A DECISION-ANALYTIC MODEL FOR ASSESSING THE INSTALLATION OF SMALL HYDROPOWER SYSTEMS IN POLLUTED STREAMS

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ABSTRACT

Usually, hydroelectric projects are developed only for rivers of high flow-rate; however, micro generation of electricity, in which small turbines are installed in rivers of low flow-rate, which may also be polluted, presents itself as a way of supplying electricity to communities far away from the main power generation plants. Installing turbines in polluted streams is an appealing alternative, as these streams do not have any other use or ecological value. This work presents the development, with an application to a hypothetical case study, of a decision model that assesses the feasibility of installing turbines in polluted streams. Using a Decision Analysis-Value Focused Thinking approach, the model includes the uncertainties inherent to the problem and relevant non-economical objectives, like those of social and environmental nature.

Keywords: *Decision Analysis, Small Hydroelectric Plant, Wastewater*

1. INTRODUCTION

Due to the growing problems related to the usage of fossil fuels, the micro generation of hydraulic energy, using small or micro-hydroelectric plants (Small Hydro Power Systems or SHPS) presents itself as an appealing alternative for energy generation. This is especially true for developing countries, where electricity generated locally can be consumed by communities far away from the main distribution networks or used by local agro industries and for road illumination [1]. The denomination "SHPS" is commonly used for capacities less than 10 MW but this varies from country to country [2]. Recently, the SHPS have been the focus of several researches, as in [3] and [4], where it is proposed to use global positioning information to find potential sites for SHPS installation. Among the research related to the feasibility and optimal design of SHPS from an economic and technical point of view, we can find [2] and [5-13], while studies introducing the social an environmental aspects are reported in [14-19].

In practice, some of the rivers that, with respect to the hydraulic head in positions along their paths and their flow rates, are suitable for electricity generation using a SHPS, are also polluted to some extent. From the literature review, only Saket in [1] considers installing a SHPS in a sewage stream, analyzing only the economic and technical impacts of the installation.

While installing a SHPS in a polluted river carries some technical and economic implications not found when it is installed in a clean stream (requirement for frequent cleaning, lower generation rates, lower equipment durability etc.), it can be argued that it also has environmental benefits (to install the SHPS in a polluted stream instead of a clean stream avoids perturbing the latter) and social ones (providing electricity to communities located far away from the main distribution network). The environmental and social aspects are sometimes regarded as non-measurable, and left out of the analysis, as often done with important relevant objectives that are deemed non-measurable [20].

The objective of this work is to provide a framework for incorporating all relevant aspects (economic, environmental and social) to the feasibility analysis of the installation of SHPS in polluted rivers. The feasibility analysis is approached from a Decision Analysis (DA) perspective. DA is a discipline which aims to bring clarity, insight and definition to messy decision situations [21,22], and has been viewed as a mixture of Systems Analysis and Decision Theory [21]. It´s usage for decision making guarantees the satisfaction of a set of desiderata (axioms) of rational choice [23] and is especially helpful in decisions involving uncertainties, several competing objectives or multiple stake holders. Specifically, the approach shown here is based on the Value-Focused Thinking (VFT) paradigm of Keeney [24], according to which, a problem should be approached by initially clarifying and structuring the objectives relevant to it. By using VFT, the problem is framed and a utility model is obtained that allows assessing the desirability of the project. To the best of the author´s knowledge, there is no reported research showing an analysis of the feasibility of installing a SHPS in polluted rivers that includes all relevant aspects of the problem or uses DA tools for the analysis.

2. DEVELOPMENT

Consider the region depicted in Figure 1, in which there are clean water streams (blue) and polluted ones (green), with flow rates and heads Q_i (m^3/h) and h_i (m), respectively. The installation of one or more SHPS units at the shown streams is being considered. Determining the feasibility of installing the SHPS and their optimal location requires developing a decision model. The decision model consists of a value model and a factual model. According to the VFT paradigm, the analysis begins by constructing the value model.

