International Energy Agency

Energy Conservation through Energy Storage

Annex 7

Innovative and Cost-Effective Seasonal Cold Storage Applications

Analysis of Economic, Energy, and Environmental Aspects

Final Report

March 1994

Published August 1995

Preface

The participating countries and national organizations of Annex 7 include:

- Canada – Public Works Canada;
- Germany – KFA;
- The Netherlands – Netherlands Agency for Energy and the Environment; and
- Sweden – Swedish Council for Building Research.

This report was prepared by Hickling Corporation on behalf of Public Works Canada, and represents the collaborative efforts of the Annex 7 participants. This report forms part of the second Sub-Task of Annex 7 of the Energy Conservation through Energy Storage (ECES) Implementing Agreement, which is part of the IEA R&D Programme.

The analysis and evaluation of innovative generic seasonal cold storage configurations – that were previously identified at a workshop of experts – are presented. These cold storage configurations are compared to conventional designs with respect to energy consumption, costs, environmental impacts, and other considerations.

Background on Annex 7

The objectives of Annex 7 are to:

> Demonstrate and document innovative, energy efficient and cost-effective cold storage designs for a variety of building types and industrial applications to encourage the adoption of seasonal cold storage as a standard design option.

The following countries have signed the Energy Storage Implementing Agreement,

Belgium, Prime Minister's Office

Canada, Public Works Canada

Commission of the European Communities

Denmark, The Ministry of Energy

Germany, Forschungszentrum Jülich GmbH

Finland, Ministry of Trade and Industry

Italy, ENEA

The Netherlands, The Netherlands Agency for Energy and the Environment (NOVEM)

Sweden, The Swedish Council for Building Research

Turkey, Çukurova University (official signing 29 June 1995)

United States of America, Department of Energy.

Eight Annexes to the Implementing Agreement have been established and two are in preparation:

Annex 1	Large Scale Thermal Storage Systems Evaluation
Annex 2	Lake Storage Demonstration Plant in Mannheim
Annex 3	Aquifer Storage Demonstration Plant in Lausanne-Dorigny
Annex 4	Short-Term Water Heat Storage Systems
Annex 5	Full-Scale Latent Heat Storage Installations
Annex 6	Environmental and Chemical aspects of Thermal Energy Storage in Aquifers and Research and Development of Water Treatment Methods
Annex 7	Innovative and Cost-Effective Seasonal Cold Storage Applications
Annex 8	Implementing Underground Energy Storage Systems
Annex 9	Electrical Energy Storage Technologies for Utility Network Optimization
Annex 10	Implementing Energy Storage Systems with Phase Change Materials

Annex Summaries

Annex 1 was a technical and economic evaluation of various storage concepts presented by the participating countries. The results of this work formed the basis for subsequent Annexes. The final report was published in October 1981. The Annex was formally closed at the Executive Committee Meeting in April 1983.

Annex 2 had the objective of developing a seasonal lake storage and to demonstrate the feasibility by the construction of a large-scale pilot plant in Mannheim, Germany. Construction of the plant was cancelled after failing to achieve an economic design.

Annex 3 involved the design, construction and operation of a high-temperature aquifer storage in Lausanne-Dorigny. The storage consisted of a vertical well with horizontal drains. The project was commonly called SPEOS. Waste heat from a municipal facility was stored in summer and used for space heating and domestic hot water of a gymnasium. Collaboration involved seven countries and terminated in 1989. Switzerland provided the Operating Agent.

Annex 4 reviewed the theory, techniques and application of hot water storage systems and produced a state-of-the-art report. It focussed on various measures to maintain thermal stratification. The Netherlands provided the Operating Agent and four countries participated. The Annex was closed in 1988.

Annex 5 involved the installation and monitoring of latent energy storage installations with the objective of evaluating their technical and economic feasibility. The Executive Committee recommended reviewing the state-of-the-art of latent heat stores and a workshop was held in 1984 sponsored by the German Ministry for Research and Technology. As a result of the workshop recommendation to concentrate on monitoring pilot and demonstration plants to provide reliable performance data, an Annex on Full-scale Latent Heat Storage Installations was initiated in 1988. Germany provided the Operating Agent. The Final Annex Report was published in 1992.

Annex 6 dealt with the chemical and environmental aspects of thermal energy storage in aquifers. A major potential problem of aquifer energy storage was the scaling and clogging of wells and heat exchangers. To avoid these problems reliable and ecologically sound methods of water treatment were required. The development and testing of the chemical, microbiological and environmental effects of groundwater treatment methods were the objectives of Annex 6. The Netherlands provided the Operating Agent and nine countries participated. The work was initiated in 1987 and extended through twelve experts' meetings into 1993. The Annex was formally closed by the Executive Committee in 1994.

Annex 7 aimed to demonstrate innovative, energy efficient and cost-effective cold storage designs for a variety of building types and industrial applications to encourage the adoption of cold storage as a standard design option. More specifically, it evaluated effective storage control and operating strategies; evaluated combined hot and cold storage for increased energy efficiency and cost-effectiveness; and conducted national market studies for the developed technologies. Canada provided the Operating Agent and four countries participated. A planning workshop in Sweden initiated the work in January 1989 and the activities extended through eight experts' meetings into 1993. The final report was written and approved during 1994.

Annex 8 aims to speed the introduction of Underground Thermal Energy Storage in the building, industrial and agricultural sectors. It will encourage the adoption of energy storage in standard project designs by developing procedures and tools based upon documented applications in various energy efficient systems. Screening and decision tools will be provided to ensure ecologically sensitive applications. Sweden is providing the Operating Agent with other participating countries including Canada, Belgium, Germany, the Netherlands and Turkey.

Annex 9 will examine the potential role of electrical energy storage technologies in optimising electricity supply and utilisation. It will identify and overcome barriers to widespread adoption of electrical energy storage technologies through successful demonstration projects. It has been proposed by EA Technology Limited in the UK as a result of the recommendations of the Energy Storage Strategy Workshop held in Montreal during January 1995.

Annex 10 will examine the role and accelerate the introduction of phase change materials into energy systems in the residential, commercial, industrial and agricultural sectors. It has been proposed by the Concordia University, Centre for Building Studies in Montreal as a result of the recommendations of the Energy Storage Strategy Workshop held in Montreal during January 1995.

- Evaluate effective and efficient system configurations using seasonal cold storage. Demonstrate and document the results to encourage the wider adoption of this technology.

- Evaluate the potential application of combined hot and cold storage for increased energy efficiency and cost-effectiveness. Demonstrate and document the results.

- Document the total energy savings and peak demand reductions from the evaluated systems in the context of national market studies. Identify the source fuel types of energy saved to permit an assessment of the associated environmental benefits.

The first Sub-Task of this Annex reviewed the state of the art of seasonal cold storage in the participating countries. The results of that review are documented in four national reports and in an Annex 7 summary of these national reports. Refer to Appendix G for the list of these Annex 7 reports. This series of reports contains descriptive information on seasonal cold storage projects that were either realized or in preparation, or for which feasibility studies had been completed but the projects had not gone forward. This list of cold storage projects has been updated as part of the second Sub-Task (see Appendix B).

The second Sub-Task of the Annex comprised the selection and evaluation of generic and innovative system configurations. The primary activities of this sub-task were:

- *Identification of Generic Innovative System Configurations.* Based on the reviews undertaken in the first sub-task and on collective experience, the Annex Participants identified generic innovative system configurations using seasonal storage for cooling. These configurations were assessed at a workshop of experts and the most promising configurations were selected for further analysis and evaluation. Results from the workshop were documented in the Proceedings for IEA ECES Annex 7 Workshop on Generic Configurations of Seasonal Cold Storage Applications.

- *Analysis and Evaluation of the Selected System Configurations.* The Participants analyzed and evaluated the selected system configurations in terms of energy usage, economics, environmental impact, and other considerations. These results were compared to conventional designs for the same applications under the same conditions.

- *Investigation of Load Type and Other Characteristics.* The analysis and evaluation of storage configurations investigated the effects of load type and characteristics, climate, energy price and other key factors on the comparison of the innovative systems with the conventional alternatives.

As part of this second Sub-Task, information on current cold storage projects (i.e. realized or in preparation) was collected and updated, and summarized in Appendix B.

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1.

Introduction

Energy use for cooling, based primarily on electricity, is increasing rapidly in North America and in Europe. Especially important in both new and existing commercial buildings, cooling is increasingly needed because of heat generation from computers and other ubiquitous office appliances. Increasing awareness of the benefits from improved indoor air quality and occupant comfort also leads to increased demand for cooling.

Seasonal thermal energy storage (STES) systems for cooling applications, or for combined cooling and heating applications, can result in energy savings, cost savings and reduced adverse environmental impacts as compared to conventional energy systems.

The Executive Committee of the Energy Conservation through Energy Storage (ECES) Implementing Agreement of the International Energy Agency (IEA) established a collaborative R&D work program (called Annex 7) specifically targeted on thermal storage for cooling. Four countries, Canada, Germany, The Netherlands and Sweden, joined in the collaborative work. The primary objective of Annex 7 is to identify, analyze and document such systems and applications which maximize energy savings and environmental benefits from the application of STES for cooling. The ultimate purpose for the results of this work is to encourage the adoption of thermal storage of cooling as a standard design option.

Begun in 1990, this multi-year collaborative R&D work program undertook a review of the state-of-the-art of storage technologies and applications in the participating countries. The review included storage technologies for building and industrial applications, design models for application of these technologies, and methods of predicting subsoil characteristics. As well, national reviews were undertaken of existing projects and feasibility studies of appropriate seasonal cold storage applications identifying costs and energy use, advantages and disadvantages, and technical and non-technical constraints to implementation. A summary of these four country state-of-the-art reviews has been published as an Annex 7 report. The list of references at the end of this report identifies the four national reports and the Annex 7 summary report.

Table 1-1 shows the basic system classification structure developed for the Annex 7 work program. The emphasis in Annex 7 is on *seasonal* applications (that is, with at least three months of storage) which have a defined *charging cycle* for cooling, and which are cost-effective as compared with conventional system designs for the application.

Table 1-1: System Classification

Qualification for Annex 7

Cold Storage:	Must be charged with cold for purpose of cooling
Seasonal Storage:	Discharging at least three months after charging

Classification: *Each system must fit into either Column 2 or Column 3 for each characteristic identified in Column 1.*

Application:	Cooling only	Heating and cooling
Storage technology:	ATES (e.g. aquifer, ground source)	Duct (e.g. duct in water bearing soil or rock)
Cold source[1]:	Natural cold	Waste cold
Load:	Building (residential or commercial)	Industrial process

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1. Natural cold source refers to cooling from ambient air or surface water. Waste cold source refers to the cooled by-products of heat pumps and heat exchangers.

2.

Methodology for Analyses

This chapter presents the methodology used for analyzing and comparing promising innovative generic seasonal cold storage configurations.

These innovative configurations were selected at the Workshop on Generic Configurations of Seasonal Cold Storage Applications, held in The Netherlands in September 1991. At the workshop, experts from the participating country presented various storage configurations that combined different applications, storage technologies, cold sources, and loads - as defined in Table 1-1. Working groups at the workshop defined a set of criteria for selecting the most promising configurations. Each configuration was assessed against the following criteria: incremental capital cost, annual costs, energy savings, simplicity and maintenance, market size, barriers and site restrictions, time schedule, meeting the load, and environmental benefits. Based on these assessments, the most promising configurations were selected for further analysis. Refer to the Workshop Proceedings for additional details.

Table 2-1 shows the promising configurations that were further analyzed by each country after the workshop - by load, application, climate, and system configuration.

Table 2-1: Configurations and Climate Analyzed by Each Country

	Configuration				
	Cooling	Heating and Cooling			
	Only No HP	Open HP	Open No HP	Closed HP	Closed No HP
Country analyzing new and existing buildings:					
Canada	extreme	extreme	N/A	N/A	N/A
Germany	N/A	moderate	N/A	moderate	N/A
Netherlands	moderate	N/A	moderate	N/A	N/A
Sweden	N/A	N/A	extreme	extreme	extreme
Country analyzing process loads:					
Canada	extreme	N/A	N/A	N/A	N/A
Netherlands	moderate	N/A	N/A	N/A	N/A

Legend:

extreme = climate with extreme high and low temperatures (e.g. Winnipeg, Canada)
moderate = moderate maritime climate (e.g. Amsterdam, The Netherlands)
N/A = no analysis to be performed

Three load types were examined for seasonal cold storage applications:

- New building;
- Retrofit building; and
- Process cooling.

The three types of load were standardized through the definition of a reference new building, a reference retrofit building, and a reference industrial process.

For the reference buildings, the following were specified: skin characteristics, occupancy, working hours, ventilation, lighting, and cooling and heating design conditions. The new and retrofit buildings are similar in floor area and layout, but differ with respect to building skin characteristics. The reference industrial process is defined as a constant cooling requirement. Refer to Appendix C for technical details.

Three reference sub-soils for cold storage were also defined to include eskers, other aquifers, and rock. Applicable physical characteristics of the storage formation, overburden, and lower confining layer were specified for the reference sub-soils. Refer to Appendix C for technical details.

The analysis of each cold storage configuration shown in Table 2-1 followed the approach outlined below.

a. Develop a conventional design based on the reference specifications, following national standards.

b. Develop storage options using the reference load and design specification.

c. Calculate the energy and cost performance characteristics for both conventional and storage options.

d. Normalize performance of storage options against conventional designs.

With the new building and the industrial process, the designer was essentially free to choose any technical installations which met the design specifications. With the retrofit building, some restrictions were placed on the technical installation. For example, the ventilation air ducts were not to be replaced, and cooling and heating loads were met by fan-coil units (refer to Appendix C for details).

To facilitate the comparison of results from different countries, a standard format for comparing the energy and cost characteristics of the various storage configurations was developed and is shown in Table 2-2.

Table 2-2: Format for Energy and Cost Comparisons of Conventional and Storage Systems

Criteria for Comparison	Conventional Design	Storage A	Storage B
System Characteristics			
Cooling Demand (kW)			
Heating Demand (kW)			
Annual Cooling (MWh)			
Annual Heating (MWh)			
Electrical Peak:			
Summer (kW)			
Winter (kW)			
Annual HVAC Energy Consumption:			
Electricity (MWh):			
Compressor (chillers and heat pumps)			
Cooling towers			
Storage			
Distribution (fans, pumps, etc.)			
Gas (1 000 m^3)			
Oil (m^3)			
District Heating (MWh)			
Heat Recovery from Ventilation (MWh)			
Costs			
Total Capital Costs			
Chillers, HPs, and CTs (piping, wiring, installed)			
Boilers (service connection, oil tank, ventilation, HRV)			
Storage (incl. design, site inspection) piping, pumps, HX			
Other (incremental costs)			
Annualized Total Capital Costs (@ 8%)			
Total Annual Energy Costs			
Total Annual Maintenance Costs (incremental)			
Total Annual Costs (@ 8%)			

To compare storage alternatives across countries, the performance of storage alternatives for each country was normalized to the corresponding conventional design (i.e. new building, retrofit building, or process cooling). Table 2-3 is an example of how a performance characteristic such as annual electricity consumption is normalized - using illustrative data for selected new building configurations.

Table 2-3: Example of Performance Normalization

	New Buildings					
	Canada			Sweden		
	Convent.	Cool only ATES no HP	Heat/cool ATES no HP	Convent.	Heat/cool ATES no HP	Heat/cool duct no HP
Electricity: estimated consumption (MWh)	250	150	200	280	210	210
Electricity: normalized by conventional use (%)	100%	60%	80%	100%	75%	75%

Note that the performance of storage configurations is measured against the conventional design for that country. Using this approach, configurations for different combinations of load type, climate, heat pump or no heat pump, and ATES or duct can be compared.

Each country presented analysis of their assigned configurations (Table 2-1) in national reports. Specifications of reference and storage designs, methodology, and results are detailed in the national reports. Highlights of the design differences between countries and their implications, and steps taken to minimize the impact of design differences across countries are listed below.

- Peak and annual heating and cooling load differences may result from the following:
    - Sweden typically uses 100% make-up air (with heat recovery) and Canada typically uses only sufficient make-up air to provide fresh air requirements of occupants as stated in specifications;
    - Canadian simulations have temperature set back at night while others do not; and
    - Swedish case includes water heating of 84 MWh.

- The net heating demand - excluding heat recovery - is reported and thus reflects what has to be supplied from energy sources.

- Only Canada used four-pipe fan coil systems in the new building simulations. Other countries used air systems which result in a difference in distribution energy use. All countries used fan coil systems for retrofit building simulations.

- Swedish ATES design is an esker which is a lower-cost shallower storage.

3.

System Concepts and Designs

3.1 Seasonal Thermal Energy Storage (STES)

The focus in Annex 7 is on STES applications which are:

- *Seasonal*: that is, with at least three months of storage;
- *Cooling*: that is, with a defined *charging cycle* for cooling (which excludes applications that may utilize ground water, say, for cooling without actively re-charging the ground system with chilled water); and
- *Cost-effective*: that is, innovative and cost-effective as compared with conventional system designs for the same application.

Figure 1-1 of Chapter 1 shows this basic system classification structure developed for the Annex 7 work program.

STES systems can be distinguished by whether they store energy that is actively gathered (e.g., where a cooling tower is used in winter as a collector of chilled water) or whether they store waste or by-product energy (e.g. groundwater heat pump projects that store the resulting chilled water during the heating season). In the former type, the various designs are often compared on the basis of COP. In the latter type, energy that would otherwise be wasted is stored. These double-effect storage projects are more likely to be economical, but the assessment of overall efficiency must be made at a system level. A comprehensive procedure that evaluates the relative efficiency of such schemes taking into account the storage time, temperature levels, and application requirements remains to be developed.

The cost-effectiveness of STES is based on the capital cost avoidance of conventional heating and cooling equipment, and on energy savings. On a broader scale, STES is even more cost-effective when environmental costs of alternative energy sources (primarily electricity for cooling) is included in the cost-benefit analysis.

3.2 Aquifer Thermal Energy Storage (ATES)

3.2.1 Definition and Characteristics

Aquifers are underground, water-yielding geological formations, either unconsolidated (gravel and sand) or consolidated (rocks). Aquifers are either *unconfined*, occurring as surficial alluvial, colluvial, or glacial deposits, or *confined*, occurring at depths ranging from tens to hundreds of meters below ground surface. Natural aquifer water temperature is close to, but slightly warmer than, the local mean annual air temperature.

Aquifers can be used to store large quantities of thermal energy to meet large cooling and heating demands. ATES has been used for process cooling, space cooling, space heating, and ventilation air preheating, and can be used with or without heat pumps. Although ATES is associated with large energy demands, groundwater source heat pumps for heating and cooling are routinely used for residential applications especially when existing wells can be used.

The length of storage depends on the local climate and load characteristics of the building or process being supplied. ATES may be used on a short-term or long-term basis; as the sole source of cooling or as partial supply; at a temperature useful for direct application or needing upgrade; or in combination with a dehumidification system such as desiccant cooling.

ATES may be separated from the application with a heat exchanger or fully-interconnected with groundwater circulating through the application systems (e.g. building distribution system). The latter is suited to process cooling applications and in low-rise commercial buildings when the storage temperatures are just sufficient for space cooling or dehumidification purposes. Pressurized systems that separate the groundwater from the building HVAC system are preferred when undesirable groundwater interaction with oxygen might be a concern.

