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Министерство образования и науки Российской Федерации
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ЗАДАНИЕ
на выполнение выпускной квалификационной работы

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Перечень подлежащих исследованию, проектированию и разработке вопросов *(аналитический обзор по литературным источникам с целью выяснения достижений мировой науки техники в рассматриваемой области; постановка задачи исследования, проектирования, конструирования; содержание процедуры исследования, проектирования, конструирования; обсуждение результатов выполненной работы; наименование дополнительных разделов, подлежащих разработке; заключение по работе).*	- Аналитический обзор применения возобновляемых энергоисточников, включая гидроресурсы. Обзор энергетического оборудования малой гидроэнергетики. - Определение нагрузок объекта электроснабжения. - Оценка гидроресурсов рассматриваемых территорий. Технико-экономическое обоснование принимаемых решений.
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Declaration

I declare that thesis has been made independently and consistent with guidelines on compliance with ethical principles for development of theses, and that I indicated all the information sources

In Prague on …………….. ………………………………

Author's signature

Abstract

This thesis is focused on small hydropower plants. Its aim is to sum up information about civil works and electromechanical equipment needed to exploit the energy of water in small hydropower plant.

Two sample projects were designed in this thesis. One in the municipality Inya, Altai Republic Russian Federation, second in municipality Josefův Důl, Czech Republic. After the selection of electromechanical equipment, annual electrical energy production is calculated.

Based on the technical part an economical evaluation is carried out.

Keywords

Small hydropower plant, economic appraisal, feasibility study

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1. Preamble

The rising demand of electric power is leading mankind to utilize more and more different power sources. Conventional power sources in remote areas for low capacity power supply are mainly diesel generators. However, the technological development is leading us to look for more nature friendly power sources, which are becoming more and more attractive today in most countries.

There are many reasons for this. Technologies are becoming cheaper, affordable, accessible and have various advantages, such as partial or full energy autonomy, decrease in carbon dioxide emissions and more decentralized power supply in large power grids, which helps for better reliability and losses compensation.

Reduction of carbon dioxide emissions is a lot discussed topic nowadays, because it is believed that carbon dioxide, whose concentration in Earth's atmosphere has risen from 288 ppm at the end of 19^{th} century to 360 ppm nowadays (1), causes global warming resulting in temperature rise and severe droughts as well as iceberg melting.

This being said along with new inventions in electric power generation and transportation leads to utilizing more renewable energy sources than ever before.

The aim of this diploma thesis is to sum up information about small hydropower plants and carry out two case studies of small hydropower plants in the Russian Federation and in the Czech Republic.

2. Renewable energy sources

Renewable energy source is defined as natural energy source, which is inexhaustible or can be naturally replenished or renewed within a human lifespan. (2) Main renewable power sources are energy of solar radiation, water, wind, biomass and geothermal energy. Renewable energy sources cover about 16 % of worlds power consumption, from which is 87 % covered by hydro energy. (3)

Those sources differ in many ways and some may be found bit complementary in a certain way. In my opinion, the least efficient source is biomass. The problem of biomass is that if there is no industry, which would generate biomass as a waste, such as wood processing industry or some sorts of agriculture, it is vital to grow biomass, which are either plants or fast growing trees. This means that you have to plant, grow, harvest, dry and possibly process them before burning it.

It is hard to keep the quality of biomass, as the energy obtained from burning one unit of biomass is strongly dependent on its humidity. There is also problem with storage. If it is too wet, it may either rot, or even get on fire, if it has enough oxygen. Not to mention, that it tends to oxidize while stored outside, which in fact is just slow burning.

On the other hand, if problems with supplies of fuel and storage are solved, it may be used as a conventional power plant or even as a cogeneration unit, which may have efficiency of up to 90 %.

Possibility of usage of geothermal power plant depends on nature circumstances. Right place is usually located at places with high geothermal gradient, usually places with geysers, volcanic activity and close to tectonic plate boundaries in general, because otherwise a great depth of drilling will be necessary in order to use it for electric power generation.

Because of the consistency of process, geothermal power plants have high capacity factor and along with biomass power stations have the most predictable power generation. Technologies include dry steam power stations, flash steam power stations and binary cycle power stations.

Dry steam stations are powered by water of such temperature, that it turns to steam when extracted to ground level or is already in steam phase when extracted. Steam is then run through steam turbine, where it expands and generates power. Water is then returned back to well to warm up.

Flash steam system works on basis of hot water, which does not turn independently to dry steam after extraction. To force the hot water to vaporize, we have to run it through a tank with lower pressure, where part of the water vaporizes. This steam is then run through turbine to generate electric energy and then returned back to well along with water, which did not vaporize in first step.

Binary cycle works on same basis as conventional power plants, but working fluid in turbine cycle has low boiling point, so it is possible to turn it into steam even with low temperature water.

Solar power plants convert solar energy into electric energy either directly (using photovoltaics) or indirectly by concentrating sun beams to one point to heat working fluid, which usually transfers heat for further exploitation, for example in steam cycle.

Although it seems to be great power source, the problem is its fluctuations in power generation. When the weather is cloudy, power generation may drop from full production to almost zero in matter of minutes and then back, which generates pulses to grid. That also means solar energy is not the best option to supply consumers and we are forced to have backup power source for case of sudden production drop.

Direct conversion has another deficiency in need of inverter, as photovoltaic panels generate DC power, which has to be transformed to AC power by inverters. That means additional losses for a system, which already has low efficiency of transformation solar energy into electric.

Wind power is very similar to hydropower. Both use turbine's mechanical power to run generator. Problem of wind power is the unpredictability of wind and in most cases its inequality. Which makes wind power without storage or backup source almost impossible to use.

Possible solution of former two system might be Hybrid system of photovoltaic panels and wind power station to supply remote places with electricity. Statistics show, that those two power sources are usually quite complementary, because if the weather is bad, from point of view of solar power generation, it is usually windy and vice versa.

Disadvantages of the last one are almost not remarkable in hydropower, because water is quite easily predictable according to long-term statistics held in most places of the world and as water has higher density than air, it generates more power within a machine with smaller dimensions. For those reasons, it had been first time utilized already in ancient times.

3. Hydropower

3.1. Distinction

Hydropower plants may be divided into groups according to several criteria, such as installed capacity, head of water, discharge, site configuration etc. However, in some cases distinction varies across the countries. As an example could serve installed capacity. As a small hydropower, plant was considered every hydro power station in Russia with installed capacity under 30 MW and diameter of runner less than 3 meters. This was until 2004. In that year building code, which specified small hydropower plant, was abolished and this term is not specified in the newer versions.

On the other hand, according to recommendation of the European Small Hydropower Association, the European Commission and International Union of Producers and Distributors of Electricity a small hydropower station is every station of installed capacity up to 10 MW. This is accepted in countries, such as the Czech Republic, Greece, Ireland, Portugal and some other, but it is not the same even across the states of the European Union. Austria, Germany, Poland and Spain consider small hydropower stations only stations up to 5 MW, and Latvia deems stations up to 2 MW, Sweden to 1.5 MW, Italy up to 3 MW, France up to 12 MW of installed capacity as small hydropower plant. Local government usually sets the threshold in legislation.

In terms of site configuration, division also differs amongst different sources. (4) (5) According to head, we classify three groups of stations:

- **Low head scheme** with head 30 (50) meters
- **Medium head scheme** with head between low and high head schemes
- **High head schemes** with head over 100 (250) meters

According to site configuration following are distinct groups:

- **Dam scheme**, where a dam is used to accumulate water. By mean of accumulated water head rises. Powerhouse is either located in dam structure or further downstream in an associate building. Building a dam is very costly, that is why this scheme is usually built only in existing structures, which makes for lower capital expenditures.

- **Diversion scheme** uses water diversion to obtain necessary head of water. Water is usually conveyed through low-slope canal alongside of river or through tunnels to water intake, where a pressure intake and penstock leads the water to the turbines. Water is then discharged back to the river through tailrace. Source (4) separates **mixed scheme**, which in fact is combination of former two, where dam rises water head and pressure pipe or penstock is used for further accumulation of head. For long penstocks, a surge tank is needed to balance for the transient processes in pipelines, which cause huge pressure fluctuations when opening and especially closing the valves.
- **Schemes integrated in canal or in a water supply pipes.** Relatively new are applications of hydropower stations in canals and water supply pipes, which primary purpose is not to generate water, but have favorable parameters.

Another distinction is upon discharge basis.

- **Run-of-river** scheme is run all the time, whenever there is higher flow in the river, than minimum technical flow of the turbine. Inflow is not regulated.
- **Daily regulation scheme** accumulates water in off peak hours in a pond or a dam, when only minimal discharge is being released and power is generated in peak hours, when price of electricity is higher.
- **Seasonal regulation scheme** is similar to previous one, but water is accumulated in rainy season and power generation runs even in dry season. Despite the obvious benefit of power production, it also smooths down the fluctuations of flow in the river. On the other hand, this scheme needs a huge dam and is not usually used in small hydropower stations.
- **Cascade scheme** is the best scheme to utilize the river gradient to the fullest. There are multiple dams located downstream, where tailrace of one hydropower station flows into another dam. So the discharge and power generation can be optimized throughout given time span.

To give a full review of schemes of hydropower plants, pumped storage power plants must be mentioned. They are used to pump water from bottom dam to the upper one, when price of electricity is low or whenever there is excess of electricity in grid mainly throughout night and then in generation mode, they run the stored river from upper dam to the lower through turbines to generate electricity. Though it is the best way to conserve electrical energy up to date, it is not used in small hydro schemes, due to higher efficiency in bigger applications.

3.2. Historical development

Hydropower is one of the oldest power sources people utilized. First waterwheels were used in ancient Greece between third and first century BC. Along with windmills, they were used for flour milling. This was the first utilization of different power source then humans and animals.

For very long time it was one of the main power sources to run different mills and blacksmith shops. One of the greatest utilizations of water energy in ancient times was Barbegal mill near Arles in France. It was built in 2nd century and had power of about 16 kW of motive power. With those impressive parameters for its era, it was the greatest source of motive power in ancient world.

It was not until 1712 that a new motive power source had been invented. Still water power has not been forgotten nor ceased to be exploited. In fact, it was one of the most common power sources in Industrial Revolution. There still had been a lot of free flowing rivers with enough height drop a flow to power small industrial plants and even surrounding area with electricity.

First of the modern turbines invented was the Francis turbine, which was invented in 1848 by James B. Francis. Well in fact he has not invented it, he has used already known turbine designed by Benoit Fourneyon in 1826 and improved its design, so that the efficiency of turbine exceeded 90 % efficiency. Still design of Benoit Fourneyon was not forgotten, because it was used in the first big electricity-generating project, which was a major advance. It was the Niagara Falls hydropower scheme, which had 37 MW.

Next from three most common turbines – Pelton wheel was invented about twenty years later in 1870s. Kaplan turbine, as the last from three major turbines nowadays was invented in 1912 but it had serious problems with cavitation, so it took another decade until 1922 when Voith Company introduced their 800 kW unit of this design.

Nowadays there are thousands of hydropower plants in operation around the world. The biggest one is the Three Gorges station in China, which has output of 22 500 MW.

3.3. Present situation

Level of exploitation of water energy in different countries is strongly dependent on power sources available and historic development. The biggest hydroelectric projects were constructed in early decades of 20th century. The biggest projects were executed in North and South America, Europe and more developed countries in Asia. Altogether, most of the sites for big hydropower projects in Europe and Northern America are already being used for power generation but Eastern and Southern Asia as well as Africa have still a lot of potential for further development.

According to International Energy Agency, it is expected that the yearly rise in energy power production on big hydro power stations will rise from 2007 to 2030 by 2 % rate every year. Despite this rise, share of energy produced by big hydro projects will lower to 12.4 %.

In following chapters historical situation, present state and possibilities for future development in the Czech Republic and Russia will be presented.

3.3.1. Russian Federation

Russia is the fifth biggest hydro energy producer in the world according to nominal power and production. Total gross hydropower potential of Russia is estimated as 2 900 TWh of annual production of which 357 TWh share is belongs to small hydro sites. However, total installed power of all 102 hydro power plants is 46 GW, which produced 165 TWh of energy in year 2010. (3)

First Russian hydro power station was constructed on Berezovka River in 1882. It was equipped with four turbines with total installed capacity of 180 kW. In 1903 second power station was constructed in Caucasus region on Podkumok River with installed capacity of 700 kW, which was enough supply four spas and many houses in surrounding area as well as two trams. Third power station was Porozhskaja power station constructed in 1910 with two turbines with total installed capacity 1.1 MW.

By 1917, there were already 78 hydro power stations with total installed capacity of 16 MW. Nevertheless, not all stations were used to produce electric energy at that time, about 2 000 of them were used as a source of mechanical energy and another 40 000 were used as mills. It is known, that two years later another 47 new power stations with total power of 1.6 MW started operation.

Between 1919 and 1945, further development of small hydro power stations was blooming. It is said, that total power output of those stations was about 32 MW with average capacity of one station about 35 kW, which was enough to run couple one or even more collective farms.

Since 1945, Russian government constructed many hydro power stations with higher installed capacity than before reaching up to 10 MW working to common local power systems. Maximum was reached in 1954, when there were 6 614 small hydro power stations with total power output of 322 MW, which was 24 % share of total power used by agriculture at that time.

A change in laws of Soviet Union made possible connection of agricultural sites to the centralized power grid. As the electric energy from power grid was quite cheap, it made small hydro power plants unprofitable and they started to cease. Another reason was low quality of such sites, which were not able to work during floods and suffered high voltage and frequency instability during load changes.

Nowadays, small hydropower is seen as a sustainable way for growth and further redirection from conventional power sources, which are in remote places diesel generators. Due to its ease of operation, long-term reliability and predictable fluctuations, it may substitute diesel generators, as it is more ecologic and in some cases even cheaper than supplies of gasoline. In addition, most of agriculture (90 %) and almost a half of cities (44 %) is located close to rivers. For this reason, it is expected that small hydro power plants will grow in Siberia and Far East in future. In European part of Russia region of North Caucasus seems to have most unused potential.

One of restrictions of places with high hydropower potential is that those places are located mainly in middle and eastern part of Russia, where is no exceptional industry, which would need so much power. Thus if this potential was used, long power lines will be needed, which would significantly decrease economic benefits of project.

Main problems for small hydro power generation in Russia is lack of information about small rivers, as well as low experience and lack of laws regulating development and operation of those plants. There are also no companies with assembly lines, which would be able to repair technological units in case of failure.

A new Power-producing strategy was accepted by Russian Federation in 2009. As a result, total share of alternative power sources in national balance should be more than 10 % of total power produced by 2030 and a sub objective is to generate more than 5 % of total power generated by 2020.

There are currently about 300 small hydro power stations in Russia with total installed capacity of 1.3 GW. Program of development of Small Hydropower Association of Russian Federation expects construction of 275 new power stations with total installed capacity of 1.86 GW that means the number and total installed capacity will more than double until 2020. (3)

3.3.2. Czech Republic

Total gross hydropower potential is estimated as 13.1 TWh of annual production. Despite this fact, technically utilizable hydropower potential is 3.4 TWh of annual production. (6) The difference is caused by locations with small and extremely small heads, though these values may change with development of better turbines aimed for locations with extremely small heads, such as vortex turbine.

The Czech Republic has a long experience with utilization of water energy. First known utilization is dated to year 718, when a water-powered mill was constructed on Ohře River as a first of its kind in middle Europe. Before invention of water turbine, water wheels have been produced. In 1870, four years after invention of Francis turbine first local producers occurred.

There have been 11 785 hydroelectric sites in 1930 with total installed power of 194.4 MW. With small fluctuations, this remained unchanged until the end of World War II. After 1945 nationalization started. Most of small hydro sites became property of ČEZ, which was state owned company engaged in production, transmission and distribution of electric energy. Unfortunately, small hydro power stations were not in the main interest of this company and thus most of them were worn out and shut down.

First financial aid was declared in 1979 when small hydro power stations with annual production up to 200 MWh had incomes from operation tax-free. In 1990, limitation of annual power production was cancelled, but two years later, it was limited only for small hydro power stations with installed power up to 1 MW.

Since 2005 due to decrees issued by European Union and implemented by law 180/2005 Sb. into Czech legislation, small hydro power stations became supported electric energy sources. Right now, there are two types of support, either by buying up of energy produced, which has a special rate, separately set for each year and guaranteed for next thirty years with annual rise of about two percent. Second form of support is called the Green bonus and producer can sell its energy on the market and, in addition to the market price, producer gets the bonus.

State Energy Concept (7), which was accepted in 2010 stated, that the share of renewable power sources should be 13 % of total end consumption by 2020, for longer term it should be approximately 17 % by 2030 and about 23 % in 2050. In 2005, the share of renewable power sources was 4.36 % of total production. This share has more than doubled until 2010, because of the so-called solar boom, when subsidies were high and price of photovoltaic panels and connected technologies was rapidly decreasing. Due to this fact share of alternative power sources was already 8.3 % in 2010 and 13.17 % in 2014 (8), which has even exceeded the goals for 2015.

Despite the fact this rise of share of alternative power sources was mainly caused by solar energy, even total hydroelectric power stations installed capacity rose by 0.6 % between 2012 and 2013, and it still produced more than one third of energy produced by renewables.

Nevertheless, States Energy Concept does not expect rise of installed capacity of hydro power stations as most of the locations favorable for construction were already used and remaining locations have mostly small and extremely small heads. Thus, those locations are not so interesting in current economic situation, due to high costs of construction work and technology as such, combined with low incomes despite special rates and subsidies, which results in long payback period. So further development will be focused either on improvements in technology, such as turbine and generator modification or replacement, or usage of existing ponds, which are not exploited nowadays and have potential to be used. Furthermore, waterworks objects may be used as well.

3.4. Hydropower principles

Hydropower generation is based upon the principle of energy conversion, where energy of steady flow between points A and B is:

$$Z_A + \frac{p_A}{\rho g} + \frac{\alpha_A c_A^2}{2g} = Z_B + \frac{p_B}{\rho g} + \frac{\alpha_B c_B^2}{2g} + \Delta H_{AB} \qquad 3.1.$$

Where:

- Z_A, Z_B are elevations above datum plane
- p_A,p_B are the pressures at the centers of gravity of the flow cross section at A and B
- c_A, c_B are the average velocities respectively at A and B
- ρ is the water density
- g is the gravity acceleration
- α_A and α_B are numerical coefficients, which account the difference in velocity of flow across the flow
- ΔH_{AB} is the head loss between points A and B

Left side of equation may be also referred to as total head at point A and right side without ΔH_{AB} component is the total head at point B. (4)

For the free surface flow, pressure is constant in all points and thus can be omitted. Total head between points A and B in this case can be calculated according to following formula:

$$\Delta H_{AB} = N_A - N_B + \frac{\alpha_A c_A^2 - \alpha_B c_B^2}{2g} \qquad 3.2.$$

Where N_A and N_B are elevations of free surfaces at points A and B.

