Optimization of the pipeline diameter for a small hydropower plant: case study

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Abstract
The goal of the paper is to find the optimal diameter and pipeline material for a small hydropower plant (SHPP) Kašići on the Jošanica river. The SHPP has nominal flowrate of 5.65 m^3/s, the head 37.76 m and the total pipeline length 3000 m. The SHPP should be functioning as the second plant in a cascade system when the above SHPP Belci has extremely low flowrates, below 17% of the nominal. During these flowrates the existing turbine in the SHPP Belci has low efficiency, which is improved by bypassing SHPP Belci and implementing two turbines in the SHPP Kašići. One of these turbines is used for low flowrates during which maximal gauge static pressure in the penstock rises from 3.776 bar to 7.23 bar. Based on the known pipeline routing and probability of the river flowrates, friction factors for different pipe materials, total pressure drop, and total electricity production were calculated. Steel, polyester (fiberglass), polyvinyl, and wood were the analyzed pipeline materials. The net present value (NPV), which was calculated as the ratio between the profit from electricity selling and the penstock investment, was used as the selection criterion for optimal diameter. The optimal is steel pipeline with the inner diameters of 1800 mm. The difference between the NPV's for two optimal solutions for the analyzed period of 12 years, which is the period of validity for incentive measures for power production from renewable resources in the Republic of Serbia, is less than 0.02%.

Keywords: pipeline, small hydropower plant, optimal diameter, net present value.

1. Introduction

The implementation of feed-in tariffs in Serbia [1] has led to the build-up of numerous electric and cogeneration facilities that use renewable energy sources. Micro and small hydropower plants (SHPP) have large share in these activities as 44 plants have been constructed [2]. The specific investment cost of these plants is in the range from 1000 to 2000 € per kW of installed power and depends on: water flow, the ratio between total head and the distance between water intake and power house, accessibility of the terrain, the composition of soil where buried pipelines are used, pipeline material, the type of water intake, the quality of installed equipment, conditions for the connection to the national power grid, and the cost of resolving property relations.
The goal of the paper is to find the optimal material and pipeline diameter for SHPP Kašići on the Jošanica river based on the given routing and flow-duration curve. This is a specific case but the performed analysis is general and could be implemented in every hydropower project. The SHPP Kašići has nominal flowrate of 5.65 m^3/s, head of 37.76 m and the total pipeline length of 3000 m. The SHPP should be functioning as the second plant in a cascade system. Figure 1-b shows the

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basic technical characteristics and the layout of this system. When the above SHPP Belci has extremely low flowrates, below 17% of the nominal, its existing crossflow turbine has very low efficiency (see Fig. 1-a)). This problem should be solved in the new SHPP Kašići by implementing two turbines, one of which would be used for low flow rates. During these flows, water should be bypassing SHPP Belci, which would be out of function, and as a consequence, the maximal gauge static pressure in the designed penstock would rise from 3.776 bar to 7.23 bar. It must be stressed that draughts, which have been causing low flow rates, have been very common and unusually long during the period 2011-2013 and 2015 (see [3]). The basic characteristics of different pipelines, the methodology for calculation of head loss and SHPP productivity, and the selection of optimal pipeline diameter based on the net present value (NPV) of the investment are given in the remainder of the paper.

