RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Power Engineering

Ansis KALNAČS
Doctoral Student of Post-graduate Program "Power Engineering"

ENERGY POTENTIAL ASSESSMENT AND EFFICIENCY IMPROVEMENT OF IN-STREAM HYDROKINETIC DEVICES

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis will be defended at a public session on the 11 of October 2017 at the Faculty of Electrical Engineering of Riga Technical University, Azenes str. 12/1 Riga, in room 306, at 13.00.

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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 and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Ansis Kalnačs …………………………….

Date: ………………………

The Doctoral Thesis is written in Latvian language and consists of an introduction, 7 chapters, conclusions and summary. The total volume of the Thesis is 169 pages including 2 appendices. The Thesis contains 31 figures. The bibliography lists 96 sources of literature.

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INTRODUCTION

Topicality of the subject

The rapid industrial development in the world of the last centuries was based on the use of fossil energy resources – such as coal and oil. This usage has been producing highly unfavourable side effects – environmental pollution and greenhouse gas (GHG) effect due to gases stemming from the pollution. As a result – apart from the adverse impact of pollution on the environment and human health – in the long term there is a pronouncedly unfavourable impact on the global climate making it warmer. Due to this, much more often natural catastrophes occur, and the humanity much more often comes up against extreme weather conditions – excessive heat or cold, droughts, floods, storms, etc. Besides, the most essential and actively used fossil fuels – coal and oil – cannot be renewed, and their reserves in a long term will be exhausted.

Taking into account the ever increasing demand for energy and the above mentioned challenges stemming from the necessity to meet this demand through using fossil fuels, in the world more and more attention is given to renewable energy resources – especially to those not producing abundant emissions and, therefore, not causing pollution and GHG effects.

Already in 2009, the European Union energy strategy up to 2020 and the EU Renewable Energy Directive among other factors set mandates for the use of renewable energy in the European Union, according to which in the time span from 2010 to 2020 it is necessary:

- to reduce the quantity of gases that give rise to the GHG effect by at least 20 %, and
- to increase the proportion of renewable resources in the EU overall energy mix by at least 20 % from the total energy consumption.

With account taken of the rapid climate deterioration in the last years, the countries of the world came to an agreement in 2015 about the following obligatory targets that should be added to those defined by EU:

- to reduce by at least 40 % by 2030 as compared with 1990 the gas emissions causing GHG effect,
- by 2030 to raise by at least 27 % on the whole the proportion of renewable energy resources in the EU overall energy mix.

The most efficient measure to be taken in order to realize the set targets is to focus on the renewables that do not produce considerable emissions and, therefore, also those of gases causing pollution and GHG effects.

The EU Renewable Energy Directive defines individual targets for each European member state based on its specificity and possibilities as to the use of renewable resources. In particular, for the Latvian energy supply – especially as concerns electricity supply – one of the most essential potentials is well-accessible hydro resources, which are both renewable and not causing large emissions. Owing to this fact, the specific weight of renewable energy resources in the Latvian energy supply mix was traditionally significant, and in 2008 this already was **29.9 %** from the total end-energy consumption. Therefore, the mandatory target set for Latvia is to achieve by 2020 that the specific weight of renewable energy resources is as great as 40 % of the overall energy use.

This means that in Latvia, the primary attention is to be concentrated on the active use of the most accessible renewable energy resources that do not cause large emissions – that is, the hydro resources.

Already now it is difficult to overestimate the contribution to Latvia made by the Daugava River cascade. At the same time, even the Daugava's potential is now utilized only partially. Here the case in point is not building a new dam or a hydro power plant (HPP) on the Daugava, but additional use of its potential for electricity production owing to fast progressing hydrokinetic technologies. The kinetic energy of river streams – i. e., a renewable, environment-friendly, stabile and sustainable energy resource – can be extracted also from other rivers or even brooks, which are abundant in Latvia. It should be stressed that this energy source is of local, regional character, and its advantages are those achievable at decentralized electricity supply in distributed electrical networks.

Latvia is importing up to 30 % from the electricity needed, while the possibilities of using its water stream kinetic energy have so far been completely ignored. However, with the development of hydrokinetic technologies, recently ever increasing opportunities are arising for their use, so it is necessary to estimate and develop them so that the mentioned technologies are introduced into practice.

Objective and tasks of the Thesis

The objective of the Doctoral Thesis is to run in and develop the method for the determination of rivers' hydrokinetic energy potential, and to find the possibilities for improving the hydrokinetic devices (HKD) efficiency under specific conditions of Latvia.

To attain this objective, the following tasks were set:

- to perform analytical review of the literature related to the river hydrokinetic technologies and the specificity of their use in the world and in Latvia;
- to work out a method for the evaluation of the river HKD energy potential;
- to perform validation of the method under real conditions;
- to develop and to test under laboratory conditions and at site the design of the prototypes for HKDs and channelling devices;
- to make conclusions based on which to put forth proposals on the future possibilities for HKD development in Latvia.

Hypothesis: Evaluation of the amount of the energy for every renewable energy resource is an important task for the nearest future both in Latvia and in the world. The potential of the river stream energy is not evaluated in Latvia, and there is no methodology developed that would allow doing that. Such methodology would allow evaluating the river stream energy as well as revealing the possibilities for its use, its strengths and weaknesses.

Methods and tools of the research

The analysis of the scientific literature on the river hydrokinetic technologies and the specificity of their use was performed to be able to utilize the latest achievements in the field.

To obtain data, experiments in laboratory and on site were performed, making measurements with the help of different measuring devices, including simple ones (measuring tapes, scales, theodolites, dynamometers, volume measuring devices, picnometers), more complicated (graduated and calibrated Pitot tubes, flow velocity measuring devices based on different operation principles, power meters) as well as complex: Doppler current meters for different depths, and satellite GPS positioning system.

Obtained data were processed, analysed and interpreted, including data validation and mathematical calculations. For this purpose, the internal software of the Doppler current meter and the PC software from its set, as well as *Microsoft Excel* software for data processing were used.

Modelling, data processing, programming and mathematical calculations required for the HKD placement and income modelling tool were performed using *MatLab* software.

Scientific novelty and practical implementation of the Thesis

The scientific novelty of the Doctoral Thesis is characterized by new information gathered in the course of the work and by new knowledge acquired from this information. In particular, the following can be mentioned:

- the previous world experience has been generalized on the design and use of stream hydrokinetic devices and on the estimation of their potential, taking into account the Latvian specificity;
- methodologies have been worked out for the estimation of the stream HKD energy potential, for the estimation of the energy potential of stream HKD channelling devices, and for the validation of the measuring data on the river depths and stream velocities as well as on the river cross-section area;
- new data have been acquired as to the possibilities of using the stream HKDs and their channelling devices, as well as on the energy potential of these technologies in downstream Daugava;
- new stream HKD elements, models, and prototypes have been worked out;
- eleven patent applications on the made inventions have been submitted to the Latvian patent office, for two of which the patents have been received and for one a decision to grant the patent has been received. The others at the time of completion of the Thesis are in different stages of consideration.