In hydropower schemes we are trying to utilize as much of total head as possible. That is why low sloping conveyance systems are used, because they accumulate dissipated head along the watercourse, which is then converted into electrical energy. For exact calculations head losses should be considered. Those are generally, but not limited to, caused by non-laminar flow and friction and will be discussed in chapters dealing with components of hydropower scheme. Net head is parameter H_N, which accounts also losses in system. It is calculated from total head lowered by head lost to hydraulic losses in system (ΔH_L).

$$H_N = \Delta H_{AB} - \Delta H_L \qquad 3.3.$$

Then net hydraulic power obtainable from flow is calculated according to this formula:

$$P = \rho Q g H_N \qquad 3.4.$$

Where Q is discharge diverted to the hydro power plant, product of g and H is called specific hydraulic energy of machine (5) and H_N is net head. This power however is also unreachable, because it must be lowered by the overall efficiency of energy transformation in turbine, generator, losses in circuits, transformers and own consumption. Thus global efficiency η is introduced, to account those. Global efficiency is product of partial efficiencies of systems components.

$$\eta = \prod \eta_i \qquad 3.5.$$

Energy output acquired over period Δt is integral of power and for constant parameters turns into simple well-known formula.

$$E = \int_0^{\Delta t} \eta P(t)\, dt = \eta \rho Q g H_N \Delta t \qquad 3.6.$$

3.5. Hydraulic structures of small hydropower plant

Following chapters will explain which parts a small hydropower stations consist of and their purposes. There are two main groups of equipment - hydraulic structures and electromechanical equipment. I will start with the former one and then continue with the letter one. Former one consists of diversion structure – dam with spillway, energy dissipation structure, fish pass, residual flow arrangements, and of water conveyance system, which starts at intake and leads water through canals, tunnels and penstocks to powerhouse. Letter ones are turbines and generators. Chapters are mainly based on information from source (5).

3.5.1. Dam/weir

Dam or a weir is mostly the highest located structure in small hydro scheme. Its purpose is generally to accumulate head, provide water storage capacity to smoothen the flow fluctuations and it is the beginning of penstocks or conveyance system, which delivers the water to powerhouse. As the water stills, another effect is, that some particles carried by water deposit as a sediment, which may otherwise cause abrasive wear on the technologies.

There are many types of dams and weirs. Type used in particular case is mostly based upon available resources and geological and topographical situation in particular location. Dams are either embankment or concrete ones.

The advantages of embankment dams are their adaptability to a wide range of foundation conditions, the use of natural materials, which are usually located within surrounding areas, with minimal transportation demands, continuous and highly mechanized process of construction and flexibility in use of fill material. On the other hand, they are extremely sensitive to overtopping and leakage, which causes erosion in dam body and its foundations. From statistical point of view, embankment dams have caused more deaths, than concrete dams, due to their failures.

Concrete dams have major advantages over embankment ones. They are suitable for most ranges of topography, but are quite sensitive to the foundation conditions. They are not as sensitive to overtopping as embankment dams, spillways, chambers and galleries can be built in within the body of dam, as well as powerhouses. The disadvantages are great sensitivity to the foundation conditions, the discontinuity of work, and processing and transport of large amount of natural materials and cement to the construction site. Altogether concrete dams are more expensive compared to the embankment dams.

Other types of dams include masonry dam, which was very common in earlier days, where masonry bears the weight the load of water and water tightness was achieved by utilization of different materials, such as timber or impervious soils. In addition, timber only dams were built, but due to their short life span and technology development, they become rare.

Last type is a spillway dam. Generally, a spillway is a passage for water over a construction, which has to be resistant to the erosion caused by the water passing at a high speed and volume, during flood. Spillway dams can be gated or ungated. The letter ones with small height are referred to as weirs. Weirs and spillways may be divided into two groups, according to the presence of moving parts as fixed or mobile. The former ones are simple, secure and easy to maintain, but they lack the possibility of water level regulation. Mobile ones, apart from regulation and accumulation function can flush debris from storage area. This makes for higher expenditures during the construction, as well as during maintenance.

Weirs are used in many small hydropower plants to divert water from streambed to diversion structure, by rising the water level. When water level reaches construction height of intake of water, it starts flowing to the conveyance system, while rest of the water, at least the compensation flow, overflows the structure of weir.

Because overflowing water usually has high kinetic energy, energy dissipation structure must be present. Most of those structures are based on hydraulic jump, where kinetic energy partly transforms into potential and partly is lost in turbulences, which cause heat.

In addition, a fish pass must be present to allow migrating fish to pass safely through site.

3.5.2. Water intake

Water intake is the place, where water is diverted from the riverbed. Two types of intakes are used. Either a power intake, which redirects the water into the penstock leading to turbine. This means, that water has already a pressurized flow. Second type is the conveyance intake, which supplies water into conveyance system, such as canals, tunnels, that usually lead into power intake.

When considering the intake design, a deep consideration of hydraulic and structural criteria should be considered, as well as operational criteria, such as percentage of diverted flow, trash handling, sediment exclusion etc. Last, but not least, environmental assessment should be carried out, especially influence on fish life. Water intakes in relation to the water flow are either lateral, frontal or drop intakes.

Lateral water intake uses a river bend to divert water from the river. It is favorable, if a strong current along the outer bank is present, because it prevents material deposition. The installed discharge should be less than half of the critical discharge, at which bed load transport starts. In addition, a gravel deposition canal should be built in front of intake to prevent suspended load from entering the conveyance system. A partly submerged wall is there to prevent floating particles to enter the intake.

Frontal water intake is able to handle large quantities of both bed and suspended load, which also predetermines its use. However, the caught bed and load have to be continually flushed through deposition tunnel, which causes large losses of water.

The drop intake is mostly used for steep sloped rivers. The French drop intake is a canal built perpendicular to the river flow, which is covered with trashrack bars, which are parallel to the flow and have a higher slope, than the streambed slope. Tyrolean intake is another type of drop intake, which is also equipped with flush gate to flush the sediments.

Power intake are usually employed in dams and lakes. The problems connected with its design are far different from those connected with conveyance systems intakes. For example, there is usually no problem with bed transportation and sediments are less likely to enter the intake, though they would certainly deposit in lake itself. Problems are usually connected with low-pressure heads, which contain the risk of a vortex formation and sucking of air into the system.

3.5.2.1. Trashracks

Trashracks are part of intake system which serves to prevent floating particles from entering the intake. Construction is quite simple, as it consists of evenly spaced parallel metal bars. Sometimes more trashracks are used one after another, where spaces between the bars are getting smaller to filter smaller particles. However more than two are not common, as they cause turbulences and head loss. Trashracks are often equipped with automatic cleaning equipment, to reduce piling up of caught material and clogging of system.

If a heavy debris is present, usage of floating boom in front of trashracks should be considered to take the strain off thrashracks.

3.5.2.2. Sediment traps

Although intakes are designed to prevent floating particles and sediment transportation into the conveyance system, they cannot effectively prevent suspended particles passage from up to certain size of particle. For this reason, sediment traps are used. Sediment trap is usually slightly wider and deeper part of conveyance system right behind intake, where the water stills. This is the result of broadening and increased cross section, which is sometimes also supported by a downstream weir. All afore mentioned causes water deceleration and turbulence, which is the reason why decantation of water occurs.

3.5.2.3. Gates and valves

Once upon a time, it is necessary to flush all the water from system and perform a reconstruction. For this reason intake should be also capable of closing the whole system to isolate it from water. Some of the used designs are stoplogs made up of horizontally placed timbers, sliding gates of cast iron, steel, plastic or timber, flap gates and different types of valves.

Power intakes must be equipped with control gate or a valve, so it is able to close in short time in case of failure. This being said, the valve must be able to close at maximum turbine flow. On the other hand it must be also able to open or partially open to fill in the conduit under maximum head.

For low-pressure applications, stop logs are usually used and supported by grooves at the ends. Stop logs cannot control the flow they can only stop it. For complete dewatering of conduit a secondary stoplog usage is recommended. Gates of sliding type are mostly used to control flow through open canals. As it takes quite a long time to close sliding gates under pressure, they are not so common in penstocks. To overcome the problem wedge-shaped stoppers are used, because it reduces the energy needed for its operation, because seal is broken over the whole face once it rises even for a small distance.

For penstocks, different types of valves are used. Butterfly valve consists of a lens shaped disk mounted on a turning shaft. When the shaft turns, it closes or opens the gap. Its advantage is easy operation under pressure, but it causes turbulence, so it is not that good for regulation and is better suited for the function of a guard valve. Globe and rotary valves provide significantly lower head losses, but it comes at the cost of higher price. Last used technology is a radial gate, which controls headwater and tailwater. As an example might serve a Tainter gate. Pros are lower force needed to operate but again causes higher head losses especially when used for regulation. Also good foundations for trunnions are key, because trunnions are transferring the pressure of headwater into foundations.

3.5.3. Channels

Usually long penstocks are very expensive. For that reason, low sloping canals are mostly used to divert water and obtain necessary head, before the water enters a penstock and its energy is converted into electricity. The flow a canal is function of a cross sectional profile, flow and roughness. It is very difficult to calculate flow in natural canals, which are not lined with materials, such as steel, concrete, wood etc., where hydraulic calculations give reasonably accurate results.

If the canal is unlined, problems with banks instability may also occur and the cross sectional profile is predetermined by the foundations. Wall erosion and aquatic plants growth should be also considered. To provide a generous freeboard, which is space for possible waves and fluctuations in canal, generous spillways should be provided in order to prevent overflows, which may endanger slope stability.

3.5.4. Penstocks

As was mentioned before, penstocks are used to transfer water under pressure to the turbine. For construction of penstock, three steps are necessary. First, material should be selected while bearing in mind ground conditions, accessibility, weight, jointing system and cost. Second step is to determine the diameter of penstock to reduce frictional losses to an acceptable level. Lastly, the wall thickness must be assessed to withstand the overpressure and low pressures including the transient surge pressures that will occur.

Materials used for penstocks are welded steel, polyethylene, polyvinyl chloride (PVC), asbestos cement, cast iron or ductile iron. As an example will serve polyvinyl chloride, which has the smallest friction but it has low resistivity to UV light, which results either in burying them in the ground or the need of protective painting on top. In general, penstocks can be led either underground or above ground. For maintenance-free materials, such as plastic, PVC or other materials that are protected by wrapping, protective painting etc., it is good idea to bury them under the ground. Especially if generation of hydropower plant is not continuous, ground can provide necessary insulation to prevent icing of the inner tube, as well as minimizes impact on landscape and wildlife.

Penstock must be well anchored, favorably to the rock, to withstand the thrust of penstocks and frictional forces, as well as thermal expansion and contraction. If the last mention phenomena is expected to be significant, usage of expansion joints should be considered. Support blocks must be present between anchor blocks. If construction of good anchor blocks is either costly or favorable foundations are not present, some of them may be omitted, but possibility of expansion/contraction must be accounted.

Penstock diameter is usually chosen to satisfy maximal losses in penstock. The lower the diameter of penstock, the lower the price of it, but friction losses rise, approximately proportionally to square of the velocity of water that rises if flow remains the same, but diameter of pipe decreases. Amongst the losses in system, the friction loses in penstock are the highest, compared to the losses on trashrack, in bends and valves. Mostly certain percentage of power loss in penstock is set and diameter is chosen to satisfy this requirement.

From economic point of view, for different pipe diameters total lost energy over lifetime of plant in calculated. Second graph is price of penstock for different diameters. Those two curves are then graphically added and the optimum diameter is the available diameter closest to the optimum.

The pressure of water at normal operating conditions, when turbine is running and the flow through penstock is constant e.g. there are no regulations performed by regulation system is dependent merely on hydrostatic head.

If regulations are carried out, pressure changes may reach up to several times the normal pressure. This phenomenon is called the water hammer. It is caused by sudden change of direction or velocity of moving water. If a change occurs, pressure wave propagates along the length of penstock as an overpressure when water decelerates, or as low pressure when water accelerates. For those cases, penstock must be prepared already throughout the planning period of construction, when calculations must be carried out to determine minimal thickness of walls. Elasticity of pipe material has dumping effect on water hammer phenomena. Exact values depend on critical time of system, closing time, elasticity of used pipes, type of turbine etc. If change in velocity occurs in more than ten times critical time water hammer effect may be omitted.

It is strongly recommended to increase the obtained thickness slightly for safety reasons. In addition, corrosion of pipes and weld quality should be taken into consideration.

For long penstocks, surge towers are used to reduce the water hammer phenomena. Surge tower is a large tube connected to the penstock, which top surface of water is open to the atmosphere and is the same as net head in normal working conditions. If sudden overpressure occurs, water in surge tower rises as a counter balance and then throughout time, as the pressure wave fades out, settles back to normal position. Some sources consider surge tower unnecessary, if pipe length is inferior to 5 times the gross head of hydro station.

For applications, where quick closure time must be provided, relief valves are being installed parallel to the turbine. Those valves open when turbine gates suddenly close to slow down the changes in penstock.

At the end of penstock right before turbine, inlet gate or valve are located. This valve is used to close the penstock to dewater turbine completely, for example in case of maintenance.

3.5.5. Tailrace

Water, which went through turbine, is returned to the river through tailrace. According to type of turbine, tailraces may significantly change. It must be always considered, that water may undermine the powerhouse. Especially impulse turbines have high exit velocities. In addition, interference with turbine runner is undesirable. For this reason, tailrace should be able to hinder those effects.

On the other hand, with reaction turbines, water level in tailrace influences the net head and onset of cavitation. Former one decreases attainable power, letter one causes faster wear out of turbine, which both have negative economic effects.

3.6. Electromechanical equipment

3.6.1. Hydraulic turbines

Turbines are divided into two groups: reactive (Francis, Kaplan turbines) and impulse (Pelton wheel), according to the energy of water, which is transformed into mechanical energy of turbine.

Reaction turbines transform water pressure (i.e. potential energy) into mechanical energy of turbine. Turbine is fully immersed in water and must withstand the pressure of water head even with its fluctuations mentioned before. Typical examples are Francis and Kaplan turbines.

Impulse turbines are designed to exploit as much of kinetic energy of water as possible. This being said, potential energy of water head is first transformed into the kinetic energy of water in a jet, and then the high-speed jet strikes the buckets mounted on the perimeter of runner, where its kinetic energy transforms into kinetic energy of runner of turbine. Typical example of this group is Pelton, Turgo or Cross-flow turbine. Design of each type of turbine, as well as its characteristics will be discussed thoroughly in following chapters.

3.6.1.1. Turbine similarity laws

For testing of turbines smaller scaled models are used. If the model is made to test the performance and then produce a full-scale model, length ratio k, area ratio k^2 and volume ratio k^3 must be maintained. For deeper explanation, it is strongly recommended to refer to IEC standards 60193 and 60041.

If all the rules and standards are followed, basic similarity laws may be used to determine parameters of turbine when creating either a model, or when a turbine designed for different head or discharge is used at site with different parameters.

$$\frac{Q_t}{Q_m} = \frac{\sqrt{H_t} D_t^2}{\sqrt{H_m} D_m^2} \quad 3.7.$$

$$\frac{n_t}{n_m} = \frac{\sqrt{H_t} D_m}{\sqrt{H_m} D_t} \quad 3.8.$$

Where index t corresponds to full-scale turbine and m corresponds to the laboratory model. Q is the discharge, H is the net head, D is the runner diameter and n is the rotational speed. (5)

For example, if a turbine designed for net head of 100 meters is used under net head of 80 meters, runner diameters are the same and rotational speed of turbine is calculated according to formula 3.8 first (considering the design parameters as model parameters and full scale parameters as the parameters of given location). Then maximum admissible flow is calculated according to formula 3.7.

3.6.1.2. Choice of turbine

Criteria that should be accounted when picking a turbine are net head, range of discharges, rotational speed of turbine, cost and cavitation problems. Net head serves to choose the type of turbine, because not all available designs are suited for all net heads. In addition, how well specific type of turbine handles head variations, if it is present, is of an important role. Discharge and its variation plays similar role to the net head. Those two can be plotted to turbine type's application diagram, which is usually provided by manufacturer and differs from another. For preliminary calculations, this would be enough, but should be specified in later stages.

Specific speed is calculated according to following formula:

$$n_{QE} = \frac{n\sqrt{Q}}{E^{\frac{3}{4}}} \quad 3.9.$$

Where n is rotational speed in turns per second, Q is discharge in m^3/s and E is specific hydraulic energy of machine in J/kg. (5)

Supposing we have a given location and do not want to use a speed increaser, nominal speed of generator will be used in formula 3.9 as a rotational speed. Obtained number indicates desired specific speed of turbine. Following table determines range of specific speed for each type of turbine (5):

Pelton one nozzle	$0.005 \leq n_{QE} \leq 0.025$
Pelton n nozzles	$0.005n^{0.5} \leq n_{QE} \leq 0.025n^{0.5}$
Francis	$0.05 \leq n_{QE} \leq 0.33$
Kaplan, propeller, bulb	$0.19 \leq n_{QE} \leq 1.55$

Table 1 Specific speed range of chosen turbines

Cavitation consideration is of great importance, as it may cause fast wear out of turbine. Cavitation occurs, when pressure in liquid drops under pressure of evaporation. Small bubbles occur and collapse in areas of higher pressure accompanied by sonic and mechanical impulses that are capable of deformation of runner blades and hub, which in repetitive way lead to formation of cracks and snatching material from the surface.

Rotational speed of turbine must be considered, as it determines used generator. If speed is too low, speed increaser is used to rise it, but it also makes the installation more costly. Runaway speed in case of load rejection is the maximum speed of runner at maximum hydraulic power and load rejected. It is up to 3 times the nominal speed of turbine and both generator and speed increaser must withstand it, which makes them more costly, if runaway speed rises.

3.6.1.3. Pelton turbine

Pelton turbine is the most known impulse turbine. It works upon principle that water flows through a nozzle at high velocity and creates jet, which strikes at buckets on periphery of the runner. Those buckets have a double spoon shape to transform as much of kinetic energy of jet as possible. Pelton turbine is used for high heads from 60 to 1000 meters.

Pelton turbines may have up to six nozzles for one runner, but there are limitations for design of runner axis. Turbines with horizontal axis may have up to two nozzles. With increasing number of nozzles, vertical axis design is introduced. This is due to the fact, that water after striking the bucket has minimal speed and falls under the turbine due to the gravitation, where it flows to the tailrace. If there would be more than two nozzles on turbine with horizontal axis, trickling water would interfere with jets in non-negligible way. Maximum number of nozzles is six, but it is unusual in small hydro schemes.

Each nozzle is equipped with a needle valve controlling the flow and deflector. Deflector diverts the water in emergency cases, so that it does not impact the runner blades and thus cannot reach overspeed. Needle valve cannot be used for emergency closing, because of its slow operation. (5)

Pelton turbines are usually directly coupled to the generator shaft and must be located above maximum downstream level of water. Efficiency is good for range from 30 % to 100 % of maximum discharge for a single nozzle design, and for multi nozzle design the bottom limit is even 10 % of the maximum discharge depending on model used. If the site allows to, two runners (one on each side) may be used installed on one generator shaft. Runner diameter is usually 10 – 20 times the nozzle jet diameter. (4)

3.6.1.4. Turgo turbines

Turgo turbines are another group of impulse turbines, very similar to Pelton turbines, but the nozzles are not in plan with the runner blades and the design of runner blades is different too. The water jet in Turgo turbine impacts the runner blades under angle of 20° and exits blades on the other side. Turgo buckets are not of a double spoon design, but more of a hyperbolic shape in sectional view.

