Ranking Hydroelectric Power Projects with Multicriteria Decision Analysis

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The Norwegian master plan for water resources called for ranking 542 hydropower projects. Two methods were used. The official one was process-oriented rather than analytical but was still intended to be formal and open to investigation. The ranked list produced was backed by the Norwegian government. We used the second method based on multicriteria decision analysis to review the first result. To our embarrassment, the two ranked lists turned out to be almost diametrically opposed to each other. In a public confrontation, political pragmatism was pitted against scientific ideals. Subsequent cooperation led to insight on a higher level and fruitful synthesis of methods.

The development of a master plan for the remaining hydroelectric sources in Norway involved ranking 542 power plant projects. The Norwegian Parliament had demanded that cheap and uncontroversial projects be developed before expensive and controversial ones. This was the overall objective. Forecasts for the construction costs and energy production of each project were available. In addition, the Ministry of Environment had collected data indicating the degree to which interests in such diverse areas as landscape, recreation, wildlife, water supply, water pollution, agriculture, flooding, transportation, climate, and reindeer herding would be affected by any particular project. The problem then was

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to develop consistent and acceptable ranking criteria to account for all the implied subobjectives. Each project was to be evaluated on its own merits rather than as part of a "portfolio" of projects. The resulting ranked list would then be approved by the Parliament and would be used by the bureaucracy to monitor the actual development of new hydroelectric sources.

Background and Mandate

Norway has an abundance of waterfalls. They have long been used as energy sources, and today they are the major source of electric energy. As of 1984, 100 TWh per year (trillion watt-hours per year) of a total potential of 173 TWh/year has been developed.

Recently, there has been mounting opposition to further development of hydroelectric power. The Norwegian Parliament therefore asked for a master plan for the possible development of the remaining 73 TWh of viable hydropower sources. The mandate was to rank hydroelectric power projects "so that the economically sounder and less controversial projects can be developed before the more expensive and more controversial ones." Current prognoses predict an additional demand of 10 TWh by the year 2000, and the government wanted to identify enough projects that could be developed in time to meet this demand. The Ministry of Environment was given responsibility for the project, and the Ministry of Petroleum and Energy and the Norwegian Water Resources and Energy Administration were official participants.

It is not surprising that such a huge project became controversial among politicians and among scientists. This somewhat typical conflict between political goals and scientific ideals was solved through a dialectical process of thesis, antithesis, and synthesis.

Data

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of Environment first established a data base containing descriptions of each of the 542 projects. For each of the 542 projects, economy was expressed as present value of construction costs computed at seven percent, divided by yearly production. As a hedge against uncertainty (or to prevent too much insight), the values were grouped into six classes.

Conflict potential was derived from 14 explicit objectives: to protect *nature*, to protect *recreational* activities, to protect *hunting*, to protect *fishing*, to provide an adequate supply of drinking *water*, to protect against water *pollution*, to protect historical *sites*, to protect *agriculture*, to protect *reindeer* herding, to protect against *flooding* and erosion, to improve *transportation* facilities (roads etc.), to control ice and water *temperature*, to avoid changes to *climate*, and to maximize benefits to *regional economy*.

For a particular project, the degree of conflict associated with a subobjective was measured on a subjective scale ranging from −4 to +4 (−4 indicates serious conflict, 0 no effect, and +4 very positive effects). Positive effects would occur when, for instance, the project provided flood protection or required new roads that improved transportation for isolated communities. The data were collected by 14 teams of experts. Scores were supposed to be comparable across projects. For instance, a score of −3 for *nature* on one project and a score of −3 for *nature* on another project would mean that the real damage to nature was about the same.

