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PHYSICAL AND TECHNICAL ENERGY PROBLEMS

POTENTIAL OF THE LOWER DAUGAVA FOR SITING HYDROKINETIC TURBINES

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The article outlines the requirements and criteria for the hydrokinetic turbine site and determines the water flow characteristics based on which the energy potential of such a turbine is calculated for lower reaches of the River Daugava. The changes in the energy potential caused by fluctuations in the water density and flow rate are evaluated. Two investigated spans (total > 22 km) are split into ten smaller subregions with similar characteristics and comparatively evaluated regarding their suitability for electricity generation by hydrokinetic turbines.

Key words: *hydroelectric power generation, microhydro power, energy efficiency, hydrokinetic turbine, water current turbine*.

1. INTRODUCTION

One of the most significant potentials for supply of energy in Latvia and, in particular, of electric energy is the hydro resource. The contribution of the cascade of hydro power plants on the River Daugava is inestimable for the country; still, the potential of this river is currently used only partially. The issue is not just construction of another hydroelectric power station with another dam, but the extra usage of the largest river in Latvia for electrical energy production thanks to hydrokinetic turbines or water current turbines – the technologies that are rapidly developing in other countries. Kinetic energy of water (its current) as a renewable, environmentally friendly, stable and sustainable energy resource [1–3] could also be used to produce electricity in other rivers and even in streams that are abundant in Latvia. The local nature of this kind of energy source and its advantages which often are provided by decentralized power supply in the electricity distribution networks [4] should be emphasized.

Latvia imports around 30% of the electricity needed, while the water (current) kinetic energy capacities are so far totally ignored. Due to development of the hydrokinetic turbine technology, recently the use of these capacities has significantly increased, which makes it possible to practically implement them at power plants in Latvia to verify the efficiency of this technology in Latvia.

The development of such technologies in Latvia is dragged due to the absence of data on the water free flow power that depends on:

a) water flow velocity,
b) flow distribution in the selected region,
c) velocity distribution in the cross-section of the flow,
d) water layer thickness,
e) possible variations in the water density.

The flow kinetic energy is calculated by the formula:

$$E = \frac{mv^2}{2} = \frac{(v \cdot S \cdot \rho) \cdot v^2}{2}, \tag{1}$$

where v is the flow velocity before turbines, m/s;
S is the cross-sectional area of the flow, m^2;
ρ is the flow (water) density, kg/m^3.
$m = (v{\cdot}S{\cdot}\rho)$ is the per-second mass of water which is running through the turbine.

Therefore, the amount of obtainable energy is dependent mostly on the water flow velocity, and – to a lesser extent – on the water density in the flow and its cross-sectional area. These three parameters are specific to a particular place where the hydrokinetic turbine operates.

The power of a single turbine and the power that can be obtained from one cross-section of the river with this type of turbines are calculated by the same formula:

$$N = k \cdot v^3 \cdot S \cdot \rho, \tag{2}$$

where k is an empirical coefficient depending on the turbine type (usually 0.1–0.3).

For example, if the power of turbine is 5 kW, the minimum flow velocity which provides a stable turbine operation is 1 m/s; at $S = 1$ m^2 and $\rho = 1\,000$ kg/m^3 we will have $k = 0.25$. The coefficient consists of number 2 from the denominator of the kinetic energy formula and the turbine efficiency (i.e. this coefficient characterises the losses caused by flow non-uniformity and turbulence). The other three parameters in Eq. (2) are the same as in Eq. (1), and are specific to the place where the hydrokinetic turbines operate. When calculating the energy produced by a turbine, the cross-sectional area of the flow depends on the turbine and is the area covered with the turbine's active parts – usually rotor blades.

To estimate the output of an electricity producing facility, the generator efficiency and losses should be taken into account. The specific location determines the size of a turbine (or of a park of turbines) that can be disposed there. The energy output is also defined by the operation time of the turbine(s).

For siting successfully a power plant that would operate on the hydrokinetic energy it is necessary, first, to determine the three parameters of the above formulas, taking into account the criteria dictated by a particular location (e.g. the maximum flow depth and width) and some other restrictions (e.g. available technologies, suppliers, etc.); of importance is also proper selection of the turbines.