Optimal head is between 50 to 250 meters and operating range is between 20 % and 100 % of maximal design discharge. Nozzles are again equipped with needle valve to control the flow and a deflector. Turgo turbines have higher revolutions compared to the Pelton ones, however the efficiency is lower than for Pelton a Francis turbines. (5)

Turgo turbine may compete with Francis turbine in case of strongly varying flow, where Turgo turbine offers better management of water hammer effect in case of load rejection, which is decreases the stress of long penstocks. (4)

3.6.1.5. Cross-flow turbines

Cross-flow turbines (sometimes referred to as Ossberger, Banki or Mitchell turbines) are another representative of impulse turbines. Design head spreads from 5 to 200 meters, which partially covers ranges of other turbines.

This type of turbine has one or more guide-vanes located upstream of the runner. Water flows through those vanes and crosses the runner twice. Once when entering and once when exiting the runner. Cross-flow turbines have low efficiency, and high mechanical stress, especially if in scheme with high head, which may cause lower reliability. As well as Pelton and Turgo turbines, Cross-flow turbines must have space between runner and tailrace water, which must be accounted in schemes with small and medium head.

However, simple design and low capital expenditures make it perfect for electrification of rural or remote locations with defined power needs and low investment possibilities. (5)

3.6.1.6. Francis turbines

First representative of reaction turbines, which will be discussed, is Francis turbine. This turbine has fixed runner blades and adjustable guide vanes and is used for medium heads, usually from 25 to 350 meters head. Water flows into Francis turbine radially, but leaves it in axial direction. Horizontal or vertical axis applications are both common.

In addition, application is not limited only to penstock schemes, but can also be utilized in an open flume, commonly used for small heads and powers. Nonetheless, Francis turbine applications in letter application ceases, because Kaplan and Bulb turbines are replacing it.

Water flows into Francis turbine through a spiral case, which keeps tangential velocity constant and distributes the water evenly into distributor. Distributor has mobile guide vanes controlling discharge going into turbine and the inlet angle between flow and runner blades. In emergency cases, those may be used to shut off the flow to the turbine. Direct coupling with rotor shaft is very common.

The draft tube is of great importance, as it recovers kinetic energy remaining in the water leaving the runner. The energy is proportional to velocity, so the aim is to minimize the speed. For this reason, conical draft tubes are used. The best angle is 7°, but to reduce the tube length it may be increased up to 15°, but attention must be paid to unwanted flow separation phenomena. (5)

3.6.1.7. Kaplan turbines

Kaplan turbines are used for head range from 2 to 40 meters. Kaplan turbines have three major subgroups:

- Double-regulated – both guide vanes and runner blades are adjustable. In this configuration, the best adaptation to head and flow variations is possible. Good efficiency is achieved between 15 % and 100 % of maximum design discharge.
- Single-regulated – only runner blades are adjustable, guide vanes are fixed. Offer good adaptation to discharge variation, but adaption to head variation is limited. Acceptable efficiency between 30 % and 100 % of maximum design discharge.
- Non-regulated – (also called Propeller turbines) neither guide vanes nor runner blades are adjustable. This type of turbine is best suited for locations with very low (practically constant) flow and head. For this reason, they are rare in small hydropower schemes.

Kaplan turbines may have either radial or axial entry of water, but water always enters and leaves runner axially. Blades of turbine may be adjusted in operation, due to hollow turbine axis, where adjusting mechanism is located. Unlike other types of turbines discussed earlier in this work, gearboxes and speed increasers are used to link turbine and generator, if turbine speed is not sufficient.

Turbine axis may vary according to site scheme from vertical, horizontal, inclined to inverted. Water may enter turbine axially or radially and S bend or siphon conduits can be used apart from those normally used.

Bulb turbines are derived from Kaplan turbines. In this case turbine, generator and gearbox (if needed), are submerged in waterproof case. Only duly protected cables leave the bulb. Water enters the turbine axially. Turbine bulb is cooled by pressurized air.

As well as with the Francis turbine, special attention should be paid to draft tube, to recover as much of kinetic energy as possible. (5)

3.6.2. Speed increasers

Usage of speed increaser is not necessary, if the turbine and the generator operate at the same speed. Then if they are in line, direct coupling is the best option with no losses. If this is not possible, speed increasers must be used.

There is a variety of possible models. According to the gears, speed increasers are classified as parallel-shaft using helical gears on parallel axis. This scheme is used mainly at medium power applications. Bevel gear speed increaser, which changes the shaft direction by 90°. This version is limited to low power schemes. Finally belt speed increasers, which are common for small power applications.

Speed increasers must withstand the most unfavorable conditions, such as full load rejection and the emergency shutdown. Stress generated in emergency situations is enormous. Thus, torque limiter is recommended. If torque surpasses given limit, connector breaks to protect generator and other equipment. Also good lubrication is essential.

Bearings are crucial part of system. Roller bearings are now used in applications under 1 MW, but some manufacturers rise the borderline up to 5 MW. For bigger applications, journal or hydrostatic bearings are used. The letter ones have advantage of almost unlimited lifetime and permit certain oil contamination over roller bearings. Maintenance is important to keep the friction and thus losses as low as possible. (5)

3.6.3. Generators

The generator is a rotating machine, which transforms mechanical to electrical power. As normal in electric power generation practice, generators are either synchronous or asynchronous, where both types are used in small hydropower.

Asynchronous generators are usually simple squirrel-cage induction motors. Those are cheap and commonly available, which makes them easy to repair or replace in case of breakdown.

On the other hand, asynchronous generators do not offer voltage regulation, as they are running at a speed related to system frequency. Asynchronous generators draw their excitation current from the grid to create magnetic field inside itself. Capacitor banks are usually installed to compensate for reactive power consumption. On start-up, asynchronous generators are accelerated to slightly above synchronous revolutions and then switched to the grid. Generator is decelerated by feeding current into the grid and deviations from the synchronous peed at steady state result in driving or resisting torque that balances in area of stable operation.

Synchronous generators are more cost effective in applications above about 1 MW, depending on circumstances. These generators can control its output voltage via excitation system, which creates the magnetic field inside the generator. Excitation systems are either DC electric or permanent magnet excitation systems. Due to the regulation possible through excitation system, synchronous generators may run in island mode, disconnected from the grid.

Exciters which are not based on permanent magnets need DC power supply. In early days, rotating exciters were used and many of them persist in operation. Rotating generators field coils are usually installed on the same shaft as rotor of generator. Brushless exciters have windings on both stator and rotor. AC current is generated at rotor winding, where it is rectified by solid-state rectifier rotating with the shaft. Last is the static exciter, which is a grid-connected rectifier, which provides DC current to generator field coils. This makes for the best response to voltage and oscillations regulation.

Synchronous generators have to be accelerated to synchronous frequency with the grid and voltage amplitude, angles and rotating sense must be the same, before the generator can be switched to the grid. In island mode, the voltage controller maintains predefined constant voltage. If it is the main power source, then it keeps predefined power factor or reactive power.

Efficiency of generator rises with its size, 100 kW generators should have efficiency of at least 95 %. In case of 1 MW machine it may be even 97 %. Small generators are designed to run at normal low voltage level of 400 V. As the size (nominal power) grows, operating voltages rise to some kV. In case generator voltage does not match normal distribution voltage, customized outlet transformers are used. In this case, another distribution transformer must be present to feed in the own consumption as an auxiliary power supply of power plant.

Generators have either horizontal or vertical axis. Flywheel is often attached to the shaft to smoothen the speed variations mechanically. Another criterion on distinguishing generators is according to bearing position. Small generators are cooled by open air, larger units have closed cooling circuits provided with air-water heat exchangers. (5)

3.6.3.1. Turbine control

Turbine control is carried out to keep given parameter in certain range. Controlled parameters are for example outlet power, frequency, level of water surface in the intake or the turbine discharge. Those may significantly change because of net head and discharge variations.

There are generally two situations. If the generator is connected to the grid, where it has a negligible power compared to other power sources and then it just keeps set parameters. If the power plant is connected in island mode or produces significant portion of electrical energy, two approaches to system stabilization exist. Either turbine is regulated to maintain constant speed, or load management has to be possible.

When the load is reduced without any regulations on turbine, speed of runner increases and vice versa. The former approach keeps the rotational speed of turbine constant using the valves, wicket-gates, vanes or nozzles, to adjust the water flow through turbine, so it matches instantaneous demand. This is conducted by speed governors, which send instructions to servomotors that control certain element that should make the regulation actions. Feedback is provided to ensure operation was successful.

Speed governors are of different types. Purely mechanical were used in the past, followed by mechanical-hydraulic, electrical-hydraulic and mechanical-electrical. Mechanical-hydraulic system used widely in pat was based on flyball mechanism. If the speed decreased, flyballs dropped and the sleeve of the pilot valve rose to let oil enter upper chamber of servomotor, which slightly opened wicket-gates mechanism, which increased the flow and rose the speed of turbine.

In present electrical-hydraulic sensors sense the speed of generator shaft. If speed derives from target value, controller sends signal to actuator, which starts the oil pump, which supplies high-pressure oil to the system and rotates wicket gates. Nowadays, sophisticated PID regulators are used to act accordingly to the deviation.

Letter approach is based upon the principle of load side management. Turbine is always running at design speed and if the load decreases, to prevent speeding up of turbine, ballast load is switched on to compensate for load drop. Rotational speed remains with minimal fluctuations constant. If contrary situation appears, load shedding must be possible. If load is higher than production, turbine will start decelerating, which in extreme case may lead to turbine stall. Thus, unimportant loads, which are not susceptible to loss of power, are being cut off.

3.6.4. Switch gear and other ancillary electrical equipment

There must be possibility to disconnect the whole power plant from the grid. For this reason, switchgear is installed to interface plant with the grid. According to local laws, transformer and generator must be equipped with circuit breakers, which will be able to disconnect them even in the worst-case scenario to minimize the losses. Differential current relays, over over-current relays and timed over-current relays have to be installed to detect inner faults on transformers and generators. Generator should also have a relay protection against ground-fault. Asynchronous generators must be also equipped with reverse-power relay, to protect it against motoring. Grounding, as well as metering and reporting are also in responsibility of independent producer.

Plant service transformer, DC control power supply, headwater and tailwater recorders and outdoor substation are ancillary electrical equipment. Plant service transformer is used to supply own consumption of the plant, such as lighting. If generator works at normal low voltage level, outlet transformer may do the job. If possible, multiple alternative power sources rise the reliability of system in case of outage.

Remotely controlled plants are often equipped with emergency 24 V DC back-up power supply, which allows to shut down the whole hydro power plant securely in case of loss of power supply and communication with the system at any time. Capacity of batteries should be such that it lasts even after loos of charging current.

Headwater and tailwater recorders record its respective values for statistical use. Placement of sensor is critical, as apparent water level changes with the fluid velocity. Therefore place with constant velocity over level variations should be used.

Substations on the interface with the grid are of indoor or outdoor style. Indoor substations are used in case of high environmental sensitivity of surrounding area. Independently on design, substation must be equipped with power and current transformers to measure energy and power supplied to the grid. Line breakers, grounding breakers, disconnectors as well as lightning arresters are usually present along with other equipment.

4. Technical evaluation of calculated projects

Two sample projects of small hydro power plants will be calculated in following chapters. First location is municipality Иня (Inya) in the Altai republic, Russian Federation, second location is municipality Josefův Důl in Liberecký region of the Czech Republic.

4.1. Small hydropower plant project in municipality Inya

Inya is located in the heart of Altai Mountains. At the beginning of year 2014 there lived 742 inhabitants. Village is located on M-52 motorway, also known as Chuya highway. The biggest industry is mixed agriculture focusing mainly on hunting, fishing, dairy and agriculture. There is also grocery, school, medical center and restaurant.

4.1.1. Electric energy consumption of Inya

In Inya live 742 people. Supposing that the average number of inhabitants in flat or house in Russia is 3.1, I have approximated following information about this village. There live about 310 people in 100 flats. From those 50 flats are equipped with cooker with rated power under 8.5 kW and 50 flats are equipped with cooker between 8.5< P <10.5 kW. According to data from third source table 2.1 on pages 18 and 19 calculated power consumption per flat for 40 to 60 flats equipped with electric cooker with rated power under 8,5 kW is 2,6 kW and with rated power between 8.5 and 10.5 kW it is 3.3 kW. Total active power demand of flats would be then:

$$P_{calc\,f} = \sum n_i \cdot P_i = 50 \cdot 2.6 + 50 \cdot 3.3 = 295 \qquad [kW] \qquad 4.1.$$

Where n_i stands for number of flats from certain group and P_i stands for calculated power per flat.

The same applies for houses, which are split into two groups – normal and luxury. The difference is that we distinguish only between houses, where gas is used for cooking and where cooker with rated power up to 10.5 kW is. The former group, cooking on gas has calculated power per house 30.3 kW if luxury and 2.6 if normal without electric sauna. With electric sauna, it has calculated power of 13.3 kW for its respective amounts. If the house is cooking on electric cooker, calculated power for luxury ones is 37.5 kW and for normal ones without sauna 2.6 and 12.9 kW with electric sauna. Active power consumption for luxury houses:

$$P_{calc\,hl} = \sum n_i \cdot P_i = 10 \cdot 30.3 + 10 \cdot 37.5 = 678 \quad \text{[kW]} \qquad 4.2.$$

And for normal ones:

$$P_{calc\,hn} = \sum n_i \cdot P_i = 26 \cdot 2.6 + 4 \cdot 13.3 + 82 \cdot 2.6 + 7 \cdot 12.9 = 421.3 \quad \text{[kW]} \qquad 4.3.$$

Stated above altogether means, that active power consumption of homes is 1397.3 kW.

Following data were adopted from (9). Table shows maximum and calculated power demand of all the industry and other consumers in village. Reactive power has been calculated according to typical power factor for each consumer.

	name	P_{max} [kW]	Q_{max} [kVAr]	S_{max} [kVA]	P_{calc} [kW]	Q_{calc} [kVAr]	S_{calc} [kVA]
housing	flats				295.0	107.1	313.8
	houses				1102.3	439.4	1186.6
industry	cowshed	10	8	12.8	7.5	6.0	9.6
	feed mill	20	17.5	26.6	15.0	13.1	19.9
	storage of oil	5	4	6.4	3.8	3.0	4.8
	garage	20	18	26.9	15.0	13.5	20.2
	administrative building	15	10	18.0	11.3	7.5	13.5
	boiler house	15	10	18.0	11.3	7.5	13.5
	dairy	25	20	32.0	18.8	15.0	24.0
other	school	10	4	10.8	7.5	3.0	8.1
	administrative buildings	7	3	7.6	5.3	2.3	5.7
	health center	15	8	17.0	11.3	6.0	12.8
	shop	2	0	2.0	1.5	0.0	1.5
	restaurant	20	10	22.4	15.0	7.5	16.8
				Total	1520.3	630.80	**1645.97**

Table 2 Power demands of Иня

Calculated power in table above is taken as 75 % of daily maximum.

If we sum up all the calculated powers stated above together, we get the active power consumption of 1520.3 kW for the whole village. Reactive power demand is 630.8 kVAr.

However, power demand is definitely not invariable throughout time. The shortest period of time when we can see similar behavior is day. Behavior during the day may also be divided into couple different groups, but two most important ones for us in this diploma thesis will be industry and public services and households. We can see, that those two large groups are actually complementary to each other, which is easy to understand, if we have a look at typical daily activities one does.

Following larger period is season, but it is hard to say exact borders, because it depends on weather variations between years. This seasonal variation is usually taken in consideration by multiplication of total power demand by seasonal coefficient, which are stated in next table and taken from (10).

		k_{winter} [-]	k_{spring} [-]	k_{summer} [-]	k_{autumn} [-]
housing	flats	1	0.8	0.7	0.9
	houses	1	0.8	0.7	0.9
industry	cowshed	1	0.8	0.7	0.9
	feed mill	1	0.8	0.6	0.9
	storage of oil	1	1	1	1
	garage	1	0.7	0.5	0.8
	administrative building	1	0.8	0.8	0.9
	boiler house	1	0.8	0.5	0.9
	dairy	1	0.8	0.7	0.9
other	school	1	0.8	0.1	0.8
	administrative buildings	1	0.8	0.8	0.9
	health center	1	0.8	0.7	0.9
	shop	1	0.6	0.4	0.7
	restaurant	1	0.9	0.8	0.9

Table 3 Seasonal coefficients

This being applied along with coefficients describing daily variations of power demand (10), one can draw graphs of power demand of a typical day of season for industry and public-services as well as four households. We have to point out, that those coefficients vary for active and reactive power, and so separate graphs must be carried out.

