HYDROPOWER AND HYDROMORPHOLOGICAL REQUIREMENTS – A TOOL TO EVALUATE THE ENERGETIC AND ECONOMIC IMPACT OF HYDROPOWER PLANTS

Dipl.-Ing. Frank Roland & Prof. Dr.-Ing. Stephan Theobald

Department of Hydraulic Engineering and Water Resources Management,
University of Kassel, Germany, Kurt-Wolters-Str. 3, 34125 Kassel
E-mail: f.roland@uni-kassel.de, s.theobald@uni-kassel.de

Abstract

On behalf of the Hessian environmental administration a location-related analysis of hydropower use has been conducted in Hessen. One objective of this project was the development of a decision support system to assess the energetic and economic impacts of measures, in order to optimize the hydromorphological or technical situation at the hydropower plant. Furthermore, this tool provides detailed data and information on 621 hydropower plants located in Hessen. This tool could thus support the development of consensual solutions between the different demands and respective mutual benefits.

Introduction

Conflicting issues between the regenerative energy source hydropower with all its undisputed positive qualities on the one hand, and the negative impacts on the hydro-ecological situation on the other hand, continue to be of particular importance. For this reason the Hessian Ministry for Environment, Energy, Agriculture and Consumer Protection (HMUELV) has commissioned the Department of Hydraulic Engineering and Water Resources Management of the University of Kassel, Germany, to conduct an analysis of the utilization of hydropower in Hessen, and to develop a planning tool for the Hessian environmental administration. This should enable rapid and clear access to the information on the hydropower plants currently loaded. A further goal was the ability to determine – on the basis of performance plan calculations – the energy capacity for any given plant location as well as energetic impacts of modified boundary conditions, for example due to hydro-ecological improvement measures. On this basis the planning tool should incorporate features to take into account the income situation, investments associated with the potential measures and thus to balance the respective financial consequences. This should enable the transparent documentation of decision-making bases and impacts of planning options, in order to support the required dialogue between individual stakeholder groups for the implementation of effective measures.

Conception of the Planning Tool

Documentation of Plant Locations

An essential part of the developed planning tool is the compact and clearly arranged presentation of the significant parameters of any hydropower plant. These include, among other things, information concerning the:

- location and geometric properties of the plant
- technical outline data, such as design discharge, design head, design power capacity and annual energy capacity
- further technical data such as installed hydroelectric generating sets, efficiency curves, head-discharge ratios or screens
- water supply (with the assignment of stored hydrological data, cf. Figure 1)
- current situation regarding water legislation
- upstream and downstream connectivity, as well as on upstream and downstream fish migration and fish protection facilities, if existing
- diverted reaches and power station channel, if existing

Auxiliary photographs and documents can be added to each dataset. On the basis of these “input data”, amongst others, the energy performance can be analysed, influence on the hydro-ecological state evaluated and any resulting need for action derived for each plant covered.

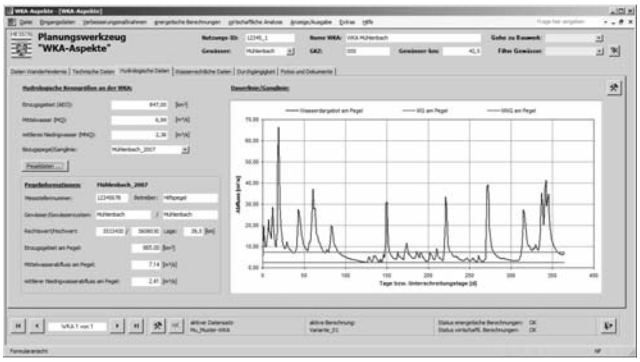

Figure 1: Screenshot from the planning tool’s user interface

Energy Computations

The algorithms implemented in the planning tool for energy computations are based on the following formula:

$$P(t) = \rho \cdot g \cdot \left(Q(t) - Q_{RW}(t)\right) \cdot \left(h_f(t) - h_v\right) \cdot \eta_T(t) \cdot \eta_A \qquad (1)$$

where:

P	Electrical power [W]
ρ	Density of water [kg/m³] = 1 000 kg/m³
g	Acceleration due to gravity [m/s²] = 9.81 m/s²
Q	Discharge [m³/s]
Q_{RW}	Residual discharge [m³/s]
h_f	Head [m]
h_v	Hydraulic losses [m]
η_T	Turbine efficiency [-]
η_A	Plant efficiency / other losses (generator, transmission, etc.) [-]

Integration of the thus determined power P(t) over a period of a year gives the resulting annual energy capacity E_A:

$$E_A = \int P(t) \cdot \Delta t \qquad (2)$$

These approaches enable – depending on the available data and on the specific question – on the one hand approximate performance plan calculations on the basis of simplifying assumptions. On the other hand they also provide, however, the detailed depiction of as well as verification calculations for complex operational situations, taking into consideration individual turbine control, specific efficiency curves and head-discharge ratios through to the analysis of energy optimization options (keyword "joint control"). Calibration and verification is achieved by comparing the resulting values with measured production data, which can likewise be stored in the planning tool.

For the input of planning variants for the improvement of the current hydro-ecological and/or technical situation the following "action types" are available in the planning tool, which have an influence on the energy capacity and must therefore be considered in the performance plan calculation:

- Discharge for:
  - diverted reaches, if existing
  - fishways (incl. attraction current)
  - fish protection and downstream migration facilities
- Technical optimization by modification of:
  - the plant efficiency η_A
  - the hydraulic losses h_V
  - the head water level
  - the hydroelectric generating set (e.g. installation of a residual flow turbine)

On this basis any number of scenario computations can be carried out by varying the individual input parameters. These include both state-wide and/or trans-regional observations and analysis of the influence of specific planning variants in individual cases. Thus, for example, the applied hydro-ecological improvement measures illustrated in Figure 2 affect the water supply available for energy usage and the power capacity for the selected hydropower plant, as shown in Figure 3.

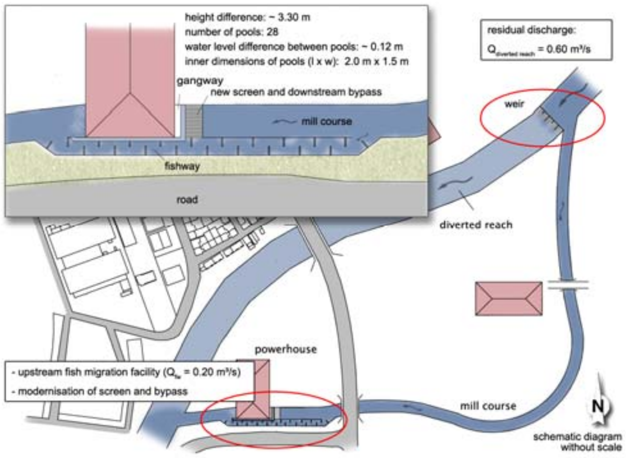

Figure 2: Examples of improvement measures for the hydro-ecological situation

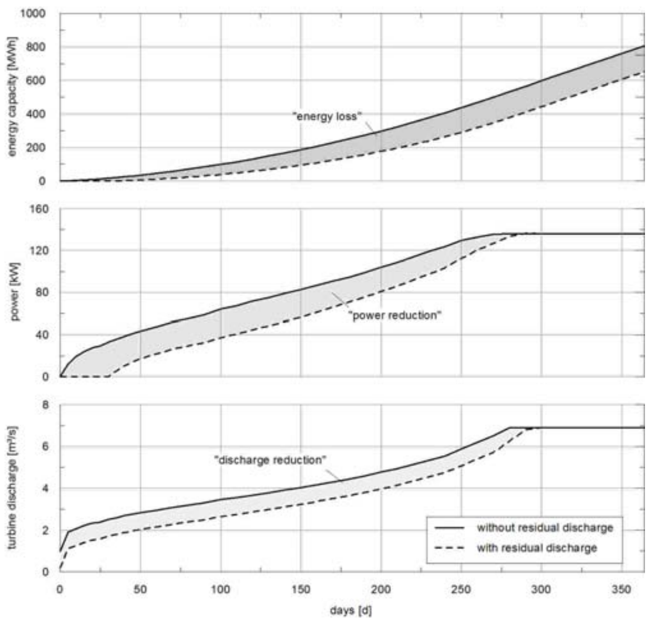

Figure 3: Results of the simplified performance plan calculation for the plant outlined in Figure 2