One of the advantages of a hydrokinetic turbine as compared with other sources of renewable energy is its predictability. For securing the day-to-day electric power, a hydrokinetic turbine's output can be relied upon to a greater extent than, for example, the output of a wind power plant with its much greater (up to 100% from the average) day-to-day variations.

2. METHODS AND EQUIPMENT FOR MEASUREMENTS AND CRITERIA FOR SITE SELECTION

A great body of data regarding the flows of Daugava (e.g. the water level and the flow velocity) are readily available thanks to the state-funded monitoring station network. However, the most important data needed for this work were not obtainable otherwise than by measurements.

For the flow velocity measurements, an acoustic Doppler tool of *Aquadopp Profilers* was used in compliance with the Worlds Metrological Organisation's manual [5] and the equipment user manual [6]. The tool was anchored to a stable boat so that it was easy to insert and remove with the adapter (head) perpendicular to the direction of the stream. For accurate depth measurements an echo-sounding tool (Echo 100) with a water temperature sensor was employed, while the boat speed was monitored during the measurements.

The cross-section measurements were performed by moving the boat from the right bank to the left by the shortest path. The GPS coordinates were fixed at each measuring point using *Trimble Nomad 900G* equipment.

For determination of the impact made by water density variations on the energy potential of the river, these – along with the nature of water admixtures – were investigated at different times of the year. The water parameters are set in accordance with the following international standards: ISO 10523 for determination of pH, LVS ISO 6060 (the chemical oxygen demand – a standard method for indirect measurement of the amount of pollution that cannot be oxidised biologically in a sample of water) – of the dry residue, and ISO 6069 – of the water hardness. Each time the density test was done at room temperature (20 ºC), and the results were recalculated for the density at an appropriate temperature in accordance with the tables of water density variations [7].

Taking into account the formula for the water flow kinetic energy [1] and the impact of turbulence, the following main criteria (i.e. allowing achievement of the maximum electricity output) are to be met at selection of the site for hydrokinetic turbine(s) in Latvia:

1. Flow with a low (the least possible) turbulence.
2. Flow with the highest possible velocity.
3. Flow of the largest possible cross-section.
4. Possibility to use an appropriate hydrokinetic turbine technology and provide the required energy output (flow cross-section configuration, usable river length, etc.).
5. Riverbank and riverbed geological structure.

The listed criteria clearly show that it is Daugava that possesses the greatest potential for electricity production with hydrokinetic turbines. Based on the relevant statistical data on water flows and assessment by the other mentioned criteria, two spans of Daugava were selected. Therefore, velocity measurements of the water flow and its further investigations were carried out in the following spans:

1. From Jaunjelgava to Aizkraukle, coordinates: N56°37, 346` E025°05, 888` and N56°35, 394` E025°13, 829` (see the map in Fig. 1). Hereinafter this span of Daugava is referred to as „FIRST part".

2. From Pļaviņas to Jēkabpils, coordinates: N56°37, 034` E025°44, 869` and N56˚31, 341`E025˚49, 372`, see the map in Fig. 2 (the „SECOND part”).

Fig. 1. Measured cross-sections in the FIRST part of Daugava.