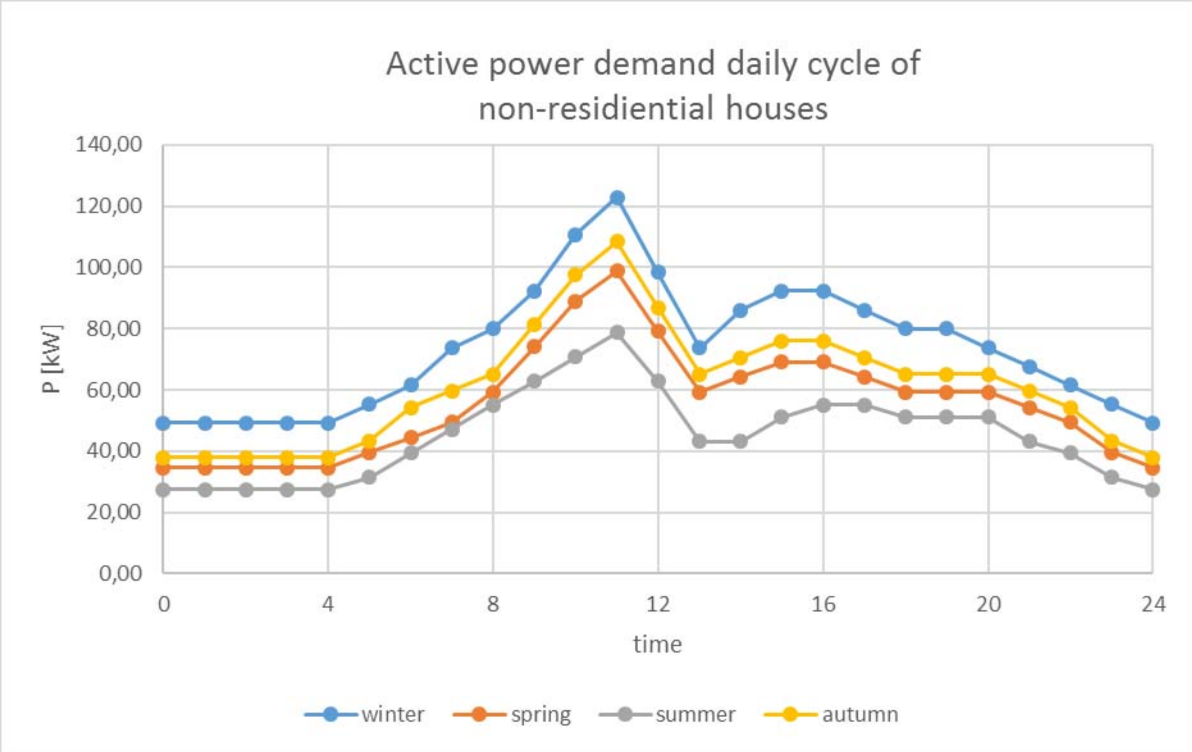

Figure 1 Active power demand daily cycle of non-residential houses

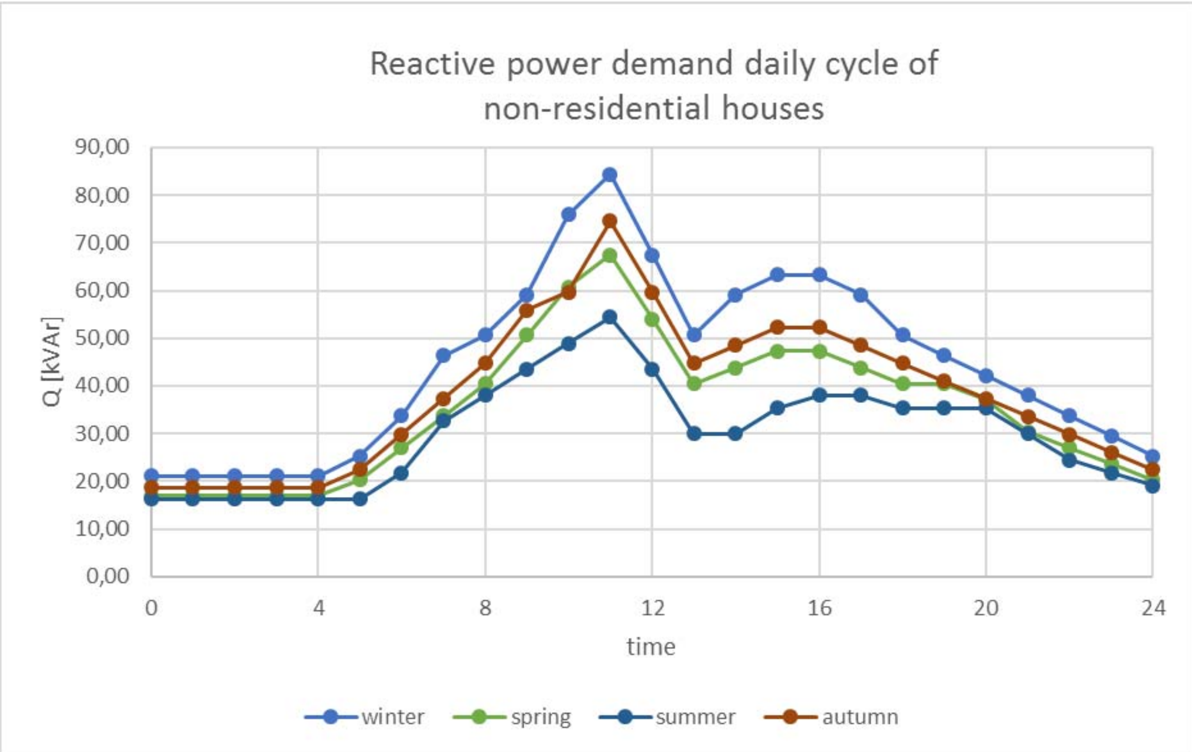

Figure 2 Reactive power demand daily cycle of non-residential houses

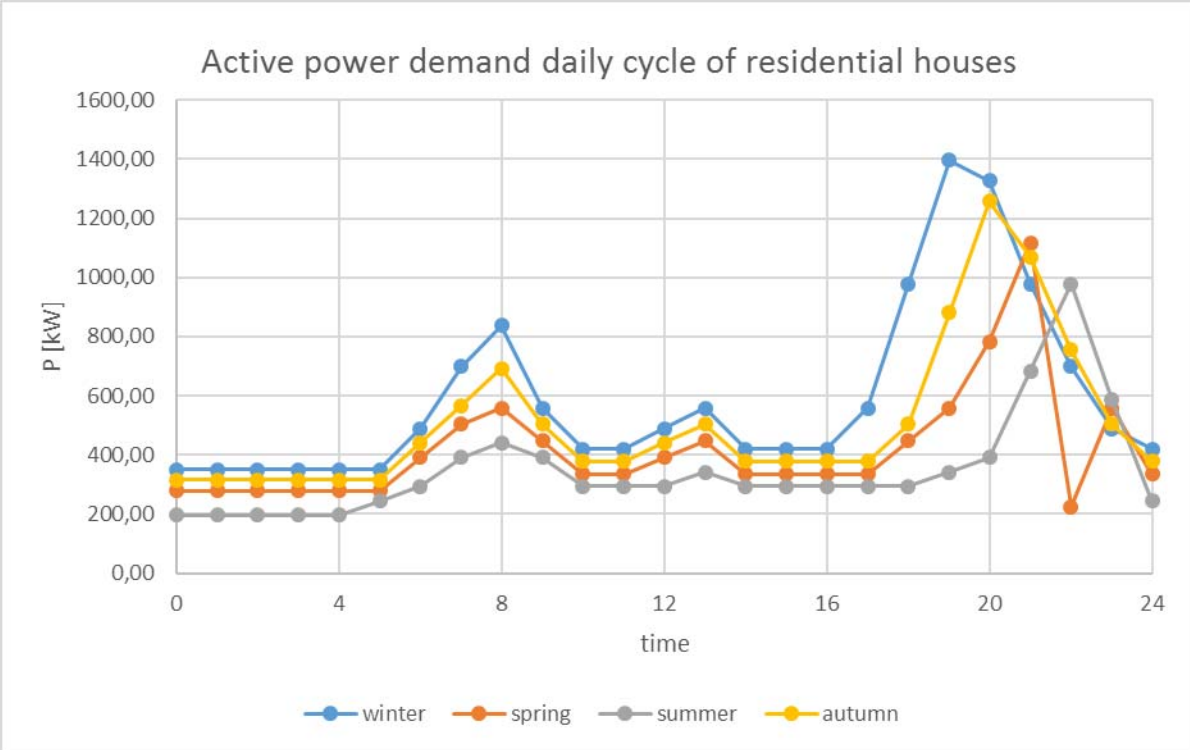

Figure 3 Active power demand daily cycle of residential houses

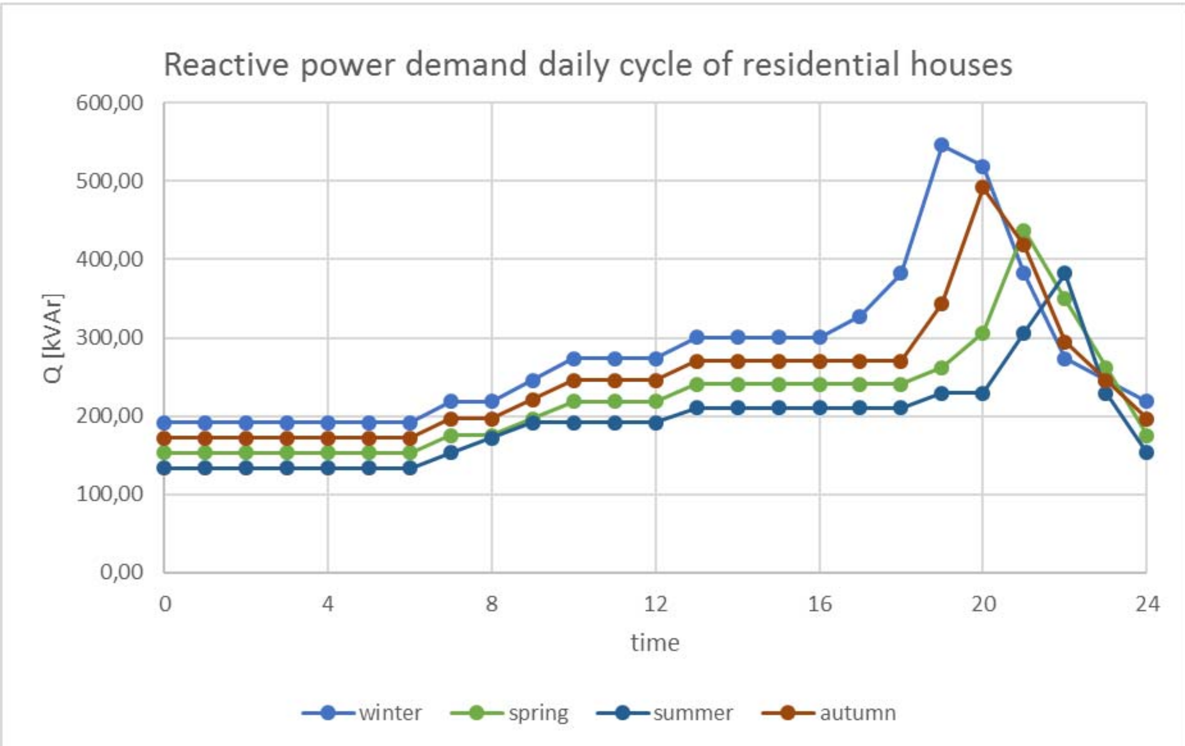

Figure 4 Reactive power demand daily cycle of residential houses

Evident fact arising from the graph is that power demand is the highest in winter and the lowest in summer. Although daily cycle of industry seems not to be much different across the seasons apart from absolute value, daily evening peak of households tends to be almost half-smaller in summer and occurs later, than in winter. This may be caused by longer daylight in summer and people spending more time outside.

4.1.2. Hydrologic data for Inya

Municipality Inya is located on the right riverbank of Katun River (Катунь), where tributary with the same name as the village joins the river. On the final kilometers before creek Inya joins Katun River, its vertical drop is about 40 meters, which makes it favorable for construction of small hydro scheme. Flow duration curve is in following graph, which was derived from river Ursul (Урсул) (11), which has quite similar landscape of drainage basin as the Inya. Accommodation was made to account different area of drainage basin.

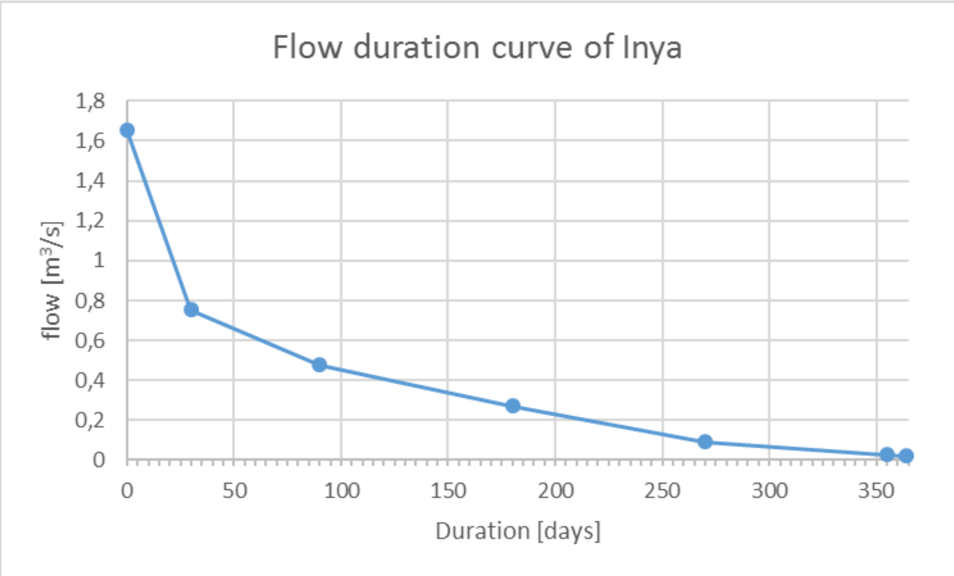

Figure 5 Flow duration curve of Inya creek in municipality Inya

Due to the fact, that water from the creek is also used for different purposes, such as watering plants, hydration of domestic animals as well as to maintain water for fish migration, reserved flow will be calculated as 0.07 m^3/s.

4.1.3. Inya hydropower power plant equipment

Firstly, the turbine has to be chosen. In addition to hydrologic data, the net head of site should be evaluated. To minimize civil works cost the best option is to create the hydropower plant on the final 500 meters of the creek, where river drops rapidly. In this case, construction will not interfere with road that leads to several houses upstream of considered site. The gross head available in this location is 27 meters. Supposing the friction and other losses in the conveyance system will be about 20%, the net head is 21.6 meters.

Discharge with the highest product of flow and flow duration according to the flow duration curve is 0.315 m3/s. To calculate specific speed of turbine, rotational speed was set as 750 revolutions per minute. According to calculation in formula 3.9, the specific speed for considered location is following:

$$n_{QE} = \frac{n\sqrt{Q}}{E^{\frac{3}{4}}} = \frac{12.5\sqrt{0.315}}{(21.6 \cdot 9.81)^{\frac{3}{4}}} = 0.126 \qquad 4.4.$$

This specific speed falls into the range of Francis turbine.

With above stated parameters an inquiry to Fuchun Industry Development co., ltd was made. Received offer closest to the desired parameters was Fuchun Industry development co., ltd horizontal Francis turbine with steel spiral case. Parameters are in following table:

Diameter [m]	Rated head [m]	Rated flow [m^3/s]	Rated power [kW]	Rotational speed [r/min]
0.4	20	0.2	30	750

Table 4 Parameters of turbine used in Inya

To avoid use of speed increaser, generator rotational speed must be equal to the rotational speed of turbine. The generator must be designed to handle the maximum power of the turbine and be capable of withstanding the over speed stress of turbine. For those reasons Fuchun Industry development horizontal synchronous generator type SFW30-8/432 with brushless excitation system. Parameters are in following table:

Output power [kW]	Rated voltage [V]	Rated power factor [-]	Frequency [Hz]	Rated rotation speed [r/min]
30	400	0.8 lagging	50	750

Table 5 Parameters of generator used in Inya

Other parts included in the offer are governor with electrical control, gate valve with nominal diameter 300 mm capable of electrical or manual control, auxiliary DC control panel with 16 Ah capacity, 110 V and installations and general control panel.

General control panel is composed mainly of programmable logic controllers. It offers on key start and on key stop functions due to the automatic quasi-synchronizing device. Manual synchronization is possible too. Control panels microprocessors control the excitation-regulating device, speed signal device, measuring instruments and contain three-phase line breaker on the output of generator as well as disconnector. Current and power transformers to measure output are included.

Besides mentioned, general control panels functions are water level control, maintaining constant power factor, low frequency inverter excitation, automatic system voltage tracking, protection against overcurrent, overload, post-acceleration, overvoltage and low voltage, unbalanced current protection, external fault protection, temperature protection and gas protection.

Prices of equipment in US dollars:

Turbine	Generator	Excitation system	Governor	Gate valve	General control panel	DC panel
21150	8650	1150	2880	4810	10580	1540

Table 6 Price of the equipment for Inya hydropower station

Price for the transportation in China to the port, where it will be loaded aboard of desired ship (INCOTERMS FOB term), is 960 $.

4.1.4. Electric power generation of hydropower plant in Inya

As a starting point for the energy production of small hydro power plant located in Inya served the flow duration curve of creek Inya mentioned above. Flows from flow duration curve were reduced by the reserved flow (Q_{res}), which must stay in the riverbed between the intake and outfall and thus cannot be utilized for energy production. Utilizable flow duration is in following figure.

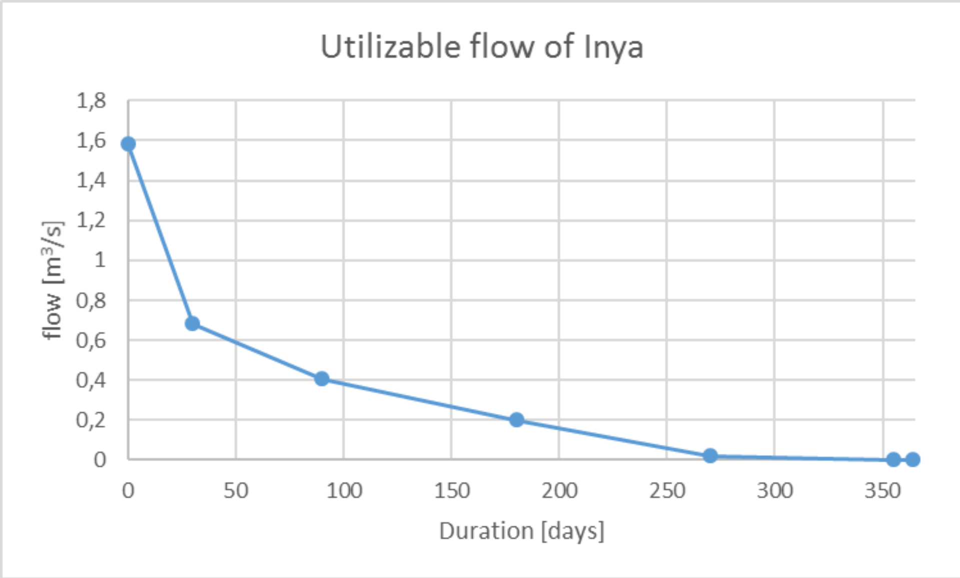

Figure 6 Utilizable flow of creek Inya

Next step was calculation of minimal discharge of turbine. According to available data, the power production of Francis turbine as a function of discharge is following.

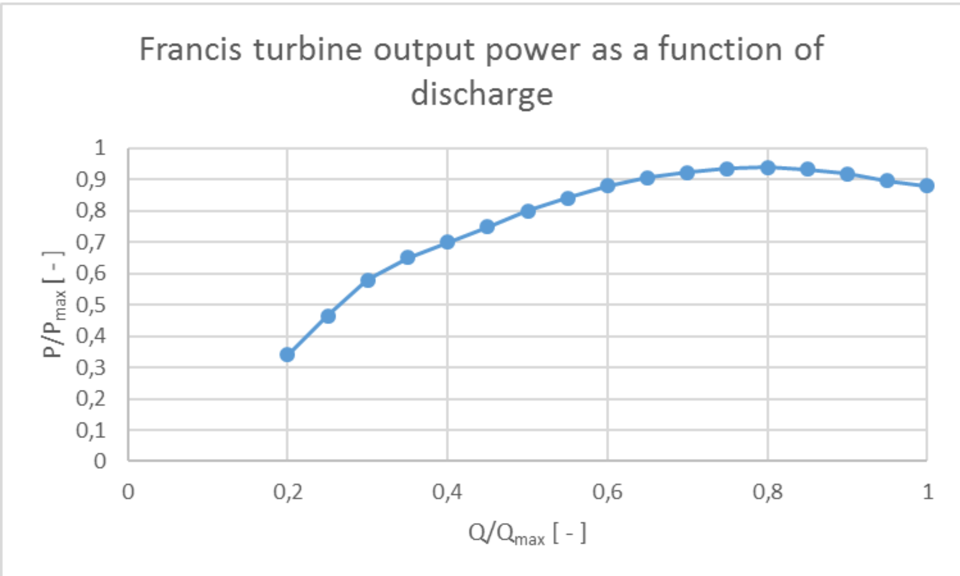

Figure 7 Francis turbine power as a function of discharge

From this figure it is clear that turbine stalls for discharges lower than 20 % of rated discharge. Therefore, minimal utilizable flow by turbine (Q_{umin}) is following:

$$Q_{umin} = Q_{rt} \cdot 0.2 = 0.2 \cdot 0.2 = 0.04 \quad [m^3/s] \qquad 4.5.$$

Where Q_{rt} is turbine rated flow.