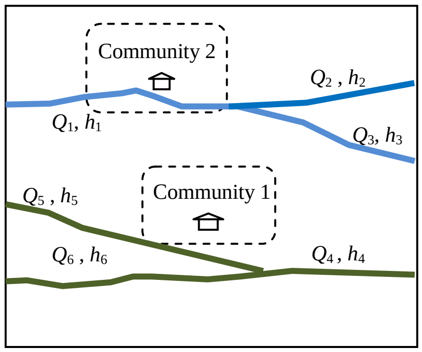

Figure 1. Region for the problem statement

2.1 Value Model

The aim of the value model is to measure the preference of the person or group making the decision (deciding entity), for different consequences that can occur as a result of the decision. To be operational, the value model needs value judgments that depend on the deciding entity's concerns (its values), thus, it is essentially subjective. DA provides several tools for including these concerns to the decision model.

The frame of the problem consists of the objectives and the alternatives. The objectives can be classified as fundamental (objectives that are important by themselves) and mean objectives (objectives that are important because they impact another, more fundamental objective). The fundamental objectives are normally structured into a hierarchy; known as the Fundamental Objectives Hierarchy. For any alternative, the relevant objectives are identified by locating the alternative to the right of the hierarchy, and drawing continuous arrows to the objectives that may be benefited by the alternative, and dotted ones to those that may be harmed.

This is done in Figures 2 and 3, the first for the decision of installing a SHPS in a clean water river and the second for installing the SHPS in a polluted one.

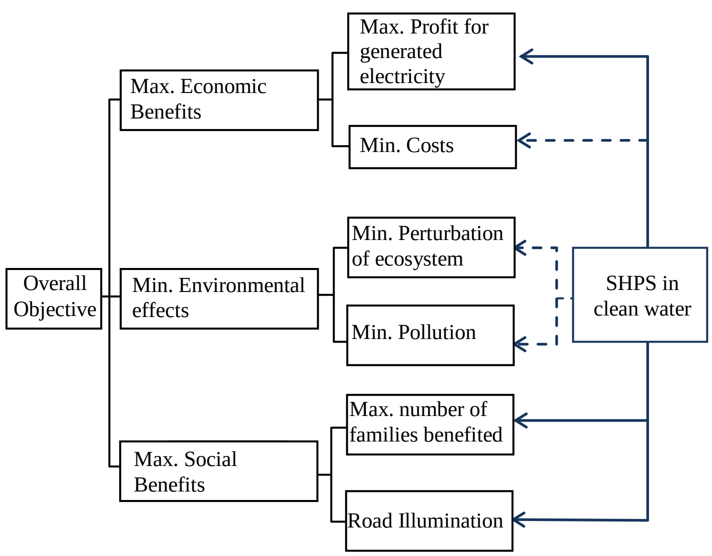

Figure 2. Fundamental Objectives affected by installing the SHPS in a clean river

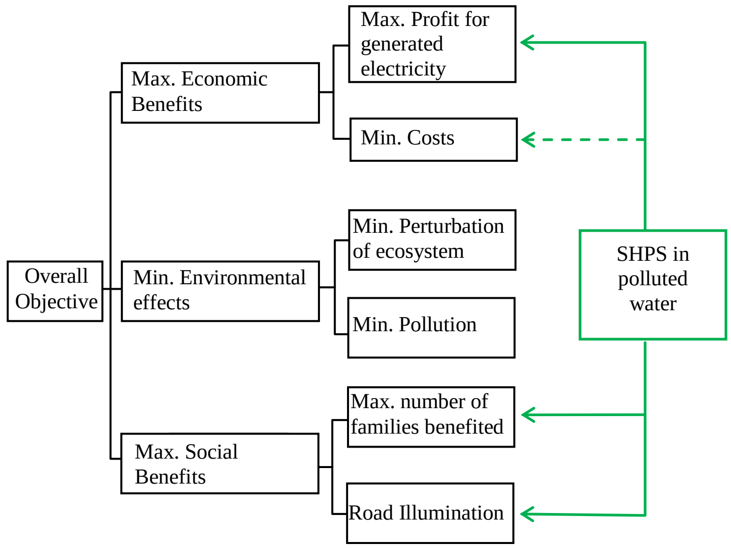

Figure 3. Fundamental Objectives affected by installing the SHPS in a polluted river

It can be noticed that the environmental objective is split into two components: "Minimize Pollution", that means avoiding the addition of exogenous substances or heat to the streams, and "Minimize Perturbation of Ecosystem", that refers to the perturbations brought about by the mere presence of the SHPS in the river and those caused by the preparation of the site.