New information and knowledge gathered in the course of the Thesis promote the development of the energy branch, widening and favouring the diversity of available energy resources.

The results obtained during the Thesis development can be used in different ways, e. g.:

- for the estimation of the energy potential of stream HKDs and their channelling devices operating both in Latvian rivers and in those of other countries, using the worked-out methods;
- for the choice of a concrete optimal place for placing either an individual HKD or a power plant consisting of several HKDs in the explored spans of downstream Daugava;
- for planning and engineering a HKD-based power plant in the explored spans of downstream Daugava;
- for choosing HKDs and channelling devices that would be best suited to a particular technical solution using the elaborated methodologies and criteria;

- for the validation of the measurement data acquired in the rivers and the related data such as stream velocity, cross-section area, depth, etc., using the methods elaborated in the course of the work;
- for creation of new and more efficient stream HKDs and channelling devices using the knowledge acquired in the course of the work and the elaborated models;
- the results of the Thesis have been used in several inventions and can/might serve this purpose further.

Approbation of the Doctoral Thesis

The results of the work have been reported and discussed at the following conferences:

- Methodology for the evaluation of the energy potential of a river for siting hydrokinetic turbines. 8th International Conference “Materials, Environment, Technology” (MET–2013), Latvia, Riga, June 19–20, 2013;
- Hydro Energy Potential Estimation for Hydrokinetic Power Plants. 15th International Scientific Conference “Electric Power Engineering” (EPE–2014), Check Republic, Brno, May 12–14, 2014;
- Ways to increase the efficiency of hydrokinetic devices and their evaluation. 11th International Conference of Young Scientists on Energy Issues (CYSENI–2014), Lithuania, Kaunas, May 29–30, 2014;
- Specifics of the Methods for Estimation of the Hydrokinetic Potential of Rivers. The 8th International Scientific Symposium on Electrical Power Engineering “Elektroenergetika 2015”, Slovakia, Stara Lesna, September 16–18, 2015.

Publications

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- A. Kalnačs, J. Kalnačs, A. Mutule. Methodology for the evaluation of the energy potential of a river for siting hydrokinetic turbines // Proceedings of the 8th International conference MET–2013 “Materials, Environment, Technology”.
- A. Kalnacs, J. Kalnacs, A. Mutule, U. Pērsis. Methods for estimation of the riverflow potential for hydrokinetic power generation. Latvian Journal of Physics and Technical Sciences, Vol. 51, 2014, pp. 3–10, ISSN 0868–8257, SCOPUS.
- A. Mutule, A. Kalnacs. Hydro Energy Potential Estimation for Hydrokinetic Power Plants // Proceedings of the conference “Electric Power Engineering 2014” (EPE–2014), 2014, pp. 297–300, ISBN: 978-1-4799-3806-3, IEEE Catalogue number: CFP1473X – USB.
- A. Kalnacs, J. Kalnacs, A. Mutule. Ways to increase the efficiency of hydrokinetic devices and their evaluation // Proceedings of the 11th International Conference of Young Scientists on Energy Issues (CYSENI–2014), 2014, ISSN: 1822–7554.
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- J. Beriņš, J. Beriņš, J. Kalnačs, A. Kalnačs. Wave Energy Potential in the Latvian EEA. Latvian Journal of Physics and Technical Sciences, 2016/3, Vol. 53, pp. 22–33, SCOPUS.

Practical realization of the results of the Thesis

The results of the Doctoral Thesis are included in the following Ltd. “Environment, Bioenergetics and Biotechnology Competence centre” projects (ERDF financing according to the agreement No. L-KC-11-0005 with the Investment and Development Agency of Latvia):

- “Investigation into the streams of downstream Daugava for the development of new hydro power plant technology”;
- “Investigation into the installation conditions for hydrokinetic electricity production and into raising the possibilities to use slow-water streams, elaboration of a model for calculation of the turbine type and parameters at small and variable water flows”;
- “Investigation into the possibilities for raising the productive capacity of hydrokinetic power plants in the cases of slow water flows”;
- “Elaboration of the methods for investigation into the possibilities of using hydrokinetic devices and into their effectiveness”.

The results of the Thesis have been used in the following patents and their applications:

- V. Entins, R. Vaitkus, A. Kalnačs, patent LV 14830 B, “A device for conversion of the sea wave or river stream energy”;
- V. Entins, J. Kalnačs, A. Kalnačs, patent LV 14957 B, 20.04.2015, “A device for conversion of the river flow energy into electric energy”;
- V. Entins, J. Kalnačs, A. Kalnačs, patent application P-14-89, 12.11.2014, “Free-flow Schenck generator”;
- V. Entins, J. Kalnačs, A. Kalnačs, patent application P-15-02, 07.01.2015, “A device for conversion of the river flow energy into electric energy”;
- V. Entins, J. Kalnačs, A. Kalnačs, R. Pihocki, V. Anaņičs, E. Bychkov, patent application P-15-51, 08.06.2015, “A method and a device for hydrodynamic energy conversion”;
- V. Entins, J. Kalnačs, A. Kalnačs, R. Pihocki, V. Anaņičs, E. Bychkov, patent application P-15-127, 12.11.2015, “Economical hydro-massage shower”;
- V. Entins, V. Anaņičs, R. Pihocki, E. Bychkov, J. Kalnačs, A. Kalnačs, patent application P-16-02, 25.01.2016, “A device for hydrodynamic energy conversion”;
- V. Entins, V. Anaņičs, R. Pihocki, E. Bychkov, J. Kalnačs, A. Kalnačs, patent application P-16-03, 28.01.2016, “A damper-accelerator of stream flow based on the Entin-Bichkov effect”;
- V. Entins, J. Kalnačs, A. Kalnačs, R. Pihocki, V. Anaņičs, E. Bychkov, patent application P-16-20, 18.03.2016, “A hydrogenerator injector / An injector for hydrogenerator”;

- V. Entins, E. Bychkov, A. Kalnačs, J. Kalnačs, A. Novikovs, A. Novikova, patent application P-16-60, 05.08.2016., “A method and device for acceleration of the flow in hydroelectric generator”;
- V. Entins, E. Bychkov, J. Kalnačs, A. Kalnačs, patent application P-17-15, 24.03.2017., “Device for acceleration of the flow”.

SURVEY OF THE LITERATURE

1.1. Technologies for the river or stream hydrokinetic power plants

In the literature, descriptions are found for many diversified technologies which, being in different stages of development, can be applied in the construction of hydrokinetic devices (HKDs) aimed at conversion of the kinetic energy of streams into the electric one [1]–[6]. These technologies are based on various solutions related to the HKD active elements and generator drives.

A schematic of a river or stream HKD is shown in Fig. 1 [7].

