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Hydrokinetic Micro-Power Generation in Small Rivers - a New Approach

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Abstract. The so called German electrical "Energiewende" is mainly based on the installation of solar photovoltaic and wind energy converters as the main new renewable European generation resources. The third renewable energy resource, the hydropower has been already developed within the last decades and grew not significantly in the last years. Since some years the development of smaller hydrokinetic turbines increased. The smaller size of some hydrokinetic turbines enables new, unused sites to be harnessed in smaller rivers. The paper deals with the key specifications of hydrokinetic turbines and their influence on a villages' energy supply. It introduces the concept of a turbine with variable immersion depths to exploit also locations with a varying water level. Based on historical hydrological data a propeller and oscillating hydrofoil type of hydrokinetic turbine are compared, it was found that the variable immersion depths increases the energy harvest. Furthermore, it is shown that in a generation portfolio of hydrokinetic and solar power plants an average Luxembourgish household theoretically renewable supplied has to exchange less energy with the power grid, the higher its share of hydrokinetic generation is.

Key words

Hydrokinetic-Generation, Renewable-Generation, Hydropower, Micro-Generation, Distributed-Generation

1. Introduction

Since some years the electricity generated by European hydropower plants does not increase significantly (EU-28 2004 327 TWh, 2012 335 TWh)[1]. About 86% of the hydroelectricity in Europe is generated by larger power plants (In 2005 installed hydropower larger than 700 kW: EU-27 115,16 GW / 296,6 TWh; Installed small power about ~ 600-700 kW 12,4 GW 42.1 TWh)[2]. Three main reasons prevent the development of new hydropower plants, namely environmental laws and public doubt, the best locations for plants in mainly larger rivers are already used, as well as no feasible and economical technologies are available to harness smaller rivers of varying flow conditions in a simple way. With the introduction of hydrokinetic turbines, smaller rivers and creeks become potential hydropower sites. Small rivers are characterized by seasonal, alternating flow conditions and levels. In the following the Our river is analysed as the power resource for the hydrokinetic turbines. At the observed water-level station the average flow velocities vary between 0,04 and 2,6 m/s, as shown in figure one. Hydrokinetic turbines do not need large civil works to be installed, a floating raft on which the turbine is fixed is sufficient, in some concepts the turbine is connected to stable structures in a river, see Fig. 2. The small amount of civil works reduces the cost of installation. Nevertheless a minimum river depths is needed to operate the mainly rotor-based turbines. The required minimum water level reduces the availability of potential sites for the propeller-type hydrokinetic turbines, since the rotating blades must be entirely immersed to ensure an efficient operation with predictable flow condition around the blades. Turbines with a variable immersion depth increase the number of exploitable spots within a river, due to the adaptability on lower water levels. Furthermore, experiments have shown that single hydrokinetic turbines do not harm fish, due to their slow motion and a construction which makes it for the fish possible to easily pass by [3].

It will be shown that hydrokinetic turbines are suitable to contribute to the renewable electricity supply of settlements close to a river. Their small size and generation peaks in wintertime reduce the power exchange of a mainly renewable by including hydrokinetic- and solar power -plants supplied village, with the power grid. The risk of grid congestions, due to renewable generation feed-in peaks is reduced, as well as the general load on the grid.

2. Motivation

To increase the number of exploitable hydrokinetic sites in a river, including the unfavourable low depth sites a variable immersion depths of the turbine with stable flow conditions around the blades, to optimize the power extraction, is useful. By introducing turbines with variable immersion depth, the energy extracted of the water increases, compared to ordinary constant depth turbines, due to the longer annual operation time.

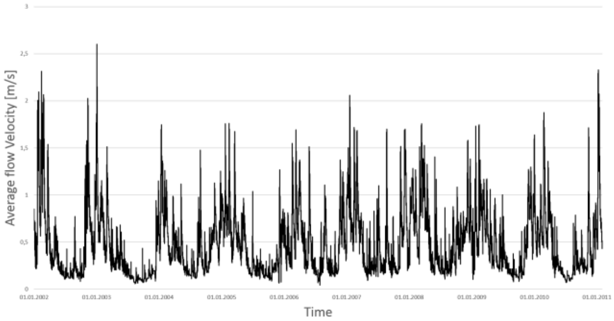

Figure 1. Average Flow Velocity of the Our river in Luxembourg for nine year with the characteristic winter peaks.