By installing the SHPS in a polluted stream, the environmental impact of the project is reduced or attenuated compared to that of the installation in a clean stream, for an already polluted stream is assumed not to have any ecological value (for example, biodiversity) or further use. While the economical objective has natural attributes that can be used to measure it´s achievement (for example, the rate of investment return [25]) the social and environmental objectives do not have natural attributes. In order to include these latter objectives in the model, it is necessary to develop constructed attributes [24]. The definition of the levels that make up the scales for these attributes, the value for the utility of each level and the trade-offs between attributes, must be carefully tuned to capture the concerns of the deciding entity, and so they are subjective by nature.

Thus, it is important to stress that the information shown in Tables 1 to 4 and Equations 1 and 2, represents a way, plausible from the author's point of view, to account for the social and environmental objectives relevant to the SHPS installation. The numbers shown in these tables represent what the authors of this research, who make up a multidisciplinary team of industrial and environmental engineers and graduate industrial engineering students, have agreed to be a plausible set of parameters for modeling the objectives of a public entity whose responsibility is to decide the installation of a SHPS.

In a real implementation of the model, however, the levels of the Tables 1 to 4, both in their definition and their utility assignation, should be adjusted to reflect the deciding entity's preferences between different consequences related to the economical, social and environmental impacts of the decision. In this respect, the parameters in Table 1 to 4 do not have "correct" or "true" values, they can only be adequate (or not) to the concerns and objectives of a concrete deciding entity [26]. There are several tests that can be performed to check the correspondence between a value model and the preferences of a particular person or group[27].

In order to measure the social benefits, different magnitudes of the change in the conditions of the benefited person (or family) are defined in Table 1. A utility for each level is determined using the "reference lottery" method [22].

Table 1. Definition of the levels of social benefit experimented by a family as a result of the project

Level	**Description**	**Utility ($U_{T,i}$)**
A	Changes from not having electricity to having constant electricity supply (no more than one interruption per month)	1.0
B	Changes from not having electricity to having an electricity supply with constant interruptions (more than one interruption per month)	0.5
C	Changes from having electricity supply with constant interruptions to having constant electricity supply	0.2
D	No change in availability of electricity	0

From examining the levels of this table, it is seen that consequences are judged better (higher utilities) the worse the original electricity supply of the family or person is. Thus, this scale will give higher marks to projects that benefit people with no current electricity supply than to projects that generate electricity that may be used by people already having a constant service, in which case a change in availability of electricity wouldn't be noticed. For a set of n_F benefited families, (where benefit to the family i causes the utility $U_{T,i}$) the average value of the benefits is used (U_T)

$$U_T = \frac{1}{n_F}\sum_{i=1}^{n_F} U_{T,i} \tag{1}$$

While U_T captures the average quality of the social benefits, the utility U_N measures the preference for the number of benefited families (n_F). U_N is defined as proportional to n_F, with values of zero and 1 respectively for zero benefits and a maximum number of them (N_{MAX}). The utility for social benefit (U_{IS}) is thus

$$U_{IS}=U_T\times U_N \tag{2}$$

To define the utility scale for the environmental objective (U_{IA}), it is necessary to define changes in the degree of pollution of the stream with respect to its original (or current) pollution level. First, a scale for the current pollution state of a stream is defined and shown in Table 2. Several established protocols [28] exist for determining BOD, Suspended Solids, and oil and gasoline content. The state of a stream relative to the content of froth and floating solids is determined using visual evidence (photographs) that is contrasted to visual scales made of pictures of rivers with different amounts of pollution. The ranges of values of the parameters that are contained into the denomination "Practically Clean", "Slightly Polluted" and "Highly Polluted", follow guidelines for water quality published in relevant literature [28, 29]. Ultimately, however, the definition of these ranges is subjective, depending on the concerns of the deciding entity.