3.2.2 Experience

ATES has a history of at least 30 years. It began at industrial sites originally dependent on direct groundwater cooling. Environmental impacts related to aquifer warming and ground subsidence when water was not re-injected led to the recharge of aquifers with chilled water.

More recently, the increasing use of groundwater source heat pumps for heating and cooling of residential and commercial buildings has stimulated ATES applications with heat pumps. Such facilities may have roughly equal heating and cooling energy requirements depending on the local climate. A groundwater source heat pump utilizing both a cold well and a warm well is a rudimentary ATES system. The warm well can be used as a heat source for the heat pump evaporator in the heating season with the by-product chilled water stored in the cold well. The chilled water is stored until the cooling season when it can be used directly for space and process cooling.

Chemical changes in groundwater caused by the temperature and pressure variations associated with ATES pose potential operational and maintenance considerations. The precipitation of minerals in heat exchangers and well screens is an example. Some groundwater is naturally corrosive to common materials used in heat exchangers, pumps and pipes. Additionally, the aquifer itself may become clogged by precipitation of minerals. Fortunately, these problems are avoidable and manageable within the operating range of most common applications. Explicit guidelines are now available that allow problems to be avoided by proper design, materials selection and operation.[1]

3.2.3 Design Considerations

Aquifer thickness, porosity and the number of wells determine the storage volume. Separation distance between supply and storage wells is approximately 25 to 30 meters for small applications, and distances of 100 to 200 meters are common for commercial building applications.

A well pair may be pumped constantly in one direction or alternately, from one well to the other, especially when both heating and cooling are being provided. To maintain well efficiency, backflushing is recommended. All wells should therefore be equipped with pumps.

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[1] Refer to Annex 6 references in Appendix G.

Seasonal ATES applied to a process cooling load requires a low-cost source of cooling to re-charge the ATES system. Typically, this source is from cold ambient conditions in winter (e.g. surface water or cooling tower) or from waste cold. In one known application of process cooling, pre-heating of building make-up air in winter provides a source of cooling where heating is a by-product.

Cold storage temperatures injected are normally 2° C to 8° C with cooling power typically ranging from 200 kW thermal to 20 MW thermal and with the stored cooling energy extending to 20 GWh. A typical single well flow rate is 3 L/s for small applications and 30 L/s for large applications.

Control is simplified by the existence of separate hot and cold wells that operate on the principle of *last water in, first water out*. This ensures that the hottest or coldest water is always available for discharge when needed.

Injection of water into a well at high rates requires special design consideration. Standard texts on well design do not usually deal with this topic and little experimental data exist. A simple rule-of-thumb is that a well, in an unconsolidated aquifer, should not be expected to accept more than two-thirds of the water that it can produce. In consolidated aquifers the opposite occurs, since fractures open up under the injection pressure.

3.3 Duct Thermal Energy Storage

Where aquifers are unavailable or unsuitable, and especially for smaller applications, energy storage systems utilizing ducts in soil or rock are applicable. In these applications, the ducts serve as heat exchangers with the surrounding soil or rock, and act together as a heat storage.

Duct thermal energy storage (DTES) is derived from the use of ground source heat pumps (GSHPs). The first GSHPs were described in the U.S. in the 1940's, using horizontal pipes in trenches. In Europe, GSHPs are known since the early 1970's, and had a fast growth with the oil crisis in 1973. Today, the market is at a low level, varying from country to country. The better opportunities are in alpine countries such as Switzerland and Austria, as well as in Scandinavia. In North America, ducts as loops or coils, buried in trenches or in boreholes are being used in increasing numbers for ground-source heat pump applications. These systems are STES cooling systems if they charge the storage with cooling in the off-season (winter). Direct use of cold from the ground with GSHPs, which is true DTES, has been used in Germany since 1987, in Sweden since the late 1980's, and in Switzerland quite recently.

Duct thermal energy storage (DTES) can utilize phase change (usually freezing of water) to extend energy storage capacity and to lower the temperature for direct cooling applications.

Technical performance and economy is highly dependent upon the ground conditions. The two major design considerations are thermal parameters controlling operational characteristics of the store and geotechnical parameters during installation (drilling etc.).

3.3.1 Thermal Parameters

The basic requirement for a good storage medium is a high value of specific heat. In soil and porous rock this is normally a function of the water content, because specific heat of water exceeds that of the solid material by far. In massive rock, variation of specific heat is not as wide as for thermal conductivity. In the literature, usually the gravimetric heat capacity is given, which is 4.2 kJ/kg ·K for water and 0.7 - 1 kJ/kg ·K for most rock types. But for a subsurface store, the volumetric heat capacity should be considered - which for a rock medium ranges from 1.9 - 3.0 kJ/L ·K.

Thermal conductivity of the storage material is important for heat transport to and from the earth heat exchanger (duct). But high thermal conductivity also allows higher heat losses from the store. The values for heat conductivity in soil and rock vary widely. For storage, mean values of approximately 2 W/m·K are a good compromise between good heat exchange and low heat losses. In rocks with very high thermal conductivity, a duct store may not be effective.

Examples for good conditions include moist, silty/clayey soils (in case of silt, freezing could induce severe geotechnical problems!), water-saturated sand and gravel with low ground water flow (which in general are also good for ATES), igneous rocks as basalt, andesite, gabbro, diorite, syenite, metamorphic rocks as gneiss or micashists, and sedimentary rocks as massive limestone, some marls, dense sandstone, clay-/mudstone and shale. Duct stores are not suitable in dry, porous sediments, in rocks with high thermal conductivity as quartzite, or in regions with high ground water velocities.

3.3.2 Geotechnical Parameters

Concerning installation of the earth heat exchangers (ducts), good geotechnical behaviour in respect to drilling ("drillability") is essential. With drilling methods well adapted to the subsurface situation, fast and cost-effective drilling can be achieved (Table 3-1).

Table 3-1: Drilling Methods Used for Installation of Vertical Earth Heat Exchangers

Ground	Method	Remarks
soft, sand/gravel	Auger	Sometimes temporary casing required
	Rotary	Temporary casing or mud additives required
	Ramming	Steel tubes (corrosion), coaxial
	Water jetting	Steel tubes (corrosion), coaxial
soft, silt/clay	Auger	Mostly best choice
	Rotary	Temporary casing or mud additives required
	Pressing	Steel tubes (corrosion), coaxial
	SGI/VIAK(1)	Plastic tubes, single-U
medium	Rotary	Roller bit, sometimes mud additive required
	DTH(2)	Large compressor required
hard	Rotary	Button bit, very slow
	DTH(2)	Large compressor required
	Top Hammer	Special equipment
very hard	DTH(2)	Large compressor required
	Top Hammer	Special equipment
hard under soft	ODEX(3)	In combination with DTH(2)

(1) Swedish Geotechnical Institute, Linköping/VIAK AB, Malmö, Sweden
(2) Down-the-Hole-Hammer
(3) Overburden Drilling Equipment (Atlas Copco, Sweden)

As heat exchangers, tube-in-tube (coaxial), single-U-tube or double-U-tube configurations are common in the ground-source heat pump market. The usual material is HD-Polyethylene. For insertion of the heat exchangers in the borehole, some techniques and tools have been developed with contractors. A major problem is adequate backfilling or grouting, in particular in deep holes; the optimal materials still have to be found. In hard rock as granite, no heat exchanger need be installed, and heat exchange with the ground is through the borehole wall directly (e.g. in Luleå).

In soft ground, the heat exchangers (ducts) can be installed in the ground directly, using either steel tubes or plastic pipes (in clayey soil). Table 3-1 shows the most important techniques; problems with backfilling do not arise in this case. When steel tubes are used, corrosion has to be avoided by electric protection. Ordinary steel, as used for drill pipes, does not last over decades (dependent upon water/soil chemistry), and stainless steel is far too expensive for use in duct stores.

3.4 Regional Distribution

In Northern and Mid-Europe, the subsurface consists of a variety of rock and soil of all geological ages. Due to the geological evolution, distribution allows two distinct regions, where aquifers as storage medium can be built, and where duct systems can have advantages.

Ideal conditions for ducts in hard rock exist in crystalline regions, as in large parts of Scandinavia, in the Bohemian Massiv and some other outcrops. Good conditions for duct storage can be found in most palaeozoic sediments, which includes e.g. the Rhenisch Massif. Volcanic rocks of permian or tertiary age can cover larger areas (as in the Vogelsberg in Germany) and are also good for duct systems.

In mesozoic sediments (e.g. in limestones or dense sandstones), duct storage can have good characteristics. The mesozoic region covers a large part of mid and south Germany and eastern France. But under certain circumstances (fractures, fissures, permeable sandstone), even ATES could be possible in those sediments. For these areas, as well as for the Alps with complicated tectonics, no general suggestion can be made.

In most cenozoic sediments, ATES has an advantage over duct storage. In whole northern Germany, Netherlands, Denmark, northern France porous sediments as sand and gravel are frequent. This does also include zones of young subsidence, as the Upper Rhine Graben or the Molasse Basin in the alpine foreland.

In Canada, younger sediments suitable for ATES can be found in the Interior Plans (Alberta, Saskatchewan, southern Manitoba) or the St. Lawrence Lowlands. In the crystalline rocks of the Canadian Shield (most of Quebec and Ontario, northern Manitoba, NWT), duct systems can be a good choice. In the Appalachian Region and Western Canada, the situation may vary from site to site.

3.5 Schematic Diagrams of System Concept Designs

As outlined in Chapter 2, the analytic results of Annex 7 are based on simulations of typical STES system designs as compared to simulations of a conventional system design for a "reference" building or process load (as defined in Appendix C). For building applications, both a new building design and a retrofit building design have been analyzed. Each building application has been simulated in both a moderate (maritime) climate and an extreme (continental) reference climate. Finally, five typical STES concept designs have been analyzed:

1. *Direct cooling, no heat pump, ATES* - STES is used only for building cooling;
2. *Heating and cooling, no heat pump, ATES*;
3. *Heating and cooling, no heat pump, duct*;
4. *Heating and cooling, heat pump, ATES*; and
5. *Heating and cooling, heat pump, duct.*

Simplified schematic diagrams for the conventional design and these five STES designs for the building applications are shown in Figure 3-1 to Figure 3-3. In addition, simplified schematic diagrams for conventional and STES concept designs meeting a constant (24 hour per day, 365 day per year) process cooling load are shown in Figure 3-4.

3.5.1 Conventional Reference Building Design

Figure 3-1 shows the major sub-systems of the conventional reference building design: a four-pipe, fan-coil distribution sub-system; a boiler for heating; and a chiller and cooling tower unit for cooling. In the conventional reference designs, the boiler is either oil-fired or gas-fired, or the boiler is replaced by a district heating source, depending on what is typical for that country.

3.5.2 Direct Cooling STES Concept Building Design

Figure 3-2 shows the major sub-systems of the cooling-only STES concept building design comprising the same distribution sub-system and a boiler for heating. The chiller is replaced by an ATES-style STES system, including a heat exchanger and a cooling tower. The heat exchanger isolates the ground water from the ATES system from the building HVAC systems. The cooling tower, although not required in summer for cooling the building, is necessary for re-charging the STES in winter months. Although this schematic illustrates an ATES-type STES system, the concept design is essentially the same for a duct-based storage system. For a duct system, the heat exchanger may not be required depending on the water and temperature conditions, and the "supply" and "recharge" wells are replaced by the duct system manifold.

Figure 3-1: Conventional Reference Building Design

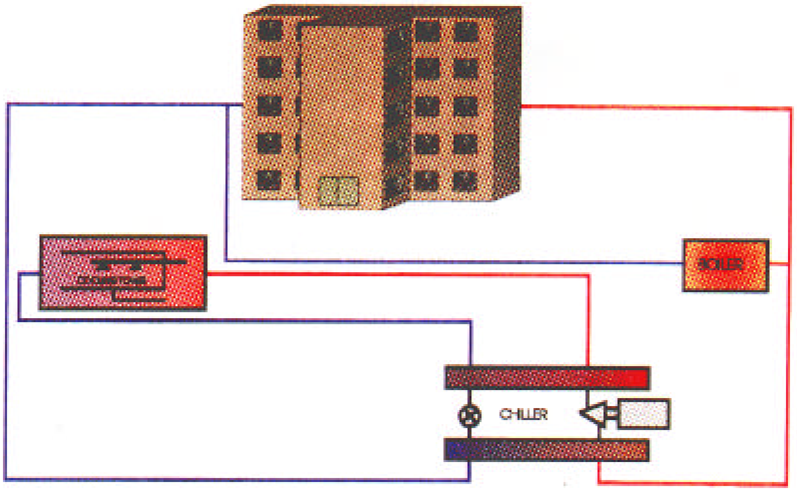
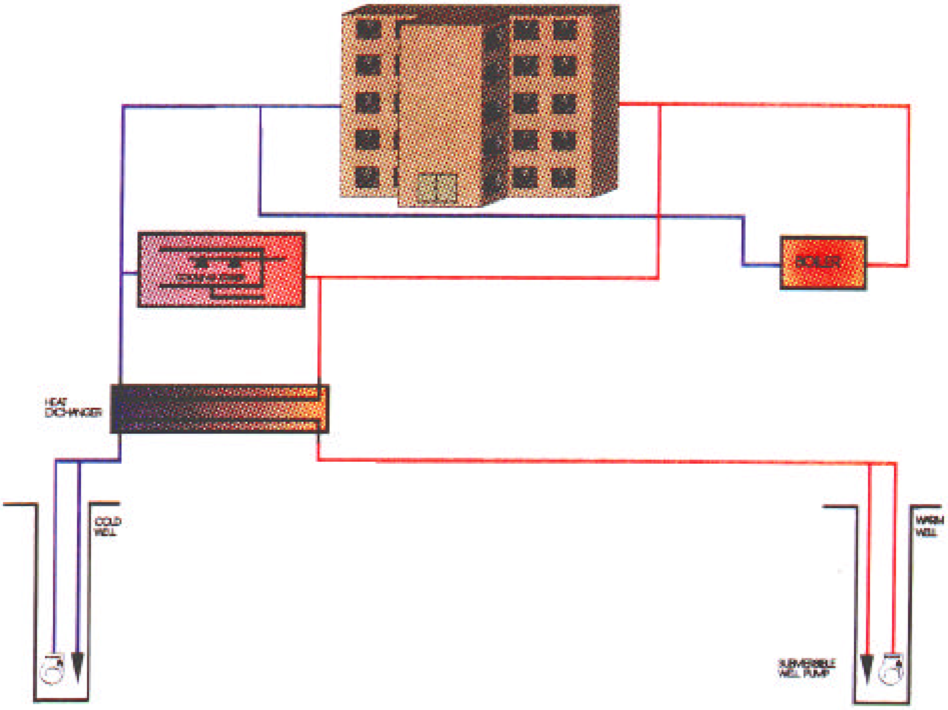


Figure 3-2: Cooling only STES Concept Building Design



3.5.3 Heating and Cooling, no Heat Pump, STES Concept Building Design

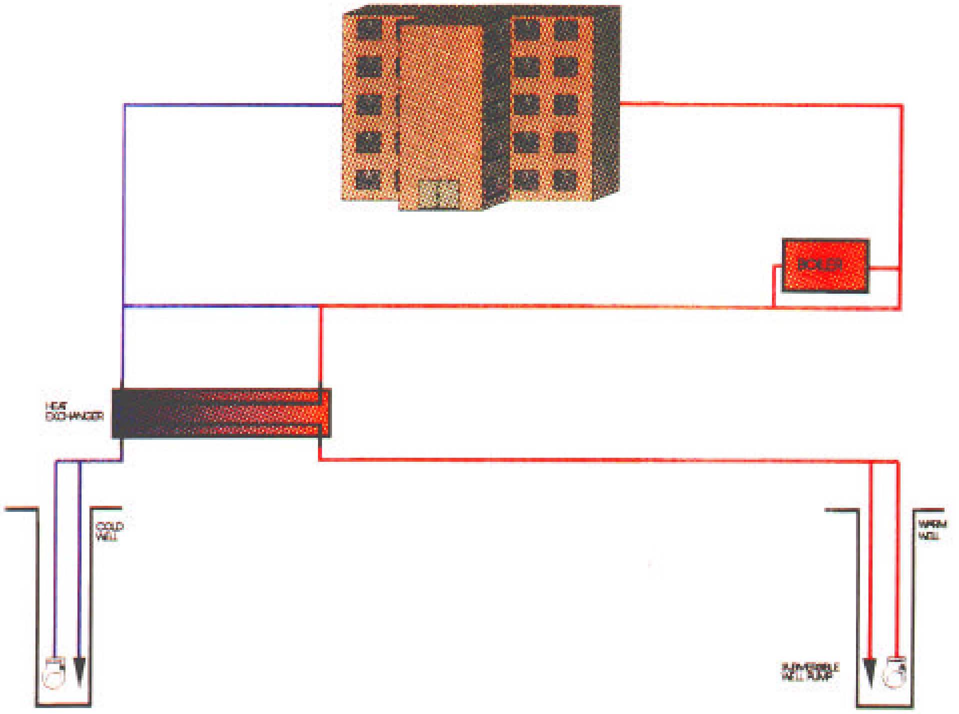
Figure 3-3 (a) and (b) show the major sub-systems of the STES concept building design for heating and cooling without a heat pump - for both ATES and duct systems. A boiler provides heating in cold weather. The cooling tower is used for directly meeting the cooling load where permitted by ambient conditions, and for charging the STES sub-system in cold weather.

3.5.4 Heating and Cooling with Heat Pump STES Concept Building Design

Figure 3-4 (a) and (b) shows the major sub-systems of the STES concept building design for heating and cooling using a heat pump - for both ATES and duct systems. A boiler is shown even though the STES system provides heating - the boiler supplements heating requirements in cold weather under the assumption that the STES sub-system is designed to meet the cooling load which is smaller than the heating load. This system configuration does not require a cooling tower since the cooling load is fully met by the STES system. The STES system is re-charged with cooling that is a by-product of heating with the heat pump in winter.