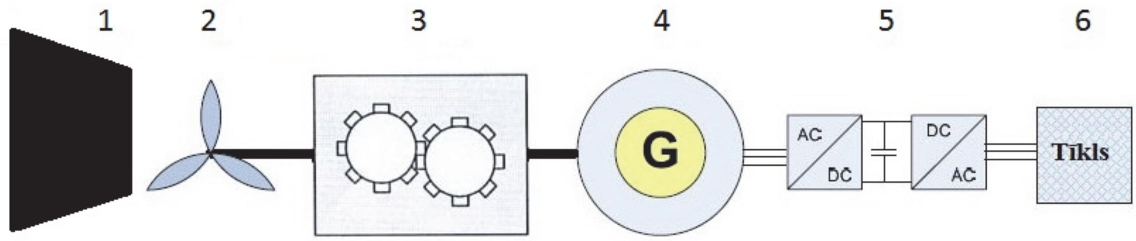

Fig. 1. Schematic of a river or stream HKD:

1 – channelling device; 2 – active element (or active elements); 3 – gearbox and generator drive solution; 4 – generator; 5 – electrical connection safety circuit; 6 – electricity distribution network or individually connected electrical device (it is not a part of HKD).

The main constituents which determine that a HKD is an essentially hydrokinetic device are its active elements. In most cases, these are the turbine or different type blades that are moving under the action of water streams thus converting the kinetic energy of the latter into movement. These active elements are the only obligatory constituents of a HKD, which, without them not producing electricity, can, for example, serve as a mechanical drive for pumps, as an irrigating device, etc.

The size and view of a HKD is fully dependent on its design.

All HKD technologies [8]–[12] can conventionally be grouped into eight technology subgroups, which, in turn, can be united in two groups, thus forming a HKD technology division (tree) shown in Fig. 2.

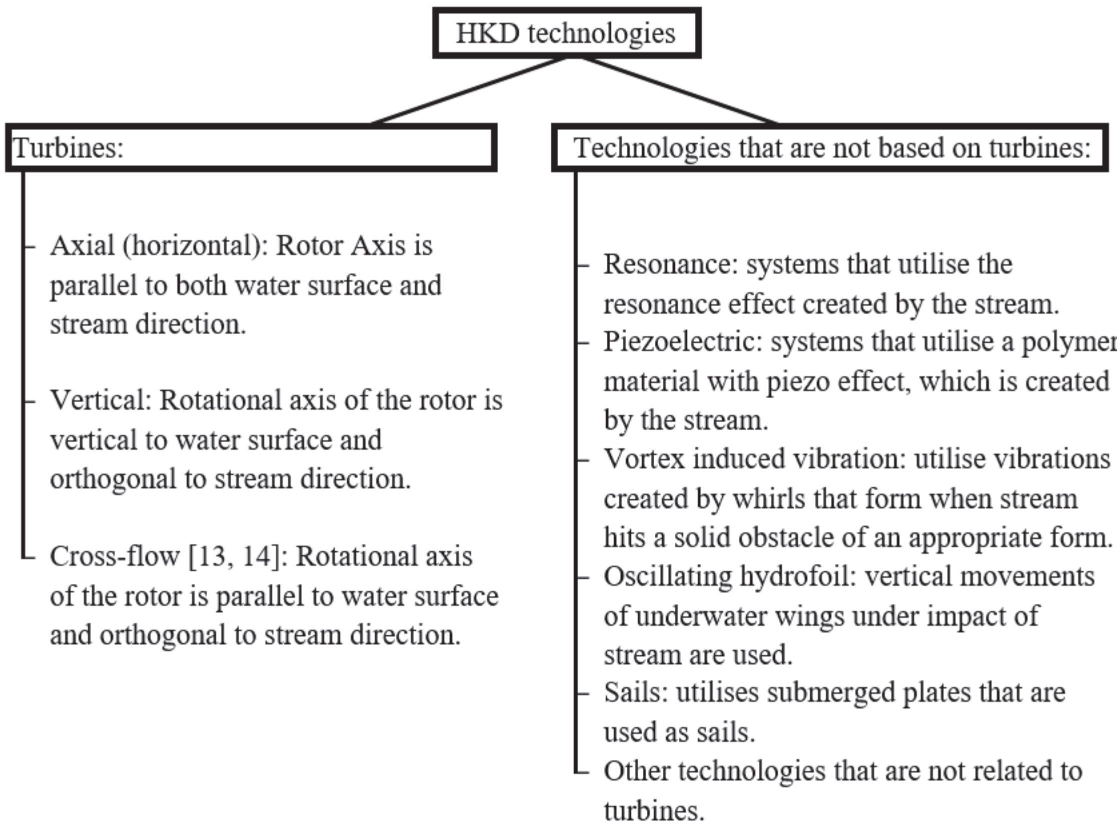

Fig. 2. HKI technologies and their division (tree).

Based on the available information, the present Thesis gives a more detailed analysis – both for the HKD components and for the relevant technologies.

1.2. Comparison of the technologies

HKD including river or stream HKD has two distinctive advantages in comparison to the majority of other energy sources:

- HKD uses only renewable energy resources, and
- HKD is producing only insignificant harmful emissions (if any at all).

Thus, it makes sense to compare HKD technologies to only those other energy production technologies that have the same two characteristics. Namely, only four:

- wave HKD,
- traditional HPP (with dams),
- wind electrical power plants,
- sun electrical power plants.

All those five electrical power plant types together can be called as renewable electrical power plants that produce only insignificant (harmful) emissions.

There are three significant areas that are influenced by energy production:

- safety (risks),

- electrical networks,
- environment.

In the Thesis, analysis is given for the (stream or) river hydrokinetic power plant (RHPP) influence in the three mentioned areas, and comparison is presented with other low-emission renewable energy production ways. Specifics for Latvia are also analysed where relevant.

As concerns RHPPs, so far the only identified safety and environmental risk for them is the possibility of blockage formation – of ice or other swimming objects. Although HKDs affect some safety spheres, they do not introduce new ones or new-type risks. Moreover, the HKD-related risks are comparatively smaller than those for other power plants. Investigation into the relevant literature has not given information about other new or HKD-specific risks. Therefore, in order to guarantee the safe operation of a HKD, it is necessary to take into account at its designing and service only well-known risks in compliance with well-known methods for this particular HKD.

In turn, concerning the RHPP influence on electrical networks, it is concluded that HKD connection and operation involves smaller risks to such influence than other type plants working on renewables with minor emissions. The more so, all HKD risks are rather easily controlled using already existing methods for the control and operation of the network and its technological equipment, which, in addition, are readily upgradable.

The RHPP is a safe and environment-friendly type of the power plant, which can easily and reliably be integrated into existing networks. In terms of cost, such a RHPP is similar to other low-emission renewable energy producing power plants [7]. Considerably cheaper electricity is produced only by traditional HPPs, which, however, much more negatively affect the environment.

1.3. Specific character of the methods for the estimation of the HKD energy potential and the related variables

To obtain the input data needed for the estimation of the river stream kinetic energy, a great many methods exist and are used. The works [15]–[18] are only a few of many possible examples. In turn, only few methods and research works can be found that make it possible to explore a river and its segments [19]–[22], or even the whole river region [23]–[26]. Moreover, these few methods have been worked out each for a particular case, and are not intended for common applications. At the same time, for planning or developing the kinetic energy industry both type methods are required, which would be applicable also in general cases at any place where it would be necessary.

