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OPTIMAL BUSINESS MODEL FOR WASTE HEAT RECOVERY FROM A HYDROPOWER PLANT

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ABSTRACT
The electrical losses during hydroelectric generator operation may account for 1 to 2% of electricity production, and represent an interesting heat potential. The generator cooling water temperature is low, and application of a mechanically driven heat pump represents, therefore, a reasonable solution when, however, it is also economically viable. A simplified techno-economic model was built in order to check the economic viability of such waste heat recovery system. The model enables the source and sink heat temperature, as well as, heat flow rate to be variated and the basic heat pump parameters estimated including its COP and investment cost. An oil boiler system is assumed as a waste heat recovery system alternative. It serves for economical comparison and evaluation of the net present value and payback period of any proposed low temperature waste heat recovery system configuration.
Keywords: hydropower plant, waste heat recovery, techno-economic model

1. INTRODUCTION
Low temperature waste heat originating from generator and bearing cooling is produced during hydropower plant operation. Depending on generator operation conditions, electrical losses may account for 1 to 2% of electricity production and effectuate a heating of the generator. Thus, it has to be cooled effectively. Closed loop air cooling is applied commonly with an opened secondary cooling water loop which simply uses a cold river water to cool the cooling air within a heat exchanger before it is released back to the river. Although the amount of cooling water is high and represent an interesting heat potential its temperature is low, and its usage is limited. Application of a mechanically driven heat pump represents, therefore, a reasonable solution when, however, it is also economically viable. A simplified techno-economic model was built in order to check the economic viability of such waste heat recovery system.

2. WASTE HEAT RECOVERY SYSTEM
The simple system presented in Fig. 1 was proposed to yield the waste heat from the generator cooling system. The Heat Pump (HP) is simply placed behind the cooling system so that the cooling water heats the HP evaporator before it is released back to the river. An isolated reservoir (heat accumulator) is placed in front of the HP in order to minimize cooling water flow rate variation, and to increase the time of HP operation. A release valve enables the release of cooling water directly into the river when the HP is not operating, or when the cooling water flow rate is higher than the one necessary for the HP operation. Similarly, the heat accumulator (not shown in Fig. 1), is placed behind the HP to cope with the heat demand variations and enable constant heat supply in the periods of generators being on standby.

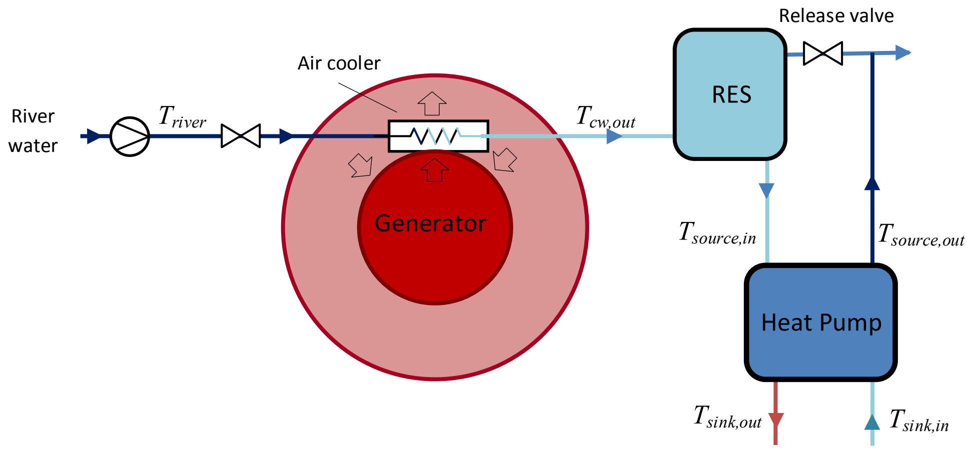

Figure 1. Waste heat recovery system

2.1. Modelling waste heat recovery system operation

Operation of the generator cooling system keeps the temperature of the stator coils within the range between 50 and 60 °C by adjusting the cooling water flow rate (m_{cw}) proportional to the ratio of actual and rated generator power (P/P_{rated}). Generator losses P_{loss} depend on operational conditions, i.e. cosφ and P/P_{rated} ratio and were simply predicted by a third order polynomial proposed by the generator producer. Knowing both cooling water flow rate (m_{cw}) and waste heat flow rate (P_{loss}) the cooling water temperature increase (ΔT_{cw}) and cooling water final temperature ($T_{cw,out}$) were easy to obtain. The latter varies seasonally between 9 °C in winter and 25 °C in summer.