Figure 3-3: Heating and Cooling, no Heat Pump, STES Concept Building Design

(a) ATES



(b) Duct

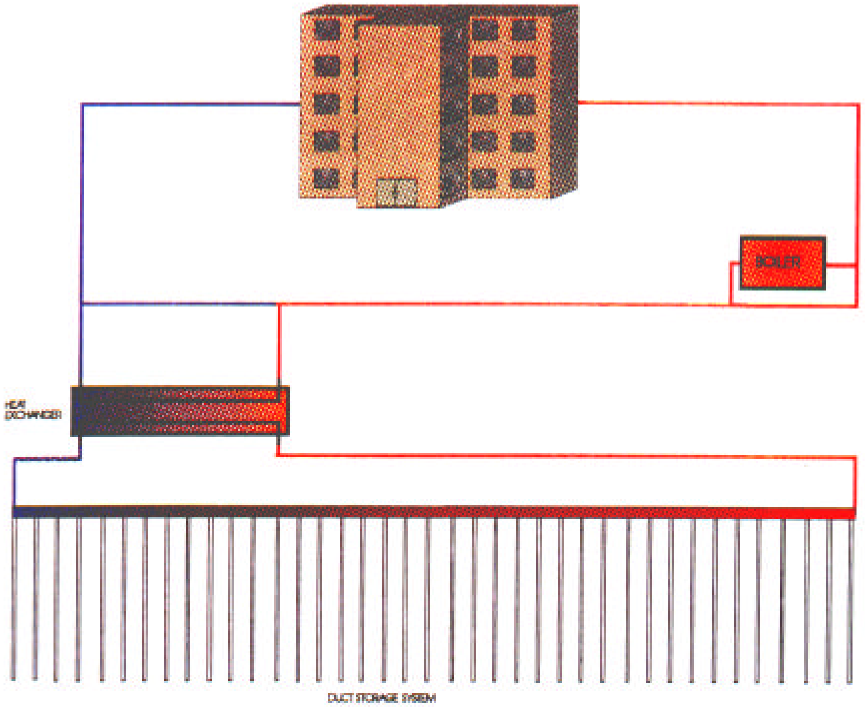
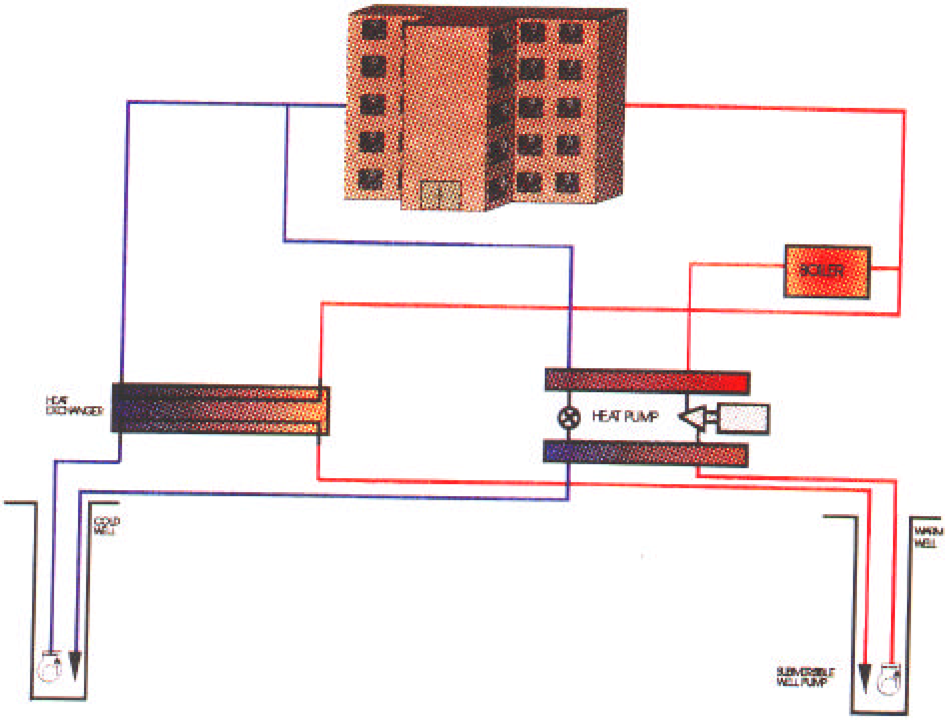
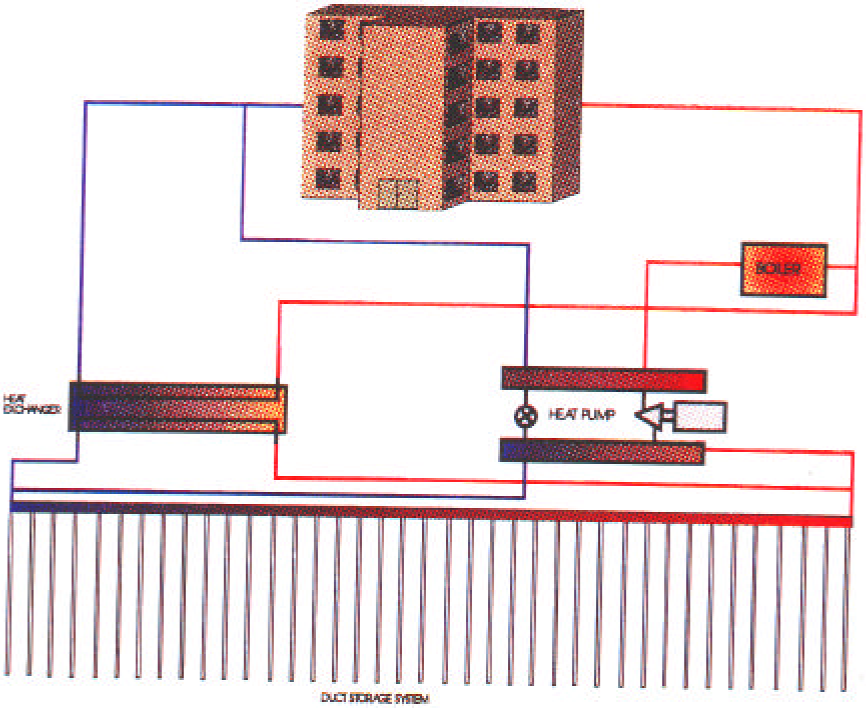


Figure 3-4: Heating and Cooling, Heat Pump, STES Concept Building Design

(a) ATES



(b) Duct

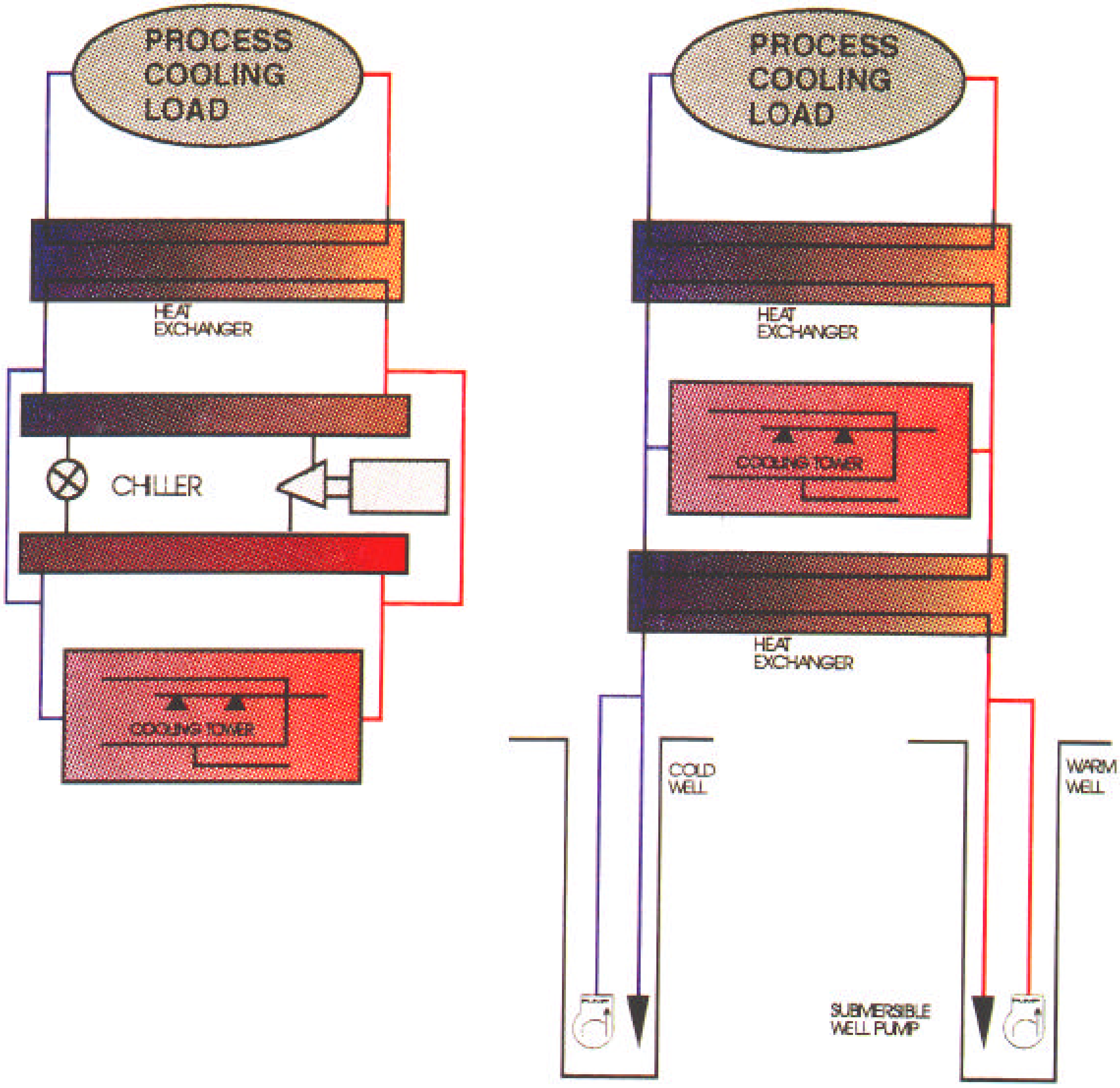


3.5.5 Process Cooling Design

A reference continuous process cooling load has been defined for comparing a conventional cooling system design with a ATES-type system design. The process cooling load has been defined as a 600 kW thermal requirement at a temperature difference of 10 Kelvin (22°C to 12°C). The conventional system design, shown in Figure 3-5 (a), comprises a chiller and a cooling tower combination that meets the cooling load either by means of the cooling tower alone (in sufficiently cold weather) or by means of the chiller operating together with the cooling tower (in warmer weather). In practice, and as simulated and analyzed, such a system design would have two or three smaller chillers and cooling towers for providing operating flexibility and redundancy. In concept, however, the system design is represented by Figure 3-5 (a).

An ATES-based process cooling design, as shown in Figure 3-7 (b), comprises an ATES system and a cooling tower without any chiller. In cold weather, the cooling tower would provide sufficient cooling capacity to meet the load requirements and to provide additional cooling for re-charging the ATES system. In summer, the ATES system would fully meet the cooling load requirements. In the shoulder seasons, the load would be met either by the cooling tower or the ATES system depending on the ambient temperature and the season.

Figure 3-5: Conventional and ATES-based Process Cooling System Design


(a) Conventional

(b) ATES

4.

Energy and Cost Comparisons

4.1 Overview

The following energy and cost performance characteristics of storage alternatives are summarized in this chapter for the three load types - new building, retrofit building, and industrial process:

- Annual electricity consumption;
- Annual thermal energy consumption;
- Total annual costs;
- Annualized capital costs; and
- Annual energy costs.

This section describes the five energy and cost performance indicators. The results presented in this chapter are normalized to the conventional design for the corresponding climate and load type. Figure 4-1 and Figure 4-2 show the ranges of energy and cost performance of storage alternatives with heat pumps and without heat pumps – for new and retrofit building loads. Detailed results, both absolute and normalized values, are presented in spreadsheet formats in Appendix E.

Figure 4-1: Energy Performance Ranges for Storage Alternatives without Heat Pumps and with Heat Pumps

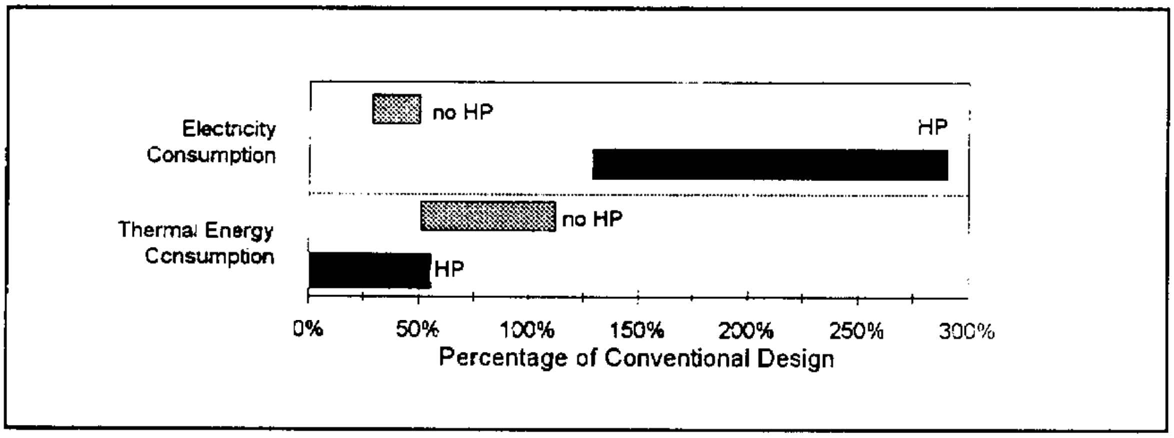
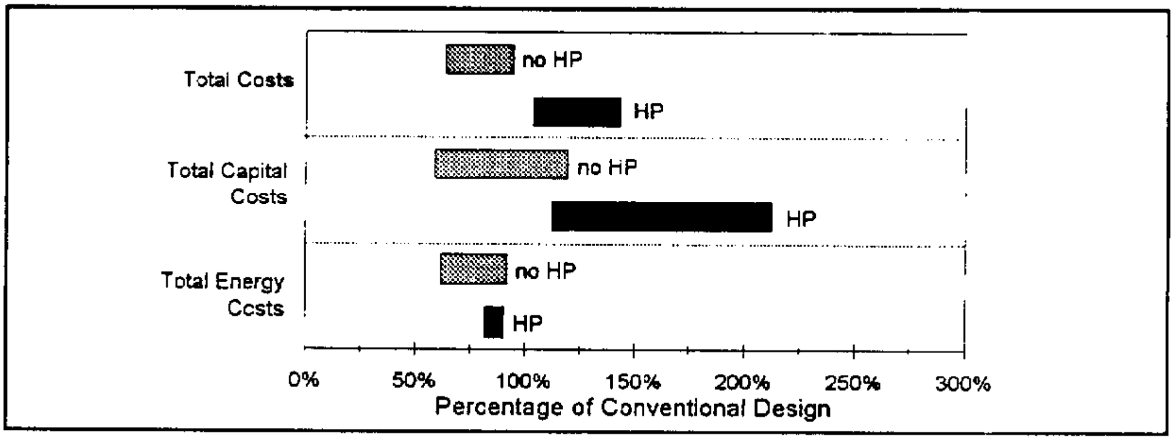


Figure 4-2: Cost Performance Ranges for Storage Alternatives without Heat Pumps and with Heat Pumps



Annual Electricity Consumption

The annual electricity consumption considers only HVAC energy consumption and includes consumption for: compressors (chillers and heat pumps), cooling towers and associated pumps, storage sub-system and associated pumps, and distribution system. For the distribution system, only the difference between the storage and conventional systems are considered.

Annual Thermal Energy Consumption

Annual thermal energy consumption includes gas, oil, and district heating[2].

Total Annual Costs

Total annual costs includes annualized capital costs, and annual energy and maintenance costs. Only the difference between conventional and storage alternatives are considered for maintenance costs.

Annualized Capital Costs

Annualized capital costs[3] include costs for: chillers and heat pumps, cooling towers, storage sub-system, boilers, distribution, controls, and other costs. Costs for each sub-system include ancillary equipment, installation, and commissioning. Only the difference between conventional and storage alternatives are considered for distribution, controls, and other costs.

Annual HVAC Energy Costs

Annual HVAC energy costs include electricity, gas, oil, and district heating. Costs for other energy used such as lighting and computer equipment are excluded.

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[2] An energy content of 38 MJ/m^3 (0.011 MWh/m^3) is assumed for gas (at 15°C and 101.3 kPa) and 40 GJ/m^3 (11 MWh/m^3) is assumed for oil.

[3] Equipment life of 15 years is assumed - with the exception of the storage sub-system which has an assumed life of 30 years. An interest rate of 8% is used.

4.2 New Buildings

Annual electricity consumption (Figure 4-3) for storage configurations that do not use heat pumps is less than half of that for conventional designs. Electricity consumption is almost three times higher than conventional for storage configurations using heat pumps for heating and cooling (Germany). However, these configurations with heat pumps do not consume any other thermal energy such as gas, oil, or district heating (Figure 4-4). Thermal energy consumption for configurations without heat pump is similar to the conventional design baseline. One exception is the heating and cooling and ATES configuration in an extreme climate (Sweden) which uses about 50% of the thermal energy of the conventional design.

Total annual costs for all configurations without HPs are less than conventional designs (Figure 4-5). Annualized capital costs for configurations without HPs range from 30% lower to about the same as conventional (Figure 4-6). For configurations with HPs, annualized capital costs range from about 125% to 200% of conventional systems.

Annual energy costs are lower than conventional for all storage alternatives (Figure 4-7).

Figure 4-3: Annual Electricity Consumption (New Building)

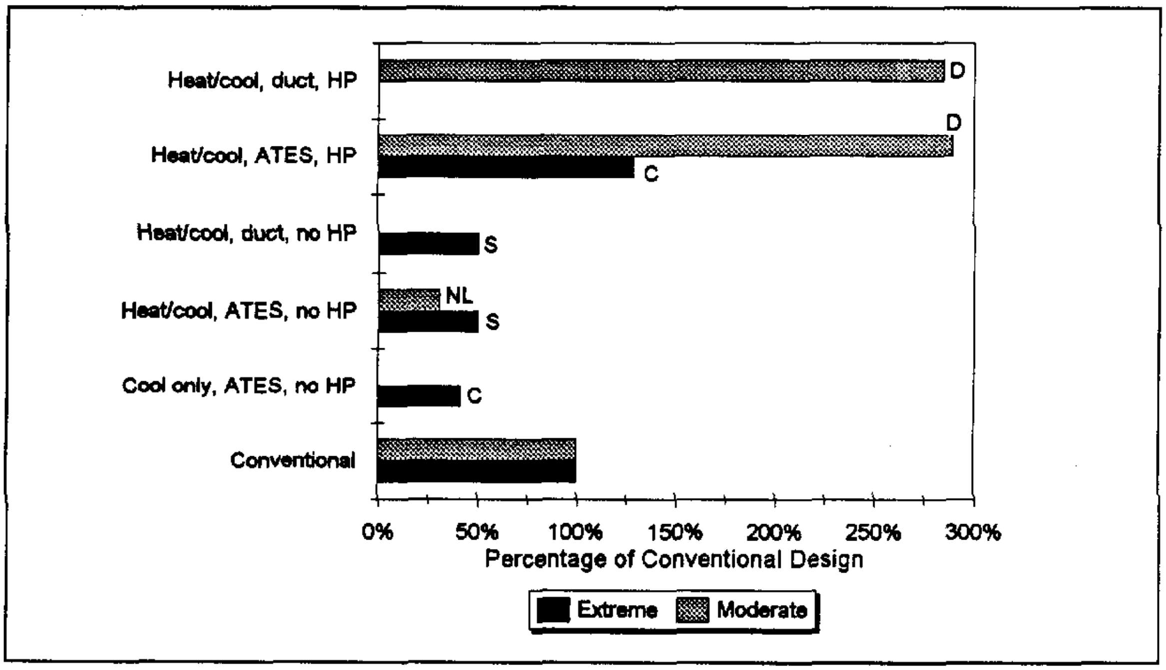


Figure 4-4: Annual Thermal Energy Consumption (New Building)