Methods that are intended for the mentioned estimation of a particular river or its segment usually involve in-river measurements, giving the most precise results on the river. Such methods are therefore suitable for the development of hydrokinetic power plants. In turn, the methods meant for the estimation of the regional energy potential are based on geographic information systems (GISs) and hydrologic observation data. Methods of the latter type are much more imprecise, still they make it possible to estimate a whole region with abundant rivers spending smaller resources for this purpose. The information obtained by these methods is essential when the case in point is the strategic development of hydrokinetic electricity generation industry and the planning of investments in it.

The kinetic energy of a stream can be calculated by the following equation [10]:

$$N = \frac{1}{2} \cdot v^3 \cdot S \cdot \rho, \qquad (1)$$

where

v – stream velocity, m/s;

S – cross-sectional area of the stream perpendicular to the stream direction, m^2;

ρ – stream (water) density, kg/m^3.

From the measurements described in the work it is obvious that the water density ρ changes insignificantly and, thus, does not have significant influence. However, there are much more variables involved in the calculations for hydrokinetic energy evaluation than it appears from the Eq. (1). This is because the stream velocity v and the cross-section area S are dependent on many other variables. The complexity of the calculations are also increased by the constraints due to other kinds of using a river as well as the ecology and requirements of the chosen hydrokinetic technology. All the mentioned factors determine the necessity of using the following additional data for the estimation of hydrokinetic potential:

- geographical (terrain);
- hydrological;
- different constraints that reduce the cross-sectional area of the river, which can be used for HKD, and define its form;
- different variables that depend on the technical solution (for example, minimum depth required to operate a particular HKD).

Either the methods are used for a definite river or for a region consist of the following steps:

1) in-river measurements (when the estimation relates to a river or its segment) or data collection (in the case of the evaluation of a region);

2) validation of the data obtained;

3) data processing, analysis, and interpretation of the results.

A power of a specific HKD placed in a specific place of a river can be calculated by the Eq. (1) to which the efficiency coefficient of the HKD is added:

$$N = \frac{1}{2} k \cdot v^3 \cdot S \cdot \rho, \qquad (2)$$

where

k – empirical coefficient dependent on the particular HKD [27], [28];

v – stream velocity before HKD, m/s;

S – cross-sectional area of the stream that enters the HKD perpendicular to the stream direction, m^2;

ρ – stream (water) density, kg/m^3.

The coefficient k from Eq. (2) can be determined experimentally. It shows the proportion of the kinetic energy in the stream that the particular HKD transforms to mechanical energy that can be used to drive mechanisms or an electrical generator.

2. METHODOLOGY FOR THE ESTIMATION OF THE POTENTIAL OF ENERGY PRODUCTION USING HKDs IN A RIVER SPAN

In order to appreciate and explore the most promising places in Latvia for the electric energy production by river HKDs using the available equipment and measuring tools, a special methodology has been worked out. The methodology can be applied for the exploration of any river or its span where it is possible to sail a boat or another floating means and to keep it immovable against the riverbanks. The methodology has been refined and elaborated in more detail in compliance with additional information that was acquired in testing it in the river of Daugava.

The procedure on a highest level consists of the mentioned above three steps: the in-river measurements, the validation of the acquired data, as well as the data processing, analysis, and interpretation of the results obtained.

Fig. 3 illustrates the elaborated procedure by the high-level block diagram.

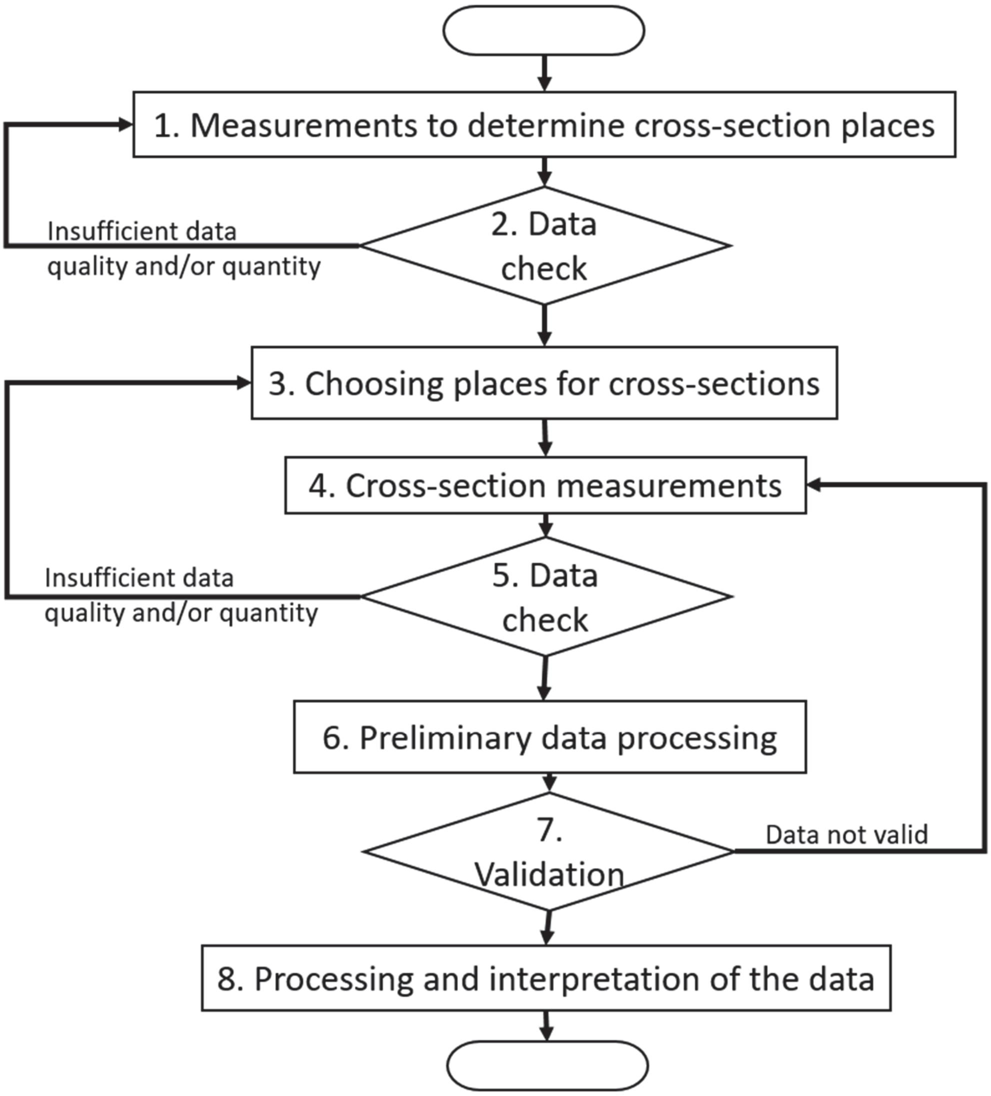

Fig. 3. High-level block diagram of the developed method:

1. – at boating parallel to the river stream, the measurements are taken in order to obtain the data for choosing the places for the cross-sections to be measured; 2. – the data obtained in

step 1 are checked and analysed; in the case their quantity and quality are not satisfactory, step 1 is repeated or continued; 3. – based on the data obtained in step 1, the places for the cross-sections to be measured are chosen; 4. – measurements in all the chosen cross-sections are taken; 5. – the data obtained in step 4 are checked and analysed; in the case their quantity and quality are not satisfactory, additionally the actions according to steps 3 and 4 are taken or repeated; 6. – preliminary data processing is performed in order to obtain the results required for their final checking and validation; 7. – the validation is performed for all the data obtained; in the case the validation results show that these data are not suitable, the process should be started from step 4; 8. – processing and interpretation of the data obtained is performed up to the end results.