2.2. Heat pump model

A simple HP model was proposed. It was built in Excel, with the REFPROP software used as add-in in order to compute the thermodynamic state of refrigerant R134a used as working fluid. Pinch point temperature difference was used to model heat exchange with both sink and source media [1]. In the condenser, the working fluid was assumed sub-cooled until it reached the pinch temperature difference at the sink entrance. The performance of the heat pump was calculated using constant efficiencies for compressor and electrical motor, as well as fixed temperature differences in the heat exchangers and compressor suction superheat.

2.3. Universal model of waste heat recovery system operation

Data on one-year operation of a representative hydropower plant (generator power and flow rate measured in 15 minute intervals) was analysed in the context of possible heat gain by application of reference HP (580 kW$_{th}$ at T_{sink}/T_{source} = 50 °C/30 °C). HP model was applied for prediction of instantaneous evaporator (Q_{evap}) and sink flow rate (Q_{sink}) and compressor power (P_{comp}). Integration of thermal power and compressor power with time made it possible to predict the heat gained and electricity consumed by the HP in any month of the year, and it was possible to find a universal correlation between these two parameters and the amount of electricity produced by the hydropower plant in a particular month. According to Eq. (1), the heat absorbed by the HP evaporator is:

$$Q_{ev,HP,m} = Q_{HP,th,50,m}\left(2.296EPE_m^3 - 4.464EPE_m^2 + 3.049EPE_m\right)\left(-0.103r^2 + 1.095r\right) \tag{1}$$

$Q_{HP,th,50,m}$ represents the theoretically possible amount of heat produced in a particular month at T_{sink}/T_{source} = 50 °C/$T_{source,av,m}$. EPE_m is electricity production effectiveness in a particular month and r is the ratio of selected and reference HP thermal power. Once the heat absorbed by the evaporator is obtained from Eq. (1), the actual amount of heat produced by the HP per month at any sink temperature is calculated as:

$$Q_{HP,m}\left(T_{source,m}, T_{sink}\right) = \frac{COP\left(T_{source,m}, T_{sink}\right)}{COP\left(T_{source,m}, T_{sink}\right) - 1} Q_{ev,HP,m} \tag{2}$$

The accuracy was tested of Eq. (1) and (2) by comparison of actual and estimated amount of heat produced by the HP per month for sink temperature T_{sink} = 70 °C and r = 1.5. The maximal differences were in the range ± 5.6%, while cumulative error over the whole year was below 1%. At any other combination of r and T_{sink}, the model performs even better.

3. ECONOMIC EVALUATION OF THE WASTE HEAT RECOVERY SYTEM

The investment cost of a waste heat recovery system has to be known in order to obtain any economic evaluation. The evaluation of the investment required for the implementation of a waste heat recovery system was considered as the sum of the costs for purchasing and installing all the equipment required, and the costs for implementing the pipelines when necessary. Cost functions were used to estimate the purchasing cost of most of the individual components. The cost functions, Eq. (3), were constructed as proposed by Bejan et al. [2], where the purchase cost of an equipment item C_y at a size or capacity X_y can be calculated based on knowledge of the cost C_{ref} at a different size or capacity X_{ref} by use of a scaling exponent α:

$$C_y = C_{ref} \cdot \left(\frac{X_y}{X_{ref}} \right)^{\alpha} \tag{3}$$

The reference values C_{ref} and X_{ref} and scaling exponent α proposed by Ommen et al. [3] are presented in Table 1. HP design parameters necessary for application of cost function (Eq. (3)) were predicted by the HP model. The sum of purchasing costs was then multiplied by Multiplication Factor MF = 2.65 in order to compute the installed cost [4]. HP investment cost estimation was performed for several combinations of operational parameters. It was shown that the HP investment cost depend on source and sink temperature, as well as on HP size, defined by the ratio r. The cost of any other HP may be calculated from:

$$\frac{C_{HP}}{C_{HP,ref}} = \left[\left(1.4\,10^{-6} T_{sink}^2 - 1.3\,10^{-4} T_{sink} + 1.5\,10^{-2}\right) T_{source} + 5.2\,10^{-3} T_{sink} + 0.4\right]\left(-4.5\,10^{-2} r^2 + 0.9 r + 0.2\right) \tag{4}$$

Where $C_{HP,ref}$ is approximately 146,500.00 EUR and represents the installed cost of the reference HP (580 kWth at T_{sink}/T_{source} = 50 °C/30 °C). Regarding the cost of any other component of the waste heat recovery system the cost functions were applied (see Table 1), or total cost ratio was assumed. Engineering cost was assumed to be 6% of total cost while the cost of existing cooling system adaptation was amounted to 20% of HP installation cost.

