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FEASIBILITY STUDIES FOR AQUIFER
THERMAL ENERGY STORAGE

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SUMMARY

Determining the feasibility of using aquifer thermal energy storage (ATES) for a particular heating or cooling application is an interdisciplinary effort, requiring (at a minimum) expertise in engineering and hydrology. The feasibility study should proceed in two distinct stages.

The first stage, which is limited in scope and detail, is intended to show if an ATES system is technically and economically suited to the application. Focus of this preliminary investigation is on revealing the existence of factors that might weigh heavily against the use of ATES methods, and, in the absence of such factors, on choosing a suitable scale for the ATES plant and well field. The results of the preliminary investigation are used to determine if more detailed investigation--including field studies--are justified, and to facilitate comparing the advantages of ATES to those of other means of providing heating or cooling.

The second stage of the feasibility study focuses on detailed aquifer characterization, refinement of engineering design and cost estimates, and economic and environmental risk analysis. The results of this investigation, if favorable, will be used to justify the expense of constructing the ATES system.

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INTRODUCTION

Designing an aquifer thermal energy storage (ATES) installation is an interdisciplinary task, one that is complicated by the fact that one major design component--the aquifer itself--cannot be modified. That is, the design specifications of this component are fixed, and must be reflected in the design of the plant superstructure in terms of both the hydraulic throughput of the plant and the total amount of heat or "chill" that can be stored within the aquifer.

There are other complications. For example, the availability, reliability, and intensity of the source of heat or chill used to charge the ATES system must be addressed. Also, some ATES systems require water treatment to prevent scaling or corrosion in hydraulic systems. Although there is much information relating to water treatment for engineered systems, there is only a relatively small amount of knowledge relating to the effects of circulating thermally and chemically altered water through an aquifer. Finally, because installation of an ATES system is intrusive to ground-water resources, both legal barriers and environmental risks must be assessed, and regulatory approval by government authorities will usually be required.

Thus, engineering skill in the design of conventional heat transfer systems alone is not sufficient to meet the demands of ATES design. Certainly, a hydrologist must evaluate the target aquifer. Chemical, legal, environmental, or other expertise may also be needed.

The ATES principle is attractive, but not universally practical. Therefore, a feasibility study must be performed to determine if an ATES proposal is worth pursuing technically, economically, and environmentally. To evaluate these factors, it is necessary to complete the fundamental design of the system and to "operate" it on paper. As noted above, this will require input from several technical disciplines.

This report was prepared by Pacific Northwest Laboratory at the request of the International Energy Agency (IEA). The U.S. Department of Energy represents the United States in the IEA for Annex VI, which is the IEA task for research and development in ATES. The intent of this report is to

simplify and expedite interdisciplinary collaboration in preparing the feasibility study by explaining what is most commonly needed for the study, why it is needed, and how it will be used. In addition, an attempt is made to identify logical stages for making a decision to proceed with the project, modify it, or abort it. This report is not all-inclusive, nor is there an intent to establish a rigid format for ATEs feasibility studies.

THE PRELIMINARY INVESTIGATION

The logical first steps in evaluating the feasibility of an ATES proposal are to do an initial survey of available resources and compare them to the objectives of the proposal. It is important to emphasize that this first effort is a "paper study," and should involve little or no detailed engineering, field investigation, or experimentation. Its intent is to determine if the scale of resource availability equals or exceeds the scale of the objectives. If so, the project--at first approximation--is feasible and should proceed to the next logical stage.

Often, the preliminary investigation will be an iterative process of attempting to match and rematch a desirable objective to the available resources. The objective will be initially described in operational terms; that is, in words that tell what and how much the ATES installation will be expected to do. However, objectives also need to be expressed in terms of economic advantage, energy conservation, or both, so that the project can be evaluated as an investment.

The following paragraphs introduce the most important elements of the preliminary investigation. The organization of what follows reflects the way that the results of the investigation might be presented to reviewers, rather than the actual conduct of the investigation. It is expected that most (if not all) of the required information will be acquired by examination of open literature and by reviewing the operational histories of existing similarly designed ATES installations.