Table 2. Current pollution state of the river

Name	**Description**
Practically clean	Organic content less than 5 mg/L of BOD Suspended solids content less than 50 mg/L There is no grease, oils or gasoline in the water There is no presence of floating solids or froth There are native animal species
Slightly Polluted	Organic content more than 5 mg/L and less than 50 mg/L of BOD Suspended solids content more than 50 mg/L and less than 110 mg/L Slight content of grease, oil or gasoline in the water Moderate presence of floating solids or froth There is no native animal species in the water
Highly Polluted	Organic content more than 50 mg/L of BOD Suspended solids content more than 110 mg/L Heavy content of grease, oil or gasoline in the water Heavy presence of floating solids or froth There isn´t any animal species in the water

Table 3 shows definitions for the increase in pollution caused by the project. It is unlikely that, by itself, the SHPS generates enough polluting agents to make the pollution state of the stream to change from one level of Table 2 to another. However, it is decided that the project should not contribute to more than one hundredth of the pollution increase necessary for the pollution state of the stream to shift levels. Other criteria that can be used can be found in literature about environmental impact calculations [29]. However, this is a subjective element and varies between countries and deciding entities.

Table 3. Definition of the increase in the pollution in the stream

Name	**Description**
No change	The project adds, per day, less than 50 mg of BOD and less that 300 mg of suspended solids per m^3/day of flow-rate. There is no addition of oil, grease or froth forming substances
Slight Increase	The project adds, per day, between 50 mg and 400 mg of BOD or between 300 mg and 600 mg of suspended solids per m^3/day of flow-rate. There is no addition of grease, oils or froth forming substances.
Strong Increase	The project adds, per day, more than 400 mg of BOD or more than 600 mg of suspended solids per m^3/day of flow-rate, or there is an addition of grease, oils or froth forming substances.

Using the definitions of Tables 2 and 3, values of utility for the environmental objective (U_{IA}) were assigned to different increases in the pollution of the river relative to its original pollution state (Table 4). Again, the level definition and utility values should reflect the preferences (under uncertainty) of the deciding entity. The equivalent probability method [22] was used for getting the shown values.

Table 4. Definition of the utility measure for the achievement of the environmental objective U_{IA}

Level	**Description**	U_{IA}
A	The project doesn´t change the pollution of the effluent	1.0
B	The project causes a slight increase in the pollution of an effluent that is already highly polluted	0.9
C	The project causes a strong increase in the pollution of an effluent that is already highly polluted	0.8
D	The project causes a slight increase in the pollution of an effluent that is already slightly polluted	0.6
E	The project causes a strong increase in the pollution of an effluent that is already slightly polluted	0.5
F	The project causes a slight increase in the pollution of an effluent that is currently practically clean	0.4
G	The project causes a strong increase in the pollution of an effluent that is currently practically clean	0

In order to assess the utility measure for the achievement of economical results (U_E), the annual profit (*Profit*) is calculated as annual income minus annual costs. If *Profit*>0, the years required for amortize the investment are calculated (T_R), and U_E is read from a graph of U_E vs. T_R (Figure 4-a). If *Profit* ≤0, U_E is calculated from a graph of U_E vs. the annual loss (Figure 4-b). The shapes of these curves depend on the risk attitude of the deciding entity, and can be regressed from points determined using the reference lottery method [22].

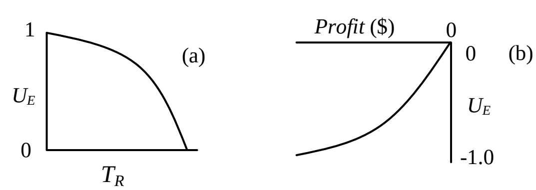

Figure 4. U_E assessment for a)Profit>0 and b) Profit ≤0

The overall utility (U), is calculated using the additive utility function (3)

$$U=k_{IE}\times U_E + k_{IS}\times U_{IS} + k_{IA}\times U_{IA} \tag{3}$$

The weights k_{IE}, k_{IS} and k_{IA} represent, respectively, the relative importance of the economic, social and environmental objectives, and are calculated using the swing-weighting method [30].