From the viewpoint of data processing and calculations, this step is the most volumetric (see Table 1). If necessary, this step can include also estimation of the influence exerted by channelling devices. Columns 12–15 of the Table are meant for the estimation of the effects of using channelling devices. Description of the results given in these columns is found in Chapter 4 of the present Doctoral Thesis. Each row of the exemplary table corresponds to one explored span of the river. Essential parts of the end results are also the interpretation of the results obtained for each river span and the conclusions drawn during the exploration of the river. These, in compliance with the methodology proposed, are described in detail in Chapter 3 of the Thesis.

Table 1

Evaluation of the potential for electrical energy production with hydrokinetic devices in the explored spans of the Daugava River between Jaunjelgava and Jēkabpils

							No channeling device				Channeling device A		Channeling device B	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#	Location in the River Daugava (number of cross-section or point)		Length (m)	Flow velocity (m/s)	Cross-section area (m2)	Flow energy potential of the whole cross-section (W)	Attainable electrical power from cross-section (W)	Amount of electrical energy per year (MWh)	Power from 1 km of the river (KW)	Amount of electrical energy per year from 1 km (GWh)	Power from 1 km of the river (KW)	Amount of electrical energy per year from 1 km (GWh)	Power from 1 km of the river (KW)	Amount of electrical energy per year from 1 km (GWh)
	Start	End												
1	45	41	750	2.416	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
2	38	30	4000	0.759	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
3	29	24	4400	0.534	697.7	53 041	6311.86	7442.948	925.740	1.692	1363.750	2.492	1947.824	3.559
4	24	21	3000	0.454	1167.5	54 671	6505.82	5230.677	650.582	1.744	958.402	2.569	1368.871	3.669
5	21	10	850	n/d	n/d	n/d	n/d	n/d	n/d	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	n/d	n/d	n/d	n/d	n/d	n/d
7	9	5	2150	0.800	536	137 288	16 337.30	9413.552	1170.840	4.378	1724.817	6.450	2463.530	9.212
8	5	3	3000	0.677	772	119 848	14 261.93	11 466.593	1426.193	3.822	2100.991	5.631	3000.814	8.042
9	3	1	4000	0.479	1181.7	64 987	7733.48	8290.287	1031.130	2.073	1519.005	3.053	2169.573	4.361
10	1	n/d	n/d	below 0.41	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d

n/d – no data

3. EXAMPLARY APPLICATION OF THE DEVELOPED METHOD

Taking into account Eq. (1) for the water stream kinetic energy and the turbulence influence, the main criteria at choosing appropriate sites for the maximum RHPP electricity production are the following:

- the stream should be with as-low-as-possible turbulence;
- the stream should be with as-high-as-possible velocity;
- the stream should have as-large-as-possible cross-section, which would allow choosing the most suitable HKD technology;
- the structure of the river banks and bed should be known, which would allow realization of the chosen technology.

From these criteria it follows that the greatest potential for electricity production using HKDs is possessed by the Daugava. Therefore, viewing through the statistical data on the water currents and estimates for other mentioned criteria, for the stream velocity measurements and for further explorations, the following Daugava's segments with a high potential expected for HKD electricity production were chosen:

A. – from Jaunjelgava to the Pļaviņas water storage;

B. – from the Pļaviņas water storage to Jēkabpils;

C. – from Jēkabpils to Līvāni.

The results for the segments A and B are given in Table 1. Example for interpretation of the results or the descriptive analysis of the tabulated data from the standpoint of the stream velocity and possibility to use HKDs, according to the numbers of spans in Table 1, can be presented as the following list.

1. The fastest streams and, therefore, the best of the explored ones suited for the operation of a few individual HKDs. For HKD parks, they are not suitable since they have rapids, so deep enough and low-turbulence places should be sought specially.

2. The 3rd by-velocity stream: is suited for the operation of both individual HKDs and HKD systems.

3. The average by-velocity stream from all explored spans. If the appropriate are found, they can already now be used for HKD operation – for large turbine systems included.

4. The 3rd by-slowness stream and a bounded span before the Aiviekste estuary: from the explored ones, the least suited for HKD operation.

5. In the Aiviekste estuary, there is no sense to place HKDs due to turbulence and confluence with other rivers since the relevant parameters are difficult to forecast.

6. The 2nd by-slowness stream: owing to the large depth and cross-section, it can be suitable in the future for the operation of HKDs with a large active area.

7. The 2nd by-rapidness stream: from the explored ones, suited best for the operation of HKD parks (also large) since the insufficient depth is only in a little zone along the riverbanks, so the turbulence is insignificant.

8. The 4th by-rapidness stream: is suited for the operation of both individual HKDs and HKD systems.

9. The 4th by-slowness stream: can become suited in the near future for HKD operation, but only after more promising spans have been developed.

10. At the beginning of the slowest stream (so far no data): potentially, due to large sizes (length), could be of interest in the remote future with the development of relevant technologies.

The exploration results for segment C are described in Chapter 5 of the Doctoral Thesis and are given in Table 2.

Several conclusions acquired in testing the proposed approach for the Daugava River and further justified in the Thesis were drawn, which are summarized below.

- A methodology has been worked out based on which it is possible to estimate which of the river spans and to what degree are suitable for electric energy production by RHPPs.
- Using this approach, it is possible make such estimations for any river or its spans where it is possible to sail a boat or another floating means and to keep it immovable against the riverbanks.
- For validation of the stream velocity measurement data and retrieving additional information needed for the estimation of a river (or its span), highly valuable are the statistical data on running water volumes obtained from the observation stations. The usage of such data is described in the methodical part of the Doctoral Thesis and in the relevant example.
- Analysis of the measurements taken in the Daugava shows that the variations in stream velocities are only slightly affected by the variations in the running water volumes.
- Data have been obtained on the Daugava's downstream velocities, and they can be used at RHPP construction.
- Appropriate places have been found for the arrangement of various individual HKDs and HKD parks.
- It is established that the variations in the water density with time do not exceed 0.2 %, so they cannot considerably affect the energy potential.
- The results of the Thesis allow a rough estimation of the potential for other Daugava's near spans so that they can be used by RHPPs in the near and remote future with advances in HKD technologies, thus making it possible to produce electric energy at lower stream velocities.
- It is established that the stream velocities even in calm rivers can vary as much as three times and more in different places of one cross-section. Therefore, before HKD arrangement in order to improve significantly their efficiency, it is always worth doing a comprehensive exploration of the streams in a corresponding river span.