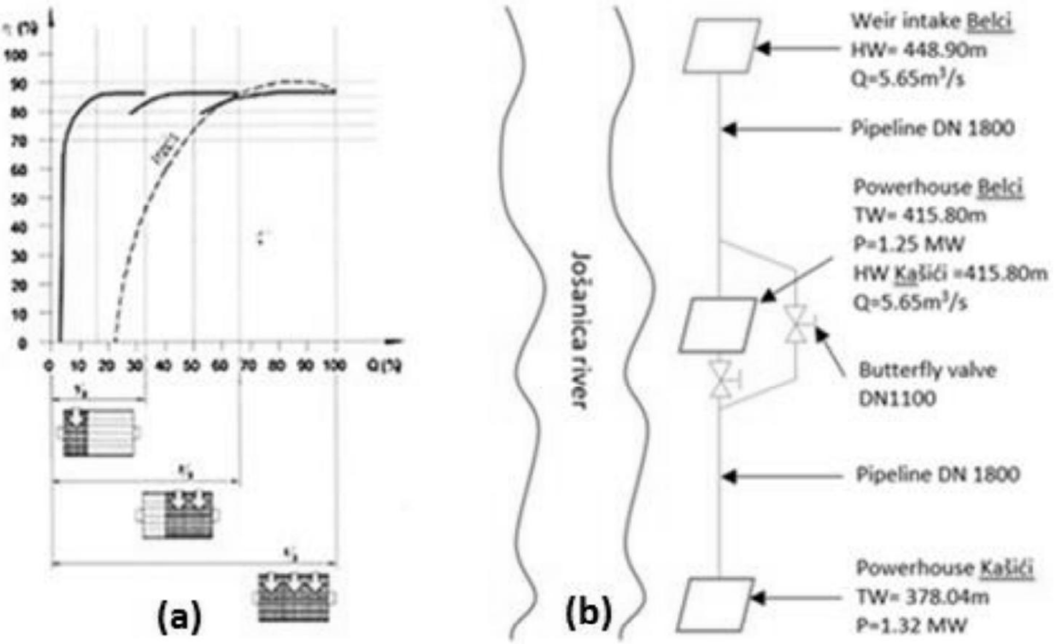

Figure 1. HW – Head water, TW – Tail water, Q – Flow,

2. Small hydropower pipe systems

The first SHPP had economically the best ratio between water flow and total vertical drop. The vast majority of them for the connection of intake weir and power house used an open channel and a penstock. The open channel is usually built of concrete, has a small vertical drop (in the range 1-3%), and nearly goes over the contour line that connects the intake weir and a forebay tank. The penstock allows water flow from a forebay tank to power house [4]. The other type of SHPPs has a pipeline, which usually follows the riverbed. These pipelines are both buried or above the ground, usually built of steel or polyester pipes. However, there are pipelines made of concrete and wood staves [5-7]. Regardless of the pipe material, almost all manufacturers produce standard fittings and support parts.

Wood stave pipeline is an old, proven technology, which has been commercially used for more than 125 years [5], initially for oil transport at distances less than 8 km. The support system for the pipeline is a wooden cradle (see Fig. 2), which is also assembled on site, eliminating the need for expensive concrete supports. Figure 3 shows the assembling process by the use of grooves in standard wooden parts. The top half of the pipe is then built on top of a moveable building form. Steel bands encircle the pipe and the building form is then moved along as the process repeats itself [5] (see Fig. 2 and 3).

Compared to other types of pipelines, there are several factors that make wood stave pipe more economical. The first one is foundation/burial savings, no thrust blocks. Number two is the fact that expansion joints are not required. Compared to other types of pipe materials, the shipping cost for wood stave pipes to the installation site is usually cheaper. These pipes can go in diameter up to 5.5 m and are used for total vertical drops of up to 120 m. The wood stave pipes have been in proven service for 40, 50 and more years [5]. The wood absorbs the water and expands against the steel restraining bands, creating a watertight pipeline. Wood's natural insulation eliminates the need to clad or bury the pipeline to combat temperature changes.

Figure 2. Wood stave pipeline: left in a trench and right above the ground.

Figure 3. The assembling process for wood stave pipeline.

Steel pipelines consist of prefabricated segments and standard fittings welded together at the installation site. Standard diameters go up to 3.6 m. The standard segments are usually 6 to 12 m long, with segments of 1,2, and 3 m. Table 1 [8] shows basic technical characteristics of steel pipes. The increase in pipe diameter makes more expensive production, transport, and mounting, which requires the use of heavy machinery, skilled workers, greater excavation volumes etc. Their large mass per unit length is the other drawback in comparison with other materials. During the transport, the rise in diameter increases the risk of deformation, which can hinder the pipeline assembling. The pipelines placed above the ground use steel clamps to fix them to the concrete support, which distance the pipes from the ground, and facilitate maintenance and control. For buried installations, different types of paints and coating s (e.g., plastic tape coats) have been used for more than 60 years and have demonstrated long service lives [9]. Comparing to other types, the steel pipelines have the advantage in pressurized systems.

Table 1. Basic characteristics of steel pipes [8].