When considering the reserved flow, minimal flow is:

$$Q_{min} = Q_{umin} + Q_{res} = 0.04 + 0.07 = 0.11 \quad [m^3/s] \qquad 4.6.$$

Then minimal flow duration was calculated (D_{Qmin}). As discontinuous data are available, I supposed changes between known points being linear. From utilizable flow duration figure was obvious, that minimal flow duration must lay within the interval of 180 and 270 days.

$$D_{Qmin} = 270 - \frac{Q_{min} - Q_{270}}{Q_{180} - Q_{270}} \cdot 90 = 270 - \frac{0.11 - 0.092}{0.27 - 0.092} \cdot 90 = 261 \quad [days] \qquad 4.7.$$

Rated discharge through turbine is possible, when flow in the creek is equal or higher than sum of rated flow of turbine and reserved flow. This flow will be called the maximum flow (Q_{max}).

$$Q_{max} = Q_{rt} + Q_{res} = 0.2 + 0.07 = 0.27 \quad [m^3/s] \qquad 4.8.$$

Duration of maximum flow can be calculated accordingly to minimal flow, however accidentally maximum flow is the same flow as flow with duration of 180 days. Therefore, the flow in creek Inya is equal or greater then maximum flow for 180 days a year, which means that turbine, will be working at its rated values without any variation.

When discharges with duration from 180 to 261 are reached, turbine output power varies according to Figure 7 Francis turbine power as a function of discharge. For relative discharges through turbine, I have calculated its absolute values and estimated its duration on linear basis analogously as in formula for minimal flow duration calculation.

Then I have calculated a difference between actual (D_{FDC}) and preceding (D_{FDC-1}) flow duration. For example:

$$\Delta D_{FDC} = \Delta D_{185.06} = D_{FDC} - D_{FDC-1} = 185.06 - 180 = 5.06 \quad [days] \qquad 4.9.$$

According to relative value of output power absolute value was calculated. Then I have calculated energy production for each interval ΔD_{FDC}. For the first interval, where output power is constant due to the flow higher then maximum flow, calculation was quite simple:

$$E_{FDC} = E_{180} = P_{180} \cdot \Delta D_{180} \cdot 24 = 26.4 \cdot 180 \cdot 24 = 114048 \quad [kWh] \qquad 4.10.$$

For other intervals, where output power of turbine changes, trapezoidal approximation was used. For $P_{FDC-1} < P_{FDC}$:

$$E_{FDC} = E_{186.06} = \left(P_{FDC-1} + \frac{|P_{FDC} - P_{FDC-1}|}{2}\right) \cdot \Delta D_{FDC} \cdot 24$$ [kWh] 4.11.

$$= \left(26.4 + \frac{|26.91 - 26.4|}{2}\right) \cdot 5.06 \cdot 24 = 3238$$

For $P_{FDC-1} > P_{FDC}$:

$$E_{FDC} = E_{206.81} = \left(P_{FDC} + \frac{|P_{FDC} - P_{FDC-1}|}{2}\right) \cdot \Delta D_{FDC} \cdot 24$$ [kWh 4.12.

$$= \left(28.08 + \frac{|28.08 - 28.2|}{2}\right) \cdot 5.06 \cdot 24 = 3418.5$$

Total annual production of electricity (E_A) is sum of productions in each interval.

$$E_A = \sum E_{FDC} = 114048 + 3238 + 3307 + \ldots = 160441.8$$ [kWh] 4.13.

All results of calculations are in table on following page.

Q_t/Q_tmax [-]	**1**	**0.95**	**0.9**	**0.85**	**0.8**	**0.75**	**0.7**	**0.65**	**0.6**	**0.55**	**0.5**	**0.45**
Q_t [m³/s]	0.2	0.19	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.1	0.09
Q [m³/s]	0.27	0.26	0.25	0.24	0.23	0.22	0.21	0.2	0.19	0.18	0.17	0.16
FDC [days]	180.00	185.06	190.12	195.19	200.25	205.31	210.37	215.43	220.49	225.56	230.62	235.68
ΔD_n [days]	180.00	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06
P/Pmax [-]	0.88	0.90	0.92	0.93	0.94	0.94	0.92	0.91	0.88	0.84	0.80	0.75
P [kW]	26.4	26.91	27.54	27.99	28.2	28.08	27.69	27.21	26.4	25.26	24	22.5
E [kWh]	114048.0	3238.1	3307.3	3372.9	3413.0	3418.5	3387.5	3334.7	3256.3	3137.9	2992.1	2824.4

Q_t/Q_tmax [-]	**0.4**	**0.35**	**0.3**	**0.25**	**0.2**
Q_t [m³/s]	0.08	0.07	0.06	0.05	0.04
Q [m³/s]	0.15	0.14	0.13	0.12	0.11
FDC [days]	240.74	245.80	250.86	255.93	260.99
ΔD_n [days]	5.06	5.06	5.06	5.06	5.06
P/Pmax [-]	0.70	0.65	0.58	0.46	0.34
P [kW]	21	19.5	17.4	13.92	10.2
E [kWh]	2642.2	2460.0	2241.3	1902.4	1465.1

Table 7 Energy production of small hydro power plant in Inya

Total energy produced annually is 160 441.8 kWh.

4.2. Small hydropower plant project in municipality Josefův Důl

Josefův Důl is a small village in located in the heart of Jizera Mountains. It has population of 901 residents according to data from year 2014. There is almost no industry, as it is focused mainly on tourism. There are plenty of guesthouses and couple of hotels and restaurants. The only industry is wood industry represented by sawmill. Village has its own kinder garden and primary school located in one building and couple of groceries.

4.2.1. Electric energy consumption of Josefův Důl

Calculations for Josefův Důl were done in a similar way as for Inya. There lived 901 residents at the beginning of year 2014. According to data obtained by census in year 2001, the average number of inhabitants in one household is 2.6. Keeping this in mind, I have approximated the number of households as follows: 114 flats and 232 houses of whom 115 are luxury ones and 117 are normal ones.

As the whole village has gas installations, the ratio of household cooking on gas and on electric cookers is almost equal. In the past, more gas stoves were used but in new houses, it is more common to install electric stoves.

Flats were again split up into three groups, where from total number of 114 flats 60 use gas for cooking and 24 use electric stove with rated power under 8.5 kW and 30 use stove with rated power between 8.5 and 10.5 kW. For the first group using gas, I calculated 1.05 kW of power demand per flat (9), for the letter group with less potent cookers I calculated 3.1 kW per flat and for the last group 4.2 kW per flat. Calculation of total power demand of flats follows.

$$P_{calc\,f} = \sum n_i \cdot P_i = 60 \cdot 1.05 + 24 \cdot 3.1 + 30 \cdot 4.2 = 263.4 \quad [kW] \qquad 4.14.$$

According to same rules as in previous chapter, I have split up houses into two groups – luxury and normal. Of the former ones mentioned of total of 115 houses, 33 cook on gas and 82 cook on electric stove with rated power under 10.5 kW.

$$P_{calc\,hl} = \sum n_i \cdot P_i = 33 \cdot 30.3 + 82 \cdot 37.5 = 4074.9 \quad [kW] \qquad 4.15.$$

From total of 117 normal houses, 48 are equipped with gas stoves and 69 with electric cooker up to 10.5 kW of rated power.

$$P_{calc\,hn} = \sum n_i \cdot P_i = 48 \cdot 2.1 + 69 \cdot 2.6 = 280.2 \quad [kW] \qquad 4.16.$$

Stated above in total makes household demand of 4618.5 kW.

Only industrial facility is a sawmill, which has approximately maximum power demand of 270 kW. From other consumers in village we have to mention school, administrative buildings of municipality, health center three shops and three restaurants. All active power demands and calculated values are in table 5. Reactive power has been calculated according to typical power factor for each consumer. Calculated power was obtained by multiplying maximal power by coefficient of utilization 0.75.

		Pmax [kW]	Qmax [kVAr]	S [kVA]	P_{calc} [kW]	Q_{calc} [kVAr]	S_{calc} [kVA]
housing	flats				263.4	101.9	282.4
	houses				4355.1	1682.7	4668.9
industry	sawmill	270	200	336.0	202.5	150.0	252.0
other	school	10	4	10.8	2.3	0.9	2.5
	administrative buildings	7	3	7.6	1.5	0.6	1.6
	health center	15	8	17.0	4.5	2.4	5.1
	shop (3x)	2	0	2.0	0.8	0.0	0.8
	restaurant (3x)	20	10	22.4	6.0	3.0	6.7
				Total	4836.1	1941.5	**5211.2**

Table 8 Power demand of Josefův Důl

As was already presented for Inya, we accepted the same daily and seasonal variations of power demand for Josefův Důl. Seasonal coefficients for groups are in Table 6.

		k_{winter} [-]	k_{spring} [-]	k_{summer} [-]	k_{autumn} [-]
housing	flats	1	0.8	0.7	0.9
	houses	1	0.8	0.7	0.9
industry	sawmill	0.3	0.5	0.9	1
other	school	1	0.8	0.1	0.8
	administrative buildings	1	0.8	0.8	0.9
	health center	1	0.8	0.7	0.9
	shop (3x)	1	0.6	0.4	0.7
	restaurant (3x)	1	0.9	0.8	0.9

Table 9 Seasonal coefficients

Previous table in joint with table of daily variations gives us following graphs of typical hourly demands during typical day of each season. As coefficients for active and reactive power vary, graphs are presented separately.

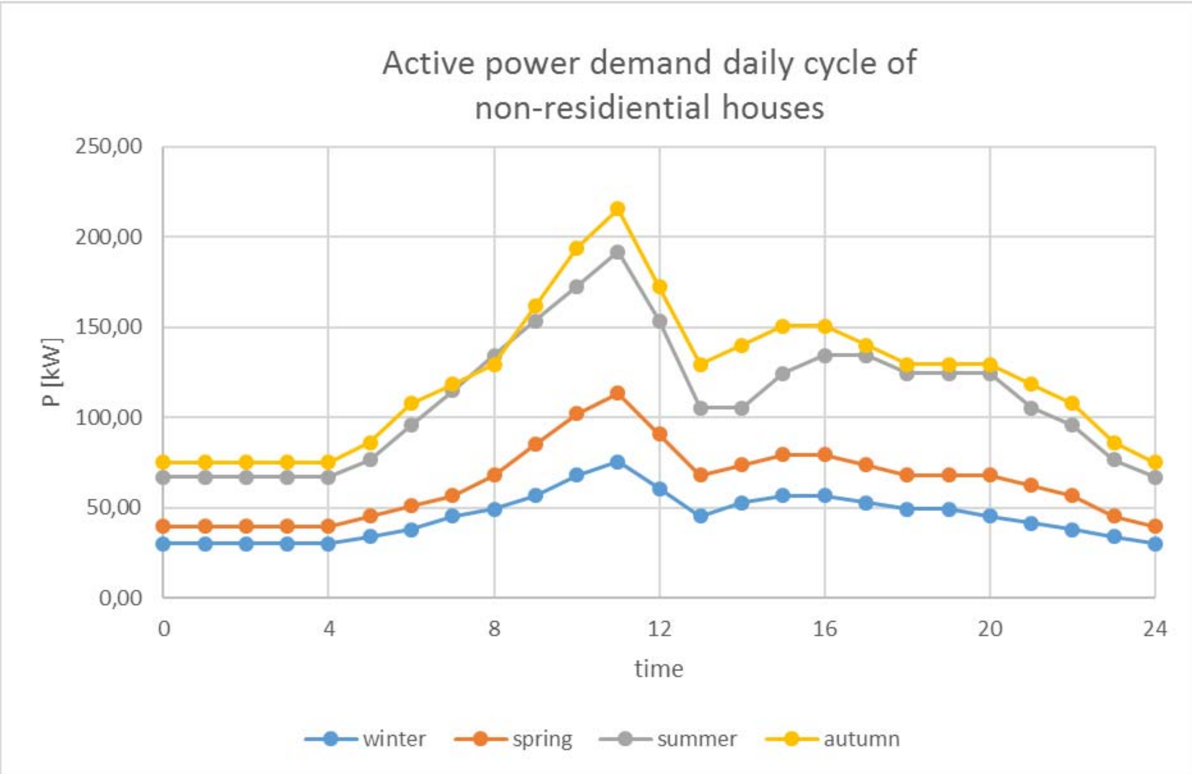

Figure 8 Active power demand daily cycle of non-residential houses

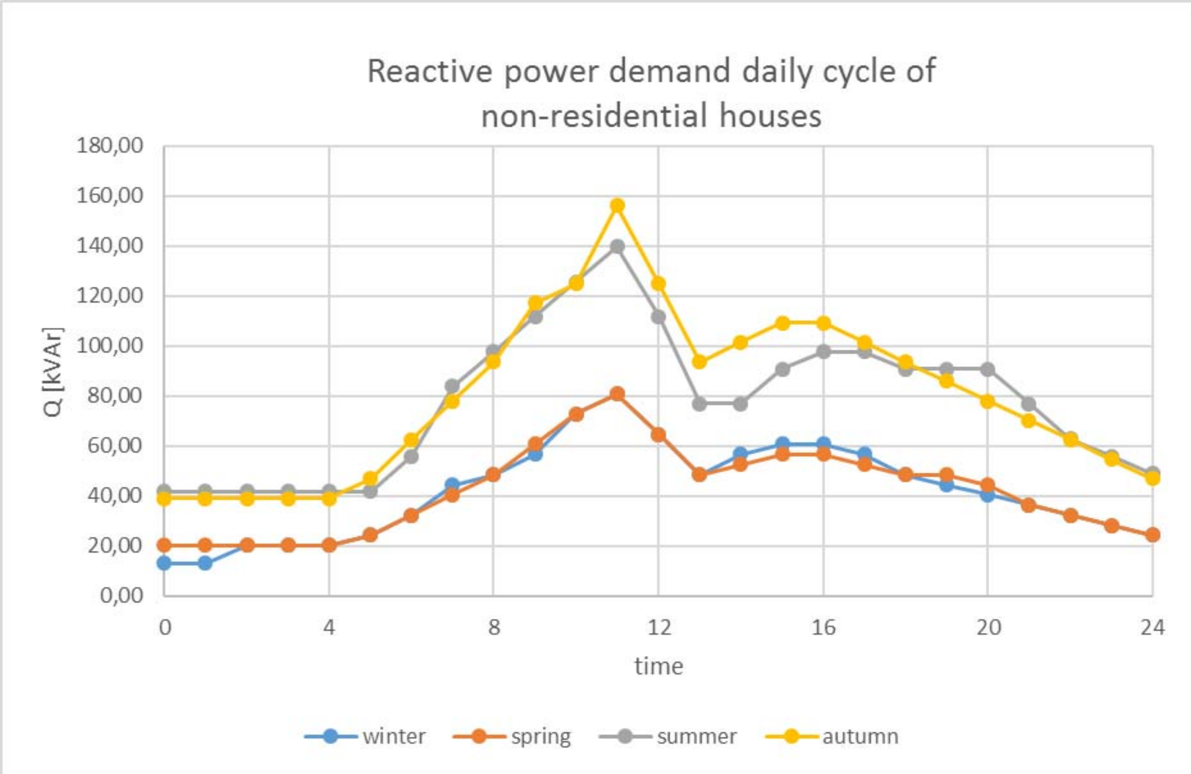

Figure 9 Reactive power demand daily cycle of non-residential houses

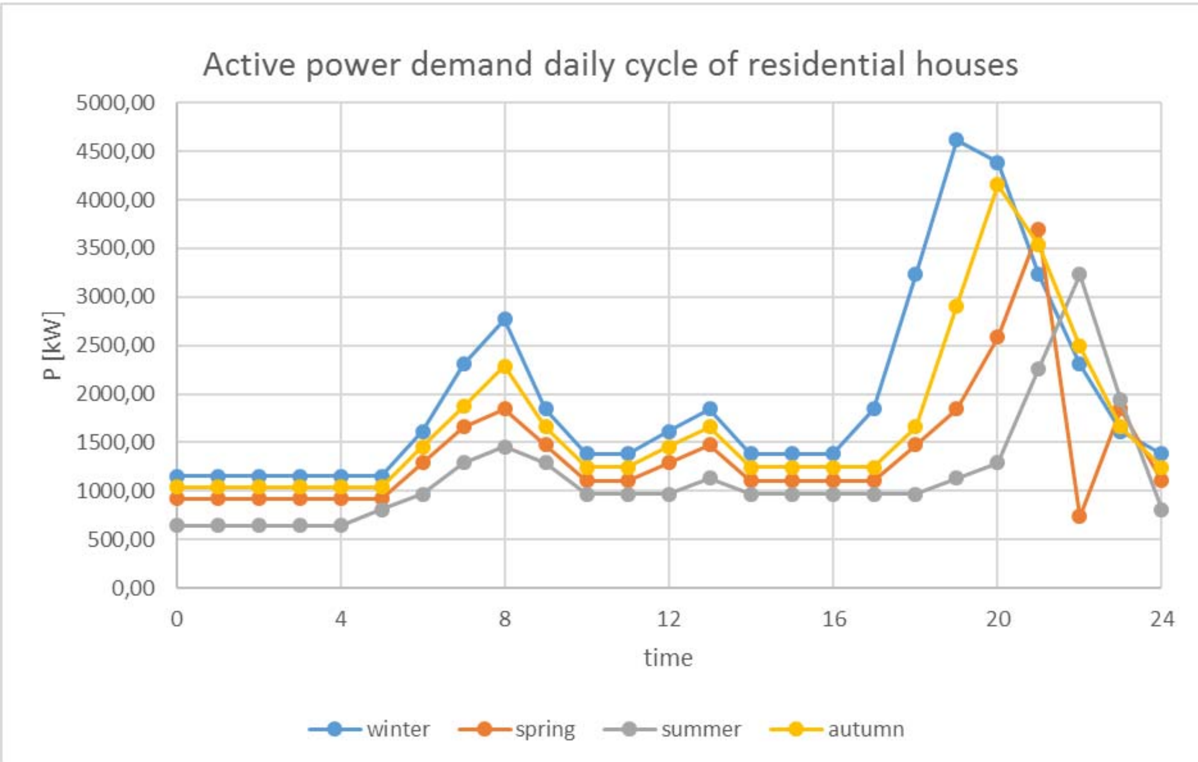

Figure 10 Active power demand daily cycle of residential houses

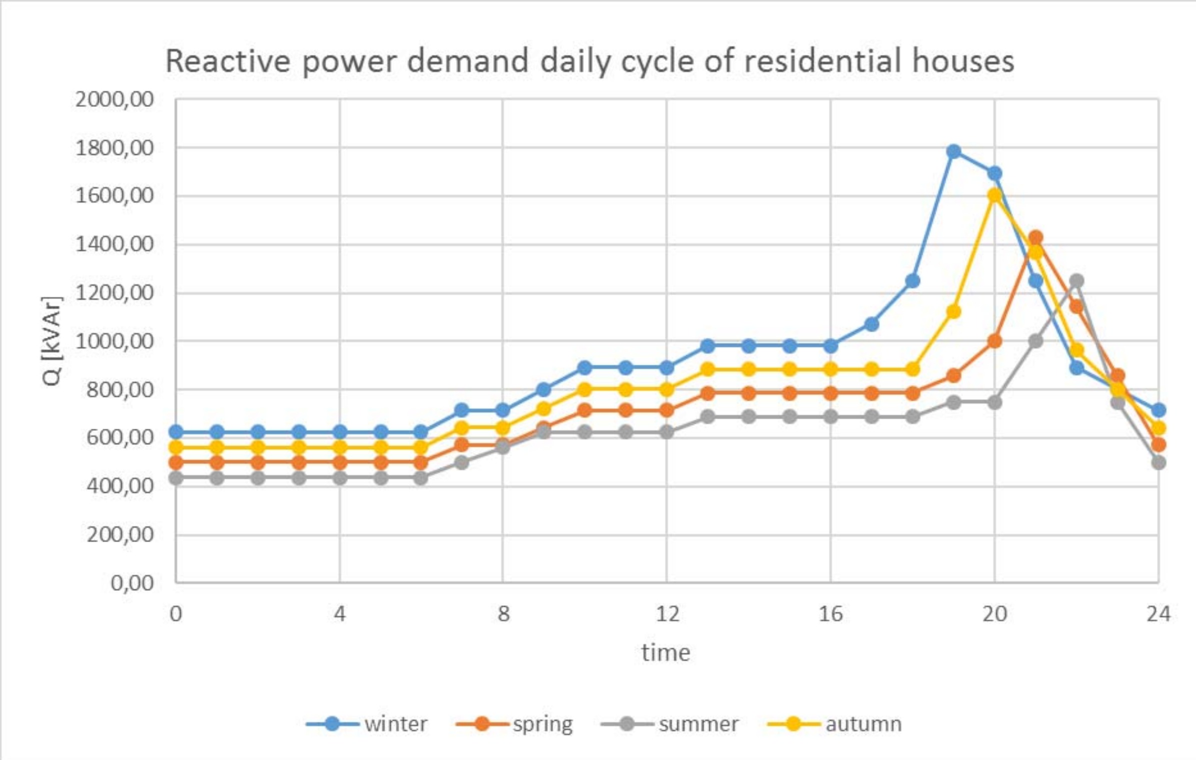

Figure 11 Reactive power demand daily cycle of residential houses

Again, complementarity is obvious, as well as evening peak occurrence later during summer season.

