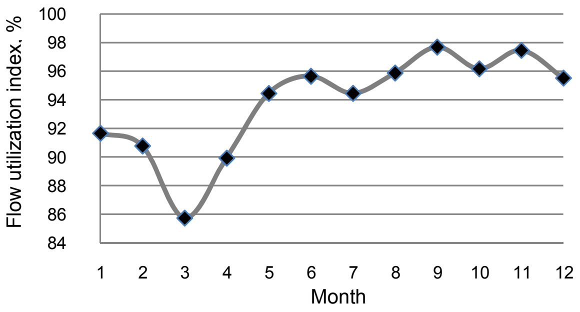

Fig. 2. Mean monthly value of the flow utilization index in the group of analysed objects (the number of monthly observations $n = 921$); source: own study

The amount of water flowing through a turbine in a given time period is decisive for electric energy produced in that time. The ratio of produced electric energy to potential energy of water flowing through the turbine (converted energy) is termed the efficiency of conversion (η_{pe}). The index may be dealt with as a constant characteristic for a given turbine since it depends on the type of turbine and its age corresponding to the degree of exploitation. It does not depend, however, on turbine's power or loading. Small variability of this index is rather an effect of already mentioned inaccuracy in determining water flow through the barrage and turbine. Larger fluctuations in the efficiency of conversion achieved by the turbine may indicate its poor technical status.

The efficiency of modern water turbines sometimes exceeds 80%. For comparison, the efficiency of electric energy production from coal, with the use of traditional technologies, does not exceed 40% [LORENC 2005]. In the studied group of hydropower plants, the efficiency of conversion ranged from 0.55 to 0.80 being typical for most currently used water turbines [ESHA 2010].

Electric energy produced in the hydropower plant is partly used for its own needs. It is used mainly to power the facilities installed there, to light the building and surrounding area. The ratio of energy entering the energetic network to the amount of energy produced by turbines is determined as an index p_{we}:

$$p_{wp} = \frac{E_{net}}{E_{gross}} \qquad (4)$$

where:

- p_{we} – the ratio of sold to produced energy;
- E_{net} – the amount of active energy produced by all generators diminished by the energy used for own purposes, kWh;
- E_{gross} – the amount of active energy produced by all generators in a given time period, kWh.

The p_{we} index rarely drops below 95% during constant operation of a hydropower plant. Lower values of the index may appear in periods of lower gross production of electric energy i.e. in summer months. They may be also an effect of interruptions caused by damages or repairs. During such breaks, the gross production decreases and the use of energy for own needs increases.

Means and medians of particular parameters affecting the α(t) parameter are given in Table 3. The parameter can be calculated as:

$$\alpha(t) = w_{wp}(t)\eta_{pe}\, p_{we}(t) \qquad (5)$$

Table 3. Statistical characteristics of parameters affecting the value of parameter $\alpha(t)$

Index of	Number of observations	Value		
		mean	median	standard deviation
Flow utilization	921	0,937	1,00	0,151
Efficiency of conversion	42	0,678	0,69	0,0568
E_{net}/E_{gross}	873	0,987	0,99	0,0137

Source: own study.

From among all indices only the efficiency of conversion η_{pe} may be dealt with as a constant, characteristic for a given hydropower plant. Other are variable in time and have a character of random variables dependent on many factors.

Due to a great number of outlying observations noted in the study period, particularly in the distribution of monthly indices of flow utilization, the α parameter was estimated as a product of medians[2)] of the indices w_{wp}, η_{pe}, p_{we}. So calculated parameter α was 0.683.

Based on parameter $\alpha(t)$, the predicted amount of sold electric energy in a given time period may be approximately calculated from the equation:

$$E_{netto}(t) = \alpha(t)\rho\, g\, h\, Q_c(t) \qquad (6)$$

where:

- $Q_c(t)$ – total amount of water flowing through a barrage (m^3) in a given time unit t.

Since standard head is a constant parameter for a given hydropower plant designed in its technical project, calculating the effect of the total flow on sold energy may be performed per 1 m of the water head. In such a case, equation (6) may be transformed to the form:

$$JE_{net}(t) = \alpha(t)\rho\, g\, Q_c(t) \qquad (7)$$

2) Arithmetic mean is more susceptible to disturbances by outliers, therefore, calculations were based on medians.

where:

$JE_{net}(t)$ – unit amount of net production of electric energy per 1 m of head (kWh·m^{-1}) in a given time period t.