2.1 Factual model

The factual part of a decision model maps the alternative courses of action into the overall objective of the deciding entity. This model incorporates the current knowledge available to the deciding entity, and, for this problem, is represented by the influence diagram of Figure 5. When the installation site is selected (rectangle to the right), the cost of the SHPS is known (double-bordered circle). However, the flow rate variability causes the quantity of electricity generated to be uncertain, and so "Energy" is shown as a circle in Figure 5. More specifically, the uncertain knowledge about the quantity of electricity generated is captured as a contingency table (Table 5), with probabilities for different energy generation levels (E_i), for *i* from 1 to *n*

Table 5. Example of contingency table for produced energy

Energy (kW)	**Probability**
E_1	p_1
E_2	p_2
:	:
E_n	p_n

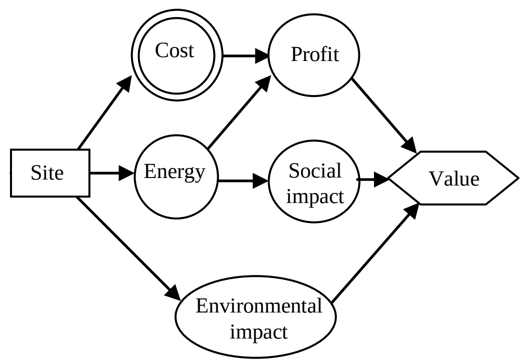

Figure 5. Influence diagram for site selection

The probabilities of different levels of social impact are conditional on the amount of energy generated (Table 6)

Table 6. Contingency table for social impact

Level of social impact	**Description**	U_{IS}	**Produced Energy (kW)**			
			E_1	E_2	**…**	E_n
Low	…	$U_{IS,1}$	p_{11}	p_{12}		p_{1n}
Medium	…	$U_{IS,2}$	p_{21}	p_{22}		p_{2n}
High	…	$U_{IS,3}$	p_{31}	p_{32}		p_{3n}

The different values of $U_{IS,i}$ follow from the description of the social impact and the information shown in Table 1 and Equations 1 and 2. Finally, for each SHPS design and site, the probabilities of different levels of environmental impact are contained in a contingency table (Table 7).

Table 7. Example of a contingency table for environmental impact

Level of environmental impact	**Description**	**Value of** U_{IA}	**Probability**
Low	…	$U_{IA,1}$	p_1
Medium	…	$U_{IA,2}$	p_2
High	…	$U_{IA,3}$	p_3

The values of $U_{IA,i}$ follow from the description of the levels, and the values shown in tables 2 to 4. Experimentation and statistical registers can be used to calculate the probabilities shown in Tables 5 to 7. However, in the absence of such information, the model should rely in subjective probabilities obtained from experts, or, in cases when none is available, from the modeler himself. These subjective probabilities should be elicited using a method that guarantees a meaningful probability value, for example, the probability wheel [26,31].

3. CASE STUDY ANALYSIS

In order to illustrate the application of the decision model, the hypothetical region of Figure 6 is considered. It should be decided whether to install the SHPS in the sewage stream or to install it in the clean water stream. The sewage stream current pollution state is "Highly Polluted" and that of the clean stream is "Practically Clean" (Table 2). The costs involved in the SHPS installation for these sites are shown in Table 8.

Table 8. Purchase and installation cost of a SHPS for each site in Figure 6

Site	Cost ($)	Cleaning cost ($/day)
In the sewage stream	250'000	3
In the clean stream	300'000	0

The shown costs are based on those produced by Ogayar [10] for installations of similar hydraulic head and flow rate. They are used here as rough approximations of the SHPS costs, so the application of the decision model could be illustrated. However, when real candidate sites for the SHPS are considered, a detailed cost calculation should be performed. The graphs, shown in Figure 4, that allow the calculation of U_E, were determined by quadratic regression over the values shown in Tables 9 and 10.