Determination of Annual Income

The anticipated annual income is calculated in the planning tool for both the current situation and the scenario, and is based on the results of the respective performance plan calculations. For this purpose the tool stores the remuneration rates according to the EEG [Renewable Energy Sources Act] (for hydropower plants < 5 MW), revisions 2000, 2004, 2009 and 2012. The determination of the respective applicable mean remuneration rate – with respect to the power classes and remuneration rates shown in Table 1 – is performed automatically. A user-defined alternative remuneration rate may also be applied, since a combination of own consumption and network feeding with a corresponding EEG remuneration is often applicable to small hydropower plants, or to enable potential self-marketing to be taken into account.

Table 1: Remuneration rates according to the EEG

power class	EEG 2000	EEG 2004		EEG 2009		EEG 2012
		new construction	moderni-sation	new construction	moderni-sation	
	[Cent/kWh]					
to 0.5 MW	7.67	9.67		12.67	11.67	12.7
0.5 MW to 2 MW	6,65	6.65		8.65	8.65	8.3
2 MW bis 5 MW	6.65	6.65		7.65	8.65	6.3

The resulting income differential for the applied planning options is obtained by comparing the revenues to be expected in the current situation and in the given scenario.

Cost Considerations

For the consideration of financial expenses, both investments (e.g. for fishways, screens, bypasses, new turbines, etc.) and variable costs (e.g. for operating resources, maintenance, servicing, repairs, insurance, etc.) associated with the given measures can be taken into account in each case. The respective cost factors can be separately input for any number of service items defined by the user. Furthermore, the most common positions are available in a selection box as predefined "standard entries" for each type of action.

Approaches for an Economic Analysis

For the assessment of the economic effects of the applied improvement measures, the planning tool contains two common actuarial approaches, namely the annuity method and the net present value method.

The annuity method compares the anticipated annual income differences with annual fixed and maintenance costs from the individual measures. For this purpose, payments A incurred over a specified period, are calculated from investments I according to the following equation:

$$A = I \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \qquad (3)$$

where:

i imputed interest rate [%]

n number of observed years [a]

Based on this, the annual expense A_{Ges} is given by the sum of the computed annual fixed costs A_{Fix} and the applicable variable costs A_{Var}:

$$A_{Ges} = A_{Fix} + A_{Var} \qquad (4)$$

In summary, this allows an initial order of magnitude of the expected additional annual revenues and/or expected annual expenses to be determined. Furthermore, the influence of possible inaccuracies in the performance plan calculations and any existing absolute errors are generally of less significance, relatively speaking, than in balance of the sum totals.

The present value of the assessed investment measures is obtained by the compounded or discounted interest respectively at the time of decision, and subsequent addition of all income and expenditure associated with the investment. The corresponding conversion of the annual income differential w and of the variable costs w_k to the "current date" is based on the following formula:

$$X_w = w \cdot \frac{(1+i)^n - 1}{(1+i)^n \cdot i} \quad \text{bzw.} \quad X_k = w_k \cdot \frac{(1+i)^n - 1}{(1+i)^n \cdot i} \qquad (5)$$

where:

X_w present value of annual income differential [€]

X_k present value of variable costs [€]

The net present value X_{Ges} of the entire measure is given, as shown in Figure 4, by these parameters while taking into account the prospective investment I at the time of assessment:

$$X_{Ges} = X_w - (I + X_k) \qquad (6)$$

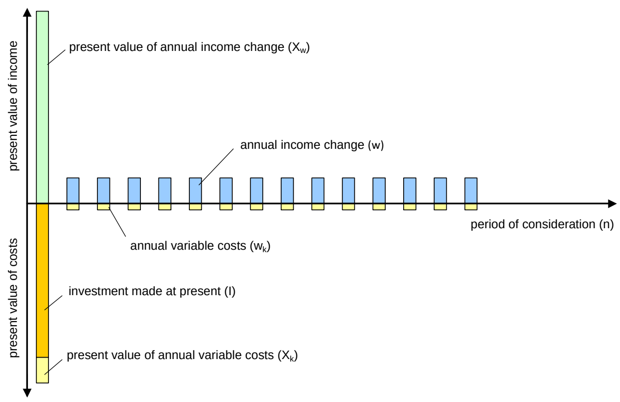

Figure 4: Illustration of the net present value calculation through the discounted and compounded interest on all income and expenditure related to the investment