4. INFLUENCE OF CHANNELLING DEVICES ON THE USE OF HKDs

4.1. Substantiation for the application of channelling devices and the principles of their operation

As shows Eq. (2) describing streams or free flows, the operation of hydrokinetic devices is affected mostly by the stream velocities. The energy output grows with stream velocity to the 3rd power. This affects the amount of energy generated by power plants not only directly (see Eq. (1)), but also indirectly with increasing efficiency included in constant k of the equation.

The velocity of stream is transformed in HKDs into the turbine rotational speed and thus to that of generator rotation. The generator efficiency increases with its rotational speed increasing. This makes it possible to raise the HKD efficiency. In compliance with Bernoulli's law, possibilities to concentrate the energy and to raise the efficiency of HKDs are realized by the use of diversified channelling devices (see, e.g. [30]–[34]). Channelling devices can also be parts of a HKD. In Fig. 1, they are marked with "1". Increasing the stream velocities, channelling devices also reduce the area available for active HKD parts (propellers, blades, etc.). Such area reduction is equal to the area covered by the channelling devices, which, therefore, cannot be occupied by the active HKD parts. As a result, factor S (see Eq. (1)) decreases, which means linear decrease in the HKD power. However, since stream velocity increments (v) increase the output proportionally to the 3rd power, the gains are here essentially higher than losses due to reduced area (S).

The channelling devices are simpler than the HKD ones, while their maintenance costs are much smaller. Therefore, a HKD equipped with appropriate channelling devices will be cheaper – both as related to their production and service; besides, such a HKD will generate more electricity than that covering the same area without channelling devices.

The use of channelling devices might also raise the HKD cost; however, the gains in this case would be considerably greater. Since channelling devices present immovable obstructions on the way of stream, they are subject to significant stream pressure [30], [35]. Therefore, the main position as to the cost whose rise and minimization should be weighed is the cost of their strengthening. This is the question that should definitely be taken into account when choosing the form and size of a channelling device or when working out new ones.

The channelling devices make it possible to extract more energy from the same streams exceeding Betz's limit [30], [36], [37]. According to this limit, the maximum amount of energy that could be extracted from a stream is equal to 60 % of the total kinetic energy of this stream, but it is stated assuming that its whole cross-section is covered by the HKD active parts while the possibility of using channelling devices is ignored.

The effectiveness of energy concentration by channelling devices is increasing with decreasing stream velocities [29]. This implies additional possibilities of using HKDs at comparatively flat reliefs where slower rivers are running – for example, as in Latvia, in the Baltic countries, as well as in many other places of the world. The measurements of stream velocity in Latvian rivers show that the most suitable places for HKD installation are those with stream velocities from 0.4 to 0.9 m/s. To ensure effective operation of HKDs, it is desirable that there are at least twice or even thrice more rapid streams. Possible solutions related to the channelling devices for streams with the velocity under or about 1 m/s, which have been explored the least, possess the highest potential for obtaining good results.

The rivers and the conditions for placing HKDs in the streams are diversified and are differing from each other. Just the same, there are many different HKDs and channelling devices from which it is necessary to choose an optimal combination that would work in a chosen river. Therefore, it is important to correctly estimate the potential of electricity production using hydrokinetic devices (in order to choose an appropriate HKD) – both for a river or its span. Also, it is necessary to be acquainted with particular technologies and their combinations in view of electricity production by hydrokinetic devices (in order to choose the best solution for a particular river). For these purposes, in this work appropriate methods are proposed the application of which would allow estimation and comparison of HKD electricity production with and without channelling devices.

4.2. Complementary methods for the estimation of the effect of using channelling devices

For appropriate comparison of the electric energy output as well as other results obtained for HKDs with and without channelling devices, it suffices to complement the methodology described above by two parameters that characterize a particular channelling device:

- the channelling device area proportion coefficient (area ratio), which is found dividing the outside/external (i. e., the greater one) cross-section area by the inside/internal (i. e., to be covered with the HKD active elements) cross-section area [30]: this parameter allows taking into account the area occupied by the channelling device – i. e., S reduction (see Eq. (1));
- the HKD efficiency coefficient in the case of its use together with a particular channelling device: this parameter involves taking into account v and N gains (see Eq. (1)).

To make it possible to compare the results for both cases (with and without channelling devices) as well as to obtain better possibilities for the comparison of the explored river spans, the table containing the end results (see Table 1 and Table 2) in compliance with the described above approach can be complemented with several columns (see columns 10–15 in Table 1 and Table 2).

The data for channelling device A are taken from [29], and the data for channelling device B are taken from [30] ("profile E1A6"). The information on channelling devices A and B is found in the mentioned works.

From the information presented in Table 1, it is seen that the use of channelling device A under given conditions allows for raising by 47 % the amount of electric energy produced using channelling device A, while using device B allows for 110 % rise in output. The information on the efficiency of device A is obtained in an empirical experimental. As evidences the relevant information from the internet, this is a channelling device possessing better efficiency, which is supported by practice. In turn, device B has twice as high efficiency, but it is only a theoretical channelling device, therefore its efficiency is also only theoretical.

4.3. Conclusions on channelling devices

Based on the results of the Thesis, several conclusions can be made regarding the use of HKDs in combination with channelling devices.

- The calculations evidence that channelling devices can raise the effectiveness of HKD electric energy production by at least 50–110 %.

- Channelling devices present a promising solution for the improvement of the river HKD efficiency.
- The gains owing to the use of channelling devices can be estimated applying the methods described in the present Thesis.
- It is promising and desirable to carry out investigations and designing works in order to create channelling devices for stream velocities ≤1 m/s, since they have been investigated the least while their operation is plausibly the most efficient.
- Decreasing the stream pressure acting upon channelling devices and their strengthening are the problems that call for proper solutions when working out new channelling devices.

5. EXPLORATORY RESULTS FOR THE 2nd SPAN OF THE DAUGAVA RIVER

The exploratory results for Daugava's segment C (from Jēkabpils to Līvāni) are presented in Table 2, which is structured similarly to Table 1. All calculation constants, expedients, the data on channelling devices and other relevant information are taken from the present Thesis, namely, from the description of exemplary application of the proposed methodology and from the chapter related to channelling devices.

The Thesis also contains maps for the explored Daugava's places, cross-sections, and points, as well as all the results of measurements and calculations.