Table 9. Values of U_E vs T_R for regression

Years to amortization	U_E
1	1
10	0.7
20	0

Table 10. Values of U_E vs Profit for regression

Annual Profit ($)	U_E
0	0
–140	-0.6
-400	-1

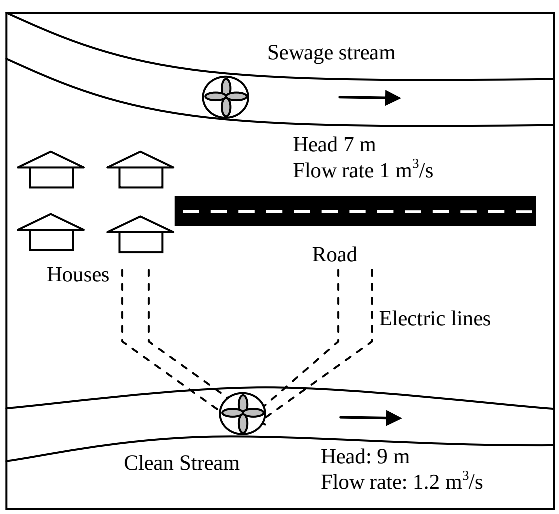

Figure 6. Region for the case study

The nominal electricity production for the flow rates and heads shown was estimated from charts provided by hydro turbine manufacturers [30]. To account for the uncertainty in flow rate, subjective probabilities were assigned to values 10 kW smaller and bigger than the nominal (Tables 11 and 12).

Table 11. SHPS energy production when located in the sewage stream

	Level	**Value**	**Probability**
Production (kW)	Low	30	0.3
	Medium	40	0.5
	High	50	0.2

Table 12. SHPS energy production when located in the clean water stream

	Level	**Value**	**Probability**
Production (kW)	Low	50	0.3
	Medium	60	0.5
	High	70	0.2

The probabilities of Low, Medium and High social impact, depend on the amount of electricity generated and the amount consumed by the families that are supposed to benefit from the SHPS operation. The average family consumption of electricity is between 6443 and 17'178 kW-h per year. As rural families are more likely to have a low electricity consumption than a high one, the consumption range is discretized into three values and probabilities assigned to them (Table 13)

Table 13. Definition and probabilities of electricity consumption per family

	Level	**Value**	**Probability**
Consumption (kW-h/year)	Low	6443	0.3
	Medium	12080	0.6
	High	17718	0.1

The social impact depends on the number of benefited families (n_F), which is obtained dividing the annual electricity production by the low, medium and high annual electricity consumptions. The utilities U_{IS} are calculated dividing n_F by one hundred. For instance, for a production of 70 kW, Table 14 shows the corresponding U_{IS} values.

Table 14. Probability of levels of social impact for 70 kW of electricity generation

	Level	**Value**	U_{IS}	**Probability**
Benefited families (n_F)	Low	35	0.35	0.3
	Medium	51	0.51	0.6
	High	95	0.95	0.1

While the SHPS is unlikely to produce organic pollution in the form of BOD, the main environmental concerns are the spillage of solvents, grease or froth forming substances to the water, and an increase in the suspended solids concentration as a result of increased water speed and shaft rotation. The utilities for these consequences, and their probabilities, provided by an environmental engineer, are shown in Table 15.

Table 15. Probabilities of levels of environmental impact for the candidate sites for SHPS installation

			SHPS installed in	
	Level	U_{IA}	**The sewage stream**	**The clean stream**
Environmental impact	Low	1.0	1.0	0.1
	Medium	0.4	0	0.5
	High	0.0	0	0.4

4. RESULTS

We consider the economic, environmental and social objectives to be of the same importance, thus k_{IE} = 0.3, k_{IS}=0.4 and k_{IA}=0.3 in Equation 3. The expected values of the amortization time (T_R), number of benefited families (n_F), the utilities for the economical (U_E), social (U_{IS}) and environmental aspects (U_{IA}) and the overall utility (U) of both candidate sites are shown in Table 16

Table 16. Model Results

	SHPS installed in the sewage stream	SHPS installed in the clean water stream
$E[T_R]$ (years)	15.4	11.1
$E[n_F]$ (families)	34	52
$E[U_E]$	0.352	0.641
$E[U_{IS}]$	0.340	0.526
$E[U_{IA}]$	1.0	0.30
$E[U]$	0.545	0.493

When the SHPS is installed in the sewage stream, it produces a bigger $E[U]$ than when it is installed in the clean stream (0.545 versus 0.493). Thus, according to the maximum expected utility criterion, the SHPS should be installed in the sewage stream instead of being installed in the clean water stream.