OBJECTIVES

It is appropriate to tell the reviewers of a proposal what the proposed project is expected to accomplish, how it is to be accomplished, how much is to be accomplished, and at what cost. The following list of questions will serve as a checklist for developing project objectives:

1. What kind of ATES plant is proposed (e.g., chill storage, heat storage)?
2. What is the source of chill or heat (e.g., ambient winter air, process waste heat)?

3. What will the stored energy be used for (e.g., summer air conditioning of one or more buildings)?
4. What is the expected output of the ATES plant in terms of power and of economic value?
5. What are the technologic alternatives to the ATES project (e.g., use of fossil fuel)?
6. Is the intended benefit lower cost, strictly environmental (e.g., conservation of fossil fuel, even if at greater dollar cost), or both?
7. What is the estimated cost to construct and operate the plant, and what is its expected lifetime?

Once the project has been introduced by answering these questions, it is necessary to show that the available resources equal or (preferably) exceed the demands of the objectives, as described in the following sections.

ENERGY SOURCE

The source of energy used to charge an ATES system is ideally free and abundant, but whether it is practical or impractical to build the ATES plant to harvest that energy depends on several factors. First, the temperature of the energy source needs to be determined relative to the temperature of the ground water that will be heated or chilled. This is important because heat exchanger efficiency--and therefore overall plant efficiency--increases with increased temperature differential. (Though the focus here is on the energy source, and therefore on energy storage, the same argument applies to recovery of stored energy from the aquifer.)

Next, the availability of energy needs to be considered. At ATES installations such as the Tuscaloosa, Alabama, projects, where ambient winter air is used to chill water for summertime air conditioning, the amount of chill that may be extracted from the air is virtually unlimited. Nevertheless, the design engineer needs to know the duration as well as the intensity of both winter and summer temperatures to calculate the capacity and thermal balance of the ATES plant as well as its efficiency. In general, the smaller

the seasonal extremes, the less feasible an ATES plant of this type is likely to be. Similarly, year-to-year variations in mean seasonal temperatures should be considered.

For anthropogenic energy sources such as industrial waste heat, there are additional considerations. The most important of these is simply that the supply of energy is necessarily limited compared to an unlimited supply of free winter air in Tuscaloosa. Thus, a consideration of energy availability takes on an added dimension: total watts available. There are other, less important questions to be addressed as well. For example, how far must the energy be transported? Pipelines are costly in terms of construction, maintenance, and energy loss. Finally, the availability of an industrial energy source needs to be evaluated with respect to the long-term stability of both the industry and the particular process that is the source of waste energy.

THE AQUIFER

Once the objectives of the ATES project have been described and a reliable source of abundant free or low-cost energy has been located, it is appropriate to show that the aquifer has the capacity to store, and to later yield, a useful quantity of the energy. It must be emphasized that the *aquifer itself is the most important design component of the ATES plant*. The reason for this is that unlike pumps, heat exchangers, wells, or other manufactured components, the aquifer cannot be altered to meet desired specifications. Therefore, the ATES plant must be designed around the characteristics of the aquifer.

In designing an ATES plant, the engineer will treat the aquifer primarily as one or more insulated storage vessels. Therefore, the aquifer characteristics of paramount importance are the bulk storage capacity of the vessel, the rate at which water can be introduced to or retrieved from it, and the ability of the aquifer to preserve the thermal benefit of stored heated or chilled water.

Estimating these characteristics and communicating them to the design engineer is the hydrologist's domain. Storage capacity is calculated from the aquifer thickness, its effective porosity, and the lateral area available for

the well field. This last factor is legally as well as technically important. As a first approximation, it may be assumed that the maximum extent of the well field will be reflected by the amount of legally owned or controlled acreage in the vicinity of the proposed ATES installation. However, the use of water resources is controlled by government, particularly with respect to interference with other users of the resource. It will be the burden of the hydrologist to show that the ATES project will not cause such interference.

The rate at which water can be pumped into or out of the aquifer will be reflected by the specific capacity of the wells that will be used in the well field. The ability of the aquifer to preserve thermal benefit depends both on aquifer characteristics and on well field design and orientation. Important aquifer characteristics are the rate and direction of ground-water flow, dispersion along the flow path (which will increase the effective bulk, but reduce the mean intensity of the thermal plume), mean ambient ground-water temperature, and the retardation of the thermal plume with respect to mean ground-water flow rate. Fortunately, geologic materials appear to be good insulators, so heat loss to the surface or to other aquifers can be usually ignored, and migration of the thermal plume can be described in the foregoing hydrologic terms.