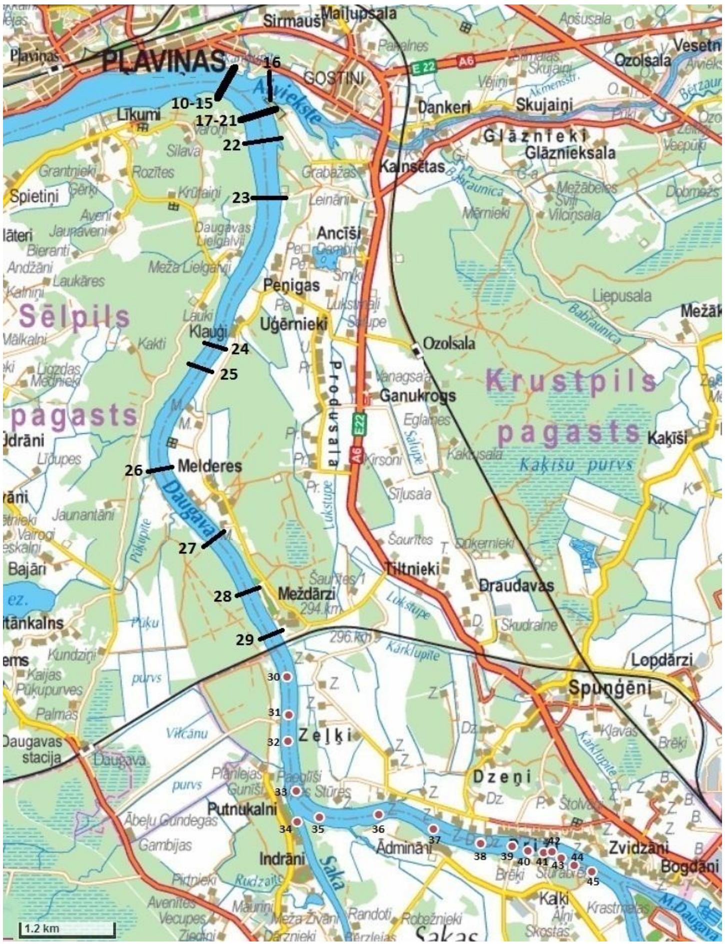

Fig. 2. Measured cross-sections and separate measurement points
in the SECOND part of Daugava.

3. RESULTS

The results of measurements are summarised in tables, each relating to one particular cross-section of the river. For example, the data given in Table 1 relate to the 8th measured cross-section of the river (see Fig. 1).

The tables are based on a matrix containing the results of measuring the water flow velocity to which the results of measuring the riverbed depth in each cross-section were added in a separate row. Other added rows contain the data on:

- the specific area of river cross-section (for each measured segment of the cross-section separately and total for the whole cross-section);
- the cross-section area available for hydrokinetic turbines: the totalmeasured cross-sectional area minus the area of segments with the depth less than 1.5 m (for each measured segment and total);
- the average flow velocity (for each measured segment and total);
- the average flow rate (for each measured segment and total)
- the flow rate available for hydrokinetic turbines (for each measured segment and total)

To Table 1 also a column was added that contains the parameters relating to the whole cross-section:

- the weighted average flow velocity (the area of each segment was taken as its weight);
- the maximal measured flow velocity in the cross-section;
- the minimal measured flow velocity in the cross-section;
- the difference between the minimal and maximal measured flow velocities in percent.

Figure 3 schematically shows the location of measuring points (marked in this figure and Table 1 with the numbers from 1 to 5) in a river cross-section. Its area is calculated as the sum of triangles A, F and trapeziums B, C, D, E.

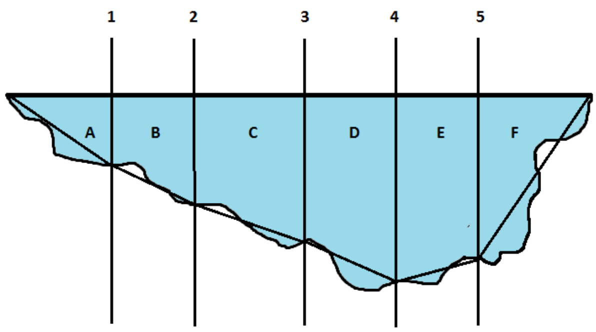

Fig. 3. Schematic of a river cross-section.

Data on the chemical composition and density variations of the Daugava water are summarised in Table 2, where a) and b) designate the water sampling points for the FIRST and the SECOND explored parts of the river, respectively (2 km after and 2 km before the Aiviekste estuary, Liepkalni).