Comparison of the net production of energy calculated with equation (7) with empirical data and the respective regression line are shown in Fig. 3. It shows a good agreements between calculated and empirical data (R^2 = 0.72). Net production of electric energy calculated from eq. (7) exceeds by c. 10% the values calculated from empirical linear regression JE_{net} = 1652.9Q_c. The proposed relationship (eq. (7)) may thus be used as an approximation to calculate the amount of sold electric energy in relation to the total amount of water flowing through the barrage. The relationship has a form of linear equation with one egzogenous variable Q_c. Other values in this relationship may be, with a high probability, treated as constants. For comparison, Fig. 3 presents also the line of full utilization of water flow. The line describes the maximum unit net production that might be achieved in a hydropower plant on condition that:

– the whole water flowing through the barrage flows through the turbine;
– the efficiency of conversion of potential water energy into electric energy is 1;
– energy is not taken for own needs.

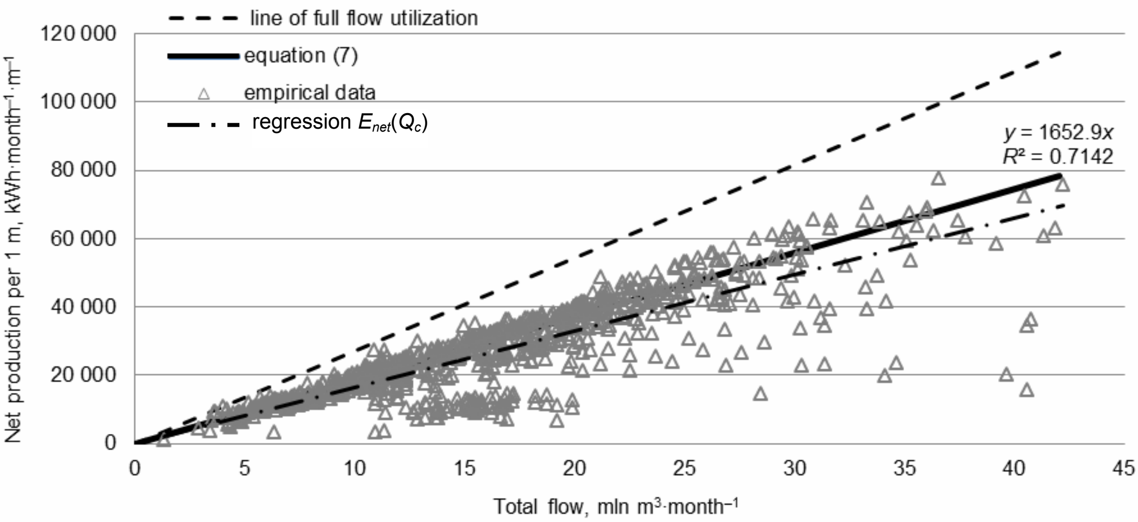

Fig. 3. The relationship between the net energy production per 1 m of water head and the total flow (number of monthly observations n = 873); source: own study

CONCLUSIONS

Performed studies demonstrated the relationship between the production of energy in small hydropower plants and water flow in the river channel above the electric power plant. Predicted amount of net sold electric energy in a given time period may be calculated from equation:

$$E_{net}(t) = 0.683 \rho\, g\, h\, Q_c(t) \quad (8)$$

So, the actual sold electric energy produced in small hydropower plants is by c. 30% smaller than the theoretical calculated from potential energy of flowing water. Low efficiency of conversion, which was 68% on average in studied plants, was responsible for the difference. The effect of two other parameters: the index of flow utilization and the share of energy used for own needs in the total produced energy was much smaller.

Proposed relationship showed a good agreement with empirical data and thus may be used to predict the amount of sold energy in a small hydropower plant at variable water flows in the river channel.

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Marcin BUKOWSKI

Wpływ warunków hydrotechnicznych na wielkość produkcji energii w małych elektrowniach wodnych

STRESZCZENIE

Słowa kluczowe: *małe elektrownie wodne, odnawialne źródła energii, polityka energetyczna, przepływ*

Wstąpienie Polski do UE spowodowało konieczność dostosowania polskiego prawa do wymogów unijnych, także w zakresie sektora energetycznego. Konsekwencją tego jest wymóg osiągnięcia 15% udziału energii elektrycznej produkowanej z odnawialnych źródeł energii w całkowitym zużyciu energii w roku 2020.W warunkach polskich cel ten może zostać zrealizowany przede wszystkim dzięki energetyce wodnej, wiatrowej oraz pochodzącej ze spalania biomasy. W artykule przedstawiono wpływ warunków hydrologicznych i parametrów technicznych elektrowni na wielkość produkcji energii elektrycznej. Przedstawiono analizę czynników wpływających na wielkość produkcji energii w małych elektrowniach wodnych. Zaproponowano formułę zależności opisującą wpływ wielkości przepływu całkowitego w rzece na produkcję energii w małych elektrowniach wodnych.