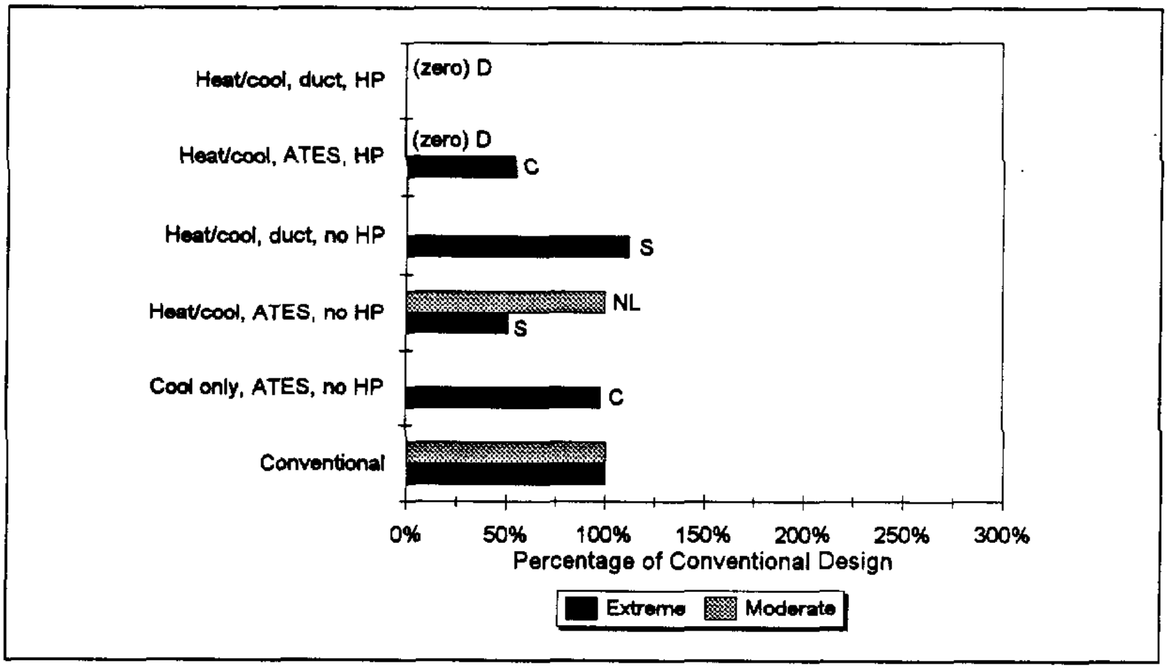


Figure 4-5: Total Annual Costs (New Building)

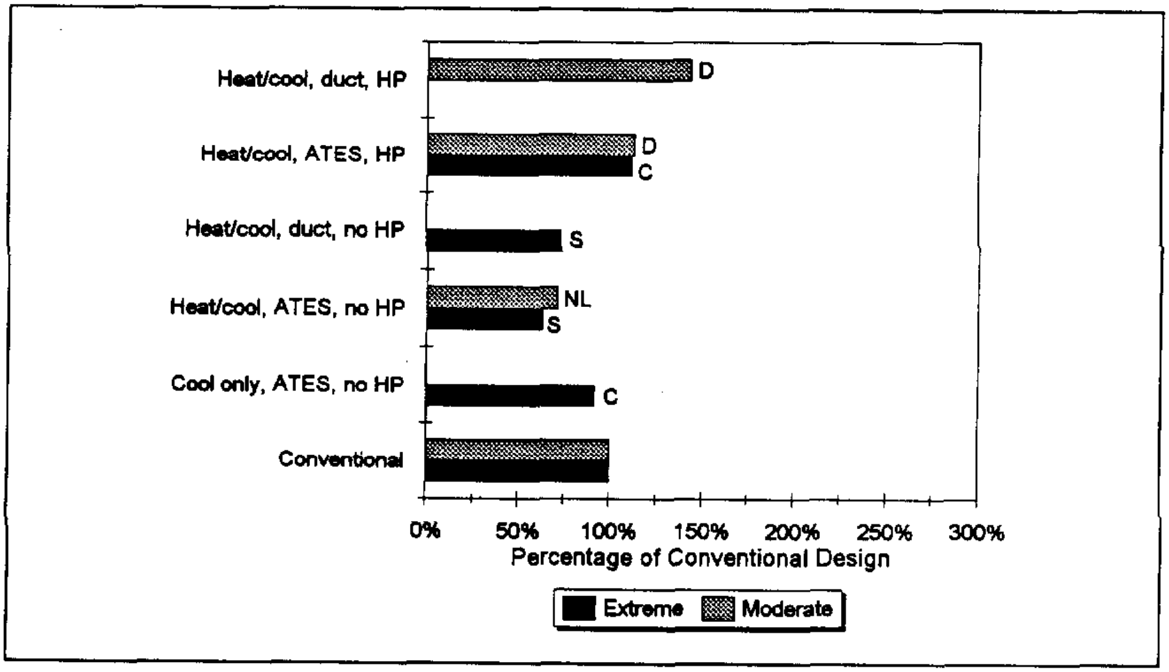


Figure 4-6: Annualized Capital Costs (New Building)

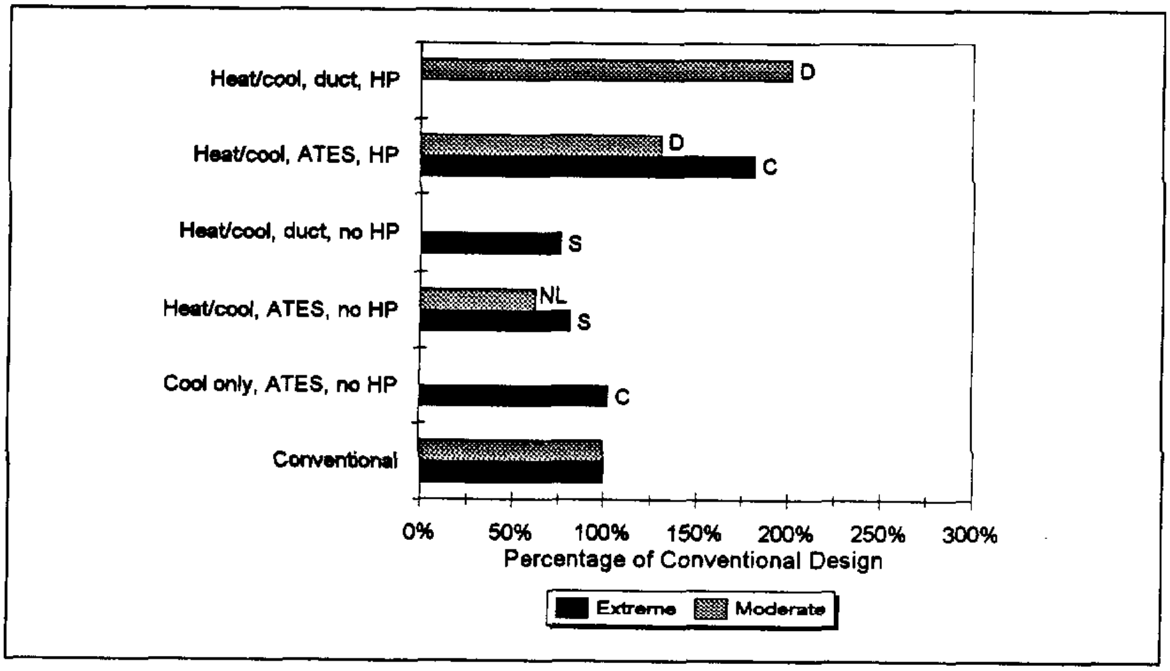
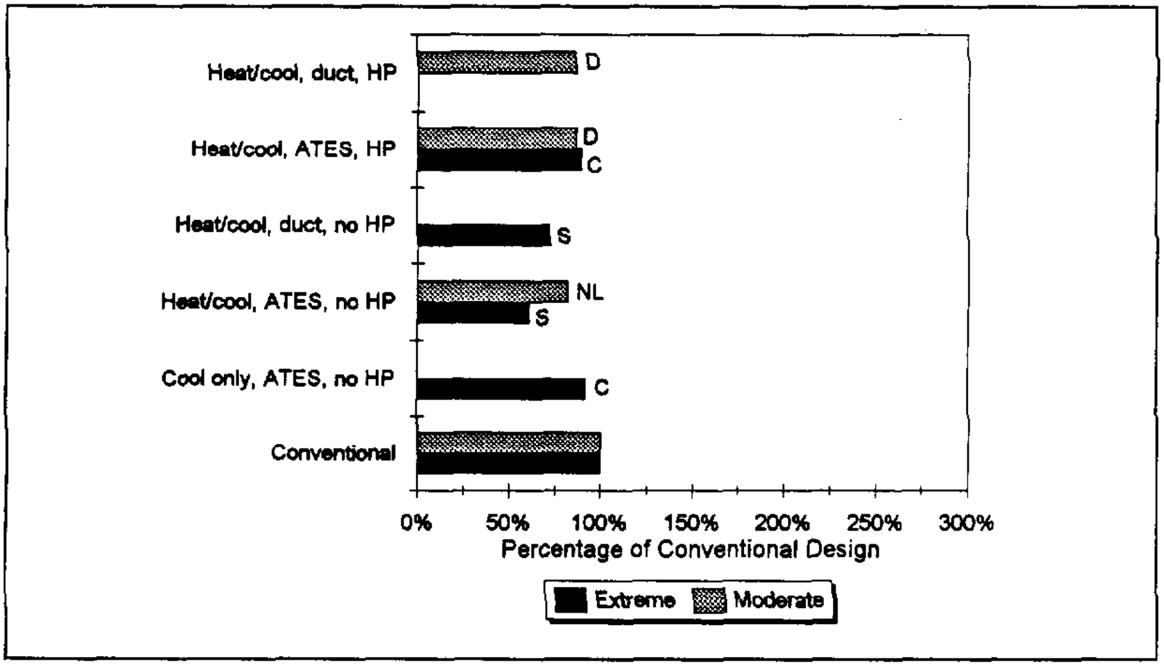


Figure 4-7: Annual Energy Costs (New Building)



4.3 Retrofit Buildings

Energy related performance characteristics of storage alternatives for retrofit buildings, when they are compared to conventional designs, are similar to those for new buildings. Storage configurations that do not use heat pumps use less than half of the electricity of conventional designs, as compared to storage configurations using heat pump which use from about 150% to just under 300% of the electricity of conventional designs (Figure 4-8).

When thermal energy consumptions are compared to conventional designs, storage alternatives again exhibit similar patterns as new buildings (Figure 4-9).

Total annual costs for all configurations without HPs are less than conventional designs, and all configurations with HPs are more expensive than conventional designs (Figure 4-10). For configurations with HPs, annualized capital costs range from about 110% to 200% of conventional systems (Figure 4-11).

Annual energy costs are lower than conventional for all storage alternatives (Figure 4-12), and are again similar to the new building results.

Figure 4-8: Annual Electricity Consumption (Retrofit Building)

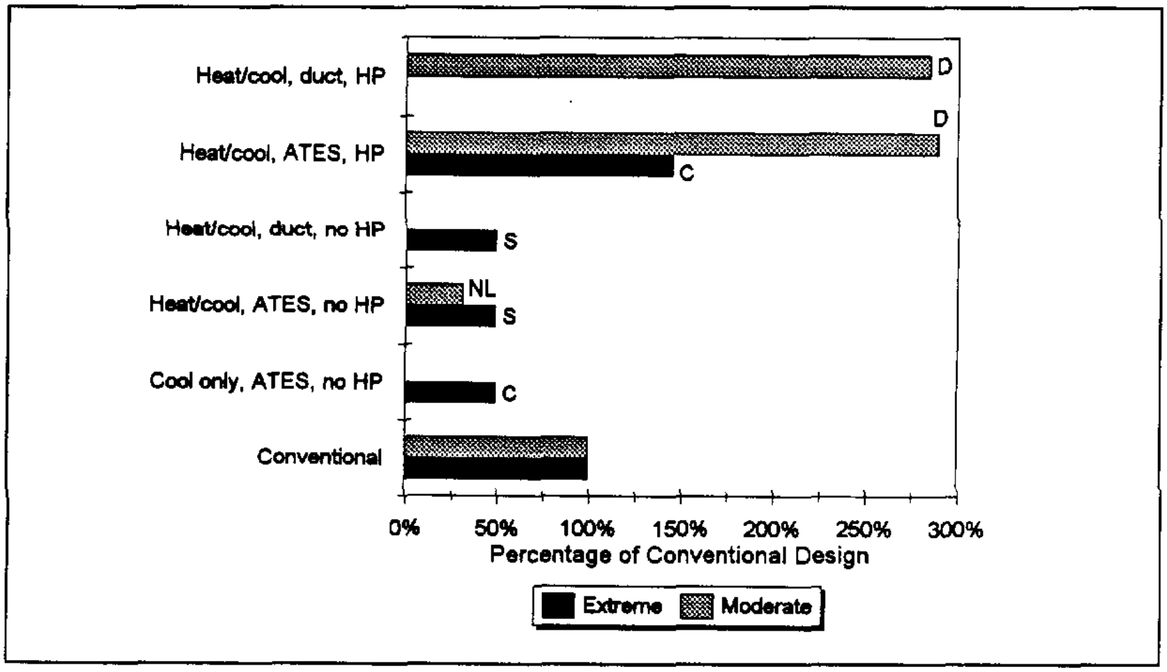


Figure 4-9: Annual Thermal Energy Consumption (Retrofit Building)

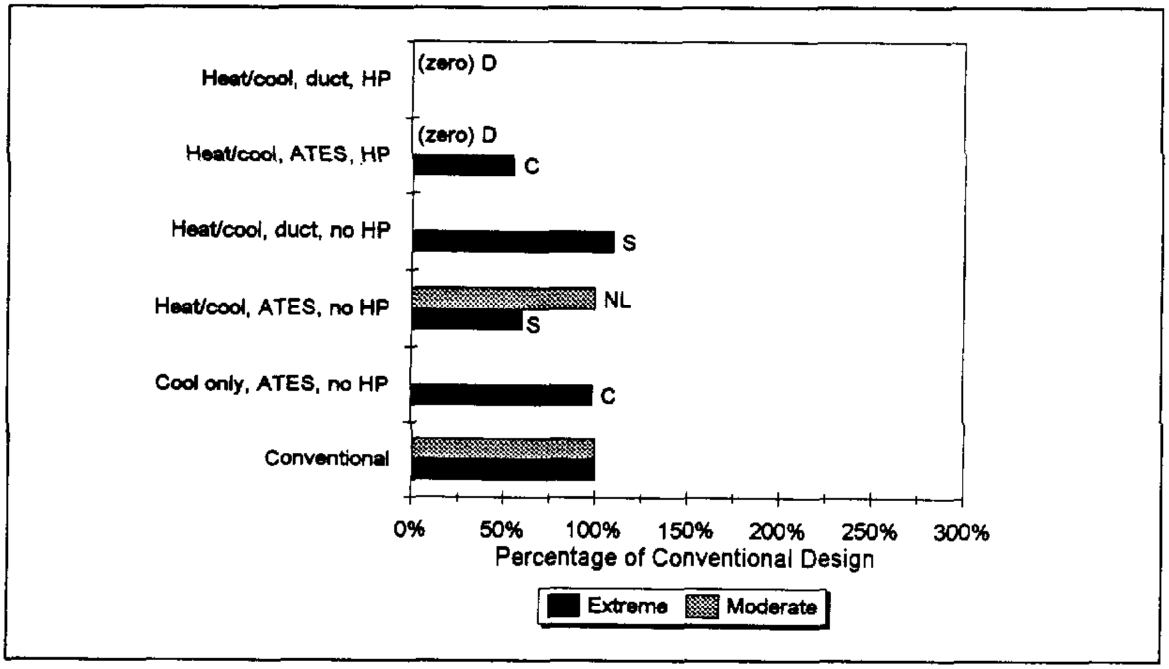


Figure 4-10: Total Annual Costs (Retrofit Building)

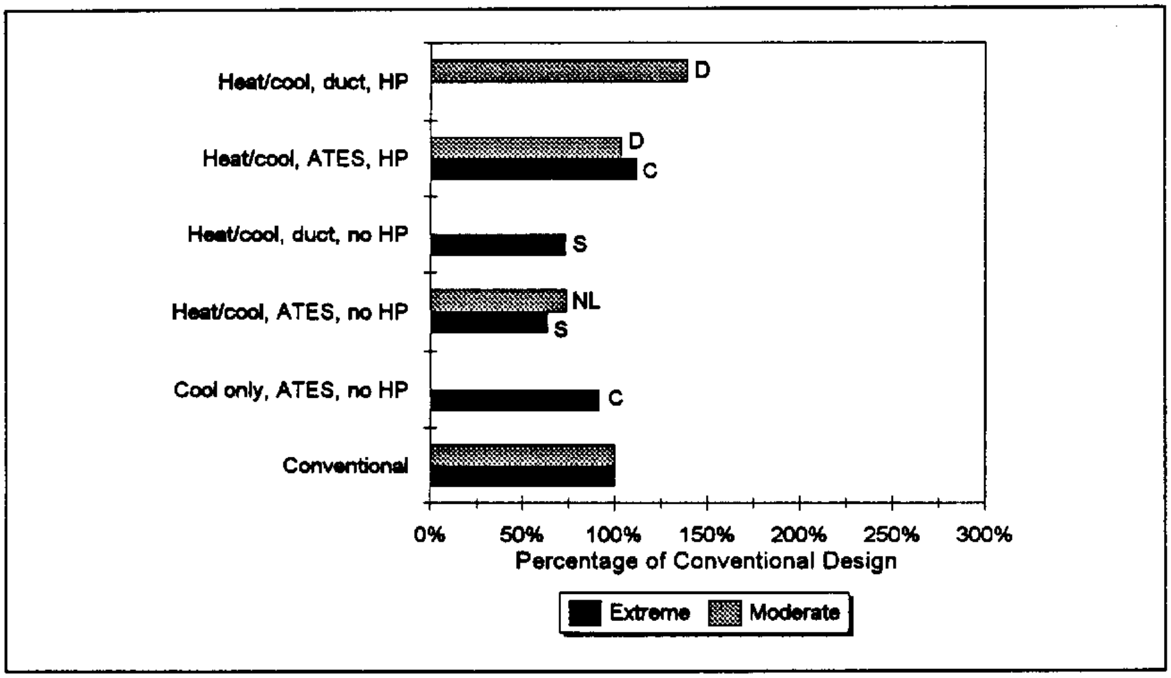


Figure 4-11: Annualized Capital Costs (Retrofit Building)