4.2.2. Hydrologic data for Josefův Důl

Municipality Josefův Důl is located about kilometer downstream of reservoir Josefův Důl located on Kamenice creek. This reservoir serves as a source of drinking water for city Liberec as well as couple smaller ones around. Apart from its primary function as a water source it also keeps the minimum discharge in the creek. For this reason, the flow duration curve is quite flat, compared to some other rivers with same drainage area and annual precipitation. Drainage are is 20.8 km^2 and annual precipitation is 1344 mm.

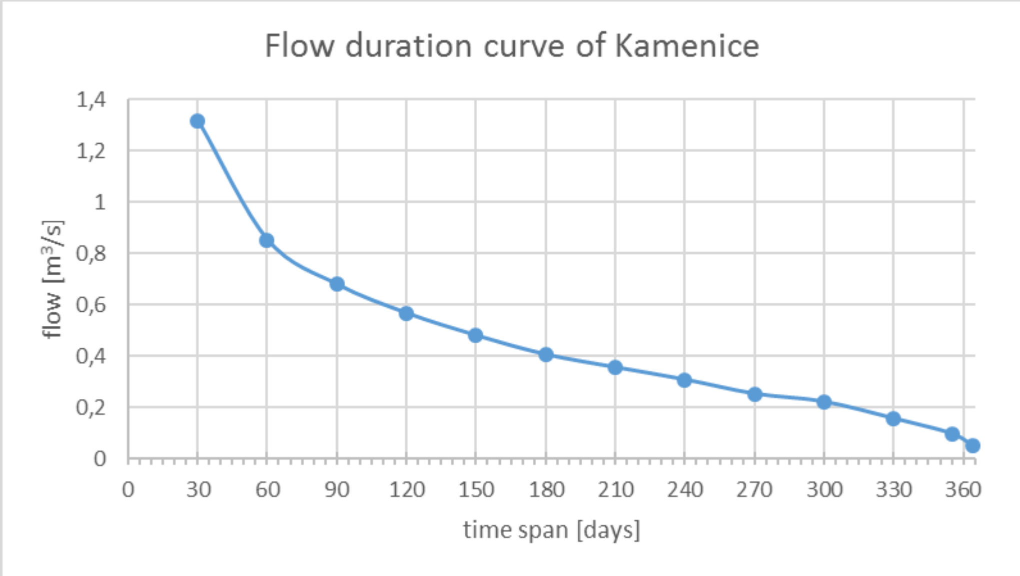

Figure 12 Flow duration curve of Kamenice creek

Although the water fauna consists mainly of invertebrates, some other animals here also have strong ties to the water, as well as for hygienic reasons. Therefore, minimum reserved flow of 0.099 m3/s has to be maintained in the riverbed.

4.2.3. Josefův Důl hydropower plant equipment

Distinction of power plant equipment starts with the choice of turbine. As was mentioned before, key parameters have to be calculated prior to the choice. Location Josefův Důl offers gross head of little over 100 meters measured from the outlet of reservoir to the municipality. Gross head depends on the decision, how much of less sloped part investor would like to utilize. Let us estimate that 100 meters of gross head is a fair tradeoff between full exploitation of head with higher cost of civil works and minimization of those costs by exploitation of the steepest part only. Supposing 10 % head losses in the conveyance system, the net head is 90 meters.

To distinguish the project discharge method of highest product of usable flow (i.e. without reserved flow) and duration was used. The highest result obtained was for usable flow 0.382 m^3/s, which has flow duration of 150 days.

Type of turbine is determined upon the value of specific speed, which in this case is following:

$$n_{QE} = \frac{n\sqrt{Q}}{E^{\frac{3}{4}}} = \frac{16.7\sqrt{0.302}}{(90 \cdot 9.81)^{\frac{3}{4}}} = 0.0636 \quad 4.17.$$

With a quick glance in the table of specific speeds in chapter 3.6.1.2 this value falls into the range of Francis turbine, however close to the borderline with multi nozzle Pelton turbine. In such cases, literature (5) suggests, Turgo turbine is an alternative for Francis and Pelton turbines in case of long penstocks or strongly varying flow. Both phenomena mentioned occur in our case so Turgo turbine will be chosen.

Found Turgo turbine with parameters closest to the desired ones is a Fuchun Industry Development horizontal Turgo turbine type XJA-W-40/1x11 with design head of 92 meters and design flow of 0.371 m^3/s. (12) Parameters of this turbine are following:

Rated head [m]	Rated flow [m^3/s]	Rated power [kW]	Rotational speed [r/min]
92	0.371	278	1000

Table 10 Parameters of turbine used in Josefův Důl

In order not to use a speed increaser, which would be another mechanical part that need maintenance and are prone to fault when proper care is not present, a generator with the same rotational speed has to be chosen. As mentioned before, generator must be capable of withstanding runaway conditions in case of fault, when speed of Turgo turbine may be up to double the nominal speed.

A suitable variant is the Fuchun Industry Development synchronous generator type SFW250-6/740. Excitation system is brushless. Parameters are presented in the table below.

Output power [kW]	Rated voltage [V]	Frequency [Hz]	Rated rotational speed
250	400	50	1000

Table 11 Parameters of generator used in Josefův Důl

The same as with the project in Inya, manufacturer of turbine and generator also offers speed governor with electric or manual operation, which adjusts the speed and power making the turbine unit stable under all conditions. Valve of the turbine is type Z941H-16 DN300.

Other components of the system, all from the same manufacturer are:

DC control panel with 16 Ah capacity and all the indoor installations plus control panel.

General control panel composed mainly of programmable logic controllers with functions of automatic quasi-synchronizing device, manual quasi-synchronizing device, microcomputer protection of generator, microcomputer excitation regulating device, speed signal device, measuring instruments, switches, outgoing line breakers, disconnectors current and power transformers for measuring of the output power. Functions of the general control panel are one key start, one key stop, water level control, maintaining of constant power factor, low frequency inverter excitation, automatic system voltage tracking, protection against overcurrent, overload, post-acceleration, overvoltage, low voltage, unbalanced current protection, external fault protection, gas and temperature protection.

Prices of equipment in US dollars:

Turbine	Generator	Excitation system	Governor	Gate valve	General control panel	DC panel
35270	13950	3280	20520	8330	19380	1540

Table 12 Price of equipment for Josefův Důl small hydropower station

Price for the transportation in China to the port, where it will be loaded aboard of desired ship (INCOTERMS FOB term), is 2030 $.

4.2.4. Electric power generation of small hydropower plant in Josefův Důl

After determination of equipment, a preliminary study on electric power generation must be calculated. As was already mentioned in chapter dealing with hydrology, not whole flow may be exploited, because reserved flow has to be kept in the riverbed to maintain the right hygienic conditions. For this reason, utilizable flow is the flow without reserved flow. Duration of utilizable flow is presented in following figure.

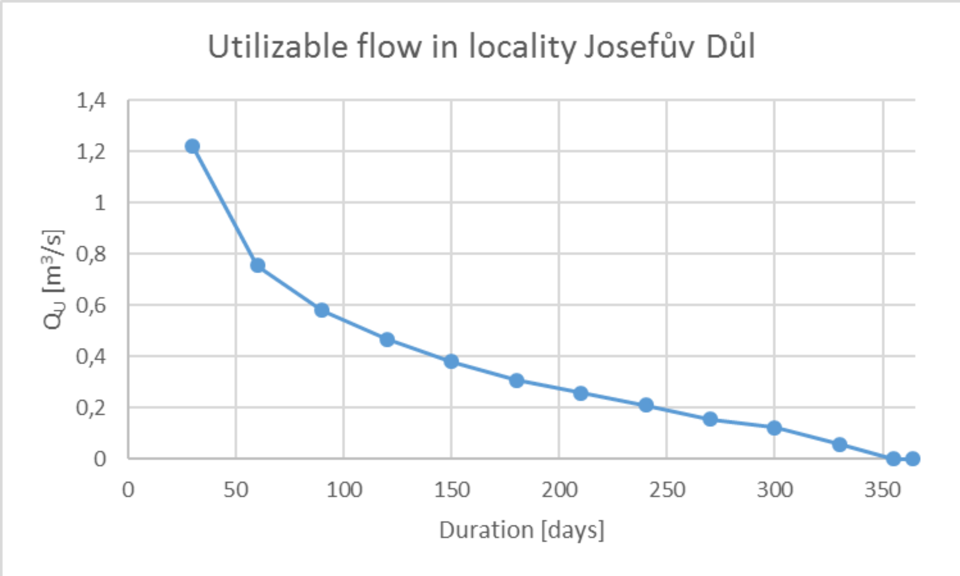

Figure 13 Utilizable flow of Kamenice in Josefův Důl

Then the actual calculation of annual energy production started. From the table of power output of Turgo turbine according to the discharge a minimum discharge was calculated.

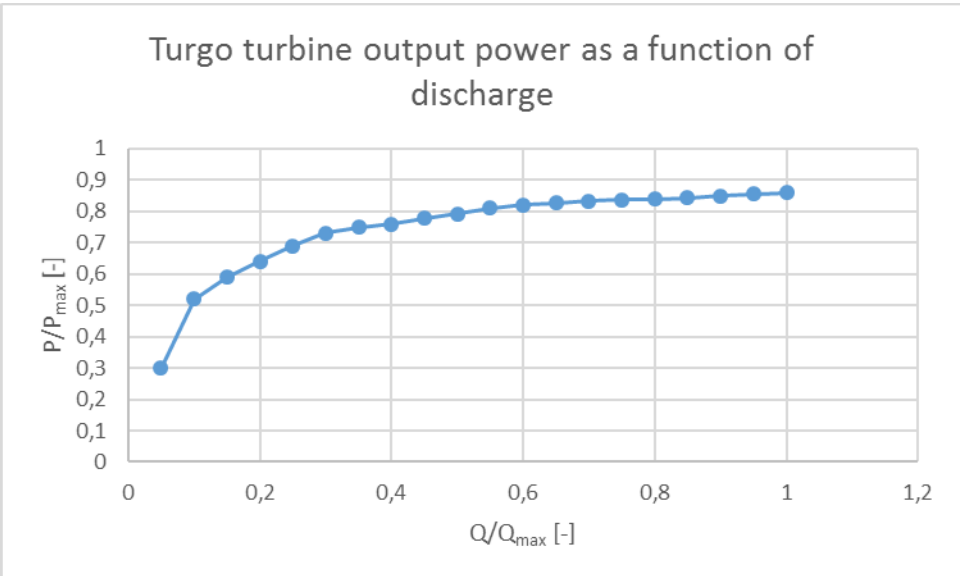

Figure 14 Turgo turbine output power as a function of discharge

Turgo turbine needs only 5 % of its nominal discharge to start rotating. Which is equal to the minimum utilizable flow of 0.0186 m^3/s.

$$Q_{umin} = Q_{rt} \cdot 0.05 = 0.371 \cdot 0.05 = 0.01855 \quad [m^3/s] \quad 4.18.$$

Where Q_{rt} is turbine rated flow.

The relation between minimum flow (Q_{min}) and minimum utilizable flow (Q_{umin}) is following:

$$Q_{min} = Q_{umin} + Q_{res} = 0.01855 + 0.099 = 0.118 \quad [m^3/s] \quad 4.19.$$

Where Q_{res} represents reserved flow.

Then minimum flow duration (D_{Qmin}) was calculated. Again, linear approximation between known states was used. From the flow duration curve, it was apparent that the flow duration will be in range between 330 and 355 days. Exact value was obtained from following calculation:

$$D_{Qmin} = 355 - \frac{Q_{min} - Q_{355}}{Q_{330} - Q_{355}} \cdot 25 = 355 - \frac{0.12 - 0.099}{0.158 - 0.099} \cdot 25 = 347 \quad [days] \quad 4.20.$$

Where Q_{355} is the flow with duration 355 days a year.

Rated discharge of turbine is reached when flow in the river reaches or exceeds maximum flow (Q_{max}).

$$Q_{max} = Q_{rt} + Q_{res} = 0.371 + 0.099 = 0.470 \quad [m^3/s] \quad 4.21.$$

For this flow, the duration will be calculated similarly to the duration of minimum flow and will fall into the range between duration of 150 and 180 days.

$$D_{Qmax} = 180 - \frac{Q_{max} - Q_{180}}{Q_{150} - Q_{180}} \cdot 30 = 180 - \frac{0.47 - 0.407}{0.481 - 0.407} \cdot 30 = 154{,}5 \quad [days] \quad 4.22.$$

Maximum flow is reached or exceeded, according to the statistical data available, for 154.5 days a year. For this period, energy production will remain constant, without any variation.

When discharges with duration between 154.5 and 347 days a year, energy production varies according to immediate flow. As in previous energy production calculation, for known relative discharges, absolute values were calculated and belonging absolute values were determined. For states between known points linear approximation was used.

Then duration of each interval was determined as the difference between actual and preceding value of flow duration.

$$\Delta D_{FDC} = \Delta D_{162} = D_{FDC} - D_{FDC-1} = 161.98 - 154.46 = 7.52 \quad [days] \quad 4.23.$$

Absolute power output was calculated as a product of rated power output and the relative value obtained for given discharge from Figure 14 Turgo turbine output power as a function of discharge Output power in the first interval was constant. Energy produced was following:

$$E_{FDC} = E_{166} = P_{166} \cdot \Delta D_{166} \cdot 24 = 239{,}08 \cdot 154{,}46 \cdot 24 = 886277 \quad [\mathrm{kWh}] \quad 4.24.$$

For all the other intervals, as the output power of turbine is decreasing with the discharge, trapezoidal approximation was used:

$$E_{FDC} = E_{161.98} = \left(P_{FDC} + \frac{|P_{FDC} - P_{FDC-1}|}{2}\right) \cdot \Delta D_{FDC} \cdot 24 = \left(237.97 + \frac{|239.08 - 237.97|}{2}\right) \cdot 7.52 \cdot 24 = 43049.5 \quad [\mathrm{kWh}] \quad 4.25.$$

Total annual production is the sum of productions in all intervals.

$$E_{A} = \sum E_{FDC} = 886277 + 43049.5 + 42799.5 + \ldots = 1815324 \quad [\mathrm{kWh}] \quad 4.26.$$

All results together are summed up in the table on following page.

Q_t/Q_tmax [-]	**1.00**	**0.95**	**0.90**	**0.85**	**0.83**	**0.80**	**0.75**	**0.70**	**0.70**	**0.65**	**0.60**	**0.57**	**0.55**
Q_t [m³/s]	0.371	0.352	0.334	0.315	0.308	0.297	0.278	0.260	0.258	0.241	0.223	0.210	0.204
Q [m³/s]	0.470	0.451	0.433	0.414	0.407	0.396	0.377	0.359	0.357	0.340	0.322	0.309	0.303
FDC [days]	154.46	161.98	169.50	177.02	180.00	186.72	197.85	208.98	210.00	220.53	232.13	240.00	243.25
ΔD_n [days]	154.46	7.52	7.52	7.52	2.98	6.72	11.13	11.13	1.02	10.53	11.59	7.88	3.25
P/Pmax [-]	0.86	0.86	0.85	0.84	0.84	0.84	0.84	0.83	0.83	0.83	0.82	0.81	0.81
P [kW]	239.08	237.97	236.30	234.63	234.19	233.52	232.69	231.57	231.42	229.91	227.96	226.07	225.18
E [kWh]	886276.9	43049.5	42799.5	42498.4	16763.6	37716.2	62266.5	62006.6	5667.1	58300.2	63700.6	42906.0	17574.2
Q_t/Q_tmax [-]	**0.50**	**0.45**	**0.42**	**0.40**	**0.35**	**0.33**	**0.30**	**0.25**	**0.20**	**0.16**	**0.15**	**0.10**	**0.05**
Q_t [m³/s]	0.186	0.167	0.155	0.148	0.130	0.124	0.111	0.093	0.074	0.059	0.056	0.037	0.019
Q [m³/s]	0.285	0.266	0.254	0.247	0.229	0.223	0.210	0.192	0.173	0.158	0.155	0.136	0.118
FDC [days]	253.36	263.48	270.00	276.39	294.34	300.00	305.86	314.42	322.98	330.00	331.42	339.28	347.14
ΔD_n [days]	10.12	10.12	6.52	6.39	17.95	5.66	5.86	8.56	8.56	7.02	1.42	7.86	7.86
P/Pmax [-]	0.79	0.78	0.77	0.76	0.75	0.74	0.73	0.69	0.64	0.60	0.59	0.52	0.30
P [kW]	220.45	216.01	212.96	211.28	208.50	206.75	202.94	191.82	177.92	166.53	164.02	144.56	83.40
E [kWh]	54108.1	52994.2	33553.1	32516.1	90428.7	28210.0	28816.7	40557.0	37986.5	28997.4	5630.6	29105.9	21501.7

Table 13 Energy production of small hydro power plant in Josefův Důl

Total annual energy production of small hydropower scheme located on Kamenice river in Josefův Důl is 1 815 324 kWh.

5. Economic evaluation of calculated projects

This chapter is focused on economic aspect of small hydropower plants. First part of the chapter gives summary of construction and operation costs in general. Second part explains methods of economic evaluation known as net present value and internal rate of return, which are in the subsequent chapters applied to the two evaluated projects.

