IEA

SOLAR R&D

INTERNATIONAL ENERGY AGENCY
program
to develop and test
solar heating
and cooling systems

task I
investigation of the performance of solar heating and cooling systems

optimization

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IEA TASK 1

Report on Subtask D

OPTIMIZATION OF SOLAR HEATING AND COOLING SYSTEMS

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TABLE OF CONTENTS

PREFACE

INTERNATIONAL ENERGY AGENCY

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for Economic Cooperation and Development (OECD) to administer that agreement. Twenty countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Program, the participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat, coordinates the energy research, development, and demonstration program.

SOLAR HEATING AND COOLING PROGRAM

Solar Heating and Cooling was one of the technologies selected by the IEA for a collaborative effort. The objective was to undertake cooperative research, development, demonstrations and exchanges of information in order to advance the activities of all Participants in the field of solar heating and cooling systems. Several tasks were developed in key areas of solar heating and cooling. A formal Implementing Agreement for this Program, covering the contributions, obligations and rights of the Participants, as well as the scope of each task, was prepared and signed by 15 countries and the Commisson of the European Communities. The overall program is managed by an Executive Committee, while the management of the tasks is the responsibility of the Operating Agents who act on behalf of the other Participants.

The tasks of the IEA Solar Heating and Cooling Program and their respective Operating Agents are:

I. Investigation of the Performance of Solar Heating and Cooling Systems - Technical University of Denmark

II. Coordination of R&D on Solar Heating and Cooling Components - Agency of Industrial Science and Technology, Japan

III. Performance Testing of Solar Collectors - Kernforschungsanlage Julich, Federal Republic of Germany

IV. Development of an Insolation Handbook and Instrumentation Package - United States Department of Energy

V. Use of Existing Meteorological Information for Solar Energy Application - Swedish Meteorological and Hydrological Institute

VI. Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors - United States Department of Energy

VII. Central Solar Heating with Seasonal Storage - Swedish Council for Building Research

Collaboration in additional areas is likely to be considered as projects are completed or fruitful topics for cooperation identified.

TASK 1 - INVESTIGATION OF THE PERFORMANCE OF SOLAR HEATING AND COOLING SYSTEMS

In order to effectively assess the performance of solar heating and cooling systems and improve the cost-effectiveness of these systems, the Participants in Task I have undertaken to establish common procedures for predicting, measuring, and reporting the thermal performance of systems and methods for designing economical, optimized systems. The results will be an increased understanding of system design and performance as well as reports and/or recommended formats on each of the task activities.

The subtasks of this project are:

A. Assessment of modeling and simulation for predicting the performance of solar heating and cooling systems

B. Development of recommended procedures for measuring system thermal performance

C. Development of a format for reporting the performance of solar heating and cooling systems

D. Development of a procedure for designing economical optimized systems

E. Validation of simulation programs by comparison with measured data

F. Development of recommended procedures for designing building and analyzing solar assisted low energy dwellings

The Participants in this Task are: Belgium, Denmark, Germany, Italy, Japan, the Netherlands, Spain, Sweden, Switzerland, United Kingdom, United States, and the Commission of the European Communities.

This report documents work carried out under Subtask D of this task.

EXECUTIVE SUMMARY

This document is a summary of work performed by the International Energy Agency (IEA) Task 1 Group in Subtask D - solar energy system economic optimization.

The scope of the work is primarily limited to the optimization of small scale (i.e. residential) active solar thermal systems. The initial objectives of the subtask were to review and evaluate approaches to the optimization of these systems by comparing the thermal performance predictions of the "simplified methods" to the results obtained from the detailed simulation programs in Subtask A of Task 1 for standard air and liquid solar systems in different climates. Subsequently, using costs, economic parameters and monthly weather data supplied by the participants for a major city in each of their respective countries, the economic optimum design was to be found for each country. The ultimate goal of the work was to identify one or more means of performing simplified dimensioning for different purposes based on a common understanding of the engineering and economic principles involved.

A variety of difficulties were encountered with this plan. Foremost among them were the lack of consensus within the group on 1) an acceptable general means of performing simplified thermal analysis, and 2) a universally applicable method of evaluating the economics of solar systems. Both of these problems have generated long and heated debate in the IEA Task 1 forum and elsewhere. Agreement on specific methods to use in simplified thermal analyses is difficult to obtain because of the wide variety of solar systems, climates, and loads and the highly complex interaction between them.