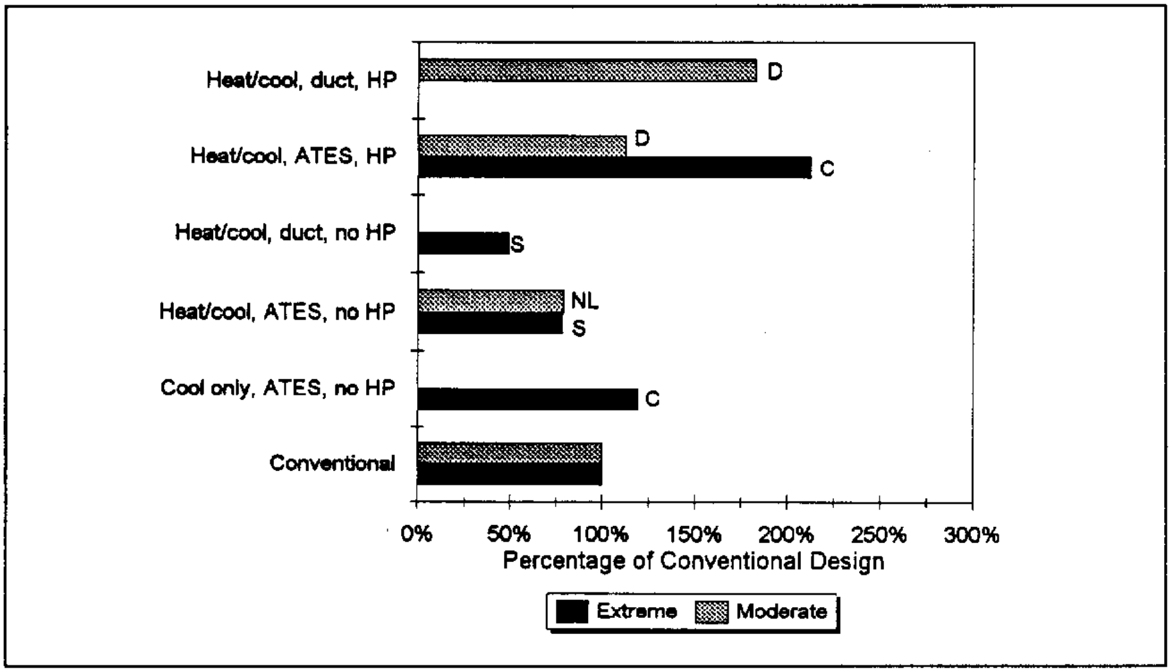
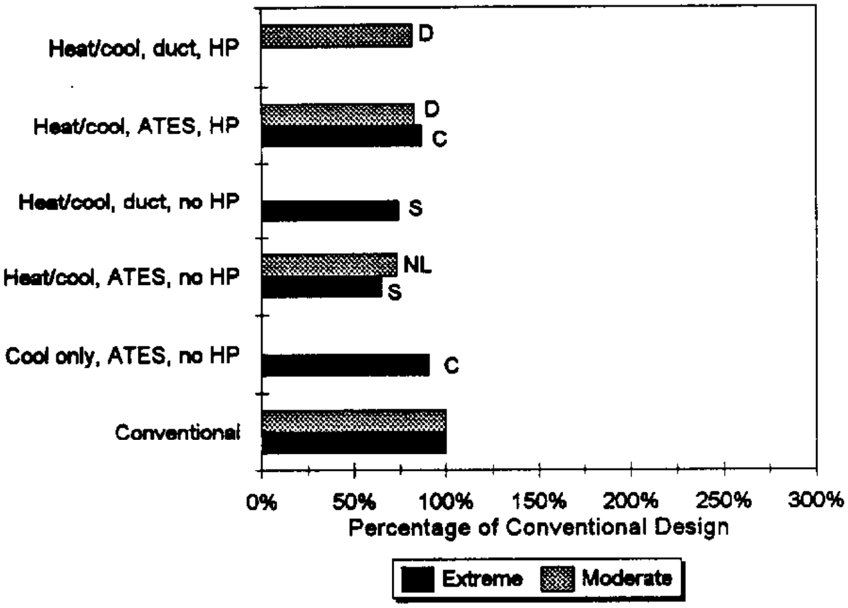


Figure 4-12: Annual Energy Costs (Retrofit Building)



4.4 Industrial Processes

Storage alternatives consume only a fraction — 15% to 50% —of the annual electricity of conventional designs (Figure 4-13). Total annual costs for storage are approximately 15% to 25% less than conventional designs (Figure 4-14). Annualized capital cost for storage is slightly higher than conventional designs (Figure 4-15).

Total annual energy costs are substantially lower for storage, ranging from 30% of conventional for the moderate climate to 55% of conventional for the extreme climate (Figure 4-16). Comparisons between the two climates should note that free-cooling contributes significantly more to the cooling load in the extreme climate. Figure 4-17 shows the contributions of free-cooling for the conventional designs for the two climates.

Figure 4-13: Annual Electricity Consumption (Industrial Process)

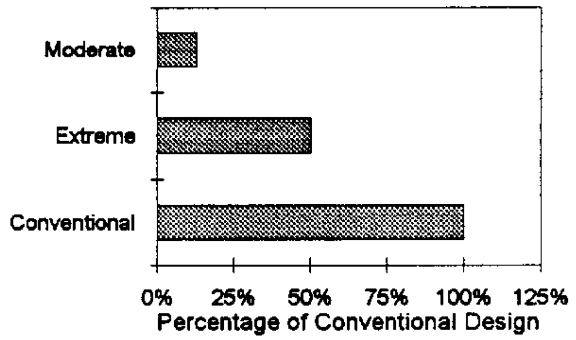


Figure 4-14: Total Annual Costs (Industrial Process)

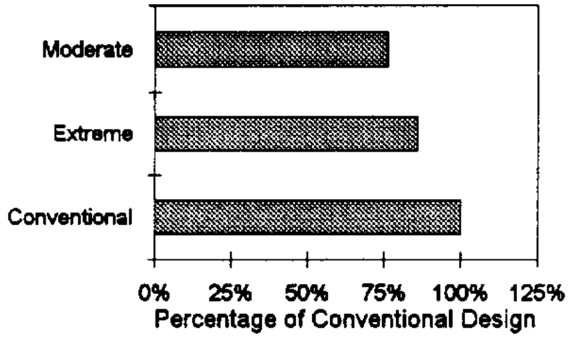


Figure 4-15: Annualized Capital Costs (Industrial Process)

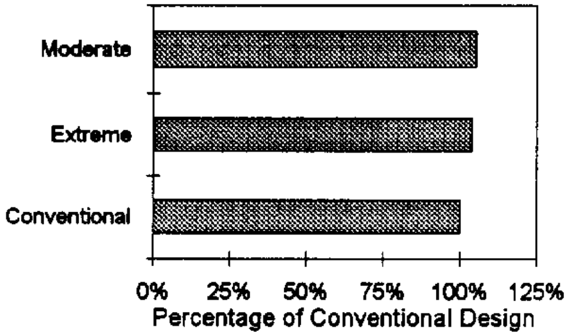


Figure 4-16: Annual Energy Costs (Industrial Process)

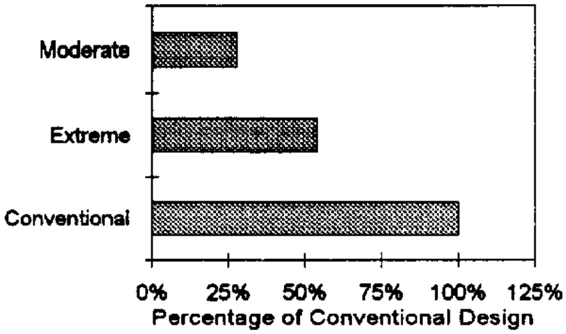
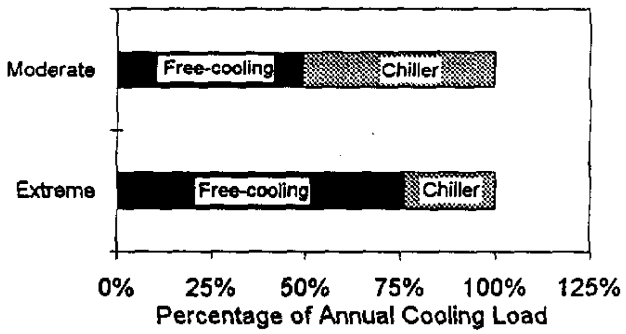


Figure 4-17: Comparison of Free-cooling between Climates (Industrial Process)



5.

Environmental Impacts
and
Other Considerations

5.1 Overview

This Chapter examines the net environmental impacts of storage design alternatives relative to conventional systems. The analysis is done on a country-by-country basis; therefore, the results reflect each country's energy mix, emission factors and system characteristics.

Emissions considered quantitatively in this analysis include carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrous oxides (NO_x). The impact of displacing CFCs is also considered on a qualitative basis; that is, the relative use of CFCs in the conventional and STES systems is examined.

5.2 Background

Environmental impacts of storage design alternatives, when compared with conventional designs, have the greatest effect on the following environmental issues:

- Greenhouse effect and potential global warming;
- Ozone depletion;
- Acid deposition; and
- Alteration of the groundwater environment.

The burning of fossil fuels (coal, oil and gas) produces gaseous emissions which include: carbon dioxide (CO_2), sulphur oxides (SO_2), and nitrogen oxides (NO_x). These gaseous effluents can result in various environmental effects:

- Greenhouse effect: Build-ups of gases in the atmosphere; energy normally radiated from the earth is trapped; contributes to global warming and climate change. From CO_2, CFCs, ground level ozone (O_3), methane (CH_4), nitrous oxide (N_2O) and other gases;
- Ozone depletion (in the stratosphere): From NO_x, CFCs, HCFCs, and halons; allows ultraviolet rays through the atmosphere, contributing to sun burn and skin cancer;
- Acid deposition: From SO_2 and NO_x; damages lakes and soil; and
- Smog (including ground-level ozone): From NO_x, volatile organic compounds (VOCs) and ozone; causes negative health effects and damage to vegetation.

As shown in Table 5-1, air quality issues cannot be addressed in isolation. The complex interactions between the various gases contribute to the greenhouse effect, ozone depletion, and acid deposition.

Table 5-1: Environmental Issues and Interactions

	Environmental Issue		
Gaseous Emission	Greenhouse Effect	Ozone Depletion	Acid Deposition
Carbon Dioxide (CO_2)	●		
Nitrogen Oxides (NO_x)	●	●	●
Sulphur Dioxides (SO_2)			●
CFCs and HCFCs	●	●	

Alternative storage designs can reduce gaseous emissions by reducing energy consumption and can reduce the escape of refrigerants to the atmosphere by eliminating the need for chillers.

The greenhouse effect and ozone depletion are the greatest environmental impacts as far as these technologies are concerned. Acid deposition and smog are not key environmental issues in this context. The greenhouse effect is caused by emissions from natural gas combustion and leakage, electrical power generation and refrigerant leakage. Ozone depletion is the impact of the anticipated refrigerant leakage to the atmosphere.

Alternative storage designs can have an impact on the groundwater environment due to perturbation of the water table and piezometric surface, and re-injection of thermally (and potentially chemically) altered groundwater. These groundwater issues have been examined in detail under Annex 6 of this same IEA ECES Implementing Agreement, and are not analyzed in this Annex 7.

5.3 Analysis and Results

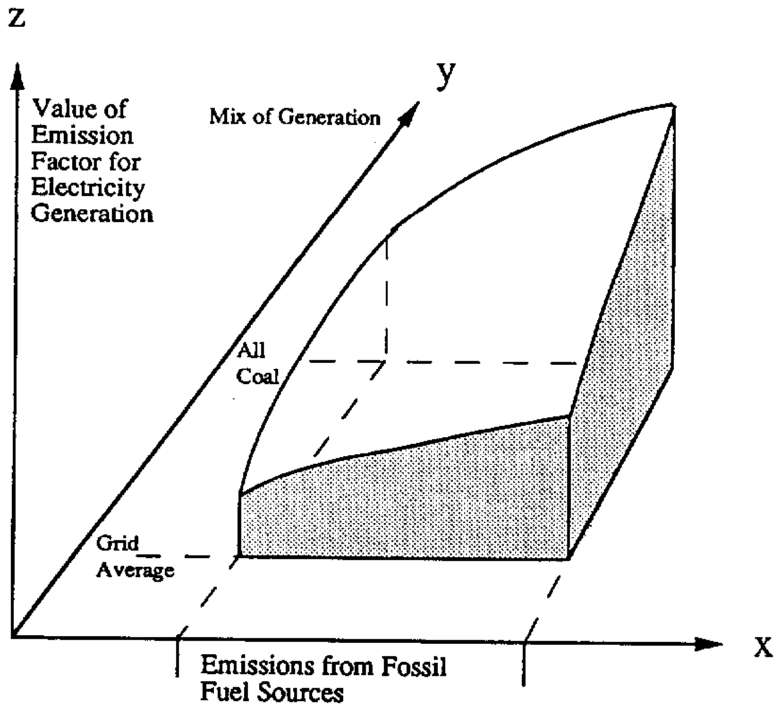
The impact of alternative storage designs on the environment was examined quantitatively in terms of their impact on emissions of CO_2, SO_2 and NO_x. CFCs are dealt with on a qualitative basis.

5.3.1 Utility Mix of Electrical Generation

In order to assess the environmental savings associated with alternative systems, assumptions must be made with respect to the source and generation mix of the displaced electrical energy. A wide range in emissions associated with electrical generation is often seen for one country or region. The reasons for this range are illustrated in Figure 5-1. The z-axis shows the range in value of emission factors associated with electrical energy production. The range is dependent on assumptions regarding: (1) the generation mix (y-axis); and, (2) the emissions associated with each energy source (x-axis). The latter consideration also includes technologies which are in place to mitigate against the environmental damage (e.g. scrubbers).

To most accurately project the fuel mix displaced a sophisticated full system simulation is required; however, this effort was beyond the study's scope. Therefore, some simplifying assumptions were made regarding the type of generation avoided. However, the most important note with respect to this issue is not an absolute, quantitative estimate, rather the recognition of the fact that any saving in energy use leads to positive environmental benefits. The magnitude of these benefits will always remain a point of discussion/contention.

Figure 5-1: Emissions - Factors and Interactions



The two major dimensions affecting the estimate of each type of emission are:

x *Range of Emissions* which depend on:

- Generating technologies;
- Control technologies; and
- Type of fossil fuel (eg. quality of coal).

y *Mix of Generation Technologies* which depends on:

- Generation plant and facilities (eg. percent fossil);
- Peak/Off-Peak and Summer/Winter timing; and
- Short-term/long-term perspective.

For our analysis, we chose to use a system average emission per unit of electricity output. That is, the estimation of environmental impacts of energy storage alternatives is based on simple, national average parameters for each country. That is, a savings of electricity by a storage alternative, as compared to a conventional design, is attributed with environmental impact reductions consistent with reduced electrical energy consumption, using the national average generation mix and associated emission factors for the most current year of available data.

This estimate is conservative in several aspects. Firstly, if the energy displaced is at the margin, this will be primarily fossil generation in most countries. Secondly, on a regional basis, the generation mix can be weighted much more heavily towards fossil generation than the national average reflects.

The emission factors and utility mix are country-specific and were provided by each participating country.

5.3.2 Comparative Results

For comparison purposes the environmental impact of the alternative storage designs are shown relative to the conventional design, with the conventional design representing 100%. Details for this analysis can be found in Appendix F.

Figure 5-2: Environmental Emissions Relative to Conventional Designs - New Building

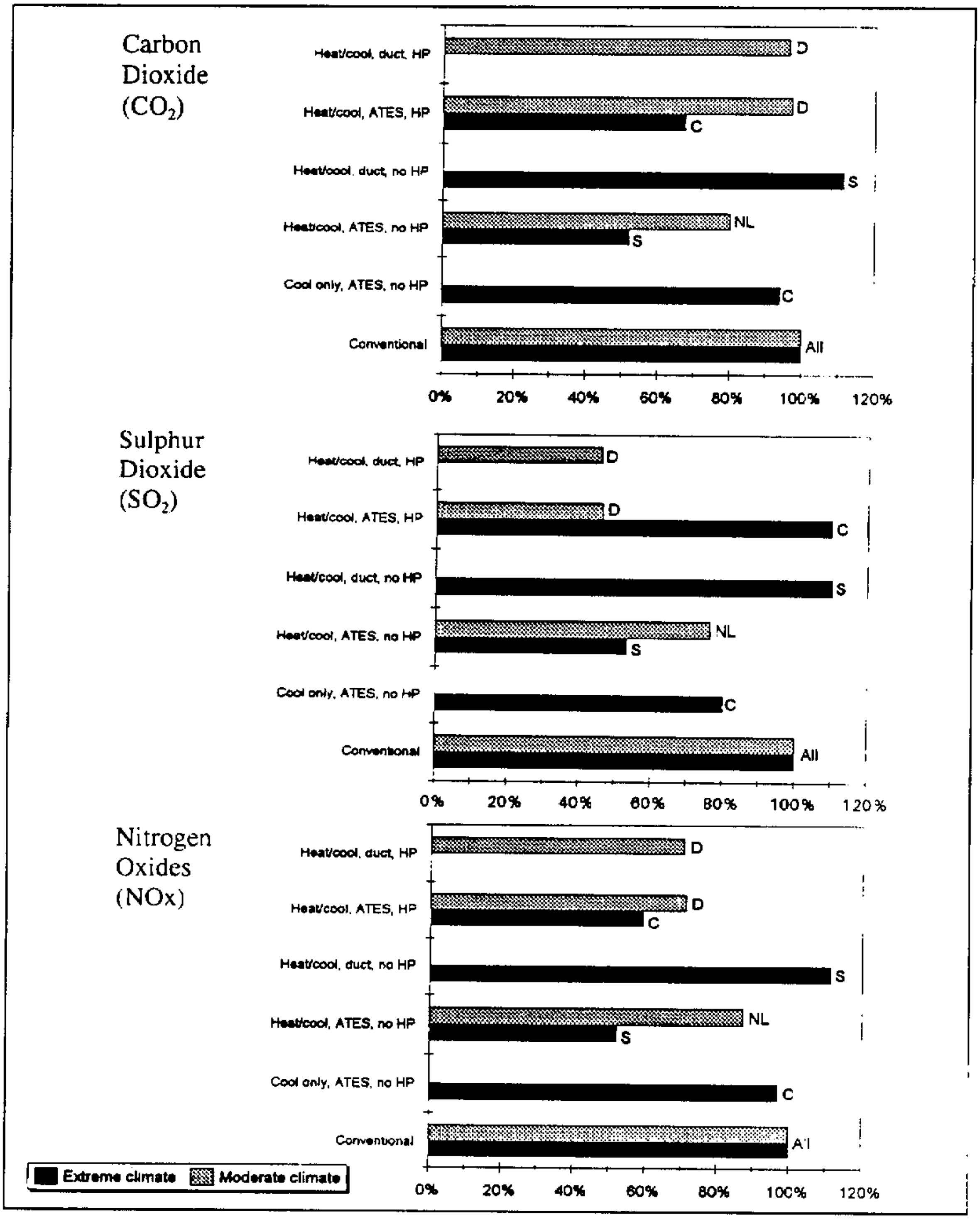
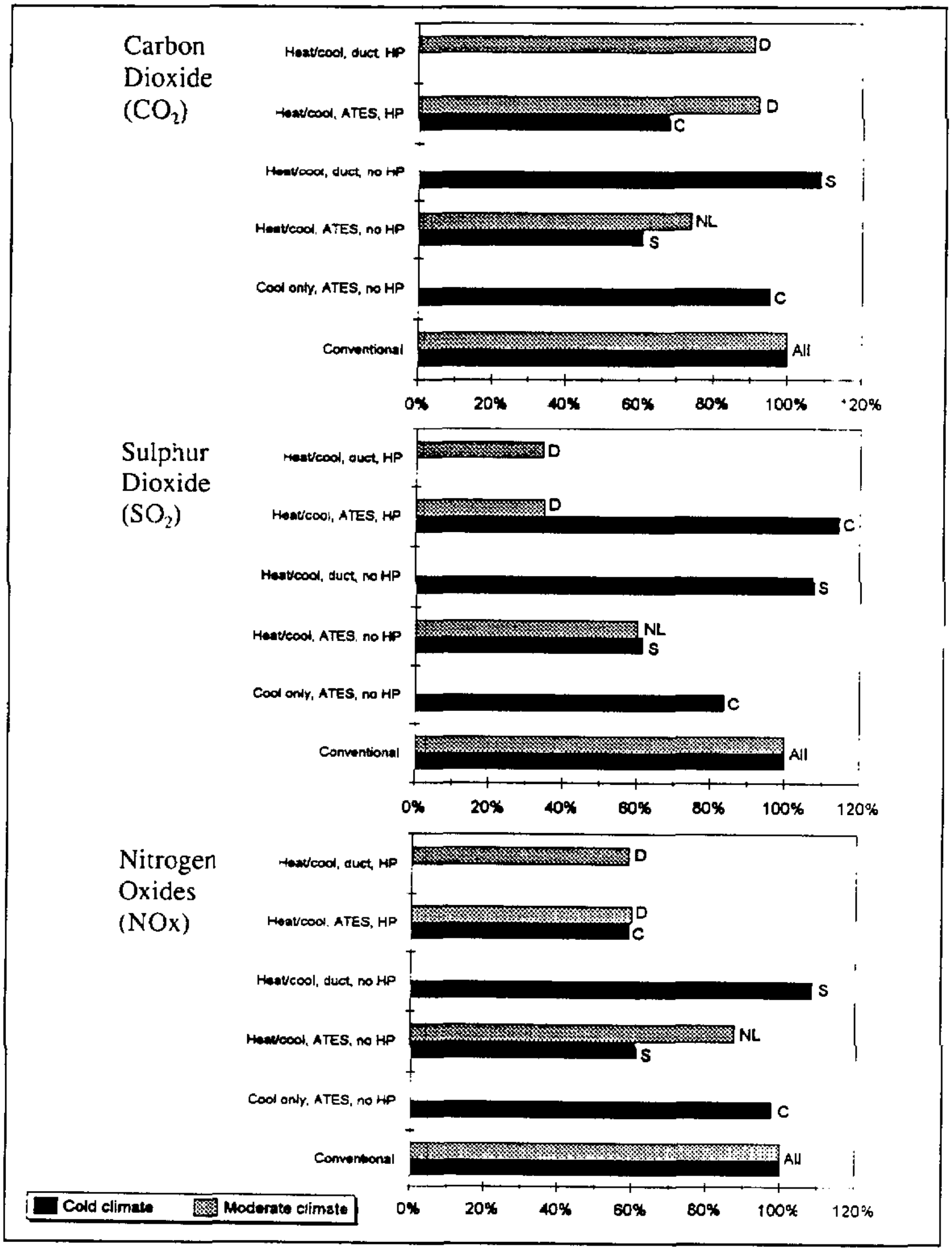


Figure 5-3: Environmental Emissions Relative to Conventional Designs - Retrofit Building



5.3.3 Commentary on Results

Figures 5-1 and 5-2 illustrate the environmental impacts of new and retrofit applications of alternative storage options.[1] The range in impact varies due to the amount and type of energy displaced and the emission factors.