Well field design and orientation are obviously not intrinsic aquifer characteristics, but poor design choices can severely compromise the efficiency of an ATES project. Generally, recovery wells must be downgradient from injection wells, and at a suitable distance. Further, the entire well field must be constructed within legally controlled acreage, as noted above. It is entirely possible that a combination of high ground-water flow rate and small acreage could make the ATES project unfeasible. Also, if well field design limitations imposed by aquifer characteristics require, for example, that a row of injection wells be drilled beneath the ground floor suite of executive offices, the project proposal is not likely to be viewed favorably.

In addition to hydraulic parameters, the chemical makeup of the ground water should be communicated to the design engineer, because the possible need for water treatment to prevent scaling or corrosion must be addressed.

The scope and intent of the preliminary investigation will usually preclude field testing to determine aquifer characteristics. However, because of the intense scrutiny given to valuable ground-water resources, there will be a significant body of technical sources from which the hydrologist can draw reasonable estimates of the foregoing parameters. These sources include drilling and test reports, water resource maps and studies, and professional periodicals.

Finally, the hydrologist should provide drilling and well construction cost estimates for inclusion in the engineer's overall cost estimates (see below).

THE PLANT

The logic and process of plant design is beyond the scope of this report, but the results of the design process warrant discussion. Now that the engineer knows the project objectives, along with the characteristics of both the energy source and aquifer, the next logical step of this preliminary investigation is to scale plant design by creating a process flow chart and by specifying and sizing major components such as pumps and heat exchangers. This preliminary design should include, at a minimum, an estimated energy budget that takes into account the available energy for charging the aquifer, power required to run the pumps to circulate water, the amount of stored energy that is both recoverable and usable, and a broad estimate of both ancillary power requirements and the plant's annual operating cycle. This study will yield the net anticipated benefit of the ATES plant in terms of watts of available energy.

It is important to note that the engineer will need to identify the ATES factor that limits maximum plant capacity. It is likely that the limiting factor will be one of the following: aquifer storage volume, maximum pumping rate for aquifer injection or withdrawal, or energy availability.

Will the plant, scaled to accommodate the limiting factor(s), be sufficient to meet the demands of the objectives? If not, the project should be

aborted, or the demands should be modified. Similarly, if the plant's anticipated energy benefit appears to significantly exceed the objectives, it may be desirable to expand the objectives.

THE COST

Up to this point of the preliminary investigation, the intent has been to find any flaws in the ATES proposal that would render the project physically unfeasible. If no such fatal flaw has been identified, the next logical step is to perform a rough cost estimate for construction and operation of the entire facility, as well as for continued investigation.

The cost estimate should also include the dollar value of the anticipated plant output along with an estimated amortization schedule. That is, how long will it take for the plant to pay for itself?

It is by now apparent that the preliminary investigation has been a feasibility study itself, but one of limited detail and scope. Its intent has been to show that, because the proposed ATES project has a high probability of both technical and economic and/or environmental success, the next step towards project completion is warranted. That step comprises detailed aquifer characterization, further engineering design, and refined cost estimates as discussed in the next section.

THE MAIN INVESTIGATION

Like the preliminary investigation, the main investigation is a feasibility study unto itself, but with a somewhat different focus. The preliminary investigation was used to search for fatal flaws and to determine plant capacity. The main investigation, on the other hand, focuses on detailed aquifer characterization, refinement of the engineering design and cost estimates, and on risk analysis. Despite the difference in focus, presentation of results should reflect organization similar to that of the preliminary investigation.

The design effort will include modeling the plant operating cycle, but will not include the detailed design drawings or specifications necessary to actually construct the plant. Its intent is to derive operating characteristics of the ATES plant overall, and of the principal design components, which include the aquifer and wells. Manufactured components should be described in just enough detail to facilitate accurate estimates of operating characteristics and construction or procurement costs.