Table 2

Evaluation of the potential for electrical energy production with hydrokinetic devices in the explored spans of the Daugava river between Jēkabpils and Līvāni

							No channeling device				Channeling device A		Channeling device B	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
#	Location in the Daugava river (number of cross-section or point) Start	End	Length (m)	Flow velocity (m/s)	Cross-section area (m^2)	Flow energy potential of the whole cross-section (W)	Attainable electrical power from cross-section (W)	Amount of electrical energy per year (MWh)	Power from 1 km of the river (KW)	Amount of electrical energy per year from 1 km (GWh)	Power from 1 km of the river (KW)	Amount of electrical energy per year from 1 km (GWh)	Power from 1 km of the river (KW)	Amount of electrical energy per year from 1 km (GWh)
1	S6	S5	2000	0.503	598.4	38 101	4534.00	2430.222	302.266	1.215	445.283	1.790	635.990	2.557
2	S5	S4	800	It does not make sense to install HKDs at the place of confluence of rivers due to turbulence and other varying conditions.										
3	S4	L27	2000	0.480	768.1	42 432	5049.38	2706.469	336.625	1.353	495.898	1.994	708.284	2.847
4	L27	J16	12 000	0.988	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
5	J16	J18	1500	It does not make sense to install HKDs at the place of confluence of rivers due to turbulence and other varying conditions.										
6	J18	S1	1800	0.535	914.1	70 068	8338.09	4022.297	500.286	2.235	736.994	3.292	1052.637	4.702
7	S1	J27	3500	0.989	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
8	J27	J29	800	It does not make sense to install HKDs at the place of confluence of rivers due to turbulence and other varying conditions.										

n/d – no data

Example fot interpretation of the results or the descriptive analysis of the data given in Table 2, from the viewpoint of the stream velocity and possibility of HKD applications, according to the numbers of spans in Table 2 is presented in the form of the list below.

1. One of the three selected spans where HKD parks can be arranged, namely, the second (medial) by velocity stream: the potential of electricity output is the least from these three. In the future, it can be used for the local (Līvāni) electricity supply.
2. It does not make sense to install HKDs at the place of the confluence of rivers due to turbulence and other varying conditions.
3. One of the three selected spans where HKD parks can be arranged, namely, the slowest stream: the 2nd (middle) potential of electricity output from the three. In the future, it can be used for the local (Līvāni) electricity supply.
4. A long river span with rapids. Along its length among the rapids, it is possible to find proper places with fast and deep enough streams where individual HKDs can be installed. Not suitable for building up HKD parks.
5. It does not make sense to install HKDs at the place of the confluence of rivers due to turbulence and other varying conditions.There are also many islands there, which introduce greater uncertainties and make the maintenance difficult.
6. From the viewpoint of the electric energy produced, the most promising of the three selected spans where HKD parks can be built up: from the three, the fastest stream and the highest output.
7. A span with rapids. Among the rapids, it is possible to find proper places with a fast and deep enough stream where individual HKDs can be installed. Not suited for building up HKD parks.
8. It does not make sense to install HKDs at the place of the confluence of rivers due to turbulence and other varying conditions.

From the works devoted to the investigation of the Daugava's potential and of channelling devices it follows that HKDs are worth developing for the use also under Latvian conditions, since these conditions as well as possibilities of using them are good and promising enough.

6. WORKS IN THE IMPROVEMENT AND DEVEPOPMENT OF NEW HKD

Various technical expedients that make it possible to significantly raise the efficiency of a hydrokinetic device are known. These possibilities are provided by channelling devices, e. g., diffusers or other specific means for the control of streams. The function of these means is to change a stream's cross-section and /or its direction, as well as to change the pressure in this stream and minimize turbulence; all this taken together considerably increases the efficiency of using the stream energy. To widen the knowledge in this sphere and to appreciate the ways of using most efficiently slow streams typical of Latvia , a research was performed on the possibilities of raising the efficiency of HKDs by using the mentioned means.

Research were also performed on how to use most efficiently the kinetic energy of slow streams, e. g., by changing the shape of the energy absorbing body placed into water. With this aim in view, experiments have been run with the bodies of various shapes inserted into a stream in order to model the stream energy distribution and to predict the acting forces. The objective was to find such shapes and accommodation of the bodies that would provide as effective as possible the use of the stream's kinetic energy. As a result, additional information has been obtained on the forces acting on a HKD in different situations. For this, various solutions were used – mainly non-traditional, i. e., most innovative and suitable for using in slow streams of Latvia.

The knowledge acquired in the course of research has been applied for designing new hydrokinetic devices. The author of the Thesis, being engaged in collectives with other inventors, has participated in designing various HKDs and their components. As a result, eleven patent applications have been submitted to the Patent Office of the Republic of Latvia, with the author of the Thesis being a co-author. Two patents are granted and decision to grant one more patent is made. The other patent applications are now in different review stages.

7. APPLICATIONS OF THE DEVELOPED METHODOLOGY IN ECONOMICS

There are only a few works available in the literature where the economic aspects of the use of HKDs are researched. These works cannot be directly used to plan the placement and count of HKDs because they are either too general [7] or devoted to one particular case [38], or they analyse the issues where placement and count of the HKDs are not taken into account [39]. Information provided by manufacturers of HKDs is also restricted to standard technical data and does not tell how to take into account different local restrictions [1], [10].

Thus, it is necessary to develop a tool that can combine HKD technological requirements and results acquired by applying the methodology developed in this work while taking into account different restrictions that are described in this Thesis. The task for the tool is to help find such HKD solution and placement in the river that gives highest income. The tool should provide the following functionality:

- HKD placement optimization by taking into account several restrictions defined by the river and its other different uses:
    - minimum distance from riverbank to a HKD,
    - minimum depth for HKD placement,
    - maximum count of HKDs that can be stacked up one on the other,

  as well as the dimensions of the HKD and potentially (when further developing the tool) different other restrictions;
- the calculation of the maximum available cross-section area, and the number of HKDs according to given restrictions;
- the calculation of the hour-by-hour and cumulative income from all HKDs in the model as well as for individual HKDs based on electricity prices given;
- conveniently add in and remove from the model any river cross-section data in the (Excel) form described in the methodology;
- graphically illustrate and compare the cross-section area used by HKDs and other information at different given restrictions;
- graphically illustrate and compare the income from different HKD solutions.

A tool that provides the defined functionality while taking into account the data described was developed using *MATLab* software.

Modelling data acquired with the use of the tool allow detailed comparison of HKD solutions according to income. The modelling allows choosing an optimal HKD placement in the river as well. By modelling several cross-sections of a river, it is possible to create a HKD solution model for a river span.

The functionality of the tool shows how the methodology developed in the present Thesis can serve as a basis to economical calculations and prognosis. It is possible to further develop the tool in several directions that are also directions for the possible future application and development of the methodologies. Methodologies and tools that have been already developed as well as the further prospects for their development and application are shown in Fig. 4.