Table 1: Reference values C_{ref} and X_{ref} and scaling exponent α used in cost functions [3]

Component	C_{ref} (EUR)	X_{ref}	α (-)
Compressor	10,631.00	178.4 (m^3/h)	0.79
Electrical motor	10,710.00	250 (kW)	0.65
Plate heat exchanger	15,526.00	42 (m^2)	0.80
Storage tank	622.50	1 m^3	1.00
Heat storage tank	1,867.50	1 m^3	1.00
Heat delivery station	20,000.00	500 kW	0.80
Building expenses	1,500.00	1 m^2	1.00
Pipeline system	6.2·DN(mm)	1 m	1.00
Boiler	1,140.00	1 (kW)	0.50
Fuel tank	1.16	1 (l)	1.00
Exhaust piping	730.00	1 (kW)	0.42

An oil boiler system was assumed as a waste heat recovery system alternative. The reference values of cost function (Eq. (3)) used for computing the purchasing costs of equipment involved in heating installations are detailed in Table 1. MF = 2 was applied to estimate the installed cost of the oil boiler system [4]. Economic comparison of a waste heat recovery system and an oil boiler alternative was performed using three economic parameters: Heat Production Cost (HPC), Net Present Value (NPV) and Pay-Back Period (PBP). Lifetime of the plant was assumed to 15 years, interest rate was 5% and 1.65% maintenance cost factor was assumed. The electricity price 43.05 EUR/MWh proposed by the hydropower plant company and the market heating oil price 0.87 EUR/litre were applied. Fig. 2 shows HPC variation with size, i.e. thermal power of the applied HP. Minimum HPC is reached at reference HP thermal power 650 kW_{th}. However, any HP size variation within ± 200 kW_{th} interval does not increase HPC by more than 1%, although it has very high influence on the produced amount of heat. This means that the system thermal power selection is very flexible, with almost no penalty on HPC in a broad range around the optimal point. Application of oil boiler increases HPC by more than 4 times, thus PBP of less than 2 years may be expected when HP is selected as heat producing unit. In case of a reduced period of system operation, such as in a case of space heating in winter, the economics of the system worsen substantially. The amount of produced heat is reduced by more than 50%, and increases the HPC by 80%. However, the system is still profitable when compared with the oil boiler alternative. The PBP is 3.2 years. Remote energy supply deteriorates the economic viability of the system even more. The investment cost more than doubles with only a 1,000 m long pipeline system. As a consequence, the HPC increases to 74.6 €/kWh (see Fig. 3) and the PBP is 8 years.

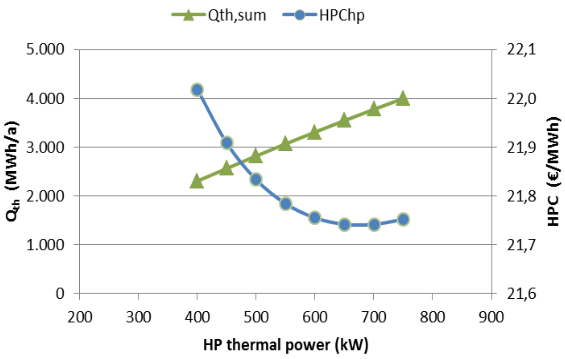

Fig. 2. HPC and annually produced heat variation with rated thermal power

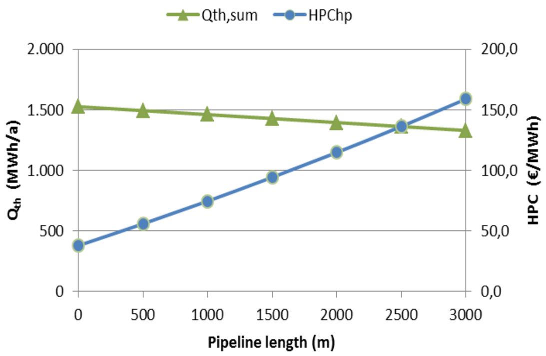

Fig. 3. HPC and supplied heat in winter season variation with pipeline length

4. CONCLUSION

A study was performed on waste heat recovery system application in a hydropower plant. A universal correlation between the heat gained by the heat pump in any month of the year and amount of electricity produced by a hydropower plant in a particular month was applied to predict gained heat in any month of the year. The economics of system were then analysed. The total investment cost was estimated by cost functions adopted from the literature or catalogue price lists. It was proved by estimated HPC, that any waste heat recovery system ensures high economic gain when the heat is used at the production site. HPC is below 25 EUR/MWh if the system operates for a whole year, while it increases up to 38 EUR/MWh when only winter season operation takes place. On the other hand, the remote heat application which needs a pipeline system increases HPC significantly. HPC more than doubles with a 1,500 m long pipeline, and exceeds 100 EUR/MWh when the pipeline length increases to 4,000 m.

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