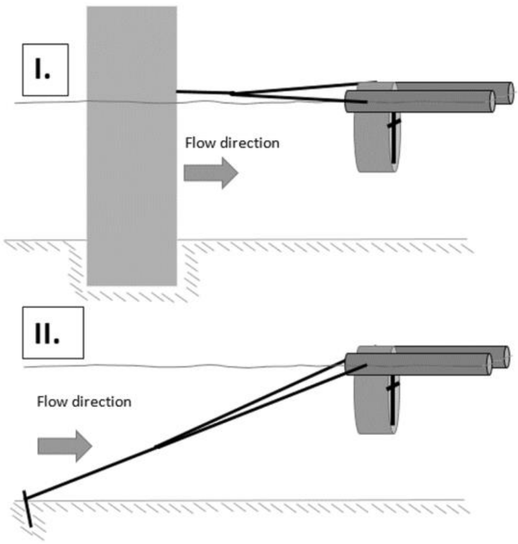

Figure 2. The two main concepts to fix a small hydrokinetic turbine in a river, I. at a stable structure, II. fixed with an anchor in the river bed.

Historical measurements show that the main parameters characterizing the flow conditions, namely flow velocity and water level, vary within summer and wintertime in the here considered Luxembourgish Our river, see figure one. In wintertime the river has higher water levels and flow velocities [4]. Hydrokinetic turbines harness the flow velocity of rivers and extract a theoretical maximum of 59,26 % of the rivers kinetic energy, theoretically limited by the hydrodynamic theory describing the free flow of the fluid around the propeller. The considered small river provides limited space, so that the size of the applicable turbines is restricted. Additionally, a low price of the system is favourable, to reduce investment barriers and to make the system competitive for private investors. The small size of the system with a maximum theoretical power generation of 18 kW makes it interesting to supply remote settlements or single houses. In combination with other seasonal variable output technologies, for example solar photovoltaic systems, a hybrid system has a more balanced annual generation curve. Predictable hydro generation peaks in wintertime and solar generation peaks in summertime reduce the mismatch between demand and renewable generation curve.

The unused theoretical hydropower potential in Luxembourg is in the range of 175 GWh/a [5]. The considered Our river has within Luxembourg a theoretical potential energy gain of 8,395 MW on its length of 51,7km, including hydrological losses of 65%, assumed for small rivers and its average volume flow of 9,3 m^3/s. The Vianden lower basin power plant, generates about 2,2MW for the average volume flow, which yields to an available hydropower potential of still 6,2MW. In figure three the location of the Luxembourgish Our River is shown. Figure four shows the height profile of the Our river over its length. Within Luxembourg the height decreases by 141.5 m, the loss of potential energy leads to an increased kinetic energy, which partly dissipates in the river bed. The local flow velocity depends on the local river gross-section.

A major challenge for the power system is the increasing peak power generation with increasing plant size caused by the main renewable technologies, namely wind power and solar power. Because of the limited renewable wind and solar energy in the middle European climate and therefore the lower full-load-hours (Luxembourg wind/solar 1650h /900h and Texas: 2500h/1800h), an increase of the renewable energy leads to a larger installed power than in other more favourable parts of the world, to get a higher annual renewable energy harvest.

Figure 3. Our River in Luxembourg.

The different renewable resources have different generation curves with a peak production of solar generators in summertime and a higher generation of wind power in wintertime [6]. The hydrokinetic Micro-Turbine has also considerable peak generation in wintertime. The size of the turbine is small, with a peak power of the generators of 18 kW, so that it is possible for private persons to increase their renewable generation by investing in their own combination of small-size solar and hydrokinetic resources.

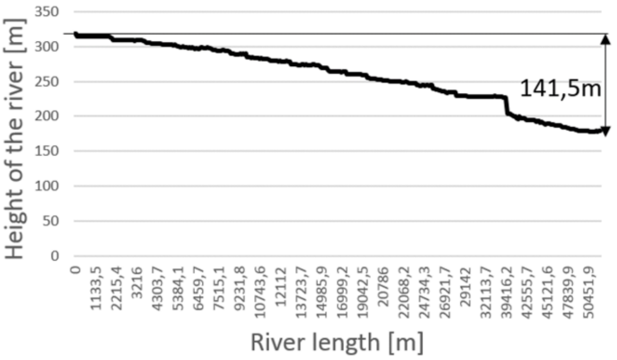

Figure 4. Height profile of the Luxembourgish Our river.

By installing hydrokinetic turbines within close vicinity of a rural settlement in combination with solar Photovoltaic plants, the power exchanged with the grid decreases compared to a pure solar supply and the electrical autarky of the system increases.