5.1. Construction and operation expenses

In 2006 investments to small hydro power plant project were between \$1 500 to \$2 500 per kW of nominal power. Two years later investments to hydro stations with nominal power over 10 MW were already between \$1 750 and \$ 6 250 per kW. For smaller sites with nominal power in between 1 and 10 MW specific investments were about \$2 000 to \$7 500 per kW, and for the smallest sites with nominal power under 1 MW even between \$2 500 to \$10 000 per kW. (3)

These values strongly depend on location and its parameters. For high flow/low head site investments are much higher than for low flow/high head project. This is due to the fact, that civil engineering works will be more expensive due to its larger scale. All three groups together for year 2008 the average specific investments were about \$4 750 per kW. Rise of price is significant. (3)

Operation costs are usually about 1.5 to 2.5 % of investment costs annually. To be more exact hydro power stations over 10 MW have usually operational costs 40 to 110 \$/MWh (\$ 75 on average), small hydro power plants about 45 to 120 \$/MWh (\$ 83 on average) and micro hydro power stations of about 55 – 185 \$ (\$ 90 on average). (3)

5.2. Net present value

The net present value is a method used to evaluate profitability of a project. It is based on the time value of money. Also known as discounting. Let me explain this on a little example.

In economics there is a huge difference between money you have available at the moment and money you will obtain in the future, because the same amount of money in the future has lower value than now. First reason for this statement in most countries around the world is the inflation, which is a general rise of price level of goods. Second reason, which is even more important is, that you can invest money you have available at the moment, and make a profit, i.e. over given time period rise the amount of money you have.

The ratio of annual profit from investment to the invested amount of money is called the discount rate (*i*). It is given by the market and represents the profit of investments with similar risk. If two or more investments are possible, discount rate is accepted according to the opportunity cost, i.e. the highest profit from the unused variants.

Let me make it clear on following example. Let us assume that you can get 1000 rubles either today or in a year. If the inflation rate was 0 and you had no opportunity to invest your money, then the value of money today and in a year would be the same.

But if the inflation was 0 and you will have the possibility of 10 % profit over a year, then the present value (*PV*) of 1000 rubles obtained in a year is 909.1 rubles today. Why? Because if I invest 909.1 rubles today and can make 10 % profit per year, I will have 1000 rubles after a year.

$$PV = \frac{CF_t}{(1+i)^t} = \frac{1000}{(1+0.1)^1} = 909.1\ RUB \qquad 5.1.$$

Where CF_t is cash flow in year t (in our example after a year), *I* is discount rate.

Inflation is rarely zero so it must be considered using Fisher formula, which sets the relationship between real discount rate r_r (without inflation) and inflation rate, which together make nominal discount rate r_n.

$$1 + r_n = (1 + r_r) \cdot (1 + i) \qquad 5.2.$$

Net present value is the sum of present values of cash flows, which are caused by considered project over the lifetime of project.

$$NPV = \sum_{t=1}^{T_l} \frac{CF_t}{(1+r)^t} \quad [RUB] \qquad 5.3.$$

Where T_l is the lifetime of project and r is the discount rate.

In the lifetime of project all actions (i.e. cash flows) must be included, including restoration of location after the end of lifetime of project, if required by laws or local authorities.

The only drawback of this method is that you have to set the discount rate correctly, as it influences the result, but it can be determined based on other projects in given section of industry.

5.3. Internal rate of return

The internal rate of return is another method of profitability evaluation or projects. As well as net present value, even internal rate of return calculates with expected cash flows, but the result is different because it gives us the value of discount rate, at which the value of future cash flows will be zero.

$$NPV = \sum_{t=1}^{T_1} \frac{CF_t}{(1+x)^t} \stackrel{\text{def}}{=} 0 \qquad \text{[RUB]} \qquad 5.4.$$

The internal rate of return is the value of *x* in this equation.

If the internal rate of return is higher than desired discount rate, project is profitable. If it is lower, it is disadvantageous.

The problem is, that this method uses the same discount rate for the whole time lifetime of project. As the result is the root of *t*-th order equation, there are possibilities, that there will be one, multiple or none results. In case internal rate of return does not exist, other methods of evaluation should be used.

5.4. Economic evaluation of project in Inya

Economic evaluation of a project is essential nowadays. Following chapter will be dealing with economic evaluation of small hydro power plant project at municipality Inya. Calculations were accommodated to the Russian system, but where information was lacking, Czech principles were used.

According to data available from [1] prices of electricity are rising substantially since 2011, however with different pace.

[1] https://www.atsenergo.ru/nreport?access=public&region=eur&rname=trade_zsp

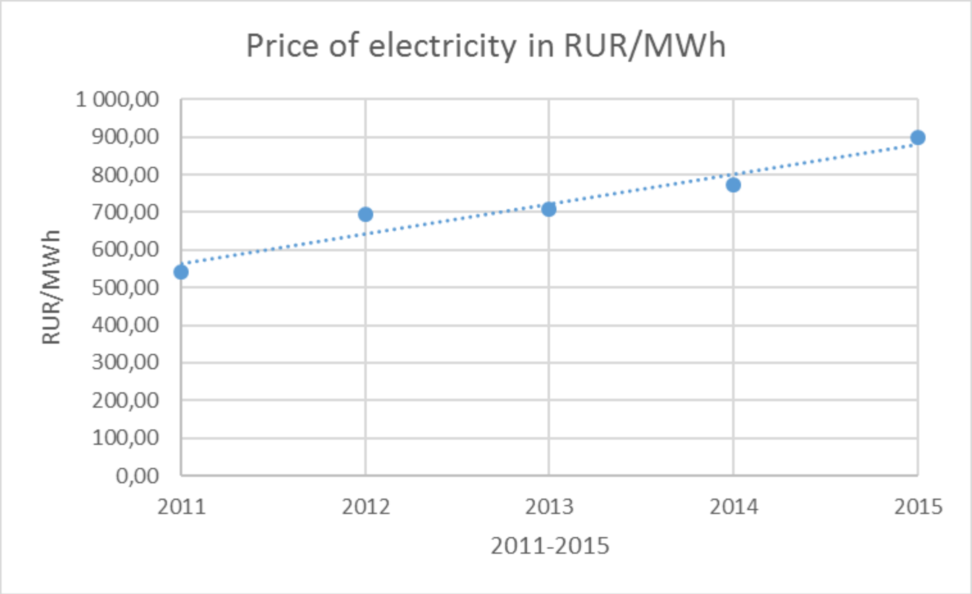

Figure 15 Price of electricity in price zone 2

It is obvious from data presented in figure above, that price of electricity is rising constantly. For each year starting with 2012, I have calculated electricity rise index as a ratio of price of electricity in given year divided by the price in year before. From those indexes, I have calculated the average rise as a geometric mean:

$$\sqrt[n]{\prod_{1}^{n} i_n} = \sqrt[4]{1{,}28 \cdot 1{,}02 \cdot 1{,}09 \cdot 1{,}16} = 1{,}13 \quad 5.5.$$

For this reason, constant 13 % rise of price of electricity was calculated in this economic evaluation with starting at the price of 897.4 RUB/MWh.

I have chosen rate of discount as 15 %, which seems adequate when considering the fluctuations of it[2].

Price of technology from Fuchun Industry Development company is 51 720 USD. With current exchange rate of 66.34 RUB/USD the price is 3 431 105 RUB. Transportation in this offer was considered only from factory to the port, where it will be loaded aboard of ship. When considering transportation to Russia, better way seems to be using either container shipped by truck or by train. In the letter case, reloading on a truck will be necessary

[2] http://www.tradingeconomics.com/russia/interest-rate

anyway, as municipality Inya is located far from any railway. Price for transport was considered 66 000 rubles. This estimation was based on 12 liter average consumption of tractor truck, 5 500 km distance from factory to the considered location and cost 100 rubles cost of 100 kilometers which seems legitimate, when considering, that diesel price in China, where most of the journey takes place, is 52 rubles.

Import value added tax (VAT) is considered 18 % of the sum of price and transportation. Civil works cost is estimated to 8 108 108 rubles. Operation cost is considered 2 % from the cost of investment and rises by annual inflation rate each year. Depreciation is linear, calculated according to Russian system explained in [3]. Expected lifetime of technology is considered 30 years without any major repairs or reconstructions, apart from normal operation maintenance. Expected lifetime of civil works is 20 years before first reconstruction carried out after 10 years, 15 years after first reconstruction. Second reconstruction is expected after 20 years in operation, which would prolong the lifetime for another 10 years. No subsidies as well as loans were considered.

Earning before tax (EBT) is computed according to this formula:

$$EBT_t = I_t - OC_t - D_t - D_{cw} = 185408 - 75484 - 186201 - 405405 = -481684\ RUB \quad 5.6.$$

Where it is income in year t, OC_t are operation costs in year t, D_t and D_{cw} are depreciation of technology and civil works respectively. Profit tax is calculated as 20 % of EBT, if it is greater than zero. Cash flow was obtained from following formula:

$$CF_t = EBT_t + D_t + D_{cw} - T_t = -481684 + 186201 + 405405 - 0 = 109923\ RUB \quad 5.7.$$

Where T_t is profit tax in year t.

With this data, I have done the following table, which sums it all up. All data is in rubles, unless stated differently.

[3] https://www2.deloitte.com/content/dam/Deloitte/ru/Documents/tax/doing-business-in-Russia-2015.pdf

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
income	185408	210393	238746	270920	307430	348860	395873	449221	509759	578455
operation cost	75484	83033	91336	100470	110517	121568	133725	147098	161807	177988
Depreciation technology	186201	114370	114370	114370	114370	114370	114370	114370	114370	114370
Depreciation civil works	405405	405405	405405	405405	405405	405405	405405	405405	405405	405405
reconstruction										500000
EBIT	-481684	-392415	-372365	-349325	-322862	-292484	-257628	-217652	-171824	-119309
Profit tax 20%										
CF	109923	127361	147410	170451	196913	227291	262147	302123	347951	-99533
Year	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
income	656408	744867	845246	959153	1088410	1235086	1401529	1590401	1804726	2047934
operation cost	195787	215366	236902	260592	286652	315317	346848	381533	419686	461655
Depreciation technology	114370	114370	114370	114370	114370	114370	114370	114370	114370	114370
Depreciation civil works	303604	303604	303604	303604	303604	303604	303604	303604	303604	303604
reconstruction										609497
EBIT	42648	111528	190371	280587	383785	501796	636707	790894	967066	1168305
Profit tax 20%	8530	22306	38074	56117	76757	100359	127341	158179	193413	233661
CF	452092	507196	570270	642444	725002	819411	927339	1050689	1191626	743121
Year	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**
income	2323917	2637092	2992471	3395742	3853357	4372642	4961907	5630582	6389369	7250411
operation cost	507821	558603	614463	675909	743500	817850	899635	989599	1088559	1197415
Depreciation technology	114370	114370	114370	114370	114370	114370	114370	114370	114370	114370
Depreciation civil works	212752	212752	212752	212752	212752	212752	212752	212752	212752	212752
reconstruction										
EBIT	1488975	1751368	2050886	2392711	2782736	3227670	3735150	4313862	4973688	5725875
Profit tax 20%	297795	350274	410177	478542	556547	645534	747030	862772	994738	1145175
CF	1518302	1728216	1967831	2241290	2553310	2909258	3315242	3778211	4306072	4907821

Table 14 Economic parameters of project in municipality Inya

Net present value of the project is -11 214 959 rubles. As it is negative, project is not economically advantageous with given parameters.

If the price of electricity rose to the level of 1177 RUB/MWh, the project would become attractive, as it is the value of minimum cost of production. The value of internal rate of return criterion is 4.72 %.

I will discuss sensitivity to chosen parameters in following chapter.

5.4.1. Sensitivity analysis of project in Inya

This chapter will analyze project susceptibility to the price of electricity as well as its development over the comparison period, influence of inflation rate, variance of operational costs, annual production and price of reconstructions.

The most important is price of electricity and its development throughout the calculated period of 30 years. As it is impossible to predict exact development, sensitivity analysis must be carried out to show the influence of different scenarios. Results of the criterion of net present value for different starting prices in year 2017 and different annual development, which is constant for 30 years is in the following table.

NPV [thousands of RUB]		annual rise o price					
		-10%	0%	10%	20%	30%	40%
2017 price of electricity [RUB/MWh]	500	- 14 707 ⍰	- 14 440 ⍰	- 13 537 ⍰	- 9 706 ⍰	13 522 ⍰	169 107 ⍰
	750	- 14 577 ⍰	- 14 177 ⍰	- 12 844 ⍰	- 7 208 ⍰	27 554 ⍰	260 884 ⍰
	1000	- 14 447 ⍰	- 13 913 ⍰	- 12 172 ⍰	- 4 738 ⍰	41 560 ⍰	352 636 ⍰
	1250	- 14 317 ⍰	- 13 650 ⍰	- 11 521 ⍰	- 2 289 ⍰	55 548 ⍰	444 369 ⍰
	1500	- 14 188 ⍰	- 13 387 ⍰	- 10 880 ⍰	146 ⍰	69 522 ⍰	536 093 ⍰

Table 15 Sensitivity analysis of project in Inya to price of electricity and its development

As we can see from the table above, project becomes advantageous with starting price of electricity at 1500 RUB and its annual rise by 20 %. For lower starting prices, it becomes favorable with higher rise pace.

The influence of inflation rate in range between 0 and 25 % is evaluated in following table.

inflation rate	0	5%	10%	15%	20%	25%
NPV [thousands of RUB]	- 10 646 ⍰	- 10 842 ⍰	- 11 215 ⍰	- 12 006 ⍰	- 14 100 ⍰	- 19 449 ⍰

Table 16 Influence of inflation between 0 % and 25 % on net present value of the project

Rise of the inflation rate by 5 % decreases the value of net present value by 7 %, where lowering of inflation rate by 5 % from the expected value causes rise of the criterion by 3.3 %.

Operation costs were approximated as 2 % of the investment to the technology. Following sensitivity analysis studies the impact of variance of this parameter.

operation cost	0,50%	1%	1,50%	2%	2,50%	3%
NPV [thousands of RUB]	- 10 467 ▯	- 10 716 ▯	- 10 966 ▯	- 11 215 ▯	- 11 465 ▯	- 11 716 ▯

Table 17 Influence of variance of operationg costs on net present value of project

Decrease of operation costs by 1.5 % induces the rise of NPV criterion by 6.7 % where rise of operation costs by 1 % lowers the value by further 4.5 %.

Varying weather may have significant impact on production of electrical energy. I have studied the impact of production in the range between 50 % and 150 % of the expected annual production of electricity.

percentage of annual production	50%	75%	100%	125%	150%
considered annual production [kWh]	80221	120331	160442	200552	240663
NPV [thousands of RUB]	- 13 015 ▯	- 12 102 ▯	- 11 215 ▯	- 10 338 ▯	- 9 471 ▯

Table 18 Influence of production variance in range between 50 % and 150 % of expected annual production

Decrease of the production due to any reason lowers the net present value by further 1 800 000 RUB where production 50 % higher causes rise of NPV by 1 744 000 RUB.

From all above stated only extremely high pace of rise of price of electricity throughout next 30 years could change the decision from do not execute the project to execute the project. Nevertheless, it is highly unlikely to be so.

5.5. Economic evaluation of project in locality Josefův Důl

Economic evaluation is the inherent part of all feasibility studies nowadays. Economic evaluation will be carried out according to the Czech accounting principles.

To begin with, price of all the technical equipment (in USD) will be repeated once again in following table:

Turbine	Generator	Excitation system	Governor	Gate valve	General control panel	DC panel
35270	13950	3280	20520	8330	19380	1540

Transportation to the nearest port in China would cost additional 2030 $. All the values were determined from the offer sent by manufacturer. With the exchange rate of 24.5 USD/CZK, which is the mean value of exchange rate of the past year[4], the price of technology in Czech Koruna is 2 555 350. Price of transportation of a container from China to the Czech Republic is somewhere between 2000 and 3000 USD[5]. Higher price was used in calculation and corresponds to 73 500 CZK with given exchange rate.

Import of such a costly equipment will impose the payment of import VAT, which is determined from the sum of price and transportation and is set as 21 %, which in this case corresponds to 552 059 CZK. Payment of customs duty is also obligatory in height of 15 % of sum of price of goods and transportation, which represents 394 328 CZK. Investment in civil works was estimated as 7 500 000 CZK.

Giving any estimations on market price of electrical energy in Europe is quite hard, as the market is distorted due to the subsidies to the renewable energy sources in different countries. According to the data from Power Exchange Central Europe website the best bid for futures in base load for the fourth quarter of 2016 it is 26.75 EUR/MWh, for 2017 it is 24.85 EUR/MWh and for the year 2018 23.95 EUR/MWh. (13) The price is decreasing yet it is expected that today's values will be probably very close to the bottom. To reduce the risk of overestimated price of electricity for the evaluation I will use the prices for 2017 and 2018 from the PXE, for 2019, I expect stagnation on the same level as in 2018 and since 2020 annual rise by 0.5 %. Yearly electricity generation is 1 815 MWh.

Operation costs were estimated as 2 % from the cost of technology and rises by annual inflation of 1 %. Although the inflation target of the Czech National Bank is 2 % annually, in last two years, after the Czech economic system recovered from the previous depression, the inflation rates have not exceeded 0.8 %[6]. Estimation of yearly 1 % rise in operation costs seems to be a little pessimist, yet better not to underestimate it.

[4] Source: http://www.kurzy.cz/kurzy-men/grafy/CZK-USD/
[5] Source: http://www.euro.cz/byznys/na-kolik-vas-vyjde-dovoz-z-cinyvyplati-se-opatrnost-894849
[6] Source: http://www.kurzy.cz/makroekonomika/inflace/

Depreciation of technology and civil works is carried out according to the Czech accounting principles with linear depreciation rate and half depreciation in the first year. The depreciation period of technology is set to be 20 years, as it falls into the fourth group. Civil works fall into the fifth group with depreciation period of 30 years.

After 10 years of operation a reconstruction is calculated with estimated price of 500 00 CZK, which is mainly considered to repair any wear of the civil works. After 20 years, another reconstruction will be held. Price is estimated as 609 497 CZK, which is 500 000 CZK and rises by 2 % annually.

From those estimations, EBT was calculated.

$$EBT_t = I_t - OC_t - D_t - D_{cw} = 1217991 - 51107 - 76868 - 105000 = 985017\ CZK \quad 5.8.$$

Where it is income in year t, OC_t are operation costs in year t, D_t and D_{cw} are depreciation of technology and civil works respectively. Profit tax in the Czech Republic is set as 15 % for physical person and 19 % for juridical persons. The letter value was used for calculations. Cash flow was computed subsequently:

$$CF_t = EBT_t + D_t + D_{cw} - T_t = 985017 + 76868 + 105000 - 187153 = 979731\ CZK \quad 5.9.$$

Where T_t is profit tax in year t.