Nominal diameter [DN]	150-3600 mm
Nominal pressure [PN]	1-32 bar
Nominal stiffness [SN]	630-1000000 N/m^2
Standard products	Pipes, Joints, Fittings, Accessories, Angular cut systems

Polyester pipe is a product of a machine for continuous filament winding and is usually called GRP, FRP or fiberglass pipe [10]. Combing a glass fiber, thermo-stable resin and special fillers in the appropriate ratio it is possible to produce the pipes with a wide range of mechanical and chemical properties. Table 2 shows mechanical, physical, and chemical properties of these pipes. The standard diameters typically range to 3.6 m and are used for pressures of up to 10 bar. There are polyester pipes that can withstand even larger pressures. The standard segments are 6 and 12 m in length, with smooth surfaces (see Table 2), and are coupled by the use of double muffs and rubber gaskets. Compared to the steel, polyester pipes have smaller transport costs due to its smaller mass.

Table 2. Mechanical, physical, and chemical characteristics of polyester pipes [7].

Density	(1800-2100) kg/m^3
Elasticity module	(6-24) GPa
Circumferential elasticity module-tensile and bending	17 000MPa – cevi niskog pritiska 24 000 MPa – cevi visokog pritiska
Tensile strength axial	(6000-12 500) MPa
Bending strength circumferential	(130-700) MPa
Elongation to break	(30-60) MPa
Linear spreading coefficient	140-500 MPa
Max. temperature of transported media	1,5-2,0 %
Temperature conductibility coefficient	24-30·10^{-6} 1/°C
Thermal conductivity	0,14-0,25 W/mK
Absolute roughness	" k" = 0,012 mm

Figure 4. Polyester pipeline with the diameter of 1.8 m on SHPP Belci, on the Jošanica river.

3. Methodology

3.1 Pressure drop

Overall head loss in a pipe consists of the loss in straight sections and local pressure drops [12]:

$$\Delta p = Rl + Z\left[Pa\right], \tag{1}$$

Equation (1) can be written as:

$$\Delta p = \left(\lambda \frac{l}{d} + \sum \xi\right) \frac{\rho_v w^2}{2}\left[Pa\right], \tag{2}$$

If the above equation is devided with the water density $\rho_v \left[\frac{kg}{m^3}\right]$, the total pressure drop can be expressed as a head loss in m [14]:

$$\Delta H = \left(\lambda \frac{l}{d} + \sum \xi\right) \frac{w^2}{2g}\left[m\right], \tag{3}$$

In equations (1-3) λ is friction coefficient, l [m] is the length, and d [m] is the pipe's inner diameter. $\sum \xi$ is the sum of minor pressure drop coefficients. The speed of water is calculated by:

$$w = \frac{Q}{A} = \frac{4Q}{d^2 \pi}\left[\frac{m}{s}\right], \tag{4}$$

where Q [m^3/s] is water flow inside the pipeline.

3.2 Local pressure drop

At the intake screen, by considering the allowable screen clogging, the local pressure drop is:

$$\Delta h_R = \xi_R \frac{w^2}{2g}, \tag{5}$$

where the minor loss coefficient ξ_R [15] is determined by:

$$\xi_R = \beta \sin\alpha \left(\frac{s}{e}\right)^{\frac{4}{3}}$$

In the above equation β - is the parameter that depends on the shape of the screen, α - is the angle of tilt between the screen and the flow; s - is the thickness of lattice in the screen.

The pressure drops at: the entering funnel (towards sand trap) $\Delta h_{ul}\left[m\right]$, bends $\Delta h_{cl}\left[m\right]$, nozzle $\Delta h_{kon}\left[m\right]$, and the butterfly valve in front of the turbine $\Delta h_z\left[m\right]$ are determined by (6), whereas the minor loss coefficients are taken from [11] and [13].

3.3 Power production

The total power production of SHPP is:

$$E = P_G \cdot t\left[MWh\right], \tag{6}$$

where $t\left[h\right]$ - is the total working hours; $P_G\left[MW\right]$ - is the power output of the generator, which is calculated by

$$P_G = Q \cdot H_n \cdot \eta_T \cdot \eta_R \cdot \eta_G \cdot g, \tag{7}$$

where Q - [m^3/s] is water flow; η_T - is the turbine efficiency taken from the manufacturer [2]; η_R - the transmission efficiency [2]; η_G - the generator efficiency [2]; g - is the gravity acceleration, and H_n - [m] the net head.