3. Methodology

Two hydrokinetic turbines and their average annual energy harvest are compared. The analysis is based on 9 years of hydrological data at the Vianden Our station. One main difference of the turbines is the constant immersion depth of one turbine, whereas the other one follows the concept of a variable immersion depth. The main second difference is the generation concept; the constant depth turbine follows an ordinary rotational motion, whereas the Luxembourgish horizontal oscillating foil concept follows an oscillatory motion of the hydrofoils, to extract the rivers kinetic energy. The generation potential for an oscillating turbine of 35% efficiency varies at that point of the Our river due to the low velocities from 0 to 4,8 kW within the analysed period. The unfavourable cross-section at the analysed Vianden water-level-station was considered as a reference station for the entire river, due to the unavailability of other stations providing hydrological data along the river. It is assumed that rivers potential is underestimated using the Vianden velocities for the entire river.

In a last step the generation potential for the two kinds of turbines and their contribution to the renewable supplied Luxembourgish settlements along the Our are considered. Following the idea of a reduced power exchange of decentralized "prosumer" to reduce potential renewable generation related grid congestions. Therefore an average Luxembourgish village with a 100% annual renewable energy supply (consisting of (I) solar and (II) solar and hydropower plants) is considered and the power exchange per capita with the grid is estimated and compared for case I and II.

The consumers' settlements electricity demand is based on a combination of six different BDEW standard load profiles which represent the average consumption of all Luxembourgish rural settlements [7]. The consumption was normalized on the number of inhabitants and recalculated for our analysis, figure 7 shows the main loads. The renewable generation profiles for wind and solar power are based on 11 years of interpolated real-time measurements at the Findel airport, as well as on a simulation of the solar generation for average Luxembourgish households. In the simulation every solar system represents the statistical average roof orientation and specific generation of all Luxembourgish houses, with shares of North/South/East/West orientation systems.

4. Results and Analysis

A. Turbines

The analysed type of oscillating foil turbine does only exist in lab-setup and is currently tested at the University of Luxembourg, within a research project in cooperation with the RWTH Aachen University. Figure five shows on the left side the dual-foil concept of the floating setup and on the right side the lab-setup with the two machines controlling two chains and a schematic test foil, indicated by the black bar. The provisional investment costs are estimated to be about 23000 Euro. This new horizontal foil turbine with four foils and variable immersion depths is proposed to be used to increase the working hours and the annual power generation of small hydrokinetic turbines. The size of the foils is 240x36x1000mmwith a platform size of 2500x2500x1500mm (LxWxH).

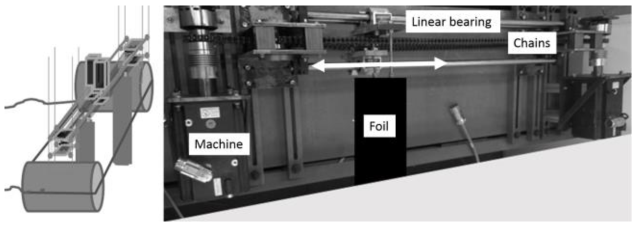

Figure 5. Schematic Setup of the turbine and lab installation. The white arrow indicates the potential directions of the moving foil (here indicated by the black bar).

The concept of a horizontal oscillating hydrofoil enables the turbine to differ the immersion depth by not varying the flow conditions around the hydrofoils. The steady flow around the foil, for different immersion depths enables the turbine to extract an optimum amount of the waters kinetic energy for every flow velocity and water depths. The concept of the lifting and lowering mechanism is shown in figure six. Seeing figure one and as mentioned above, it is obvious that a large variations of the water depths and the flow velocity need to be harnessed by hydrokinetic turbines in small creeks.

Once the water level varies and the immersion depths of the foils has to be reduced, the foils are lifted by a simple chain driven mechanism out of the water, so that a minimum distance of 20 cm between lower tip of the foil and the riverbed are ensured. In figure 6 the dotted line indicates the distance bar, a rod parallel to the turbine blades 20 cm longer than the maximum immersed foils, which detects when it touches the ground (dotted bar). Once a ground-contact is detected the whole system is lifted until the bar loses contact and the immersion depths is reduced.