However, as shown by the values of $E[U_E]$ and $E[U_{IS}]$, installing the SHPS in the clean stream is the preferred alternative with respect to the economical and social objectives, being the inferior alternative only with respect to the environmental objective ($E[U_{IA}]$). Thus, a question that should be probed is how the preferred alternative changes when the parameters that measure the environmental aspect of the decision change. These parameters are: the importance of the environmental objective relative to the other objectives, given by the constant k_{IA} of equation (3); and the probabilities of different levels of environmental impact given that the SHPS is installed in the clean water stream (right column of Table 15).

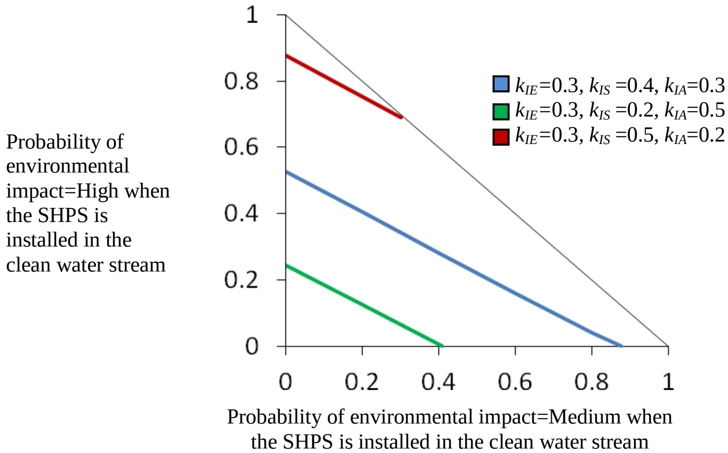

Figure 7. Sensitivity Analysis

Figure 7 shows the sensibility of the decision with respect to these parameters. The horizontal and vertical axis are, respectively, the probabilities of causing an environmental impact of level "medium" and the probability of causing a "high" environmental impact. Both probabilities are conditional on the installation of the SHPS in the clean stream. Three lines are shown: the blue one is the original (k_{IA} =0.3), the green one emphasizes the environmental objective (k_{IA}=0.5) and the red line the social one (k_{IS}=0.5). For all lines, the emphasis on the economical objective is the same (k_{IE}=0.3). If a point lies in the zone above the relevant line, this means that the SHPS should be installed in the sewage stream, instead of installing it in the clean water stream.

For instance, if the concern about the environmental impact is big (green line in Figure 7), it suffices that there is a probability greater than 0.4 of causing a "medium" environmental impact by installing the SHPS in the clean stream, to prefer its installation in the sewage stream instead. On the other hand, if, when installed in the clean stream, the probabilities of the SHPS causing environmental impacts "medium" and "high", are, respectively, less than 0.2 and 0.1, the SHPS should be installed in this stream.

If the social objective is more important than the environmental one (red line), the zone of Figure 7 in which the installation of the SHPS in the sewage stream is preferred over its installation in the clean water stream, is very narrow. Only if the probability of causing a "high" environmental impact by installing the SHPS in the clean water stream is greater than 0.7, then it is preferable to install the SHPS in the sewage stream.

5. CONCLUSIONS

The aim of this work is to present the development of a decision model for assessing the feasibility of installing SHPS in polluted rivers. By using Decision Analysis, the model accounts for all relevant aspects of the problem, and introduces the information available at the moment of making the decision. For incorporating non-measurable objectives, like those of environmental and social nature, attributes should be constructed, and utilities assigned to different results described in terms of those attributes. The attribute definition and the actual values of the utilities are subjective, depending on the particular concerns of the deciding entity. The ones presented here, and used for the calculations in a simple case study, represent, from the point of view of the researchers involved in the preparation of this article (industrial, environmental engineers and graduate engineering students), a plausible set of values for a public entity responsible for the decision. When a real life problem is considered, however, care should be taken to assure that the value model adequately represents the concerns of the deciding entity, which can be a public or private electricity company. While several methods are available for testing the value model, most of them imply checking the consistency between a list of consequences, ordered by preference, provided by the deciding entity, and the preference order of the same consequences implied by the value model [27].

Once the results of the case study are obtained, a sensibility analysis was presented, in which the changes of the optimal decision caused by changes in factual and value parameters were investigated.

Currently, real information (population, state of the electricity services, water streams and their state of pollution, etc.), of a real, medium sized region, is being gathered in order to apply the decision model to a more realistic, complex problem.

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