The methods presented for the economic analysis of individual cases were verified on and applied to various Hessian sample plants. These include micro-plants with a design power below 10 kW, medium sized hydropower sites with a design power between 100 and 500 kW, as well as large hydroelectric plants with an installed power exceeding 1 MW.
Table 2 shows the documented annuities and net present values for the example given in Figure 2. Various deliberations can be made concerning the financing of the respective hydro-ecological improvement measures based on these computations.

Table 2: economic effects of the measures outlined in Figure 2 over an assessment period of 20 year and an imputed interest rate of 5.0 %

(1) Energetic impacts			
Current state	785 MWh/a		
Modified variant	686 MWh/a		-99 MWh/a
(2) Annuity method			
Annual changes in revenues			
Current state	0,0767 €/kWh	60 210 €/a	
Modified variant	0,1167 €/kWh	80 060 €/a	+ 19 850 €/a
Annual expenses for improvement measures			
Upstream fishway	185 000 €	14 850 €/a	
New screen and bypass	40 000 €	3 200 €/a	
Variable cost (maintenance)		1 900 €/a	- 19 950 €/a
Change in the result			**- 100 €/a**
(3) Net present value method			
Present value from annual income change			246 850 €
Present value of investment			-225 000 €
Present value of variable costs			-23 680 €
Net present value			**-1 830 €**

Advanced Features

Several advanced features were built into the planning tool to support its practical usage. These include:

- an assistant for the automated addition of missing input data and plausibility checks of technical parameters
- a menu for the update and addition of hydrological information stored in the tool such as gauge data, annual load duration curves or discharge hydrographs
- an automated form for the determination of the minimum water discharge that must remain in a diverted reach according to the corresponding Hessian regulations
- pre-prepared and clearly laid out profiles and tables for the display of input data and calculation results
- standardised enquiries for the summarized evaluation of the currently loaded dataset as well as display in the form of longitudinal river sections

Usage of the Planning Tool

In future, the planning tool should be put into operation by the Hessian environmental administration in the scope of the implementation of the programme of measures related to the European Water Framework Directive, as well as in the context of other planning processes. Therefore the Hessian environmental administration closely monitored the developments. Furthermore, the tool was also put to practical use, among others, with the abovementioned analysis of hydropower usage in Hessen and enabled associated efforts to be efficiently carried out. The following section will present selected outcomes of this study.

Analysis of Hydropower Utilization in Hessen

The central data basis for the performed investigations is provided by the Hessian environmental administration’s database (DB) “migration obstacles” which was enhanced by additional research in the Water Register, as well as automated testing and verification routines within the scope of the project mentioned. Thus a comprehensive dataset was initially prepared containing the information for the Hessian hydroelectric plants.

Accordingly, 621 hydropower plants are in operation in Hessen, excluding pumped-storage power plants, with a cumulative design power of around 92 MW. Categorization into various power classes shows that the overwhelming majority of plants in Hessen belong to the small and micro-plant categories. Thus, 545 of the 621 hydropower plants – corresponding to a share of 88 % – have an installed power capacity below 100 kW. In contrast, a mere 12 sites possess a design power rating above 1 MW.
The mean annual energy capacity of the Hessian plants can be specified as around 425 GWh per annum (p. a.). Excluding output from pumped-storage power plants, the proportion of hydropower within the total net electricity consumption in Hessen is thus between about 1 and 2 %.

With regard to connectivity, approximately 84 % of the Hessian hydropower sites are classified as non-passable or largely non-passable with respect to upstream passability and 64 % with respect to downstream passability, according to the “migration obstacles” database. In total, the assessment results illustrate that the numerous small hydropower plants in particular impair the hydromorphology in many river sections. On the other hand, the few effective hydropower plants are often located on “key hydro-ecological locations” in the lower reaches of the rivers.