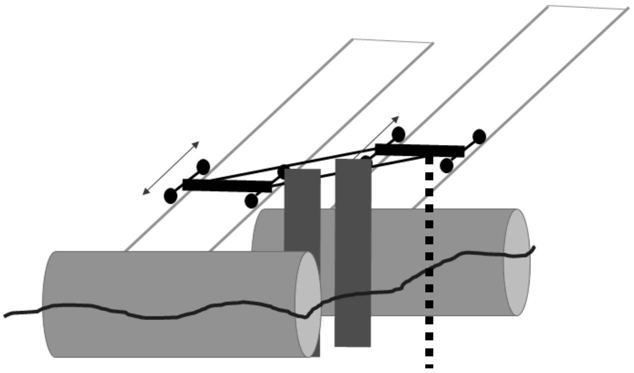

Figure 6. Mechanism of immersion depth variation for a dual hydrofoil oscillating hydrokinetic turbine. Dotted bar indicates the distant limiter between river bed and turbine immersion depths.

This simple mechanism makes the turbine suitable for rivers and creeks with a limited water depths. Additionally, the mechanism can be used by a controlled lifting of the system out of the water to remove any debris blocking the setup.
The reference turbine is a rotating turbine from the German company Smart-Hydropower with a minimum immersion depths of 180cm and a rated power of 5 kW for 2,75m/s. The size is 1850x1740x1970 mm (LxWxH). The investment cost is 12500 Euro plus installation.

B. Performance Analysis of the turbines

Both turbines power output is calculated from the average flow velocity at the Vianden cross-section of the nine year dataset. Due to missing experimental data for the horizontal oscillating turbine an average efficiency derived for a horizontal oscillating turbine of 35% was assumed [8]. The output of the Smart-Hydro-Power turbine was calculated from its power-curve. Three different cases of turbine operation and type are compared [9].

1) Operation all year long of the Oscillating turbine with a generation larger than 50W
2) Operation of the Oscillating turbine with a generation just above 200W
3) Operation of the rotating turbine when the river is deeper than 200cm

Case one yields to 1117h of operation per year with an annual energy output of 420kWh. Case two yields to 436h of operation per year with an annual energy output of 304kWh. Case three yields to 41h of operation per year with an annual energy output of 80kWh. It can be easily seen that the variable immersion depths increases the electricity harvest in this creek with a variable depths and an average annual depths of about 70cm. The minimum value of 50W is assumed to cater for the oscillating systems friction losses.

C. The consumer along the river

Knowing the two turbines annual electricity generation the rural consumer's power consumption is analysed as well as the size and number of settlements along the Our river, to calculate the theoretical need of turbines to meet the consumption.

There are several villages and small settlements along the Our river on the German and Luxembourgish shore of the river which can be supplied potentially by hydrokinetic turbines. Especially, remote single settlements along the river are prominent to be supplied by a portfolio of decentralized renewable generators including hydrokinetic turbines. There are 8 settlements on the Luxembourgish side of the Our with 2409 inhabitants, including the city of Vianden with 1705 inhabitants. On the German side are 11 settlements located with 1131 inhabitants. A very good location for the turbine with a limited consumption have the 6 remote settlements, former mills and a farm, three are located on the Luxembourgish side of the Our. In the following only consumer on the Luxembourgish side of the river are considered.

The average national Luxembourgish village power consumption is has the distribution shown in figure 7.

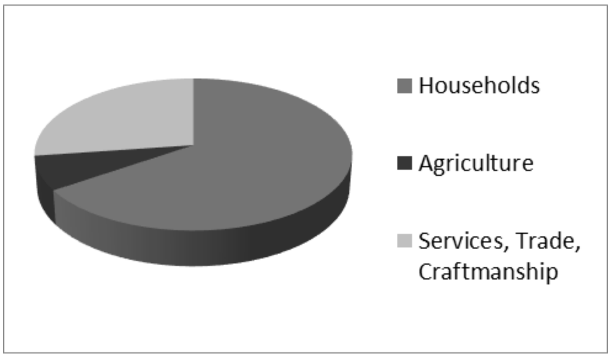

Figure 7. Average national Luxembourgish distribution of rural Energy consumer.

The demand curve of the aggregated Luxembourgish villages along the Our river with a total number of 2409 inhabitants is shown in figure 8.

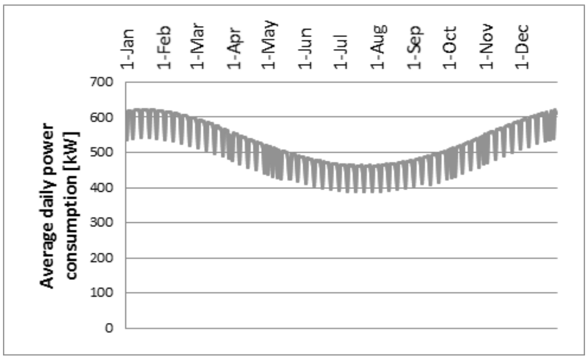

Figure 8. Aggregated annual daily averaged power consumption of all Luxembourgish villages along the Our river.