The net head H_n is calculated by:

$$H_n = H_b - \Delta H\left[m\right], \tag{8}$$

where H_b - is the total head, and ΔH - is the total head loss.

3.4 Net present value

The selection of the optimal diameter is determined based on the maximal NPV for the period of 12 years, which is the period of validity for incentive measures for power production from renewable resources [1]. NPV is calculated by

$$NPV = \sum_{i=1}^{t} \frac{C_i}{\left(1+r\right)^i} - C_0 , \tag{9}$$

where $C_i\left[Eur\right]$ - is the net income in the i - th year, $C_0\left[Eur\right]$ - is the total investment; $r\left[\%\right]$ - is the discount rate; $t\left[god\right]$ - the period of validity for the incentive measures.

4. Results

Figure 5 shows the total head loss in 3000 m long steel pipeline depending on the pipe diameter. The diameters are varied in the range from 1.6 to 2.2 m. The maximal and minimal water flows are 5.65 m^3/s and 0.339 m^3/s, respectively. The letter value is the minimal water flow through the turbine.

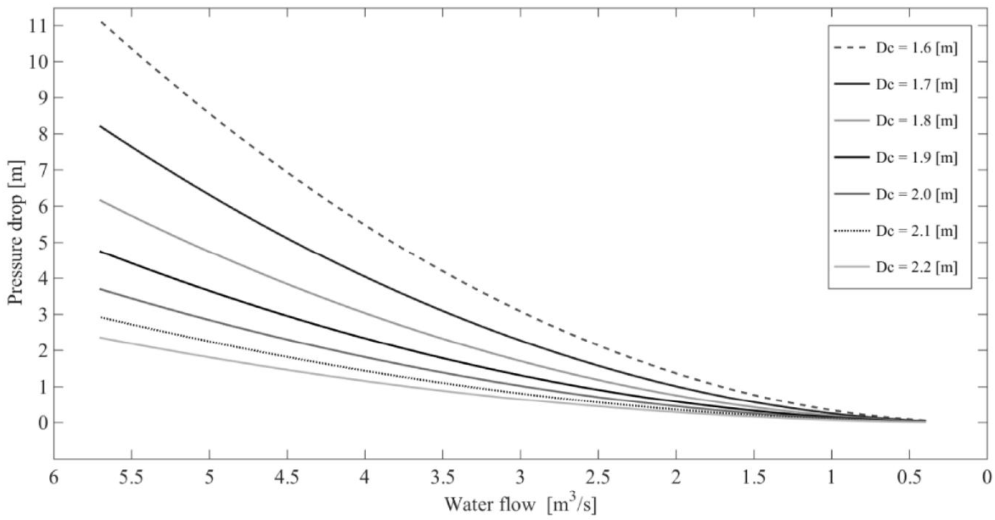

Figure 5. The total head loss depending on the flow and pipe diameter.

To calculate power production, the net head is calculated as the difference between the total head, which is 37.76 m (see Fig. 1-b), and the total head loss (see Fig. 5). The flow-duration curve is the basis to calculate the electricity production. The net flow used to calculate electricity production is the difference between the flow from the flow-duration curve and minimal (environmental) flow, which is 0.72 m^3/s.

Table 3 shows the total power production for the inner pipe diameter of 1.8 m and the period of 1 year The total power output is 4803.42 MWh/year.

Table 3. The total power output for 1-year period for the SHPP Kašići and the inner pipe diameter of 1.8 m.

Tabela 3.	Dc = 1,8 m	Proizvodnost MHE Kasici											
		2	5	10	20	30	40	50	60	70	80	90	100
Q [m³/s]		12,70	9,16	6,85	4,91	3,82	2,99	2,47	2,10	1,76	1,41	1,16	0,32
Qmin [m³/s]		0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72	0,72
Qt [m³/s]		11,98	8,44	6,13	4,19	3,10	2,27	1,75	1,38	1,04	0,69	0,44	0,00
Qt1 [m³/s]		5,65	5,65	5,65	4,19	3,10	2,27	1,75	1,38	1,04	0,69	0,44	0,00
Hbruto [m]		37,76	37,76	37,76	37,76	37,76	37,76	37,76	37,76	37,76	37,76	37,76	37,76
ΔH [m]		6,051	6,051	6,051	3,328	1,822	0,977	0,580	0,361	0,205	0,090	0,037	0,000
Hneto [m]		31,71	31,71	31,71	34,43	35,94	36,78	37,18	37,40	37,55	37,67	37,72	37,76
η turbine		0,84	0,84	0,84	0,84	0,84	0,84	0,84	0,84	0,84	0,81	0,79	0,00
η reduktora		0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98	0,98
η generatora		0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95
Snaga generatora [kW]		1374,46	1374,46	1374,46	1106,82	854,71	640,58	499,16	395,95	299,64	192,29	119,76	0,00
Vreme rada [h]		175,20	262,80	438,00	876,00	876,00	876,00	876,00	876,00	876,00	876,00	876,00	876,00
Proizvodnost MWh		**240,80**	**361,21**	**602,01**	**969,58**	**748,73**	**561,15**	**437,26**	**346,85**	**262,48**	**168,44**	**104,91**	**0,00**
								Proizvodnost MWh/god:				**4803,42**	