During the data collection period, some people felt uncomfortable with the subjective scales because they lacked anchor points and had to resort to gross approximations. Earlier the ministry had successfully conducted a related task where the objective had been to select areas to become national parks. Areas were selected on the basis of their uniqueness in one or more respects. In the case of national parks, subjective scales had turned out to be efficient, since an area with a sufficiently high score on one objective would automatically be a national park candidate, regardless of the scores on other objectives. No trade-off analysis had been necessary. This is similar to lexicographic ordering, where one objective is infinitely more important than others. It was therefore natural to try to apply the same ideas to the hydropower problem. It was not immediately understood that the two problems might be fundamentally different. By building a hydropower plant, one sacrifices environment to get energy. There is a trade-off to be considered, which should be accounted for by a proper ranking procedure. Trade-off analyses weigh objectives, which is difficult without good scales. Having already spent $10 million to collect data, however, the ministry could not be persuaded to do it again with objective scales.

The data base contains 542 economy scores between 1 and 6. For a particular project, the lower the figure, the less the construction costs per unit of energy produced. The data base also includes 542 times 14 scores between −4 and +4, one score for each of the 14 subobjectives. The lower the score, the more the project is in conflict with that subobjective.

These data indicate the social and economic costs associated with hydropower development.

The *benefits* were expressed by 542 energy production rates. They range from 1 to 2,500 GWh (billion watt-hour) per year. The distribution of the 542 production rates is shown in Figure 1.

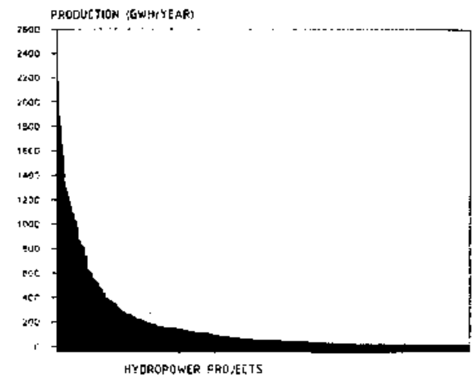

Figure 1: A bar chart of the energy production of the 542 projects considered in the master plan. To show the distribution of project sizes, the projects are ordered along the horizontal axis, each represented by a bar. The separate bars are hardly visible. Together they form a profile which reveals that a major problem of the project is to consistently rank a large number of insignificant projects and a small number of projects that are up to three orders of magnitude bigger.

The Ministry's Ranking Method

According to the mandate, the ranking should achieve economy and should minimize conflict. This was interpreted literally: The more economical and the less controversial a project was, the higher its priority. Hence, two data reduction processes were performed: first, the 14 variables expressing conflicts with subobjectives were reduced to one representing the overall conflict potential for each project; then, the economy index and the conflict potential were combined into a rank index.

To compute the overall conflict potential of a project, the Ministry adopted an ad hoc procedure with the following general features (the details have not been made public). For a given project, two parameters were calculated. First, the number of occurrences of −4 and −3 scores for the 14 subobjectives was counted. The result indicated whether the project was at all viable. Then the scores were totalled to indicate the general conflict potential of the project. The two parameters were then combined (but exact information on how this was done is not available). The result was a number between 1 and 8. This was called the *consequence class* of the project. The higher the consequence class, the higher the conflict potential of the project.

From a multi-criteria decision making point of view, the process is akin to using a multiplicative utility function where the attributes are treated as substitutes. The process did not discriminate between the subobjectives, except for agriculture which was counted twice, the argument being that it consists of both forestry and farming. Explicit differentiated weights were avoided, thus giving most readers an impression of objectivity. In reality, of course, this process implicitly uses equal weights. Using equal weights is certainly more arbitrary than using carefully chosen differentiated weights. Nevertheless, by using a poorer set of weights, the Ministry was politically better off: they evaded the controversies that would have arisen had they tried explicit differentiation.

The last step was to combine the economy index and the consequence class to obtain a single priority score (Table 1).

Table 1 is akin to a two-dimensional utility function which assigns a priority class to any project, based on a combination of economy and its classifications for consequence. The lower the cost of the energy produced and the more limited the project's adverse effects, the lower is its priority class figure. A low priority class means that the project has high priority. For example, Project A is

	Consequence Class							
	K1	K2	K3	K4	K5	K6	K7	K8
E1	1	1	2	3	5	7	9	12
E2	1	1	2	3	5	7	9	12
E3	2	2	3	4	6	8	10	13
E4	3	3	4	6	7	9	11	14
E5	4	4	5	6	8	10	12	15
E6	5	5	6	7	9	11	13	16
	Priority Class							

Table 1: The priority class is found by combining the economy index (E1 . . . E6) and the consequence class (K1 . . . K8) of a project. The priority class (P1 . . . P16) scores are inside the matrix.

