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Exploring the impact of technology development and adoption for sustainable hydroelectric power and storage technologies in the Pacific Northwest United States

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ABSTRACT

A wide range of literature streams and methods were examined for this research, including sustainability, integrated resource planning, and construction of portfolios of electricity generation technologies. The research then focused on current and emerging HPSTs (hydropower generation and storage technologies), and technical, economic, social, and environmental sustainability objectives associated with those technologies in the PNW (Pacific Northwest) region of the United States. Candidate technologies obtained from the literature were examined using the Delphi Method, and then rated according to their perceived impacts using the AHP (Analytical Hierarchy Process). GP (Goal Programming) was then used to determine an optimal mix of technologies to achieve sustainability objectives, using these weightings and assumptions related to specific scenarios regarding technology development, adoption, and availability. This research is important because few previous studies have systematically considered multiple objectives and criteria from multiple stakeholder experts for creating portfolios of sustainable electricity generation technologies. Previous research has also not comprehensively investigated the manner in which changing scenarios of technology development and availability rates may lead to various technological, economic, environmental, and social sustainability impacts with regard to planning of regional electrical generation and storage systems.

1. Introduction

After examining a wide range of literature related to sustainability [1–4], integrated resource planning [5–7], and construction of portfolios of electricity generation technologies [8–10], this research determined that few previous research studies have systematically considered the overall effects of technical, economic, social, and environmental sustainability objectives related to constructing electricity generation portfolios according to multiple stakeholder perspectives [11]. Past research has also not systematically investigated the probabilities that changing scenarios of technology development and availability rates may lead to changing scenarios for sustainability [12] in the planning of regional electrical generation and storage systems. Further, these issues have not been addressed with regard to HPSTs (hydropower generation and storage technologies) in the PNW (Pacific Northwest). After examining various methods for conducting this research, a combination of GP (Goal Programming), technology forecasting of HPST related technology development and adoption trends, and expert importance weightings determined via the AHP (Analytical Hierarchy Process) were found to be promising methods for addressing this topic.

The following sections describe the process of executing the research for this study. The research design is explained in greater detail, along with assumptions that were necessary to make in order to conduct the research. Experts and other resources are identified in order to perform the data collection. The data are then processed and analyzed to determine implications, limitations, and further research directions.

2. Data collection

The first part of this research involved data collection. Data from knowledgeable experts in fields related to sustainable energy played an essential role in this research. In discussions with leading energy experts in the region, it was found that many aspects of the planning process have not been formally codified. A great deal of knowledge has typically been tacit and informal. Thus, knowledge capture was

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needed. The Delphi method was used for this initial knowledge capture because it has a proven track record for collecting and synthesizing information from independent experts in order to develop a consensus outlook on a topic under consideration [13]. Experts were selected from organizations in the PNW that focused on one or more aspect of technological, economic, environmental, and social factors regarding sustainability and energy-related issues. A number of these organizations are focused on issues that overlap one or more of these categories. Thus, they were categorized by their primary activity to the best of the researcher's ability. Although many experts were contacted from a wide range of organizations, the following results were obtained from respondents who filled out the entire questionnaire, had acceptable levels of consistency in their responses, and returned the information soon enough to be included in this study: *Technological* (3); *Environmental* (2); *Economic* (3); and *Social* (4).

Literature established that typical categories of factors related to sustainability and energy development often have involved technological, economic, social, and environmental issues [11,14–16]. A short questionnaire was prepared listing a few start concepts in each category and then asking experts to add or remove suggested concepts, as well as ranking the relative importance of these attributes toward achieving a sustainable HPST portfolio in the PNW. An advantage to this type of research was that it was a relatively fast and easy process which was also a good way to initiate a conversation with the target group of experts. Appendices for the questionnaire used, technology descriptions, and definitions are omitted here for brevity. The candidate technologies were then selected based on an assessment of those deemed most likely to offer reliable and sustainable hydroelectric power generation and storage. Experts were then asked to rank the technologies they considered most appropriate for HPST applications and to provide those along with any comments on the initial questionnaire.