The optimal pipe diameter has the maximal NPV for the period of 12 years and for the discount rate of 5%. As it was previously stated, 12 years is the period of validity for incentive measures for power production from renewable sources, whereas 5 % is the standard discount rate in the Republic of Serbia.

Table 4 shows the NPV for steel pipes depending on the pipe diameter. In the table, the total production, the gross income, and the total investments are also given.

Table 4. The NPV for steel pipes depending on the pipe diameter.

Dc [m]	Power productivity [MWh/year]	Installed power [kW]	Incentive purchase price [eur/kWh]	Gross income [eur/year]	Investment for pipeline [eur]			**Net present value (NPV) [eur]**	Time [year]	Discount rate [%]
					Pipes	Other works	In total			
1,6	4490,26	1163,00	0,1036	464.969,40	813.000	330.000	1.143.000	**2.978.141**	**12**	**5,00%**
1,7	4674,40	1287,33	0,1031	482.078,47	888.000	330.000	1.218.000	**3.054.783**	12	0,05
1,8	4803,42	1374,46	0,1028	493.974,81	990.000	330.000	1.320.000	**3.058.223**	12	0,05
1,9	4892,97	1434,92	0,1026	502.186,34	1.089.000	330.000	1.419.000	**3.032.004**	12	0,05
2,0	4958,84	1479,40	0,1025	508.203,97	1.185.000	330.000	1.515.000	**2.989.340**	12	0,05
2,1	5007,34	1512,15	0,1024	512.621,52	1.293.000	330.000	1.623.000	**2.920.494**	12	0,05
2,2	5043,81	1536,78	0,1023	515.936,99	1.407.000	330.000	1.737.000	**2.835.879**	12	0,05

The optimal inner diameter for steel pipes is 1.8 m as can be seen in Table 4. Although this is the optimal value, the NPV has not so sharp maximum as can be seen in the previous table.

Figure 6 shows the change of the NPV for steel pipes depending on the pipe diameter and the analyzation period. It is interesting to note that for the period of 11 years, the optimal diameter is 1.7 m due to its highest NPV. For larger periods, 12 and more years, the optimal diameter is 1.8 m.

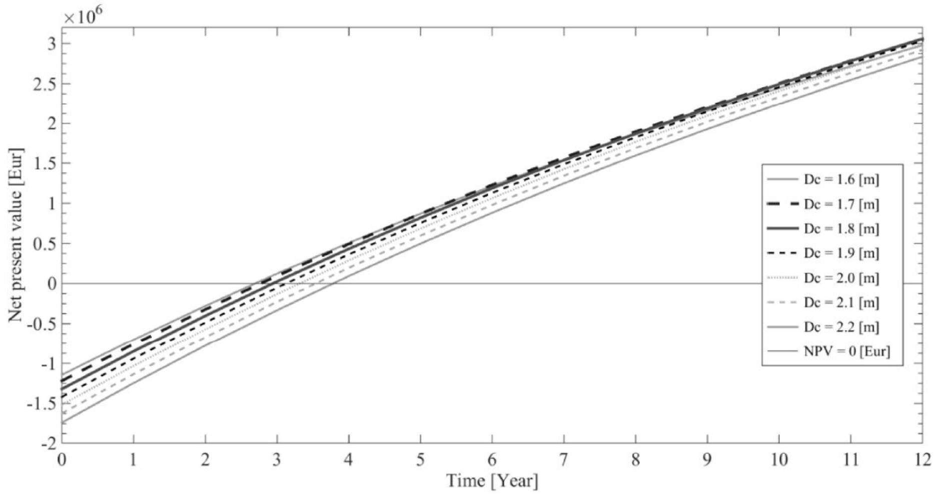

Figure 6. NPV for steel pipes depending on the pipe diameter and the analyzation period.