Table 1

The results of river cross-section measurements (the 8th cross-section)

Point No.		1	2	3	4	5		Distance from the last point to the left coast, m	
Geographic coordinates of the point		N56°35,430′ E025°13,513′	N56°35,419′ E025°13,514′	N56°35,397′ E025°13,499′	N56°35,387′ E025°13,489′	N56°35,359′ E025°13,489′			
	Distance from the right coast, m	33.0	53.0	95.0	114.0	167.0		51	
Depth, m	0.8	0.85386274	1.04115254	0.90992063	1.04780327	0.82304545			
	1.3	0.78815028	0.85701694	0.88325396	0.89240983	0.72253030			
	1.8		0.79064828	0.69869841	0.90881967	0.72875384			
	2.3			0.69818282	0.67890163	0.74138461			
	2.8				0.69081967	0.68013852			
	3.3				0.77158201				
	3.8								
Bed depth, m		2.1	2.2	2.9	3.7	3.2			2.820
Cross-section area, m^2		34.65	43	107.1	62.7	182.85	81.6		511.900
Area available for turbines, m^2		16.97142857	43	107.1	62.7	182.85	63.6703		476.292
Average flow velocity, m/s		0.82100651	0.86616616	0.83983909	0.81803919	0.78965353	0.73917		0.812
Flow rate, m^3/s		28.4478757	37.2451449	89.9467663	51.2910575	144.388148	60.3163		411.635
Flow rate available for turbines, m^3/s		6.9668267	18.6225725	44.9733832	25.6455287	72.1940741	23.5316		191.934

Average weighted flow velocity, m/s	0.8041
Maximal flow velocity, m/s	1.0478
Minimal flow velocity, m/s	0.6789
Difference between minimal and maximal flow velocities, %	35.2071

Table 2

Seasonal variations in the chemical composition and density of water in the explored sections of the River Daugava

Season	Parameters				
	pH	COD, mg/l	Dry residue, mg/l	Hardness, mg/l	ρ, g/cm^3
a) 2 km after the Aiviekste estuary (Liepkalni)					
Winter	6.68	112	186	25. 7	1.00330
Spring	6.54	200	205	28.3	1.00212
Summer	6.36	205	278	30.5	1.00185
b) 2 km before the Aiviekste estuary (Liepkalni)					
Winter	6.75	104	195	27.5	1.00343
Spring	6.62	133	210	29.0	1.00164
Summer	6.52	215	374	31.0	1.00173

4. ANALYSIS OF THE RESULTS

The water density variations are caused mainly by two factors – the impurity concentration and the temperature. The measured impurity concentration can be judged by the integral parameters – pH and COD, the dry residue from water evaporation and hardness. Table 2 shows that there are significant changes in the composition of water and that the impurity concentrations are increasing with temperature. This can be explained by increased solubility and concentration of suspended particles. The data on the density variations show small fluctuations, which is due to water density decreasing with temperature rise and its increasing with impurity solubility and suspended particle concentration. The resultant density fluctuations do not exceed 0.2% and are insignificant as compared with other factors.

The area of a usable cross-section of the river for producing electricity with hydrokinetic turbines is limited by the following factors:

- The hydrokinetic turbines should be sited only in the segments of a river cross-section where water is flowing all year long, which is important for optimal investment covering. The sites which are shallow more than 1.5 m are not intended for the use owing to:
  - a threat to animals and people because of easy access;
  - higher costs per kWh for smaller turbines;
  - turbulence (characteristic of shallow water), which hinders the running of hydrokinetic turbines or reduces considerably their efficiency. Also, there might be risk that turbulence in shallow waters can arise after the installation of turbines.
  - siting the turbines in shallow waters could be risky owing to probable dikes and wash-outs.
- If in some of cross-section places the water flow velocity is lowered by barriers, the turbulence increases; this causes a rise in the flow velocity and water level in other places. While these phenomena are not fully researched for the impact of hydrokinetic turbines on the environment, it could be assumed that this impact is insignificant in the cases when such turbines occupy only a small part of the river cross-section.

- The necessity to leave place in the river cross-section for all securing and constructive elements of the turbines.
- Space must also be left for navigation of the river, swimming and other possible uses of water (it should be stressed that the possibility to keep river navigable without extra costs is the plus of hydrokinetic turbines, not a constraint).