Experts in this study were selected from a variety of backgrounds in order to gain insights from as many key stakeholder perspectives as possible, including the technological, economic, social, and environmental viewpoints. Many experts were contacted, but only 15 returned the initial survey form in a way that was complete, timely, and usable in the initial phase of this study. Of those respondents, three had levels of inconsistency that were unacceptable on the final questionnaire. Attempts were made to resolve this, but in the end, only 12 total responses were useable. Responses were collected, along with any comments and then an overall set of criteria was created for the next round of the questionnaire. Further research was then done on each of the criteria identified. A set of directions was then given to guide experts in completing the next phase of this research, an assessment of the various criteria related to HPST alternatives using the PCM (pairwise comparison method).

The PCM instrument used in this study included criteria related to the technological, economic, social, and environmental impacts of HPSTs. These criteria were evaluated on a scale ranging from −9 to 9, which indicated the importance of each to sustainable hydroelectric power production and storage in the PNW. Scores of −9 corresponded to factors which were deemed "Extremely Less Important" to the topic, while higher scores were progressively more important, up to a score of 9, which indicated factors that were "Extremely More Important." Additional details are described below regarding the implementation of this process. When the final results were obtained, an AHP model was constructed, and the resulting priorities were used as weighting factors for a GP model. This model was used to find the mix of HPSTs that provided optimal target values for each of the technological, economic, environmental, and social sustainability criteria, as well as the mix that provided the minimum weighted percentage deviation from these targets. Trend data, obtained primarily through literature, technological analogy, and trend extrapolation was used in the model to predict possible changes in future performance related to criteria and technology availabilities, and the scenarios resulting from these projections were analyzed.

3. Results

The results obtained from the various implementation phases of this study are summarized in this section. After reviewing relevant literature, the first step in this research was to attempt to capture expert knowledge and judgment. Expert judgment is particularly important for energy resource planning problems, because they inherently involve tradeoffs and dynamic complexity that is not easily modeled with simple cost curves or individual econometric indicators [11]. It is also not easy to describe exactly how certain conclusions were reached in a formal or structured way, so as previously mentioned, there appears to be a fair amount of unspoken knowledge in the processes. Thus, a goal of this research was to begin capturing and, where possible, quantifying expert judgment on the subject. A quick form of the Delphi Method was used to gather information on criteria and technology alternatives judged to be most significant for sustainable HPST development in the PNW. There was only time to gather the information once, provide feedback, and then gather final judgments for assimilation. The information gained through the surveys and follow up interviews was then used for creating the PCM instrument used in the next phase of the research.

4. AHP

When the initial Delphi process was complete the PCM instrument was created and distributed. After all responses were returned, the data was analyzed using AHP [17]. Calculations were performed using software called *Super Decisions*. The software automates much of comparison process, making it unnecessary to manually enter data into matrices and perform normalizations. The overall index of consistency was 0.092, which was slightly better than the 0.100 threshold that is considered acceptable for AHP.

A HDM (Hierarchical Decision Model) is shown in Fig. 1, illustrating the structure of the problem of HPSTs in the PNW. The model is labeled with the calculated priorities. The HDM structure was used to create the LP (linear program) model in the next section, which describes each of these variables in greater detail. The Definitions and assumptions section contains further discussion and trend projections regarding this.

Graph 1 shows the overall impact of the criteria with respect to the goal.

Graph 2 shows the final prioritization process for the technology sub-criteria.

It makes sense that IHP (Incremental Hydropower) scores high on Graph 2, since this technology also has very good scores regarding investment cost and emissions, which were the two highest ranked criteria. It scores moderately regarding multiplier effects (i.e. jobs). The same points are true regarding PHS (Pumped Hydropower Storage), which is ranked the next highest, though considerably less than IHP.

The goal of performing this relatively brief assessment of the technical, economic, environmental, and social sustainability factors related to HPSTs was several fold. It is always beneficial to understand the structure of a problem and be able to decompose it into its key elements. However, the primary objective in this study was to use a quick AHP process to establish importance weighting for technology factors as they related to an overall assessment of sustainability. So, while many studies have quite successfully used AHP for technology selection, the goal of this study is to go beyond