Based on this analysis of the current situation, the effects of various residual flow scenarios on hydro-energy production in Hessen were established. The basis for these was provided by the performance plan calculations for each hydropower site (cf. Figure 2). The purpose was to generate an orientation guide using the scenarios, for each individual location, and, using the overall results, to demonstrate the range in which potential energetic effects of residual discharge releases on the annual energy capacity of Hessian hydropower can vary.

The study results illustrate that losses in individual hydropower plants, that are associated with the applied residual flow releases, vary very strongly depending on the degree of hydraulic development and on the technical equipment. Thus the energy losses at, for instance, a residual discharge of 1/3 of the mean low water discharge (MNQ) at individual sites could attain as much as 30 %. With this scenario, the capacity of hydroelectric plants in Hessen is reduced in total by 35 GWh p. a. while a residual flow scenario of 1/2 MNQ gives a reduction of 56 GWh p. a. This corresponds to losses to the mean annual capacity of 8 % and 13 % respectively.

Determination of the Hydropower Potential in Hessen

Likewise, using the developed planning tool, a calculation of the hydropower potential in Hessen was carried out in the context of a site-related investigation. This comprised the currently utilized potential and the existing further development potential. According to investigations carried out, the additional technical development potential, taking into account essential hydro-ecological requirements, can be given as 24 MW, or 100 GWh p. a. This gives a mean technical total hydroelectric potential in Hessen of between 490 and 540 GWh p. a. according to the abovementioned scenarios.

Summary

On behalf of the Hessian environmental administration a planning tool was developed, that incorporates, among others, the following features:

- Collection and provision of essential hydropower plant data and guarantee of rapid and clear access
- Provision of functions for the determination of the energetic capacity in the current state and under consideration of improvement options
- Provision of methods for the analysis of the corresponding economic impacts
- Provision of functions for the determination of parameters for any river systems and sections with respect to number, output, annual energy capacity of the respective hydropower plants, the hydro-ecological situation at the plant locations and the consequent “need for action”

Together with the planning tool, the Hessian environmental administration was provided with a dataset containing the current details for the Hessian hydropower plants, enabling the above-mentioned process and analyses to be carried out without further preparation.

The planning tool can therefore support the consensual resolution of existing or foreseeable conflicts of use between the hydro-ecological, water resources and usage-related requirements and the conception of possible “mutual benefits” related to hydropower plants. The systematic and verifiable approach furthermore supports the constructive dialogue between water authorities, hydropower plant operators and representatives of nature conservancy.

Acknowledgements

We would like to thank the staff of the Hessian environmental administration as well as the representatives of the stakeholder groups of hydropower and nature conservation for their cooperative and constructive support during the development of the planning tool.

References

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, BMU (2005). *Leitfaden für die Vergütung von Strom aus Wasserkraft nach dem Erneuerbare-Energien-Gesetz für die Neuerrichtung und Modernisierung von Wasserkraftanlagen.*

Department of Hydraulic Engineering and Water Resources Management, University of Kassel (2011). *Analyse der hessischen Wasserkraftnutzung und Entwicklung eines Planungswerkzeuges „WKA-Aspekte“.* Project report on behalf of the Hessian Ministry for Environment, Energy, Agriculture and Consumer Protection (HMUELV).

Giesecke, J.; Mosonyi, E.; Heimerl, S. (2009). *Wasserkraftanlagen – Planung, Bau und Betrieb*. 5. Auflage. Berlin, Heidelberg and New York: Springer-Verlag, 2009.

Hessisches Ministerium für Umwelt, Energie, Landwirtschaft und Verbraucherschutz, HMUELV (2009). *Energiebericht 2008 der Hessischen Landesregierung, Aktivitäten der Landesregierung, Aktivitäten der Landesregierung und Energiestatistischer Teil.*.

Hessisches Ministerium für Umwelt, ländlichen Raum und Verbraucherschutz, HMULV (2008). *Datenbank Wanderhindernisse*.

Roland, F.; Rötz, A.; Theobald, S. (2011, 7/8). Wasserkraft und Gewässerökologie - eine Entscheidungshilfe für Optimierungsansätze. *WasserWirtschaft*, pp. 48-52.

Theobald, S.; Roland, F. (2011, 7/8). Wasserkraftnutzung in Hessen. *WasserWirtschaft*, pp. 24-28.