Since only scant information exists regarding restrictions on the river cross-section area that could be maximally covered with hydrokinetic turbines, we can suggest that there should be such restrictions. They are listed above as the restrictive factors for the river cross-section area used for hydrokinetic turbines.

Therefore, when calculating the electrical energy potential of the river (see Table 3) we made two basic assumptions:

1. As a safe minimum, the river cross-section area to be covered with active elements of hydrokinetic turbines should be ≤ 25% from the total area of the cross-section – only 1/4 of the total energy in one cross-section will be used for electricity generation.
2. One river cross-section with turbines and free zones between them should be ≥ 50 m of the river length[1] in order to prevent the impact of the turbulence caused by upstream turbines, to eliminate the threats for the downstream ones in case of accident, and to provide easy service.

Table 3

Evaluation of the potential for electrical energy production by hydrokinetic turbines in the explored spans of Daugava

No.	Location in Daugava (number of cross-section or point)		Length, m	Flow velocity, m/s	Cross-section are, m^2	Flow energy potential of the whole cross-section, W	Electrical power attainable from cross-section, W	Amount of electrical energy per year, MWh
	Start	End						
1	2	3	4	5	6	7	8	9
1	45	41	750	2.416	n/d*	n/d	n/d	n/d
2	38	30	4000	0.759	n/d	n/d	n/d	n/d
3	29	24	4400	0.538	697.70	53040.86	2254.24	1596.072
4	24	21	300	0.454	1167.48	54670.73	2323.51	1121.671
5	21	10	850	n/d	n/d	n/d	n/d	n/d
6	10	n/d	n/d	below 0.45	n/d	n/d	n/d	n/d
7	9	5	2150	0.800	556.91	142529.15	6057.49	2095.711
8	5	3	3000	0.677	772.23	119848.17	5093.55	2458.906
9	3	1	4000	0.479	1181.65	64987.20	2761.96	1777.776
10	1	n/d	n/d	below 0.41	n/d	n/d	n/d	n/d

* no data

[1] Restrictions of the type are known for wind turbines (see e.g. [8, 9]), although in the water environment the distances could be much shorter.

For further analysis and convenient representation of the results, two spans of the River Daugava were divided into smaller segments based on the measured flow average velocity (Table 3).

The data of Table 3 by columns are:

(1) Number of the segment for identification.
(2) Number of the first cross-section or point of the segment from Fig. 1 or Fig. 2.
(3) Number of the end cross-section or point of the segment from Fig. 1 or Fig. 2.
(4) The length of the river segment, m.
(5) The average water flow velocity in the river segment calculated by averaging the measurement results for all cross-sections that correspond to this segment (Table 1, the last column).
(6) The average cross-section area in the segment calculated by averaging the measurement results for all cross-sections that correspond to the segment (Table 1, the last column).
(7) The average kinetic energy of water flow (taken from [1]) using the data from the 5th and the 6th columns, and the water density indicator of 1.00 g/cm^3 (the rounded-off average indicator from Table 2).
(8) The average electrical power obtainable from a river cross-section using hydrokinetic turbines (taken from [1]) using the data from the 7th column and the following constants:
    a) the river cross-sectional area utilised by hydrokinetic turbines: 25%;
    b) the hydrokinetic turbine efficiency: 0.2 [10];
    c) the generator efficiency: 0.85.
(9) The volume of electricity that can be obtained from a river segment calculated using the data from the 8th column and the following constants:
    d) the distance between the turbines in the downstream direction of the river: 50 m;
    e) idle standing days in a year: 30.

5. DISCUSSION

In Table 3 the most significant data that characterise each explored river segment are given. In more detail, the segments can be characterised from the viewpoint of flow velocities and siting of hydrokinetic turbines as follows.

1. The fastest flows. This segment is suited best for operation of particular hydrokinetic turbines while not appropriate for a turbine park owing to abundant rapids. Therefore, special exploration is needed to find enough deep and less turbulent places for individual turbines.
2. The third by flow velocity. This segment is appropriate both for individual hydrokinetic turbines and for a turbine park.
3. Middle flow velocity. Already now in this segment the hydrokinetic turbines and parks (large included) could function provided suitable technologies are selected.
4. A slow-flow segment (the third velocity from end) with a limited area before the Aiviekste estuary. From the explored segments this is the least suitable for hydrokinetic turbine operation.