In all but two cases, the environmental impact of these alternatives are favourable. The two exceptions occur in both the new building and retrofit cases:

- Sweden: Heat/cool, duct system without a heat pump. While the ATES storage design decreases the demand for both district heating and electricity, the duct system decreases the demand for electricity and partly replaces electricity with district heating during the summer. This results in a net increase in all three emissions (CO_2, SO_2, NOx) because the emission factors for district heating are significantly higher than those for electricity generation.
- Canada: Heat/cool, ATES system with a heat pump. In this case, the alternative system requires more electricity and less gas than the conventional system. The net result is a decrease in CO_2 and NOx emissions, but an increase in SO_2 emissions. Since gas does not emit SO_2, the increase in electricity use results in a net rise in SO_2 emissions.

5.3.4 Chloroflourocarbons (CFCs)

Since the 1930's, millions of kilograms of CFCs and related chemicals have been emitted by the industrialized world. These substances have migrated to the upper atmosphere, where, through a series of chemical reactions, the ozone has progressively been depleted. This has resulted in a worldwide erosion of the protective layer and a pronounced seasonal reduction in ozone concentration over a large area of the southern polar region. Recently it has been discovered that these same chemicals act as greenhouse gases and their past release to the atmosphere will cause an estimated 20 to 25% of future global warming.[2]

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[1] CO_2 and SO_2 emissions factors for electricity generation for the Netherlands are calculated on the basis of data reported in terms of greenhouse effect and equivalent acid deposition. Since NOx contributes to both these issues, the estimated absolute value of emissions may be higher than actual. Gas emission factors were not provided for the Netherlands; therefore, Canadian data were used.

[2] Deadly Releases CFCs (Part I of "Our Changing Atmosphere" Series), The Standing Committee on the Environment, House of Commons, Canada.

In 1989, Canada and 46 other countries signed the Montreal Protocol on Substances that deplete the Ozone Layer. The Protocol establishes a schedule to reduce the global consumption of five CFCs and three halons. This agreement calls for a 50% reduction in the production and consumption of CFCs in the signatory countries by the year 1998. Changes in refrigeration and cooling technologies can go a long way to meeting this goal. In 1989, 30% of the global use of controlled CFCs was for refrigeration; in Canada, refrigeration accounted for 45% (the balance is aerosols, foams and solvents).

Depending on the configuration of cold storage design, these technologies can reduce or completely displace the need for CFCs. All conventional options have chillers and use CFCs. Cooling options without heat pumps do not use CFCs and therefore completely displace the CFCs used in the standard technology. Cooling options designed with heat pumps may use CFCs; however, these options may require a lower volume of CFC use and there may be a net benefit with respect to CFCs.

Table 5-2: Impact on CFCs

Country and Technology	Reduction in CFCs and HCFCs Relative to Conventional Design
Canada	
Cool only, ATES, no HP	Yes
Heat/cool, ATES, HP	No
Sweden	
Heat/cool, duct, no HP	Yes
Heat/cool, ATES, no HP	Yes
Germany	
Heat/cool, duct, HP	No
Heat/cool, ATES, HP	No
The Netherlands	
Heat/cool, ATES, no HP	Yes

5.4 Other Considerations

A number of other factors - in addition to the energy, costs, and environmental impact already discussed - must be considered in the selection of a heating/cooling system. These factors are more difficult to quantify and are summarized qualitatively in Table 5-2.

Reliability and maintenance of HVAC systems are obviously important issues. Storage systems tend to require less maintenance because they have fewer moving parts. They are however more difficult to maintain or repair because of the limited working experience with these systems and their limited accessibility.

The space requirements for equipment consist of indoor and outdoor space. For conventional systems, indoor space is required for chillers or heat pumps, circulating pumps, and heat exchangers; and a rooftop area is required for cooling towers. Storage configurations have less indoor space requirements if chillers or heat pumps are eliminated. Accessibility to an appropriate storage medium is of course required for storage configurations.

Table 5-3: Other Considerations for Storage Relative to Conventional Designs

	Storage Considerations Relative to Conventional	
Reliability:		
Technical reliability	+	Fewer moving parts, fewer breakdowns[†]
Availability of cold	-	Sensitive to climatic influences for storage temperatures < 12 °C
Emergency power backup	+	Small system needed
Repair time	o	Comparable
Back-up capacity	o	Comparable
Maintenance and Management	-	Unfamiliarity
	-	Extra parties involved
	-	Limited accessibility
Environmental Aspects	+	No refrigerants[†]
	+	Less emissions of harmful, energy related substances
	+	Less noise nuisance
Various Aspects:		
Procedure for permitting	-	More extensive procedure, more time
Starting period	-	A consideration if load requirements are lower than ambient temperature
Space requirement	+	Smaller technical room[†]
Expansion	+	Typically expandable

[†] For storage systems without heat pumps.

6.

Findings and Conclusions

The findings from the system designs, energy simulations and economic analyses are based on comparisons of storage systems designs with conventional system designs. These comparisons have been made based on typical design practice in each of the four participating countries. Two climate regimes (extreme and moderate) have been analyzed. For building applications, both new and retrofit cases have been examined. For the process cooling load case, only new system designs were analyzed.

For the building applications (new and retrofit, moderate and extreme climate):

- Total energy cost of the storage design is less than that for the conventional design in all cases;

- Electrical energy consumption is higher (than the conventional design) for the storage design cases which included (electrical) heat pumps but significantly lower for storage designs without heat pumps;

- Thermal energy consumption is lower (than the conventional design) for the storage with heat pump cases but is generally about the same in the designs without heat pumps;

- Capital cost is higher (than the conventional design) for the heat pump cases but generally lower in the designs without heat pumps; and
- Total (energy and annualized capital) cost is higher (than the conventional design) for the designs with heat pumps but lower for the designs without heat pumps.

In the building applications analyzed, the relative difference between new and retrofit applications (as compared to conventional) is negligible, as is the relative difference due to the two climates.

For the process cooling load application:

- Electrical energy consumption (and cost) are significantly reduced in the storage design as compared to the conventional design;
- Capital costs are slightly higher (than the conventional design) for the storage design, but total costs are significantly lower;
- There are significant differences between the moderate climate and the extreme climate simulations due to the level of "free cooling" that is available in each climate--free cooling satisfies more of the cooling demand in the extreme climate so that the energy savings possible from eliminating the chiller in the extreme climate is more limited.

Environmental emission levels were calculated for the building applications based on differences in energy consumption between the conventional designs and the storage designs. Emissions were estimated using national average emissions per unit of energy used (electricity, oil, gas, district heating).

Generally emission levels of CO_2, SO_2 and NO_x are significantly lower for the storage design cases as compared to the conventional designs. One design (heating and cooling, with duct storage and no heat pump) in Sweden exhibited higher emissions because the storage design required higher levels of thermal energy. Storage designs without heat pumps also have the environmental advantage that CFCs in the chillers of the conventional design are eliminated.

Based on the analyses of these cases, it is concluded that seasonal thermal energy storage (STES) for cooling only, and for heating and cooling applications of buildings, is attractive as compared to conventional system designs especially for storage designs without heat pumps. For a continuous cooling load such as an industrial process, the application of STES designs in very attractive as compared to conventional designs based on the use of chillers.

Appendix A

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and

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Appendix B

Selected Data on Current Cold Storage Projects

Selected Data on Current Cold Storage Projects

	Proj. No.	Project Identifier	Feasib. Study Year	Storage Cooling Cap. (kW)	Stored Cold per Cycle (MWh)	Pay Back (years)	Capital Cost (Cdn $)	Status	Load Type	Open/ Closed Store	Storage Medium	Heat/ Cold Storage	Heat Pump or Chiller	Freez-ing?	Cold Storage Product.
CAN	1	Winpak	1987	1,500	8,500	0	(507,600)	Real	Ind	O	Aquifer	H & C	No	No	HX
CAN	2	Scarborough	1984	1,500	534	5	350,000	Real	Comm	O	Aquifer	H & C	Yes	No	HP, CT
CAN	3	Carleton	1988	2,500	7,500	4	4,720,000	Real	Comm	O	Aquifer	H & C	Yes	No	HP
CAN	4	Natural Ice	1989	32	18	0	(14,500)	Real	Ind	O	Surf. W.	C only	No	Yes	Air
CAN	5	Sussex	1992		8,500		0	Real	Comm	O	Aquifer				
GER	1	Hund	1987	3	2	NA	NA	Real	Res	C	Rock	H & C	No	Yes	HP
GER	2	Koch	1988	5	4	NA	NA	Real	Res	C	Rock	H & C	No	Yes	HP
GER	3	Geotherm	1990	11	11	6	1,900	Real	Comm	C	Rock	H & C	No	Yes	HP
GER	4	Duisburg	1990	340	500	NA	NA	In Prep	Comm	C	Soil	H & C	Yes	Yes	HP
GER	5	Stuttgart	1990	50	40	NA	NA	Real	Comm	O	Wat.Pit	H & C	No	No	HP
GER	6	Technorama	1989	40	80	21	47,400	Real	Comm	C	Soil	H & C	Yes	Yes	HP
GER	7	Ophthalmica	1992	20	10	NA	11,400	Real	Comm	C	Soil	H & C	Yes	Yes	HP
GER	8	UEG Laboratory	1992	40	139	2.9	8,200	Real	Comm	C	Rock	H & C	Yes	Yes	HP
GER	9	Reichstag	1993	3,500	675	NA	316,000	In Prep	Comm	O	Aquifer	H & C	Yes	No	HP
GER	10	Nickern	1993	4,000	2,000	NA	NA	In Prep	Comm	C	Soil	H & C	Yes	No	HP
NETH	1	Perscombin.	1986	450	1,030	14	387,400	Real	Comm	O	Aquifer	C only	Yes	No	DC
NETH	2	Stadhuis	1989	3,300	1,400	8	216,100	Real	Comm	O	Aquifer	C only	Yes	No	CC
NETH	3	BAM Office	1990	330	80	6	28,100	Real	Comm	O	Aquifer	C only	No	No	DC
NETH	4	IBM Office	1990	1,000	1,700	5	437,900	Real	Comm	O	Aquifer	C only	Yes	No	CT
NETH	5	Groene Hart	1990	800	550	4	131,400	Real	Comm	O	Aquifer	H & C		No	CC
NETH	6	Nursery Gameran	NA	120	230	NA	NA	Real	Ind	O	Aquifer	C only		No	CT
NETH	7	Nursery Luttelgaas	NA	325	250	NA	NA	Real	Ind	O	Aquifer	C only		No	SW
NETH	8	Jaarbeurs	1992	2,600	440	0	(101,100)	Real	Comm	O	Aquifer	C only		No	CC
NETH	9	Mussonder	NA	13	5	3	8,400	Real	Comm	O	Aquifer	H & C	Yes	No	HP
NETH	10	Schiedam Office	NA	880	250	5	66,200	Real	Comm	O	Aquifer	H & C		No	CC
NETH	11	Provinciehuis Utre	1992	465	200	NA	NA	Real	Comm	O	Aquifer	H & C		No	CC
SWE	1	DTU-Hofors	NA	100	14	NA	NA	Real	Comm	C	Soil	H & C	Yes	Yes	HP
SWE	2	Sparven Malmö	1990	800	6,500	2	349,400	Real	Comm	O	Aquifer	C only	No	No	FC
SWE	3	Ystad Hospital	1988	300	265	6	111,800	In Prep	Comm	O	Aquifer	H & C	Yes	No	HX
SWE	4	Triangle Malmö	1987	600	1,000	4	349,400	Real	Comm	O	Aquifer	H & C	Yes	No	HP,HX
SWE	5	SAS Office	1985	2,000	3,000	5	698,800	Real	Comm	O	Aquifer	H & C	No	No	HP,FC
SWE	6	Edz Wiik	1987	800	2,500	1	384,300	In Prep	Comm	O	Aquifer	H & C	No	No	HP
SWE	7	Norrviksstrand	1989	4,500	3,500	0	(349,400)	In Prep	Comm	O	Aquifer	H & C	No	No	GW,SW
SWE	8	Ericsson	1983	400	900	2	262,100	Real	Ind	O	Aquifer	H & C	Yes	No	HP
SWE	9	GLG-Center	1987	480	720 (1)	8	611,500	Real	Comm	C	Rock	H & C	No	No	HP
SWE	10	Höstvetet	1983	NA	NA	NA	NA	Real	Comm	C	Rock	H & C	No	No	HP
SWE	11	Capella	1987	40	60 (1)	6	69,900	Real	Comm	C	Rock	H & C	No	No	HP
SWE	12	Vintergatan	1990	180	270 (1)	4	87,400	Real	Comm	C	Rock	H & C	No	No	HP
SWE	13	Viberga	1982	90	135 (1)	5	52,400	Real	Comm	C	Rock	H & C	No	No	HP
SWE	14	ONOFF	1989	130	195 (1)	6	87,400	Real	Comm	C	Rock	H & C	No	No	HP
SWE	15	Hyllie, Malmo	1991	70	500	3	122,300	Real	Comm	O	Aquifer	H & C	Yes	No	FC/HP
SWE	16	Dalaplan, Malmo	1992	50	400	4	104,800	Real	Comm	O	Aquifer	H & C	Yes	No	FC/HP

Appendix C

Standard Formats for Reference Building, Process Load, and Sub-Soil

IEA ANNEX 7

- Reference cooling/heating loads
- Sub-soil design conditions
- System design format

June 1992
3/9210/AS

IF Technology
De Wit Adviesbureau

1. INTRODUCTION

As part of Annex 7 of the IEA Storage Programme entitled "Innovative and Cost Effective Seasonal Cold Storage Applications" generic configurations of systems with seasonal cold storage will be analysed by each of the participating countries. This analysis will be performed for various options, that arise from the combination of applications, climate types and system configurations, shown in the following matrix:

Table I: Configuration Responsibility Matrix by Country

	CONFIGURATION			
	Cooling Only No HP	- - Heating and Cooling - - Open HP	Open No HP	Closed HP
Country responsible for Storage Configuration	Netherlands	Canada	Sweden	Germany
Country analyzing new and existing buildings:				
Canada	cold	cold	N/A	N/A
Germany	N/A	moderate	N/A	moderate
Netherlands	moderate	N/A	moderate	N/A
Sweden	N/A	N/A	cold	cold
Country analyzing process loads:				
Canada	cold	N/A	N/A	N/A
Netherlands	moderate	N/A	N/A	N/A

Legend:
cold = cold climate with extreme high and low temperatures (e.g. Winnipeg)
moderate = moderate maritime climate (e.g. Amsterdam)
N/A = no analysis to be performed

The analysis will start with the design of both the conventional energy systems as well as the alternatives with seasonal cold storage.

In order to make the results from the different countries comparable to each other, a common starting point will be defined consisting of a "reference building", a "reference process" and a "reference soil".

The conventional and alternative systems for the building involve both heating and cooling. The analysis for the process load is resricted to cooling only. To facilitate the comparison of the designs a format is presented to prepare the conventional system design and the alternative system design.

2. REFERENCE BUILDING

As a starting point for the evaluation of the cooling systems with seasonal energy storage for building applications an office building has been choosen with 4 floors and a gross floor area of 12000 m². The net floor area amounts to 8400 m². The main dimensions and the lay-out of the building are shown in figure 2.1. The technical rooms are located on the roof of the building.