One of the most important elements of the main investigation, and therefore a logical first step, is verification of aquifer characteristics. Because of the obvious necessity to design and install test wells, aquifer characterization is a costly undertaking, but one that cannot be avoided. Otherwise, the operating characteristics of the ATES system cannot be predicted with any suitable degree of confidence.

The main test wells used for aquifer characterization should reflect a design suitable for the ATES well field. However, small-diameter piezometers will be suitable for the observation wells needed for hydrologic pumping tests. Piezometers are similarly suitable for obtaining water-level measurements. The field testing program should be designed to determine specific capacity of the production-type wells in both injection and withdrawal modes, the rate and direction of ground-water flow, and the effective porosity of the aquifer. In addition, the vertical variability of transport within the aquifer should be studied to determine the most useful water-producing strata within the aquifer. At some sites, seasonal variations in water level, rate,

and direction of flow will have to be taken into account. The number of test wells that will be needed depends on the variability of the aquifer itself in the vicinity of the ATES site, and on the size of the proposed well field.

The stability of the mineralogic matrix of the aquifer with respect to circulation of thermally or chemically altered water must be considered. This is particularly important for heat storage ATES systems, or where water treatment is anticipated. Samples of the geologic matrix can be collected during the construction of test wells.

Once the aquifer characteristics are accurately known, plant and well field design can be completed, modified as necessary, and the plant operating cycle, output, operating costs, and efficiency can be calculated. Operating costs should include manpower, power requirements, auxiliary processes such as water treatment, major scheduled maintenance e.g., predicted lifetime of components), land or building rental, and any other cost or fee that is likely to affect the budget of the ATES installation in perpetuity.

Construction costs should be considered separately from operating costs, and should include buildings, plant components, pipelines, well construction, land acquisition, one-time fees, and so forth. In addition, a construction schedule should be developed.

RISK ANALYSIS

Using the foregoing estimates, the *most probable* plant output, budget, plant life, and payback time can be presented to management for review and approval. However, there is no absolute certainty in predicting costs, performance, or schedules. Therefore, it is necessary to consider the risks associated with these kinds of factors, and to assign reasonable probabilities to them. For example, there is some finite probability that the cost of materials for construction will increase before the plant can be built. Also, there is a chance that plant performance will be worse (or better) than predicted. What would be the effect of an unseasonably warm winter on a chill storage project?

By assigning probability factors to the major cost and performance risk factors, the likelihood of success of the ATEs project can be expressed in probabilistic terms. For example, the risk analysis may show that there is a 90% probability of meeting or exceeding the project goals (usually expressed in economic terms), and a 98% probability of at least breaking even. Techniques for probabilistic risk analysis are beyond the scope of this report, but are not particularly difficult, and are within the realm of basic business investment analysis.

Another aspect of risk analysis pertains to the environmental risk associated with construction and operation of an ATEs plant, particularly with respect to the well field, and the injection of chemically and/or thermally altered water into the aquifer. For a discussion of environmental risk assessment, the reader is referred to the companion report *Environmental Risk Assessment for Aquifer Thermal Energy Storage* (PNL-8365).

CONCLUSION

Except for those projects designed strictly for the benefit of research, no ATES proposal is likely to be funded unless the following questions can be satisfactorily answered.

- What good will it do to construct the ATES plant?
- What are the chances of success?
- How long will it take to pay for itself?
- Is it safe?

The feasibility study, as outlined in this report, is designed to answer these questions. By performing the study in two major stages, where fatal flaws, if any, are identified early, the investment in time and money in the feasibility study itself can be minimized.

It should be noted that each of the two stages of the feasibility study--actually two separate studies--represents a stage of review and approval for funding. That is, favorable results from the preliminary investigation are insufficient justification to approve construction of an ATES system. They are, however, reasonable grounds for requesting funds to commence the more detailed main investigation.

Finally, the ATES principle is likely to be one of several candidate methods to solve a particular heating or cooling problem, in which case the preliminary investigation takes on added significance. The scope and level of detail of the preliminary effort are appropriate to compare the relative technical, economic, and environmental advantages of ATES methods to those of competing technology.

RELATED READING

The following material will be useful for aquifer characterization, design and operation, and environmental risk assessment for ATEs systems.

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