Figure 7 shows the impact of material price fluctuations to the NPV. This sensitivity analysis is performed for steel and polyester pipes in the range of inner diameters from 1.6 to 2.2 m with the price fluctuation range of ±20%.

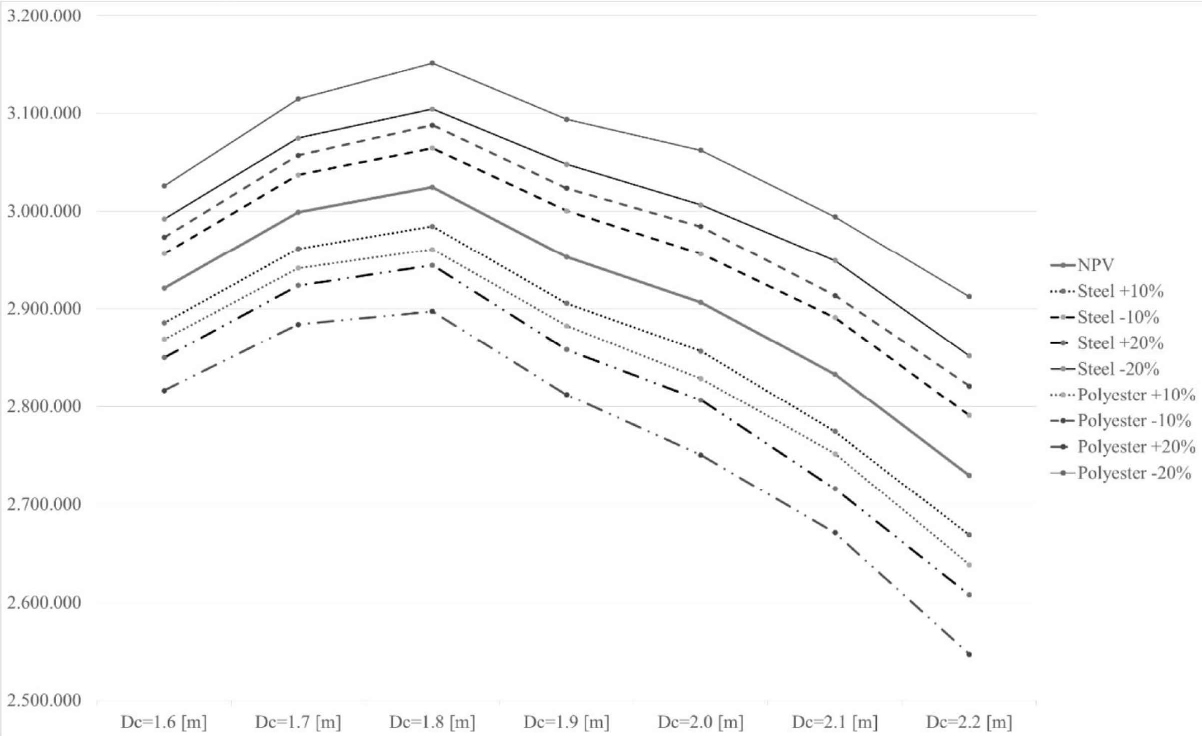

Figure 7. The impact of material price fluctuations to the NPV for steel and polyester pipelines.

5. Conclusions

The maximal water speed in the pipeline is recommended to be less than 2 m/s. The selection of pipe material and diameter with the water speed less than recommended should be performed by techno-economic analysis, which should be performed for the period of validity for incentive measures for power production from renewable sources. Shorter analyzation periods favor smaller diameters, whereas longer periods favor only the optimal pipe diameter. The material price fluctuations are so frequent that the each SHPP project requires a new analysis.

For the SHPP Kašići, the performed NPV analysis gave steel pipeline with the optimal inner diameter of 1800 mm. Compared with the optimal, the increase or decrease of the pipe diameter reduces the NPV regardless of the pipe material (see Fig. 7).

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