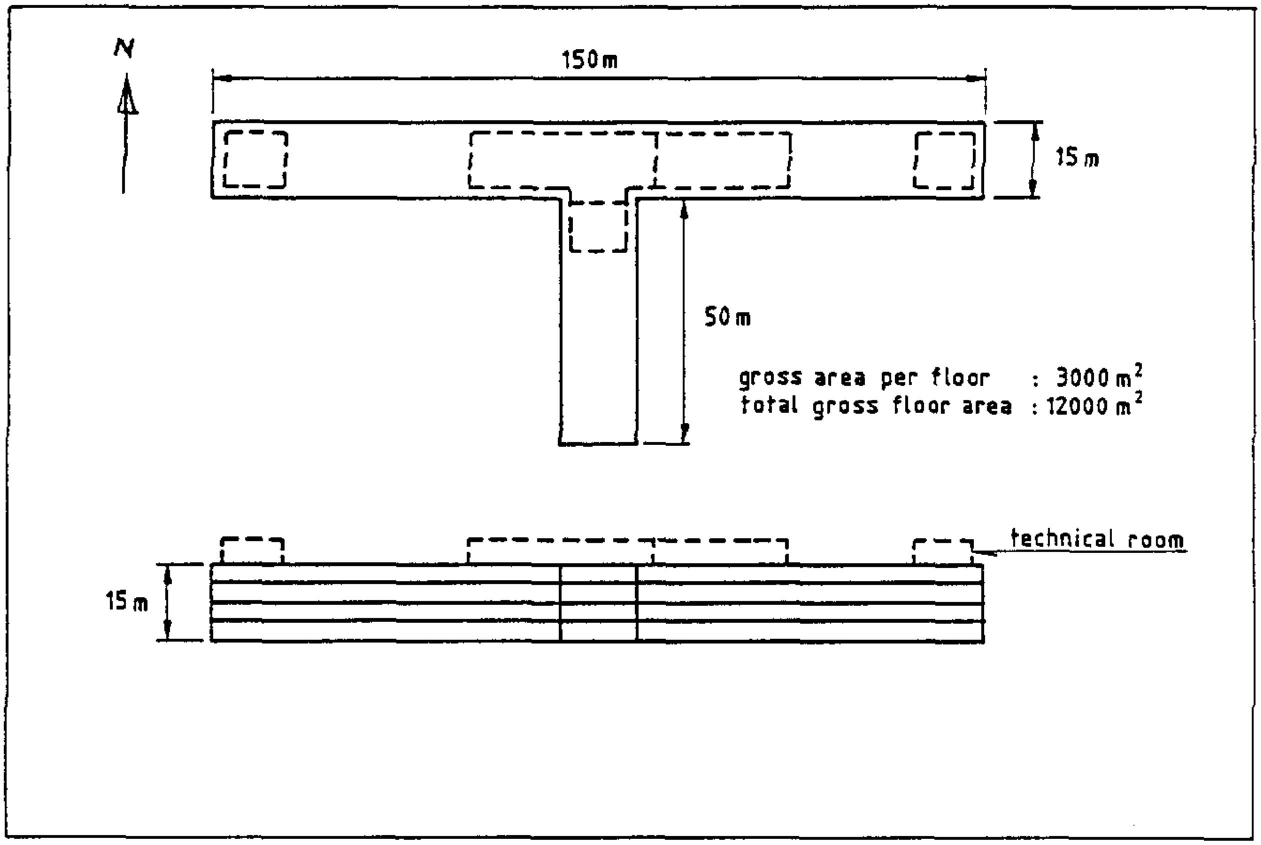
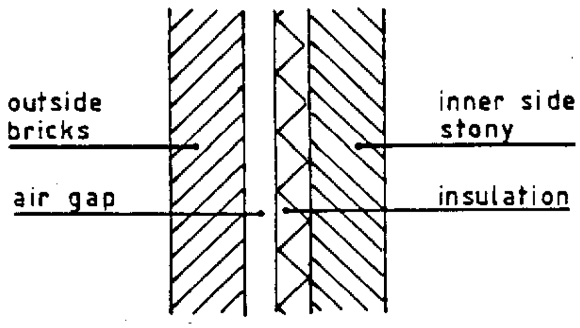


Figure 2.1 Lay-out of the office building.

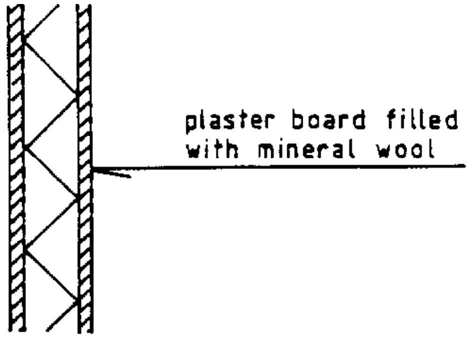
New building and retrofit building

The new building and the retrofit building are similar with respect to the floor area and the lay-out. The difference is mainly in the skin characteristics, as will be defined in the following table.

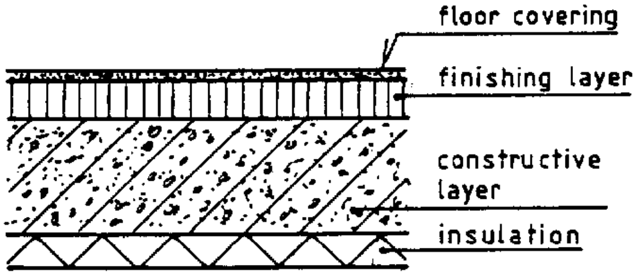
External walls



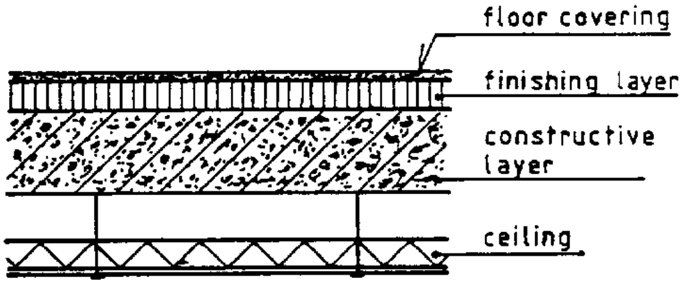
Internal walls



Ground floor



Intermediate floor



Roof

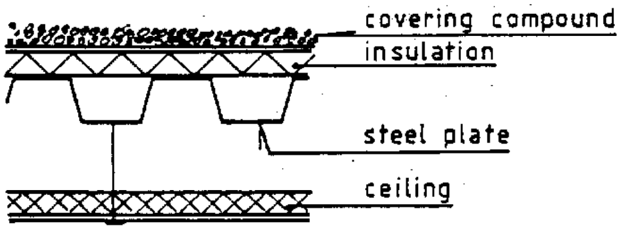


Figure 2.2 Characterization of the walls, the floors and the roof

It is obvious that the technical installations in the new building are completely new, which means that the designer has a free hand. The retrofit building however, has some restrictions with respect to the cooling/heating installations. The equipment in the technical rooms will be retrofitted completely. However, the ventilation air ducts in the building, designed to meet the minimum outdoor air requirement (35 m^3/h per person, see next table) will not be replaced. Additional cooling and heating is provided by fan-coil units in the rooms. The fan-coil units will be renewed, so the cooling/heating capacity of these units is free to choose. However, it is not possible to change from fan-coil units to other means to provide the additional cooling and heating.

Building characteristics

The building characteristics are shown in table 2.1. See also figure 2.2 for a characterisation of the walls, floors and roof.

Table 2.1 Building characteristics	New building	Retrofit building
Dimensions of an office-unit (width x depth x height from floor up to the ceiling)	3.6 x 6.1 x 2.7 m^3	3.6 x 6.1 x 2.7 m^3
Heat transmission coefficient of the exterior walls, the roof and the ground floor	0.3 W/m^2K	0.6 W/m^2K
Percentage glass area in respect of the total frontage area	30%	50%
Heat transmission coefficient of glass	1.8 W/m^2K	3.0 W/m^2K
Sun entry factor of glass + shading	0.30	0.66

Occupancy

The occupancy in the office building is 1 person per 10 m^2 net floor area, corresponding to 840 persons for the whole building.

Working hours

The working hours are from monday till friday from 8.00 - 18.00 hour, corresponding to 2500 hours per year.

Ventilation

The following criteria apply to the ventilation in the building:

- Minimum outdoor air: 35 m^3/h per person.
- The ventilation air is supplied to the office-rooms by air grates. Room air is exhausted via the armatures and the plenum.

Lighting

The lighting intensity in the office rooms is 500 lux. The installed power for lighting is 15 W per m² net floor area.

Cooling

The design criteria for the cooling system are:

- Outdoor conditions	* moderate climate:	28 °C, 55% r.h.
	* extreme climate:	31 °C, 45% r.h.
- Room conditions	* setpoint temperature:	22 °C
	* relative humidity:	40 - 60 % r.h.

It is allowed to exceed the nominal room temperature for a restricted number of hours, in accordance with the country's common practice.

The contribution of the internal heat production to the cooling load in Watts per m² net floor area is:

- occupants	6 W/m²
- equipment	15 W/m²
- lighting	9 W/m²
Total	30 W/m²

The total internal heat production for the building is: 30 W/m² x 8400 m² = 252 kW.

Heating

The design criteria for heating are:

- Outdoor temperature	* moderate climate:	-12 °C
	* extreme climate:	-37 °C
- Wind velocity	* moderate climate	8 m/s
	* extreme climate	no wind
- Room temperature	* setpoint:	20 °C

3. REFERENCE INDUSTRIAL PROCESS

For the evaluation of process cooling with and without seasonal cold storage a reference process is defined below. The cooling load has been simplified by assuming a constant and continous load all over the year. Industrial processes requiring a nearly constant and continous cooling load can be found for instance in the food processing and chemical industry.

An industrial production process requires cooling to discharge low temperature waste heat. The process cooling medium is water, which has to be cooled from 22 °C down to 12 °C. The cooling capacity is constant and amounts to 600 kW. As the process runs continuously, the waste heat has to be discharged during 8760 hours per year.
It is assumed that the process cooling medium is separated by a heat exchanger from the cold production facilities (chiller, cooling tower, cold storage, etc.)

4. REFERENCE SUB-SOIL

To be able to design the seasonal storage sub-system, "reference sub-soils" will be defined below.

For the open storage type both an aquifer and an esker are defined as storage formations. The esker has a higher permeability than the aquifer and offers the possibility to complete wells without artificial gravel pack. For the closed storage type the storage formation is supposed to be rock.

The relevant properties of the various reference sub-soils are summarized in table 4.1. As can be seen from this table, the moderate and extreme climate result in different values for the natural groundwater temperature.

Table 4.1 Relevant parameters for the "reference sub-soils"

parameter		esker	aquifer	rock
storage formation				
thickness	[m]	10	20	> 50
hor. permeability (averaged)	[m/s]	$1.0\ 10^{-3}$	$1.0\ 10^{-4}$	n.r.[1]
hor.perm./vert.permeability	[-]	1	5	n.r.
porosity	$[m^3/m^3]$	0.30	0.30	<0.10
heat transfer coefficient (av)	[W/Km]	2.5	2.5	3.0
heat capacity (averaged)	$[kWh/Km^3]$	0.75	0.75	0.60
natural temperature moderate climate	[°C]	11	12	11
natural temperature extreme climate	[°C]	7	8	7
hor. hydraulic pressure gradient[2]	[m/m]	$1.0\ 10^{-3}$	$1.0\ 10^{-3}$	n.r.
vert. hydraulic pressure gradient[2]	[m/m]	n.r.	n.r.	n.r.
piezometric head	[m.b.s][3]	2	2	n.r.
groundwater quality	[mg/l Cl]	50	50	50
	$[mg/l\ O_2]$	0.0	0.0	0.0
	[mg/l Fe]	5	5	5
overburden				
characterization	[-]	locally absent	aquitard	aquitard
thickness	[m]	0-10	40	5
heat transfer coefficient	[W/Km]	1.5	1.5	1.5
heat capacity	$[kWh/Km^3]$	0.75	0.75	0.75
lower confining layer				= storage formation
characterization	[-]	aquiclude	aquiclude	-
thickness	[m]	>30	>30	-
heat transfer coefficient	[W/Km]	3.0	1.0	-
heat capacity	$[kWh/Km^3]$	0.60	0.75	-

---

[1] n.r. indicates: not relevant

[2] hydraulic pressure gradient in meters water column per meter distance in horizontal or vertical direction;

[3] meters below surface. The piezometric head is supposed not to vary over the year.

5 CONVENTIONAL SYSTEM DESIGN

To be able to compare the conventional system design from one country to another and to understand why a specific choice was made, the following information should be presented for the conventional system for the new building, the retrofit building, and the industrial process. For the industrial process, no information on the heating installation is required.

Overall system

Required information:

- Calculated cooling/heating load under design conditions
- Calculated number of full load hours. How is the climatic averaged year defined?
- Calculated number of hours that the nominal room temperature will be exceeded. What will be the maximum room temperature?
- Choose the cooling/heating system that most probably will be applied for this specific situation (e.g. all air system, ventilation air combined with fan-coil units, etc.) What are the main arguments for this choice?
- What cooling/heating capacity will be installed based on the above-mentioned cooling/heating load? What is the main reason to install spare capacity, if any?
- Present a process schematic of both the cooling and heating system (summer and winter mode) indicating the flows and temperature levels under design conditions of both air and water.
- Give a short description of the control of the cooling/heating system.

Main components

Summarize the following information for the main components (e.g. chillers, boilers, air-handling units, main circulation pumps, etc.):

- the total number of components. For instance, for the choice of chillers it is important to know how many chillers will meet the complete load.
- flow and pressure difference of air and/or water under design conditions.
- inlet and outlet temperature of air and/or water under design conditions.
- the required power connection in kW (electricity) or m^3/h (gaz or oil).
- energy conversion efficiency based on the electrical power input or on the upper calorific value of the fossil fuel input.
- other specifications relevant to the choice that was made (such as compressor type for the chillers, etc.).

Technical rooms

Give a lay-out of the technical rooms, indicating the location and space requirement of the of the main components in each technical room.
Specify for each technical room the total (kW, m^3/h of the required power connections.
Indicate where in the building the main control equipment and where the step-down transformers for the electrical power will be located.

6 STORAGE SYSTEM DESIGN

The heating/cooling system with storage should be the optimum choice given the reference cooling/heating system. So, if an all air system was applied for the reference new building for example, it should not be replaced by a system with fancoil units. However, it is allowed to change the specifications of the components (with some restrictions for the retrofit building, see chapter 3). The following information should be presented for the heating/cooling system for the new building, the retrofit building and the industrial process (cooling system only).

Overall system

Required information:
- Present a process schematic of both the cooling and heating system (summer and winter mode) indicating the flows and temperature levels under design conditions of both air and water.
- Give a short description of the control of the cooling/heating system.
- Is the cooling/heating capacity installed the same as for the conventional system? If not, why?
- Are the calculated number of full load hours and the calculated number of hours that the nominal room temperature will be exceeded the same as for the conventional system? If not, what are the differences?

Main components

Summarize the following information for the main components as far as these components are different from the conventional system:
- the total number of components.
- flow and pressure difference of air and/or water under design conditions.
- inlet and outlet temperature of air and/or water under design conditions.
- specify for the storage also:
  * number of wells/bore holes
  * distance between wells/bore holes
  * give a drawing of a single well/bore hole indicating depth, diameter, material and diameter of tubing, well completion, completion of well/bore hole at surface.
- the calculated thermal efficiency of the store as a part of the heating/cooling system. What definition was used for storage efficiency?
- the required power connection in kW (electricity) or m^3/h (gaz or oil).
- energy conversion efficiency based on the electrical power input or on the upper calorific value of the fossil fuel input.
- other specifications relevant to the choice that was made.

Technical rooms

Give a lay-out of the technical rooms, indicating the location and space requirement of the of the main components in each technical room.
Specify for each technical room the total (kW, m^3/h of the required power connections.
Indicate where in the building the main control equipment and where the step-down

transformers for the electrical power will be located.

Location of wells/bore holes

Indicate the location of the wells/bore holes relative to the office building, using the lay-out given in figure 2.1. Indicate the routing of the tubing connecting the storage with the building heating/cooling system. (No lay-out is required for the process cooling application).

Appendix D

Key Characteristics of Storage Designs Used in Simulations

Key Storage Characteristics – New Building

	Extreme			Moderate	
	C		S	D	NL
	Cool only no HP	H/C HP	H/C no HP	H/C HP	H/C no HP
ATES					
Number of wells	2	2	4[†]	4	
Cold-warm well separation (m)	150	150	70	140	
Casing diameter (mm O.D.)	150	150	194	120	
Screen length (m)	60	60	2	20	
Maximum flow rate per well (m^3/h)	40	40	40	94	52
Duct					
Drilling pattern			hexagonal	rectangular	
Number of holes			24	90	
Hole spacing (m)			4.15	4.5	
Hole depth (m)			103	90	
Total hole length (m)				8 100	
Total pipe length (m)				32 400	
Storage land area (m^2)			630	1 420	
Storage volume (m^3)			37 000	128 000	
Brine volume (m^3)				16	
Maximum brine flow (m^3/h)				128	

[†] Although two wells are enough to meet energy demand, four wells are specified to provide backup and to meet peak load.

Key Storage Characteristics - Retrofit Building

	Extreme			Moderate	
	C		S	D	NL
	Cool only no HP	H/C HP	H/C no HP	H/C HP	H/C no HP
ATES					
Number of wells	2	2	4[†]	6	
Cold-warm well separation (m)	150	150	70	140	
Casing diameter (mm O.D.)	200	200	194	120	
Screen length (m)	60	60	2	20	
Maximum flow rate per well (m^3/h)	72	72	40	150	70
Duct					
Drilling pattern	▨	▨	hexagonal	rectangular	▨
Number of holes	▨	▨	24	90	▨
Hole spacing (m)	▨	▨	4.15	4.5	▨
Hole depth (m)	▨	▨	103	90	▨
Total hole length (m)	▨	▨		8 100	▨
Total pipe length (m)	▨	▨		32 400	▨
Storage land area (m^2)	▨	▨	630	1 420	▨
Storage volume (m^3)	▨	▨	37 000	128 000	▨
Brine volume (m^3)	▨	▨		16	▨
Maximum brine flow (m^3/h)	▨	▨		128	▨

[†] Although two wells are enough to meet energy demand, four wells are specified to provide backup and to meet peak load.