The annual electricity consumption of the settlements and the small commerce's within the settlements is about 4563 MWh.

Starting from the still in the Our river available theoretical potential of 6,2MW, which is an annual energy of 54312MWh/a. An estimation is done for hydrokinetic turbines needed to harness this potential. The estimation is based on the unfavourable flow conditions at the Vianden site, due to the non-availability of data for the other sites.

Several cases are distinguished, namely the whole year generation case with an average annual generation of 420 kWh/a , the minimum 200W generation per turbine with 304 kWh/a and the Smart Hydro turbine case with just 80 kWh/a generated. The three cases lead, due to the limited power generation of the small devices to the following number of turbines to be installed to guarantee a 100% renewable energy supply: 10864, 15010, 57037, which leads to a turbine distance of 4,75m, 3,44m, 0,9m along the river. It can be directly seen that this amount of turbines is not feasible due to massive investment, of a minimum of 100k€ per capita and the uneven distribution of inhabitants along the river. Therefore it can be said that those hydrokinetic turbines are more useful to supply remote settlements.

D. The combination of solar and hydrokinetic generation

Taking into account that the hydrokinetic turbines cannot be a single renewable solution for the sustainable energy supply of the considered villages, also the two other technologies, solar- and wind power should be considered. To get a general overview about the annual fluctuations of each technology figure 9 shows the annual fluctuation of the national Luxembourgish wind and solar generation in 2013 as well as the theoretical hydrokinetic fluctuation at the Vianden location for 2002.

Based on the analysis of the renewable supply of a Luxembourgish model village with a similar load curve as seen in figure 8, it can be shown that the hydrokinetic turbines reduce the village’s energy exchange with the electricity grid.

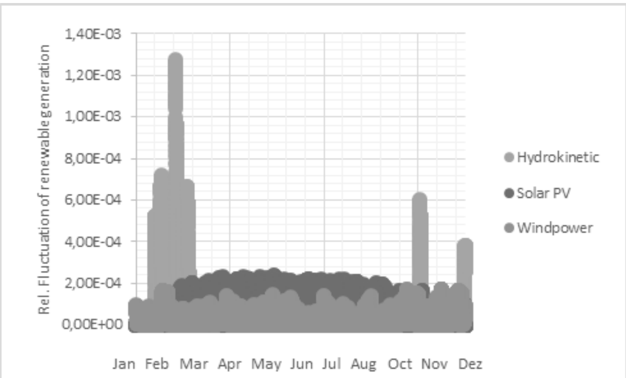

Figure 9. Rel. Fluctuation of the renewable generation within Luxembourg for different technologies.

The higher hydrokinetic power generation in wintertime, seen in figure 9, is in line with the higher electricity consumption in wintertime, see figure 8. An analysis of different 100% renewable rural electricity generation scenarios for villages based on different generation portfolios, consisting of varying shares of solar-, and hydrokinetic power plants, show that the hydrokinetic turbines reduce the power exchange. Wind power plants are not considered due to the sheltered locations along the river within a valley. Therefore, just hydrokinetic and solar systems are compared. The per capita annual energy exchange (imports and exports) with the power grid reduces for a hybrid system consisting of a 14 kW hydrokinetic and a 1,6 kW solar system to 129 kWh per capita, compared to a purely solar supplied setup of 2,3 kW and an exchange of 549 kWh, assuming an annual consumption of 1891 kWh per person. It is shown that the hydrokinetic system reduces the energy exchange on about 23% of the former annual exchange.

4. Conclusion

This paper has introduced and analysed the concept of hydrokinetic turbines with variable immersion depth. Compared to an ordinary hydrokinetic turbine with a minimum operation water depth of 180cm the proposed horizontally oscillating foil turbine can adapt its immersion depths on the rivers water level. An analysis of the theoretical potential of both turbine concepts with real measurements of nine years at a Luxembourgish water level station was used to calculate the power output. It was seen that the new turbine operates in average 1117h and generates 420 kWh in a year whereas the rotating turbine just operates 41h and generates 80kWh. Due to their small size hydrokinetic turbines do not harm fish, which is a large advantage compared to the run-off river barrage power plants [3,10].

Acknowledgement

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