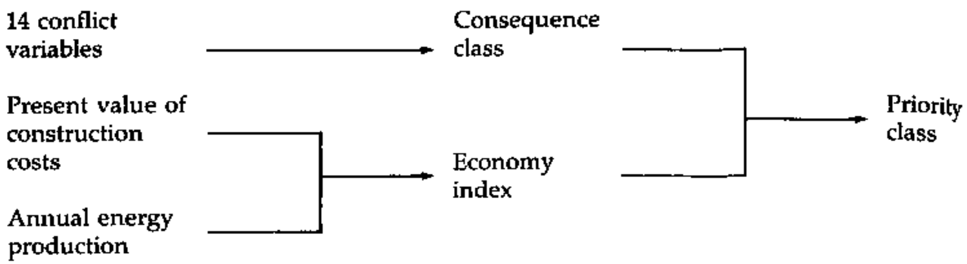

Figure 2: In the ministry's data reduction process, 16 variables that completely describe a hydropower project are reduced to a priority score.

expensive (E6) but has little potential to arouse conflict (K3). According to Table 1, it belongs to priority class 6. Project B is inexpensive (E1) but has a greater potential to produce conflict (K6). It is assigned to priority class 7 and hence is ranked after project A.

The table was constructed on a heuristic basis by evaluating some well-known projects and assigning them a reasonable priority. Figure 2 summarizes the Ministry's ranking method.

The Ministry's Ranking Method Is Irrational

One basic tenet of rationality is that of efficiency; if you are insatiable and A offers you more for the same price than B, it is rational to choose A. Using this assumption, one may conclude that the ministry's ranking method, although it seems reasonable and appears to conform with the mandate, is actual irrational. Look again at the table. A project that is cheap per GWh and is by itself uncontroversial will get high priority, as intended. However, small projects will be favored. If instead of considering single projects in isolation, we look at their effect nationally, we see that the method does not control the cumulative damage of many small projects! It is likely to produce a ranking list where the nationwide sum of damages will be larger than necessary for any given production level.

As a matter of fact, it turned out exactly so. For example, the ministry classified two projects, the Otta/Lågen project and the Staurset project, as both having the same economy class and consequence class, E4 and K4.

Both projects were judged as carrying the same costs per GWh and the same conflict potential (which is an absolute measure, not relative to GWh). They are therefore considered identical with respect to the preference rating scheme (Table 1) and, accordingly, they were given the same priority.

However, Otta/Lågen produces 1,117 GWh/year whereas Staurset only produces 12. This information never entered the ranking process.

The Government's Proposed Master Plan

The ministry ended up with a list of 153 projects to produce an additional energy supply of approximately 10 TWh. This corresponds to the first four priority classes P1-P4. Figure 3 is a bar chart showing the energy production of each of the 542 projects in the order in which

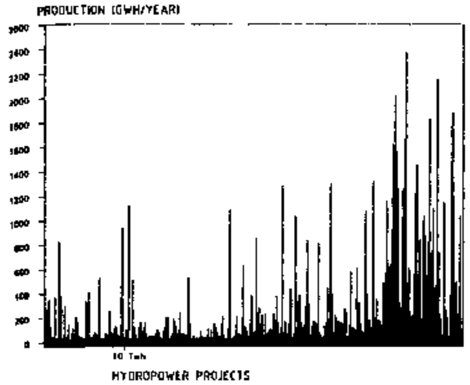

Figure 3: The bar chart shows the 542 projects ordered according to the ministry's ranking list. Each bar represents one project, and its height indicates the project's energy production. Big projects tend to appear to the right, indicating low priority for these projects.

they were ranked, with a bar representing each project. It is obvious that small projects are given the most favorable priority ranking. Figure 4 shows the projects in the same order as Figure 3, with the bars representing consequence classes. The black area to the left of the 10 TWh-mark visualizes the national sum of negative consequences if the list were to be followed.