Appendix E

Comparisons of Cost and Energy for Storage and Conventional Designs

22-Feb-94

Summary of Energy and Cost Comparisons Between Conventional and Alternative Systems
New Building

		Extreme						Moderate				
		Canada			Sweden			Germany			The Netherlands	
		Convent.	Cool only ATES no HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP	Heat/Cool duct no HP	Convent.	Heat/Cool duct HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP
System Characteristics												
Cooling Demand	(kW)	701	642	642	500	500	500	548	548	548	585	585
Heating Demand	(kW)	952	923	923	650	650	650	511	511	511	425	425
Annual Cooling	(MWh)	318	316	316	348	348	348	274	274	274	328	328
Annual Heating	(MWh)	705	694	694	1,062	1,062	1,062	511	511	511	250	250
Electrical Peak Demand (HVAC)												
Summer	(kW)	476	340	344	140	40	40	280	260	260	285	100
Winter	(kW)	352	359	554	25	40	40	110	260	260	100	105
Annual HVAC Energy Consumption												
Electricity	MWh	270	216	296	328	270	270	340	497	501	371	284
Compressors	MWh	72		83	116			70	220	220	126	
Cooling Towers	MWh	20						15				
Storage	MWh		23	21		58	58		22	26		12
Distribution	MWh	178	193	193	212	212	212	255	255	255	245	272
Gas	1 000 m3	107	106	59							26	26
Oil	m3							57				
District Heating	MWh				1,062	542	1,192					
Costs												
Total Capital Cost		146	167	283	620	660	630	541	1,301	799	621	453
Chillers, HPs, and Cooling Towers		114	9	131	620			360	326	326	575	
Boilers		32	31	26				181			47	47
Storage			75	75		640	661		875	373		266
Other (incremental)			53	51		20	(31)		100	100	0	140
Annualized Capital Cost (@ 8%)		**17**	**17**	**31**	**72**	**59**	**55**	**63**	**127**	**83**	**73**	**45**
Total Annual Energy Cost		**72.7**	**66.8**	**65.2**	**620**	**380**	**450**	**74**	**64**	**64**	**87**	**71**
Incremental Annual Maintenance Cost		**0.0**	**(2.1)**	**3.9**	**0**	**0**	**0**	**0**	**5**	**8**	**0**	**(3)**
Storage Component			1.7	1.9					5	8		9
Total Annual Costs (@ 8%)		**90**	**82**	**100**	**692**	**439**	**505**	**137**	**196**	**155**	**160**	**114**

Notes:

1. Costs in national currencies (k Cdn$, k DM, k Hfl, k SEK)
2. Equipment life = 15 years, except for storage components = 30 years

06-Apr-94

Summary of Energy and Cost Comparisons Between Conventional and Alternative Systems
Retrofit Building

		Extreme						Moderate				
		Canada			Sweden			Germany			The Netherlands	
			Cool only ATES	Heat/Cool ATES		Heat/Cool ATES	Heat/Cool duct		Heat/Cool duct	Heat/Cool ATES		Heat/Cool ATES
		Convent.	no HP	HP	Convent.	no HP	no HP	Convent.	HP	HP	Convent.	no HP
System Characteristics												
Cooling Demand	(kW)	828	769	769	750	750	750	800	800	800	800	800
Heating Demand	(kW)	1,317	1,285	1,285	1,160	1,160	1,160	770	770	770	765	765
Annual Cooling	(MWh)	477	479	479	396	396	396	486	486	486	360	360
Annual Heating	(MWh)	1,220	1,209	1,209	1,404	1,404	1,404	770	770	770	520	520
Electrical Peak Demand (HVAC)												
Summer	(kW)	514	362	365	250	40	40	340	270	275	310	55
Winter	(kW)	398	389	663	25	40	40	60	270	275	100	65
Annual HVAC Energy Consumption												
Electricity	MWh	430	359	493	344	276	276	255	477	484	286	172
Compressors	MWh	109		142	132			121	336	336	159	
Cooling Towers	MWh	31						26				15
Storage	MWh		38	30		64	64		33	40		35
Distribution	MWh	291	321	321	212	212	212	108	108	108	127	122
Gas	1 000 m3	175	173	96							55	55
Oil	m3							87				
District Heating	MWh				1,404	847	1,535					
Costs												
Total Capital Cost		174	226	388	820	805	640	813	1,799	1,047	628	570
Chillers, HPs, and Cooling Towers		135	13	182	820			540	489	489	544	151
Boilers		39	38	32				273			84	84
Storage			75	75		685	671		1,310	558		313
Other			100	98		120	(31)					22
Annualized Capital Cost (@ 8%)		**20**	**24**	**43**	**96**	**75**	**56**	**95**	**173**	**107**	**73**	**58**
Total Annual Energy Cost		**90**	**82**	**78**	**770**	**500**	**570**	**82**	**67**	**68**	**77**	**56**
Incremental Annual Maintenance Cost		**0.0**	**(2.0)**	**6.3**	**0**	**0**	**0**		**5**	**8**	**0**	**(4)**
Storage Component			1.7	1.9					5	8		
Total Annual Costs (@ 8%)		**110**	**104**	**127**	**866**	**575**	**626**	**177**	**245**	**183**	**150**	**110**

Notes: 1. Costs in national currencies (k Cdn$, k DM, k Hfl, k SEK)
2. Equipment life = 15 years, except for storage components = 30 years

22-Feb-94

Summary of Energy and Cost Comparisons Between Conventional and Alternative Systems
New Building

		Extreme						Moderate				
		Canada			Sweden			Germany			The Netherlands	
		Convent.	Cool only ATES no HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP	Heat/Cool duct no HP	Convent.	Heat/Cool duct HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP
System Characteristics												
Cooling Demand	(kW)	100%	92%	92%	100%	100%	100%	100%	100%	100%	100%	100%
Heating Demand	(kW)	100%	97%	97%	100%	100%	100%	100%	100%	100%	100%	100%
Annual Cooling	(MWh)	100%	99%	99%	100%	100%	100%	100%	100%	100%	100%	100%
Annual Heating	(MWh)	100%	98%	98%	100%	100%	100%	100%	100%	100%	NA	NA
Electrical Peak Demand (HVAC)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Summer	(kW)	100%	71%	72%	100%	29%	29%	100%	93%	93%	100%	35%
Winter	(kW)	100%	102%	157%	100%	160%	160%	100%	236%	236%	100%	105%
Annual HVAC Energy Consumption												
Electricity (*)	MWh	100%	41%	129%	100%	50%	50%	100%	285%	289%	100%	31%
Compressors	MWh	100%	0%	115%	100%	0%	0%	100%	314%	314%	100%	0%
Cooling Towers	MWh	100%	0%	0%	NA	NA	NA	100%	0%	0%	NA	NA
Storage	MWh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Distribution	MWh	100%	108%	108%	100%	100%	100%	100%	100%	100%	100%	111%
Gas	1 000 m3	100%	98%	55%	NA	NA	NA	NA	NA	NA	100%	100%
Oil	m3	NA	NA	NA	NA	NA	NA	100%	0%	0%	NA	NA
District Heating	MWh	NA	NA	NA	100%	51%	112%	NA	NA	NA	NA	NA
Costs												
Total Capital Cost		100%	115%	194%	100%	106%	102%	100%	240%	148%	100%	73%
Chillers, HPs, and Cooling Towers		100%	8%	115%	100%	0%	0%	100%	91%	91%	100%	0%
Boilers		100%	97%	82%	NA	NA	NA	100%	0%	0%	100%	100%
Storage		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Annualized Capital Cost (@ 8%)		**100%**	**103%**	**182%**	**100%**	**82%**	**76%**	**100%**	**202%**	**131%**	**100%**	**63%**
Total Annual Energy Cost		**100%**	**92%**	**90%**	**100%**	**61%**	**73%**	**100%**	**86%**	**86%**	**100%**	**82%**
Incremental Annual Maintenance Cos		**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Storage Component		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total Annual Costs (@ 8%)		**100%**	**91%**	**111%**	**100%**	**63%**	**73%**	**100%**	**143%**	**113%**	**100%**	**71%**

1. Costs in national currencies (k Cdn$, k DM, k Hfl, k SEK)
2. Equipment life = 15 years, except for storage components = 30 years

(*) Electricity consumption of distribution components are excluded from the calculation of percentages in this row.

23-Feb-94

Summary of Energy and Cost Comparisons Between Conventional and Alternative Systems
Retrofit Building

		Extreme						Moderate				
		Canada			Sweden			Germany			The Netherlands	
		Convent.	Cool only ATES no HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP	Heat/Cool duct no HP	Convent.	Heat/Cool duct HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP
System Characteristics												
Cooling Demand	(kW)	100%	93%	93%	100%	100%	100%	100%	100%	100%	100%	100%
Heating Demand	(kW)	100%	98%	98%	100%	100%	100%	100%	100%	100%	100%	100%
Annual Cooling	(MWh)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Annual Heating	(MWh)	100%	99%	99%	100%	100%	100%	100%	100%	100%	NA	NA
Electrical Peak Demand (HVAC)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Summer	(kW)	100%	70%	71%	100%	16%	16%	100%	79%	81%	100%	18%
Winter	(kW)	100%	98%	167%	100%	160%	160%	100%	450%	458%	100%	65%
Annual HVAC Energy Consumption												
Electricity (*)	MWh	100%	49%	145%	100%	48%	48%	100%	251%	256%	100%	28%
Compressors	MWh	100%	0%	131%	100%	0%	0%	100%	278%	278%	100%	0%
Cooling Towers	MWh	100%	0%	0%	NA	NA	NA	100%	0%	0%	NA	NA
Storage	MWh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Distribution	MWh	100%	110%	110%	100%	100%	100%	100%	100%	100%	100%	96%
Gas	1 000 m3	100%	99%	55%	NA	NA	NA	NA	NA	NA	100%	100%
Oil	m3	NA	NA	NA	NA	NA	NA	100%	0%	0%	NA	NA
District Heating	MWh	NA	NA	NA	100%	60%	109%	NA	NA	NA	NA	NA
Costs												
Total Capital Cost		100%	130%	223%	100%	98%	78%	100%	221%	129%	100%	91%
Chillers, HPs, and Cooling Towers		100%	9%	135%	100%	0%	0%	100%	91%	91%	100%	28%
Boilers		100%	98%	82%	NA	NA	NA	100%	0%	0%	100%	100%
Storage		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Annualized Capital Cost (@ 8%)		**100%**	**119%**	**212%**	**100%**	**78%**	**58%**	**100%**	**183%**	**112%**	**100%**	**79%**
Total Annual Energy Cost		**100%**	**91%**	**87%**	**100%**	**65%**	**74%**	**100%**	**82%**	**83%**	**100%**	**73%**
Incremental Annual Maintenance Cost		**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Storage Component		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total Annual Costs (@ 8%)		**100%**	**94%**	**115%**	**100%**	**66%**	**72%**	**100%**	**139%**	**103%**	**100%**	**73%**

Notes:

1. Costs in national currencies (k Cdn$, k DM, k Hfl, k SEK)
2. Equipment life = 15 years, except for storage components = 30 years

(*) Electricity consumption of distribution components are excluded from the calculation of percentages in this row.

23-Feb-94

Summary of Energy and Cost Comparisons
Between Conventional and Alternative Systems
Industrial Process

		Extreme		Moderate	
		Canada		The Netherlands	
		Convent.	Storage	Convent.	Storage
System Characteristics					
Cooling Demand	(kW)	600	600	600	600
Heating Demand	(kW)				
Annual Cooling	(MWh)	5,250	5,250	5,250	5 250
Freecooling	(MWh)	4,000	4,000	2,590	3,350
Chillers	(MWh)	1,250		2,660	
Aquifer Storage	(MWh)		1,250		1,900
Annual Heating	(MWh)				
Electrical Peak Demand (HVAC)					
Summer	(kW)	131	17	131	17
Winter	(kW)	70	44	70	44
Annual Energy Consumption					
Electricity	MWh	564	330	980	171
Compressors	MWh	279		887	
Cooling Towers	MWh	189	137	43	69
Storage	MWh		128		37
Distribution	MWh	95	66	50	65
Costs (1)					
Total Capital Cost		549	615	1,128	1,322
Chillers and HPs		185		547	
Cooling Towers		53	44	117	260
Boilers					
Storage			186		554
Other		311	385	464	508
Annualized Capital Cost (@ 8%)		**64**	**67**	**132**	**139**
Total Annual Energy Cost		**21.6**	**11.7**	**94**	**26**
Incremental Annual Maintenance Cos		**0.0**	**(4.8)**	**0**	**7**
Simple Payback (years)			**4.6**		**3.2**
Total Annual Costs (@ 8%)		**86**	**74**	**226**	**172**

Notes:

1. Costs in national currencies (k Cdn$, k DM, k Hfl, k SEK)
2. Equipment life = 15 years, except storage components = 30 years

23-Feb-94

Summary of Energy and Cost Comparisons Between Conventional and Alternative Systems Industrial Process

		Extreme Canada		Moderate The Netherlands	
		Convent.	Storage	Convent.	Storage
System Characteristics					
Cooling Demand	(kW)	100%	100%	100%	100%
Heating Demand	(kW)				
Annual Cooling	(MWh)	100%	100%	100%	100%
Freecooling	(MWh)	100%	100%	100%	129%
Chillers	(MWh)				
Aquifer Storage	(MWh)				
Annual Heating	(MWh)				
Electrical Peak Demand (HVAC)					
Summer	(kW)	100%	13%	100%	13%
Winter	(kW)	100%	63%	100%	63%
Annual Energy Consumption					
Electricity (*)	MWh	100%	50%	100%	13%
Compressors	MWh	100%	0%	100%	0%
Cooling Towers	MWh	100%	72%	100%	160%
Storage	MWh	NA	NA	NA	NA
Distribution	MWh	100%	69%	100%	130%
Costs (1)					
Total Capital Cost		100%	112%	100%	117%
Chillers and HPs		100%	0%	100%	0%
Cooling Towers		100%	83%	100%	222%
Boilers					
Storage		NA	NA	NA	NA
Other		100%	124%	100%	109%
Annualized Capital Cost (@ 8%)		**100%**	**104%**	**100%**	**105%**
Total Annual Energy Cost		**100%**	**54%**	**100%**	**28%**
Incremental Annual Maintenance Cos		**NA**	**NA**	**NA**	**NA**
Total Annual Costs (@ 10% int.)		**100%**	**86%**	**100%**	**76%**

Notes:

1. Costs in national currencies (k Cdn$, k DM, k Hfl, k SEK)
2. Equipment life = 15 years, except storage components = 30 years

(*) Electricity consumption of distribution components are excluded from the calculation of percentages in this row.

Appendix F

Comparisons of Environmental Emissions for Storage and Conventional Designs

30-Mar-94

Summary of Environmental Comparisons Between Conventional and Alternative Systems
New Building

		Extreme						Moderate				
		Canada			Sweden			Germany			The Netherlands	
		Convent.	Cool only ATES no HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP	Heat/Cool duct no HP	Convent.	Heat/Cool duct HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP
System Characteristics												
Cooling Demand	(kW)	701	642	642	500	500	500	548	548	548	585	585
Heating Demand	(kW)	952	923	923	650	650	650	511	511	511	425	425
Annual Cooling	(MWh)	318	316	316	348	348	348	274	274	274	328	328
Annual Heating	(MWh)	705	694	694	1,062	1,062	1,062	511	511	511	250	250
Electrical Peak Demand (HVAC)												
Summer	(kW)	476	340	344	140	40	40	280	260	260	285	100
Winter	(kW)	352	359	554	25	40	40	110	260	260	100	105
Environmental Impacts												
Annual Energy Savings		Total	--Decrease from conv.--		Total	--Decrease from conv.--		Total	--Decrease from conv.--		Total	--Decrease f
Electricity (kWh)		269.5	53.8	(26.4)	328.0	58.0	58.0	340.0	(157.0)	(161.0)	371.0	87.0
Gas (1000 m3)		107.4	1.8	48.2	---	---	---	---	---	---	26.0	0.0
Oil (m3)		---	---	---	---	---	---	57.0	57.0	57.0		
District Heating (kWh)		---	---	---	1,062.0	520.0	(130.0)	---	---	---		---
Annual Emission Savings (kg)												
CO2		258,390	15,131	83,842	218,960	105,160	(24,840)	201,285	7,455	5,895	298,338	58,986
SO2		197	39	(19)	2,288	1,069	(231)	486	263	261	557	131
NOx		2,044	63	833	1,095	526	(124)	253	75	73	1,014	131
Annual Emssion Savings (% of conv.)												
CO2		100.0%	94.1%	67.6%	100.0%	52.0%	111.3%	100.0%	96.3%	97.1%	100.0%	80.2%
SO2		100.0%	80.0%	109.8%	100.0%	53.3%	110.1%	100.0%	46.0%	46.3%	100.0%	76.5%
NOx		100.0%	96.9%	59.3%	100.0%	52.0%	111.3%	100.0%	70.6%	71.1%	100.0%	87.1%

Table 2: Emission Factors

EMISSION FACTORS	Canada			Sweden			Germany			Netherlands		
	CO2	SO2	NOx	CO2	SO2	NOx	CO2	SO2	NOx	CO2	SO2	NOx
Electricity (kg/MWh)	217.6	0.7	0.6	20.0	0.5	0.1	390.0	0.5	0.4	678.0	1.5	1.5
Gas (kg/1000 m3)	1,860.0	0.0	17.6	---	---	---	---	---	---	1,800.0	0.0	17.6
Oil (kg/m3)	---	---	---	---	---	---	1,205.0	5.9	2.3	---	---	---
District Heating	---	---	---	200.0	2.0	1.0	---	---	---	---	---	---

Worksheet comments

Based on 22% fossil
(19% coal, 2.3%oil)

Based on 5-10% fossil

Based on 65% fossil fuel.
Netherlands: Data provided for elec. only and in terms of
and acid deposition eqivalen. Emissions for NOx from elec.
calculated on based on Cdn. data. Gas emission data also based
on Cdn. data. Factors calculated on basis of total emissions provided.

30-Mar-94

Summary of Environmental Comparisons Between Conventional and Alternative Systems
Retrofit Building

		Extreme						Moderate				
		Canada			Sweden			Germany			The Netherlands	
		Convent.	Cool only ATES no HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP	Heat/Cool duct no HP	Convent.	Heat/Cool duct HP	Heat/Cool ATES HP	Convent.	Heat/Cool ATES no HP
System Characteristics												
Cooling Demand	(kW)	828	769	769	750	750	750	800	800	800	800	800
Heating Demand	(kW)	1,317	1,285	1,285	1,160	1,160	1,160	770	770	770	765	765
Annual Cooling	(MWh)	477	479	479	396	396	396	486	486	486	360	360
Annual Heating	(MWh)	1,220	1,209	1,209	1,404	1,404	1,404	770	770	770	520	520
Electrical Peak Demand (HVAC)												
Summer	(kW)	514	362	365	250	40	40	340	270	275	310	55
Winter	(kW)	398	389	663	25	40	40	60	270	275	100	65
Environmental Impacts		Total	--Decrease from conv.--		Total	--Decrease from conv.--		Total	--Decrease from conv.--		Total	--Decrease f
Annual Energy Savings		Total										
Electricity (kWh)		429.9	71.1	(63.1)	344.0	68.0	68.0	255.0	(222.0)	(229.0)	286.0	114.0
Gas (1000 m3)		175.1	2.4	79.3	---	---	---	---	---	---	55.0	0.0
Oil (m3)		---	---	---	---	---	---	87.0	87.0	87.0		
District Heating (kWh)		---	---	---	1,404.0	557.0	(131.0)	---	---	---		---
Annual Emission Savings (kg)												
CO2		419,221	19,844	133,686	287,680	112,760	(24,840)	204,285	18,255	15,525	296,208	77,292
SO2		314	52	(46)	2,980	1,148	(228)	624	409	406	429	171
NOx		3,327	82	1,359	1,438	564	(124)	292	120	118	1,397	171
Annual Emssion Savings (% of conv.)												
CO2		100.0%	95.3%	68.1%	100.0%	60.8%	108.6%	100.0%	91.1%	92.4%	100.0%	73.9%
SO2		100.0%	83.5%	114.7%	100.0%	61.5%	107.7%	100.0%	34.4%	34.9%	100.0%	60.1%
NOx		100.0%	97.5%	59.2%	100.0%	60.8%	108.6%	100.0%	58.8%	59.7%	100.0%	87.8%

Table 2: Emission Factors

EMISSION FACTORS	Canada			Sweden			Germany			Netherlands		
	CO2	SO2	NOx	CO2	SO2	NOx	CO2	SO2	NOx	CO2	SO2	NOx
Electricity (kg/MWh)	217.6	0.7	0.6	20.0	0.5	0.1	390.0	0.5	0.4	678.0	1.5	1.5
Gas (kg/1000 m3)	1,860.0	0.0	17.6	---	---	---	---	---	---	1,860.0	0.0	17.6
Oil (kg/m3)	---	---	---	---	---	---	1,205.0	5.9	2.3	---	---	---
District Heating	---	---	---	200.0	2.0	1.0	---	---	---	---	---	---

Worksheet comments

Based on 22% fossil
(19% coal, 2.3%oil)

Based on 5-10% fossil

Based on 65% fossil fuel.
Netherlands: Data provided for elec. only and in terms of
and acid deposition eqivalen. Emissions for NOx from elec.
calculated on based on Cdn. data. Gas emission data also based
on Cdn. data. Factors calculated on basis of total emissions provided.

Appendix G

List of Publications

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Annex 7 Publications

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Hickling Corporation, on behalf of Public Works Canada, **Proceedings of Workshop on Generic Configurations of Seasonal Cold Storage Applications**, IEA ECES Annex 7.

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