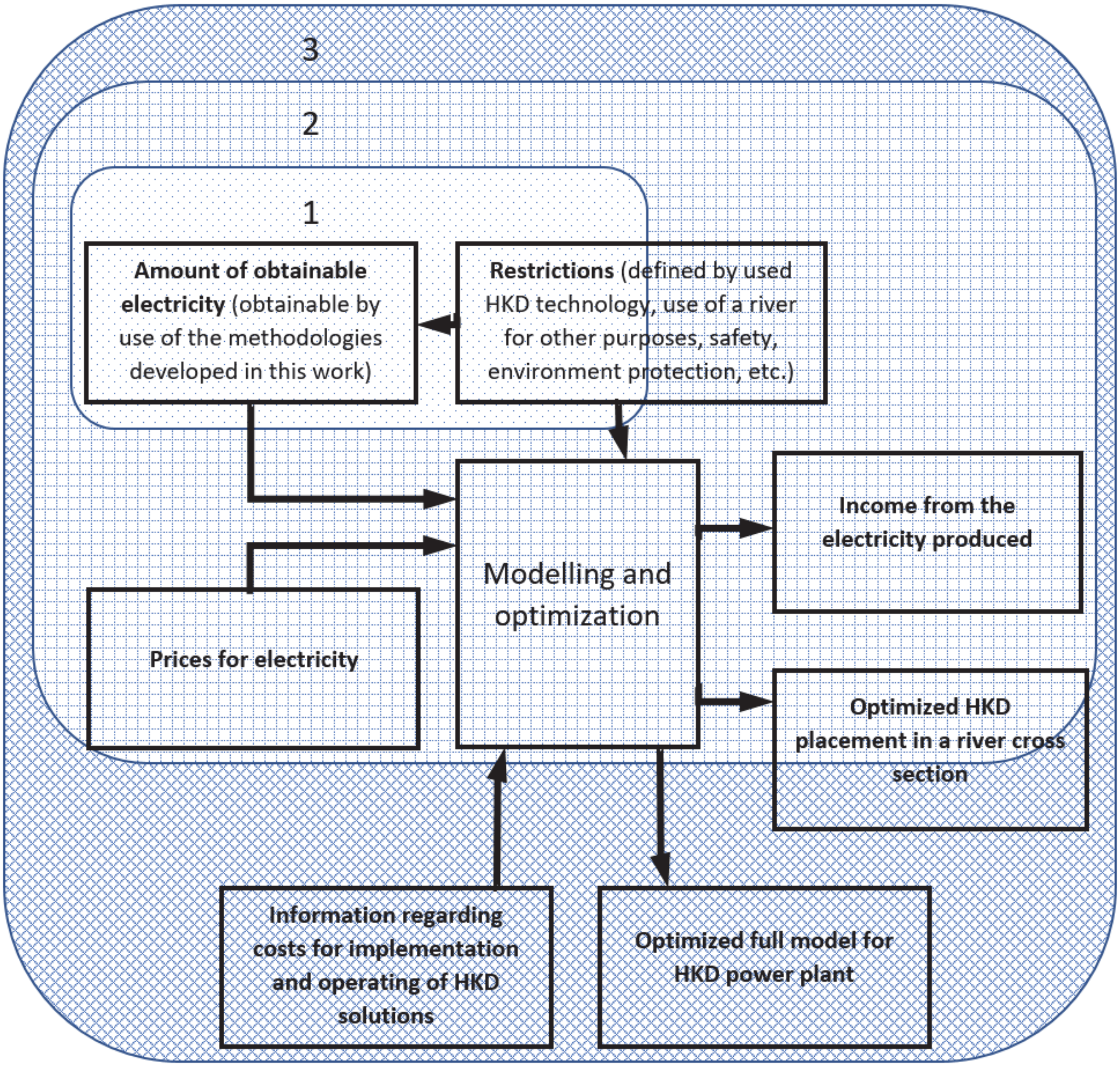

Fig. 4. Methodologies and tools developed in the present Thesis and further prospects for their development and application.

Data that can be obtained with the use of the methodologies that are developed in this Thesis are marked with the number “1” in Fig. 4.

The tool and extension of the application of the methodologies that are described in this chapter are marked with the number “2” in Fig. 4.

Possible future development and applications in the field of economy of the developed methodologies and the tool are marked with the number “3” in Fig. 4.

The optimized distribution of HKD in a river cross-section is only partly included in additions that are described in this section (e. g., “2”), because supplementing the model with economic cost data, it will be possible to improve the selection and optimization of the HKD solution (e. g., “2” will be further improved).

Briefly summarising the information in this Chapter, it can be concluded that the methodologies and their applications that are developed in this Thesis have very promising further development prospects. New efficient applications can be obtained both in short and long term by gradually realizing those prospects.

CONCLUSIONS AND A SUMMARY

It can be concluded from the literature analysis performed in the Thesis that hydrokinetic technologies are developing rapidly and becoming relevant for use also in Latvia. In turn, there are very few and deficient methodologies with which to estimate hydrokinetic energy potential and plan electricity production with HKDs.

Based on the research carried out regarding the methodologies for estimation of the river kinetic energy, the following conclusions can be made:

- the methods for the estimation of the river kinetic energy based on the amounts they predict can be divided into two types:
    - methods for the estimation of the kinetic energy potential of one river or its segment,
    - methods for the estimation of the kinetic energy potential of a region (with several rivers);
- due to a large number of variables, these methods are labour-intensive, sensitive to errors, and might be imprecise. Therefore, the check and validation of data obtained before their further processing is a needed and relatively easy implementable task;
- the energy output can be affected by the variables which at the time of estimation could be unknown (e. g., those regarding future achievements in the hydrokinetic energy) but which should be taken into account in the stage of devising relevant methods (e. g., concerning the ratio of the energy amount in a river to that obtainable from this river can vary depending on the technical solution);
- since the hydrokinetic technologies are developing fast, also the methods for the estimation of hydrokinetic energy potential should not lag behind. Both type methods should be developed further so that they would help to treat the data obtained and to store them in the form that would allow their use for the prediction of possibilities embedded in future technologies.

The methodologies developed in this Thesis include the evaluation of the amount of energy obtainable with HKD and the planning of HKD placement based on in-river measurement and other required data, as well as the validation of the in-river measurement data. While performing measurements and data processing according to the methodologies developed in this Thesis, several places have been found in the Daugava River, where in a near or remote future it is possible to efficiently operate both individual HKDs and power plants based on HKD arrays. The results of the present Thesis can serve as a basis for the database that can be used to successfully find and select new places for HKD installation.

According to the research performed, promising solutions for efficiency improvement of the river HKDs and other stream HKDs can be expected through the perfection of channelling devices. Their use in HKD solutions enables rising considerably the stream velocity in HKDs, especially in slow rivers (rivers with the stream velocity ≤1.5 m/s), and thus the effectiveness of operating HKDs – that is, of those operating in the typical Latvian rivers.

The research performed in the Thesis regarding possible HKD improvements shows: when designing new HKDs, special attention should be given to the shape of active elements (e.g. the objects that absorb water energy) and their mutual placement in order to achieve the maximum yield. Besides, attention is to be paid to the 3D shape of an active element but not only to its receiving surface, selection of which is usually considered in the literature. Although valuable properties – e. g., shorter turbulence zones and/or stronger F forces that act on a body – are not much more profitable as to selecting them instead of simple plates, still the use of many such elements would give a considerable effect.

It is possible to plan HKD placement in the river and anticipated economical gains with the modelling tool developed in this Thesis.

The use of water stream energy is a promising direction for energy economy development, and the present Doctoral Thesis is a step in this direction.

The results obtained allow concluding that the hypothesis of the Thesis is proven, the tasks are completed, and the goals are reached.

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