Figures 3 and 4 reveal the essentials of the proposed master plan: A few large projects and a large number of almost insignificant projects were given the highest priorities, making it necessary to build a large number of projects to generate the 10 TWh expected to be needed by the year 2000.

Reception of the Master Plan Proposal

One would think that the master plan proposal would be rejected immediately, based as it is on an irrational ranking procedure. Not so. The proposal was generally well received by politicians and environmentalist organizations. Industry spokesmen and the Norwegian Water and Electricity Board, however, disliked it.

The politicians had neither the insight to comprehend the total impact of the proposed plan, nor the analytical skill needed to discover its methodological inconsistencies. The big picture was hidden by details.

The politicians were primarily concerned with possibilities for conflict. Since the projects were geographically well distributed, and no single conflict threatened to become overwhelming, they were satisfied.

Environmentalists traditionally advocate that "small is beautiful," and therefore they prefer smaller power stations as a matter of principle. Besides, since the project was directed by the Ministry of Environment, they probably thought it was in safe hands.

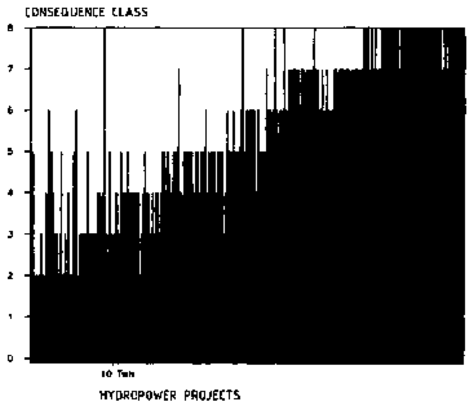

Figure 4: A bar chart with the 542 projects in the same order as in Figure 3. The height of a bar now indicates the conflict or damage associated with that project. The black area to the left of the 10 TWh mark shows the nationwide damage that would be inflicted if 10 TWh were to be developed according to the ministry's ranked list.

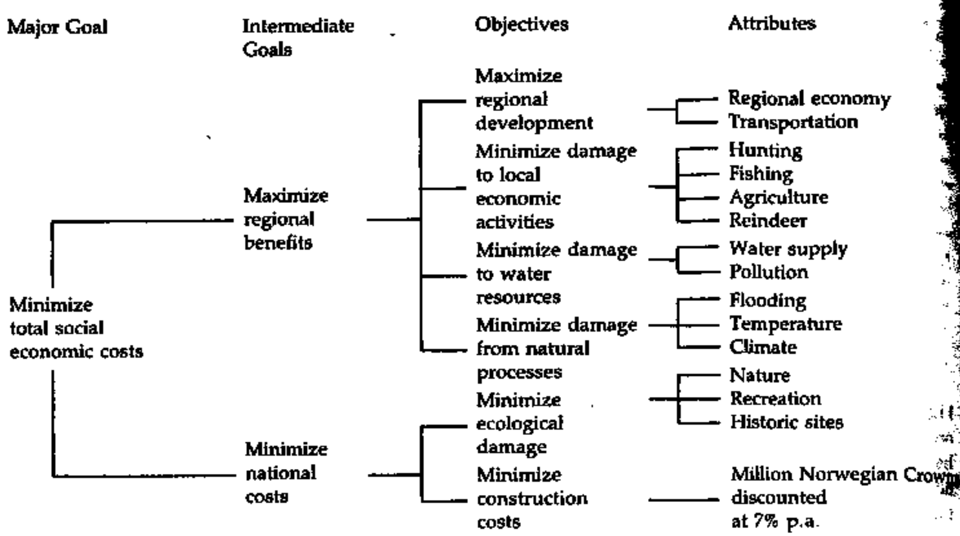

Figure 5: The goal hierarchy used to construct a decentralized utility function in the alternative analysis. All objectives are per energy unit.