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
income	1078302	1079381	1080460	1081540	1082622	1083705	1084788	1085873	1086959	816034
operation cost	50277	50780	51287	51800	52318	52841	53370	53903	54443	54987
Depreciation technology	76868	184125	184125	184125	184125	184125	184125	184125	184125	184125
Depreciation civil works	105000	255000	255000	255000	255000	255000	255000	255000	255000	255000
reconstruction										500000
EBIT	846158	589476	590048	590616	591179	591738	592294	592845	593392	321923
Profit tax 20%	160770	112001	112109	112217	112324	112430	112536	112641	112744	61165
CF	867255	916600	917063	917523	917980	918433	918883	919329	919772	699882
Year	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
income	1089134	1090223	1091313	1092405	1093497	1094590	1095685	1096781	1097878	824232
operation cost	55537	56092	56653	57220	57792	58370	58953	59543	60138	60740
Depreciation technology	184125	184125	184125	184125	184125	184125	184125	184125	184125	184125
Depreciation civil works	272000	272000	272000	272000	272000	272000	272000	272000	272000	272000
reconstruction										609497
EBIT	577472	578006	578535	579060	579580	580096	580607	581113	581614	307367
Profit tax 20%	109720	109821	109922	110021	110120	110218	110315	110411	110507	58400
CF	923877	924310	924738	925163	925585	926002	926416	926826	927232	705092
Year	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**
income	1100074	1101174	1102276	1103378	1104481	1105586	1106691	1107798	1108906	1110015
operation cost	61347	61961	62580	63206	63838	64477	65121	65772	66430	67095
Depreciation technology										
Depreciation civil works	292723	292723	292723	292723	292723	292723	292723	292723	292723	292723
reconstruction										
EBIT	746004	746491	746972	747449	747920	748386	748847	749303	749753	1312465
Profit tax 20%	141741	141833	141925	142015	142105	142193	142281	142368	142453	249368
CF	896986	897381	897771	898157	898538	898916	899289	899658	900023	1355820

Table 19 Economic parameters of project in municipality Josefův Důl on Kamenice creek

Net present value of the project was calculated according to following formula:

$$NPV = \sum_{t=1}^{T_l} \frac{CF_t}{(1+r)^t} \qquad [CZK] \qquad 5.10.$$

Where T_l is the lifetime of project and r is the discount rate.

The net present value of the project with discount rate of 6.725 % is 1 631 876 CZK. Internal rate of return is 8.1 %.

5.5.1. Sensitivity analysis of project in Josefův Důl

I will consider susceptibility to the same parameters as were considered for Inya. The first analysis will be studying impact of variance of electricity price and its development. Considered price at the beginning of project is in between 270 and 1650 CZK/MWh, which is 10 to 60 EUR/MWh.

NPV [thousands of CZK]		annual rise o price				
		-5,0%	-2,5%	0,0%	2,5%	5,0%
2017 price of electricity [CZK/MWh]	270	-2 997 Kč	-1 509 Kč	568 Kč	3 544 Kč	7 891 Kč
	540	-2 625 Kč	-1 137 Kč	940 Kč	3 916 Kč	8 263 Kč
	810	-2 253 Kč	-765 Kč	1 312 Kč	4 288 Kč	8 635 Kč
	1080	-1 881 Kč	-393 Kč	1 684 Kč	4 660 Kč	9 007 Kč
	1350	-1 509 Kč	-21 Kč	2 056 Kč	5 032 Kč	9 379 Kč
	1620	-1 137 Kč	351 Kč	2 428 Kč	5 404 Kč	9 751 Kč

Table 20 Sensitivity analysis of influence of electricity price and development variation

As we can see from the table project is highly susceptible to the variation of price and development variation. If the price will keep its decreasing trend, it will make the project disadvantageous. However, stagnation or rise is more likely in upcoming years, so the project will be probably expedient. Inflation rate will be studied next.

inflation rate	-1%	0%	1%	2%	3%	4%
NPV [thousands of CZK]	1 737 Kč	1 688 Kč	1 632 Kč	1 566 Kč	1 488 Kč	1 397 Kč

Table 21 Influence of the inflation on project

If the inflation dropped by 2 % from expected value, it would rise the NPV by 6.4 %. On the other hand, if it rises by 2 %, it will cause decrease in NPV by 8.2 %. Analysis on operation costs follows.

operation cost	0,50%	1%	1,50%	2%	2,50%	3%
NPV [thousands of CZK]	2 070 Kč	1 924 Kč	1 778 Kč	1 632 Kč	1 486 Kč	1 339 Kč

Table 22 Influence of operation cost's value expressed as ratio to the technology investment

If operation costs were only half the expected height, it would rise the net present value of project by 18 %, where on the opposite side when increased by one half, it would make decrease of NPV of 18 %. Variation of annual production will be studied next.

percentage of annual production	50%	75%	100%	125%	150%
considered annual production [kWh]	907662	1361493	1815324	2269154	2722985
NPV [thousands of CZK]	- 4 707 Kč	- 1 537 Kč	1 632 Kč	4 801 Kč	7 970 Kč

Table 23 Sensitivity to the annual production analysis

Annual production of electricity is the main source of income. If it decreased by 25 %, it will make the project disadvantageous. The margin is probably somewhere around 87 % of expected annual production. On the opposite hand increase by one half results in almost five times higher NPV.

price of reconstruction [CZK]	250000	500000	750000	1000000	1250000	1500000
NPV [thousands of CZK]	1 800 Kč	1 632 Kč	1 464 Kč	1 296 Kč	1 128 Kč	960 Kč

Table 24 Influence of variation of price for reconstruction on the net present value of project

If the price of reconstruction would be half, the increase in value of NPV is 10.3 %. On the other hand, if it would be twice the expected value, it would decrease the value of NPV by 20.6 %.

As obvious from above stated, only extreme sudden changes in combination with long term unfavorable development would make the project not expedient. Nevertheless, this development is highly unlikely to happen.

6. Environmental impact of small hydropower scheme

Environmental impact assessment (EIA) is one of the parts of projects, which were earlier omitted, but nowadays they became inherent part of most of projects, where nature is affected. In Europe EIA may be the documentation which decides, whether the project will or will not be executed, because nature protection is in the first place nowadays. It is understandable because everything on the planet Earth is interconnected through very complex relationships. Thus, insensitive interventions may have far-reaching impact on close as well as far surroundings.

A universal answer cannot be given, regarding the question, what should we do to avoid any impact. Generally said there is always a significant impact on the biota at the site, but we must keep looking for the solutions that have the least possible impact. Of course, solution, which works for a site located high in the mountains, will certainly not work in case of a small hydropower plant located in the lowlands. So individual approach to the problems is the key.

When considering the impact of a hydropower station on surroundings, various aspects and full life cycle of power station should be considered. The most obvious impacts are deforestation, construction of conveyance systems that has usually significant impact on the landscape, pollution and noise. Nevertheless, some less noticeable phenomena are also affected or hindered, such as natural hydrologic cycle, which is in relation with agriculture, migration of different species and its breeding. Those aspects will be considered in the following paragraphs.

At the early stage, when a hydropower plant is being designed and constructed, major decision have to be taken. Regarding the design, an important role plays the setting in the nature and design of the powerhouse itself. Small hydropower plant, as well as other power stations, should not disrupt the overall appearance of the landscape. If there is a possibility to put at least part of the technology underground or partly bury it in the hillside, it is recommended to do so. As a bonus, which comes with such construction is that ground is a good soundproofing material, so that less noise pollution will be outside of the plant.

Another point when considering the design is construction of conveyance system and penstocks. If it is possible, it is better to bury such constructions underground as well, so it does not obstruct animals and people from passing through. It is quite easy to bury iron penstocks underground. For open surface canals and such good idea is to cover it at least with prefabricated concrete blocks and a possibly a bit of soil, so that flowers may grow atop. Another positive impact is reduced possibility of unintentional material (i.e. leafs, stones, tree branches or even whole trees, not to forget fauna also) entering the conveyance system after it has been cleaned by the trashracks.

Safety equipment should be also present at the open surface reservoirs and channels as some people may see an opportunity in having a refreshing swim in the artificial reservoir, but overlook the danger of being sucked into the system by strong flow near the intake.

At the early stage of construction, a lot of transportation is necessary which rises the noise in location and the pollution with dust in dry environments and exhaust gases. Excessive transportation also makes the construction more costly. For this reason, using local materials is good choice to reduce transportation to the minimum. For example if excavation is needed at the penstocks, unnecessary material can be used for flattening the area for foundations of powerhouse.

In most cases a deforestation is necessary to obtain are for big enough for construction of hydropower scheme. Nevertheless, it should be done in the minimum acceptable way, as it changes the overall appearance of the landscape. However, the impact is not limited to the appearance. Deforested areas are more prone to erosion by wind and water. In addition, trees retain water in the environment. Deforested areas are more prone to flash floods in case of huge storms or long lasting excessive rain periods.

Construction of hydropower plant causes huge alternations in the river cycle. Rivers without any constructions on it have its own year cycle, which depends on the location and drainage basin. For rivers which drainage area consists of high alpine terrain the highest flow occur from late spring throughout the summer when it reaches maximum and start to decrease in autumn. The lowest water levels are in winter when rivers freeze.

For rivers, which drainage area consists of smaller hills the highest flows appears during spring snowmelt and then it settles down. After the snowmelt has finished, these rivers are entirely reliant on precipitation, which brings the water in the drainage area. Long-term rainy periods rise the water levels significantly for longer term while summer storms with heavy rain may cause flash rise in the water level, which usually does not last for long. However, this is dependent also on the ground saturation with water. After a long dry period, even longer rainy period may not rise the levels significantly.

When a small hydropower station is built on the river, water is diverted from the riverbed, if it is not a run of river scheme located at a weir. In this particular stretch of river, where water is diverted, this natural fluctuation is interrupted, which causes changes to the organisms dependent on the water source. Sudden rise of the water has the ability to flush the riverbed and debris, which has fallen into it, is being transported down the river. Organic material forms humus that makes the soil fertile again. Some civilizations in the past were highly dependent on fertilization of soils by annual floods. When water regulations started and floods were no longer present, soil nutrients have been depleted over several years.

Enough water must be left in the riverbed to allow fish to migrate. Dams and weir are often unsurpassable barriers for fish, in case they are not equipped with fish ladders. Some of the fish like salmon for example, live in the sea, but breed in the upper sections of the rivers. However, not only fish live in the rivers. Many other species of animals and insects are bound to water source.

With lower discharge in the natural riverbed the concentration of oxygen in the water changes, which again is of a huge importance to fish.

Construction of a dam or weir also increases sedimentation in reservoir upstream, which prevents the material against being transported downstream of construction. That may cause lack of material and thus new one being carried away by increased erosion.

When in service many possible water pollutants are used to maintain the right service of the equipment. Lubricants used to decrease friction in bearings are of good example. If they leak into the water, if they are based on oil, they make a film on the water, which prevents oxygen from entering the water and thus kills water wild life. Flowers may also be negatively influenced. If the hydropower plant has generator operating on different voltage level than network it is working to, transformers are being used to change the voltage level. Transformers are mostly submerged in special oil, which is highly flammable and toxic. For this reason, special water treatment systems should be present.

Turbines and generators spinning in rapid manner are source of noise and vibrations. Wild life is usually highly susceptible to the noise pollution. As was mentioned before, partly or fully underground variants are of great advantage however, they make the construction more costly. In most cases, in order to satisfy laws about nature protection, soundproofing materials as well as vibration dumping devices have to be used.

Large reservoirs induce great powers in the ground, which may lead to the changes in the geomorphology of surrounding area. As a result landslides may occur. In addition, fogs are about to be present more often. However, this is the case of large structures only.

However, not only nature is affected by such constructions. Social and economic impacts should be carefully studied. If construction induces forced relocation of people, or flooding of private property, proportionate compensations should be made. In this case, not only market value should be considered, but also personal relations.

Building of such structures is also questionable in locations, where archeological or historic heritage is in risk. We should conserve such monuments for future generations.

It is also questionable to dam a river, if the river is the main source of livelihood for surrounding area. It is not only limited to fishing and agriculture, which may be the main sources of food, but also to the exploitation as a tourist attraction. If the river is used for recreational purposes, such as rafting, fishing, canoeing, hiking, canyoning etc. If such activities are the main source of living for local people, or they bring non-negligible amount of money into the area, then a construction of hydropower plant is questionable, because small hydropower schemes do not need many personnel to stay in operation. Construction of such ecologically friendly technology without considering such impacts may rise the unemployment in the area.

7. Conclusion

The aim of this work was to sum up information about small hydropower plants. I have started this work with a sum up of renewable energy sources and description of their operation. Then I have buried a little deeper into the theory behind hydropower schemes and its operation.

Part about hydropower plants starts with distinction of types of schemes. It is of great importance to know the type of scheme, as it has great influence on operation and design of power station. Moreover, each location is specific, which induces that different schemes may have different results. Optimal solution should be carefully chosen.

Hydropower principles were discussed in the next part. Principle of energy conversion for steady flow was discussed. Net head was explained. Simply said it is the head is equal to the head, which would make produce the same power without any losses. Along with the flow duration curve the net head is used for determination of the most efficient solution for target location.

Following chapters were dealing with the civil works essential for small hydropower schemes, which are in most cases dams and weir, water intakes with all the associated parts, such as trashracks, sediment traps and gates, channels and overall conveyance system including the tailrace.

After the civil works description I have described electromechanical equipment. Mentioned and described were all types of hydraulic turbines including similarity laws and specific speed, which is later used for determination of the best type of turbine for chosen locations. From electrical equipment generators, speed increasers and control systems with switchgear are discussed. Next is a little insight into economy of construction and operation.

In the two case studies, I have calculated construction of small hydropower schemes in Josefův Důl, north part of the Czech Republic and in Inya, Altai Republic, Russian Federation. In both cases, the procedure was the same. I have calculated the energy consumption of both cities according to the statistical data available. Minimum daily load in Inya should be about 200 kW in summer. Maximum should be about 1400 kW in winter.

Through municipality Inya flows creek with the same name. Due to the similarity with river Ursul, I have estimated the flow duration curve according to this river with accommodation to different area and drainage basin. Reserved flow is counted as 0.07 m^3/s.

The net head of location is estimated to be 21.6 meters and design flow is 0.315 m^3/s. This flow was chosen for the fact, that it had the highest product of discharge and its duration. Specific speed for the rotational speed of generator of 750 revolutions per minute is 0.126. This value falls into the range of Francis turbine.

As the equipment supplier, I have chosen Fuchun Industry Development co., ltd based in Shenzhen, China. Turbine closest to the desired parameters was Francis turbine with rated flow of 0.2 m^3/s and runner diameter of 0.4 meter with nominal rotational speed 750 revolutions per minute. With the use of this turbine, a speed increaser becomes obsolete.

Generator is of synchronous type with output power of 30 kW and rated voltage of 400 V. Thus, outlet transformer is unnecessary. Control equipment and circuit breakers are also provided by this manufacturer.

According to hydrologic data and characteristics of Francis turbine, the annual production of this scheme will be 160 442 kWh.

With a 2 % operational costs, 15 % discount rate and inflation of 10 % with annual 13 % rise in the price of electricity and operation costs rising by inflation yearly, the net present value of the project is -11 214 959 rubles, which means it is not economically favorable.

The results of sensitivity analysis show, that only growth of the prices of electricity over 20 % could make it feasible. Other parameters including annual production in volume of 150 % of expected would not make it advantageous.

For Josefův Důl the calculations went in a similar way. However, as it is a bit bigger, power demand varies from Inya. Minimum power demand is about 647 kW in summer nights and highest is Just above 4500 kW in winter evening peak.

Hydrologic data for chosen location were acquired from the Czech Hydrometeorological Institute. Minimum reserved flow is 0.099 m^3/s.

As the net head is about 90 meters and design flow, which was determined the same way as in case of Inya, is 0.382 m^3/s. The specific speed is 0.0636, which is on the border between Pelton wheel and Francis turbine. This area is more efficiently covered by Turgo turbine, which was chosen.

The rated head of Turgo turbine from the same manufacturer as before is 92 meters and rated flow is 0.371 m^3/s with rotational speed of 1000 revolutions per minute. As the rotational speed of chosen synchronous generator is the same, no speed increaser is needed. Chosen generator is of synchronous type and output power of 250 kW at nominal discharge. Rated voltage is 400 V and frequency 50 Hz. With this voltage, it can be connected straight to the distribution network without usage of outlet transformer.

As the nominal power of generator is lower than minimum power consumption, no special regulation systems are necessary.

According to hydrologic data and equipment parameters the annual energy production is 1 815 324 kWh. The net present value of this project is 1 631 867 CZK with discount rate of 6.725 %, inflation rate 1 % and operation costs of 2 % of technology price.

Sensitivity analysis suggests, that only long term lowering trend of price of electricity could make the project possibly disadvantageous.

To conclude this thesis, small hydropower plants are one of the best ways to stable energy production over a long period of time. However, severe droughts in certain parts of world may make those projects unfeasible, or disadvantageous. Thus, thorough evaluation of each site should be carried out before the beginning of any construction, or even planning.

References

1. **Ghosal, M and Tiwari, G.** *Fundamentals of renewable energy sources.* Oxford : Alpha Science International, 2007.

2. **Surkov, M. A. a Lukutin, B. V.** *Alternative power sources.* Tomsk : Tomsk Polytechnic University Publishing House, 2013.

3. **Ясинский, В. А., Мироненков, А. П. а Сарсембеков, Т. Т.** *Современное состояние и перспективы развития малой гидроэнергетики в странах СНГ.* Алматы : Евразийский банк развития, 2011.

4. **Ramos, Helena, and others.** *Guideline for Design of Small Hydropower Plants.* Belfast : Western Regional Energy Agency & Network, 2000.

5. **European Small Hydropower Association.** *Guide on How to Develop a Small Hydropower plant.* [Document] 2004.

6. **Bouška, Jan, Knížek, Petr and Kašpar, Josef.** *Sborník technických řešení malých vodních elektráren.* Praha, Czech Republic : s.n., October 31., 2000.

7. **Ministry of Industry and Trade of the Czech Republic.** *Akutalizace státní energetické koncepce České republiky.* Praha, Česká republika : anonymous author, February 2010.

8. **Energy Regulatory Office, Department of Statistics and Quality Control.** *Roční zpráva o provozu ES ČR.* Praha, Czech Republic : anonymous author, 2015.

9. **Будзко, И. А., Лещинская, Т. Б. а Сукманов, В. И.** *Электроснабжение сельского хозяйства.* Moscow : Колос, 2000.

10. **Гельман, Г. А., Карлов, Г. С. а Крючков, В. В.** *Проектирование электроустановок квартир с улученной планировкой и коттеджей (на базе электрооборудования компании Schneider Electric).* 2007.

11. **Суменов, В. А., [editor].** *Ресурсы поверхностных вод СССР - Алтай и Западная Сибир.* 1. Ленинград : Гидрометеорологическое издательство, 1969.

12. **Anonymus.** Fuchun Industry Development Company., Ltd. [Online] [Cited: 2. May 2016.] http://www.fuchunind.com/product_show.asp?bid=134&tid=134&id=75.

13. **Power Exchange Central Europe.** [Online] [Cited: 3. May 2016.] http://www.pxe.cz/On-Line/Futures/?language=czech.

14. **Anonymus. Краткая характеристика крупнейших гидроэлектростанций (ГЭС) России.** *Рейтинговое Агентство "Эксперт РА" (RAEX).* [Online] 13.. 4. 2015. http://www.raexpert.ru/researches/energy/electric/part_2_3.

15. **Ministry of Industry and Trade of the Czech Republic.** *Státní energetická koncepce.* Praha, Czech Republic : s.n., December 2014.

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