5. In this segment (around the Aiviekste estuary) the siting of hydrokinetic turbines is not purposeful because of turbulence and river interflows.
6. The second from end by flow velocity. Owing to big depth and cross-section area, this segment can be used in the future for siting hydrokinetic turbines with large active area.
7. A fast-flow (the second by velocity) segment. Best of all the explored segments suits for hydrokinetic turbine parks (including large ones); also because there is only a small zone along the riverbanks with small depth, so turbulence is insignificant.
8. A fast-flow (the fourth by velocity) segment. Appropriate for operation both of individual hydrokinetic turbines and of a turbine park.
9. The fourth from end by flow velocity. This segment can be suited for hydro-kinetic turbine operation in the nearest future, but is to be considered only after more promising segments.
10. The slowest flow in the beginning (no further data). Thanks to its potentially big size (length) can be of interest in the future when appropriate hydrokinetic turbine technologies are available.

In the analysis of measurement and calculation data on the adjacent cross-sections (where the measurements were taken at different times and on different flows volumes) it was found that the water level increases with flow rate, which leads to variations in the flow cross-sectional areas. This means that the flow velocities vary insignificantly and specifically to each particular location. In the FIRST part the flow velocity variations are also levelled off owing to the operation of the Pļaviņas hydroelectric power station – a classical water power plant that accumulates a surplus flow in the reservoir located between the FIRST and the SECOND parts.

Since the hydrokinetic turbines are intended to be used only in the cross-sectional river segments where water is flowing all over the year, the seasonal variations in the flow volumes could be ignored, and relevant calculations should be done without taking such variations into account.

6. CONCLUSIONS

Conclusions that can be drawn based on the measurement results and their analysis are as follows.

1. The data obtained for the flow velocities in the lower Daugava can be used for the development of power plants producing electricity with hydrokinetic turbines.

2. The potential for electricity production with hydrokinetic turbines in the lower Daugava is estimated to be up to 1 GWh per km per year.

3. For placement of hydrokinetic turbines or turbine parks suitable sites have been found.

4. The water density variations in time have been found not to exceed 0.2% and, therefore, would not affect significantly the energy potential.

5. In different places of the same cross-section the flow velocity can differ up to 3 times and more even in slow waters. Therefore, to significantly increase the

efficiency of a hydrokinetic turbine it is always worth making a detailed study of the flows in a particular area of the river before siting a power plant.

Apart from that, results of the work allow approximate evaluation of the potential for electrical energy production with hydrokinetic turbines also in other (not yet explored) adjacent parts of the River Daugava. This is increasingly relevant for the nearest and more distant future when hydrokinetic turbine technologies have been developed, making possible the electricity production at lower flow velocities.

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DAUGAVAS LEJTECES ENERĢĒTISKAIS POTENCIĀLS HIDROKINĒTISKO TURBĪNU IZMANTOŠANAI

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K o p s a v i l k u m s

Īsumā rakstā apskatītās tēmas var rezumēt sekojoši:

1. Aprakstīti iegūtie dati un secinājumi par Daugavas lejteces straumes ātrumiem, kas var tikt izmantoti elektrostaciju, kuras darbina hidrokinētiskās turbīnas, ierīkošanai. Izvērtēts hidrokinētisko turbīnu izmantošanas enerģētiskais potenciāls Daugavas lejtecē (vairāk nekā 22 km upes garuma).

2. Aprakstītas un pamatotas atrastās iespējamās vietas dažādu atsevišķu hidrokinētisko turbīnu un to parku uzstādīšanai.

3. Darba rezultāti ļauj aptuveni novērtēt arī citu Daugavas tuvāko posmu potenciālu hidrokinētisko turbīnu izmantošanai tuvākā un tālākā nākotnē, kad hidrokinētisko turbīnu tehnoloģijas attīstīsies, dodot iespēju ražot elektroenerģiju pie zemākiem straumju ātrumiem.

12.07.2012.