Industry's primary concern was that building many small power stations was likely to involve delays, and they feared that this would cause a shortage of energy in the near future.

The Water Resources and Energy Administration was most insightful on the subject. They were also the most critical and voiced a suspicion that the implied nationwide damage was unnecessarily large. We were at the time members of a scientific advisory board on methodology for the project. Being vocal critics of the work done so far, we were engaged to perform an alternative analysis.

The Alternative Analysis

We were alloted neither time nor money to collect better data. We had to rely on the same data base as the ministry. We decided to use the classical MCDM approach of Keeney and Raiffa [1976]. We first constructed a goal hierarchy (Figure 5).

We structured the goal hierarchy to allow for geographical differences with regard to the importance of the 11 regional attributes. We did this by dividing Norway into five regions. From each region, a group of three to four persons were interviewed during a half-day session with computer-interactive questions and answers. We used the answers to construct five independent regional multiplicative utility functions. In addition, we constructed one national utility function for the national objectives in the goal hierarchy. Thus we could decentralize decision authority for regional issues and at the same time centralize it for national issues. One of the results of the interviews was that we established weights for the 15 attributes that were significantly different from each other. The ministry's use-

...ual weights had been a poor approx...ion. Another result was regional dif...es. Climate, transportation, and ...control appeared to be more important in the western and northern parts of ...ountry where living conditions are ...precarious. Recreation and agricul... ...ended to be emphasized in the more ...nt southern and eastern parts.

...were not able to fully carry through ...ambitious program, however, because ...er factors disrupted the project.

...r Alternative Ranking Method

...ur ranking method was as follows: ...used the (hierarchical multiplicative) ...ity function to calculate the total util... of each project based on the 15 varia... (the term *utility* may be misleading, ...ce all 15 variables represent some kind ...social or economic cost associated with ...project). Energy production is not yet ...luded. To account for it, we calculated ...e social and economic costs per energy ...it produced [Wenstöp 1983]:

...*king index* = (1 − *utility*)/*production*.

...s we saw it, our method was rational ...d would lead to a master plan with the ...west social and economic costs per en...y unit produced, seen on a national ...le. When we applied our ranking cri...a, however, we came up with a list of ...y seven projects (compared to the gov...ment's 153) to produce the 10 TWh of ...rgy. The nationwide damage from the ...en projects appeared to be about one-...d of that of the official proposal.

...r Project Is Aborted — and Started ...in

...fter seeing the results of our ranking ...thod, the Water Resources and Energy ...ministration abruptly dropped the project. From their point of view, our highest ranked projects were politically impossible. Therefore, they reasoned, a method which produces such results is clearly not suitable. We were, however, given two days to come up with new information that might make them reconsider their decision.

We could find no errors in the method and we concluded that something must be wrong with the data. Exploratory data analysis produced an interesting diagram.

In Figure 6, the vertical axis shows the sum of the 14 conflict numbers, an approximate measure of the damage or conflict associated with each project. As the figure shows, the data base clearly underestimates the damage associated with larger projects. This problem could be

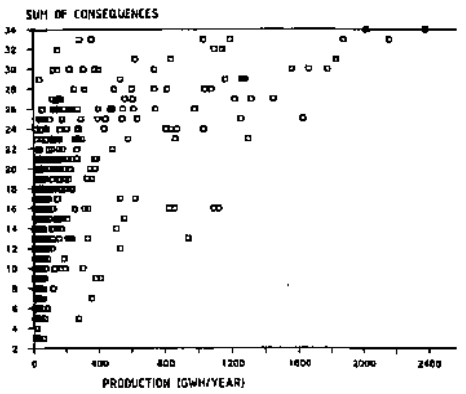

Figure 6: Data analysis of the relationship between estimated damage and energy production. Each dot in the diagram represents a project. The sum of consequences, a measure of the conflict or damage associated with a project, is evidently only weakly related to the size of the projects. The graph made people at the Water Resources and Energy Administration immediately realize that the data base seriously underestimated the damage associated with large projects.