Agreement on a single economic perspective is even more difficult to attain. Because virtually all of the widely used methods of economic analysis are at the "micro-economic" level, many important benefits of solar energy utilization are not accounted for. Another serious difficulty in economic analyses is the high degree of uncertainty in the values of the parameters, particularly fuel inflation rates. Because of this lack of consensus it was agreed that the results of the optimization performed for each of the participating countries would not be published in this report. Furthermore, it was agreed that specific methods and techniques should not be recommended. What has been done in this work is a review of the approaches now available, an analysis of the main issues in solar system optimization, and the illustration of typical results with examples.

The purpose of this report is to document the tools and techniques which are available to do solar system optimization and to present some of their advantages and disadvantages. Overviews of both simplified thermal prediction methods and economic analysis methods are included. A comparison of the results of one well known and widely used simplified thermal prediction model to the detailed simulation results from subtask A is presented as well as sample economic analyses.

A methodology for performing economic sensitivity studies using the life cycle cost approach is presented as well as specific results for a typical system. Finally, a simple graphical optimization technique based on the life cycle cost approach is presented.

1.0 INTRODUCTION

Basic to solar optimization methods is the separation of the analysis into two distinct parts: a thermal analysis, and an economic analysis. Any method which also "optimizes" the solar system must find the thermal system size or design whose thermal performance results in an economic optimum. In most methods, particularly the computerized methods, this involves an algorithm which iteratively selects system designs, solves for the thermal performance and then the economic performance, until the optimum is located.

It is clear that a computationally simple thermal analysis method must be employed in optimizations due to the large number of evaluations that must be made to determine the optimum. Within the Task 1 group considerable evidence and discussion has been presented on the effects of climate, building design, and energy use profile. These factors interact in a complex way that is very difficult to handle in a "simplified" method. The importance of many second order effects clearly varies greatly among applications and the need to account for them in various situations has not been fully established.

Although many questions persist about the validity of various thermal performance analysis techniques, the controversy associated with the economic analysis method is even more difficult to resolve. In a thermal analysis, an "actual" performance is being estimated and can theoretically be measured and/or predicted. In a economic analysis, however, there is no "actual" economic performance which one can estimate, thus removing the possibility of a definitive resolution. Instead, one must establish economic criteria such as life cycle cost, payback period, return on investment, etc., which hopefully reflect the concerns of the consumer. The difficulty associated with establishing a single economic criterion lies in the fact that the various consumers (homeowner, government, industry, etc.) have different motivating concerns. For example, a homeowner may simply want to maximize savings with a fixed amount available for investment. A more sophisticated residential consumer may wish to minimize the life cycle cost or payback period. In industry, where many investment opportunities often compete for limited capital, maximizing "the return on investment" is often the primary goal. A government agency on the other hand, may wish to maximize the energy savings given a fixed budget expenditure.

In practice it must be remembered that a number of subjective factors including owner confidance and aesthetics, and constraints imposed by the building architecture or by the owner's financial situation will significantly affect solar system dimensioning. In commercial applications, considerations such as "cash flow" or immunity from fuel supply rationing or curtailment may be of primary concern. Nevertheless, rational and consistent methods of analysis are needed so that various approaches can be fairly compared once an appropriate criteria and the various constraints have been identified.

2.0 OVERVIEW OF SIMPLIFIED THERMAL PREDICTION METHODS

A large variety of simplified methods of solar thermal system performance analysis have been proposed and used. These vary considerably in their degree of simplicity, the range of systems for which each is applicable, and the accuracy of the results. Several surveys have been published [1,2,3] that identify and classify specific simplified methods available in the United States. Bruno and Kersten [4] have classified solar analysis methods based on the modeling approach and have compared the accuracy of representative codes from each category.

2.1 Survey of Methods Used in the U.S.

Hughes et al. [1] classify the simplified methods as "utilizability methods", "semi-empirical methods", "approximate simulation methods", and "hybrid methods". "Utilizability methods" make use of or expand upon the concept of utilizability first proposed by Whillier [5] and later generalized by Liu and Jordan [6]. The utilizability function (ϕ) relates collector performance to the average ratio of insolation incident on a surface above a "critical" value, to the total insolation incident on the surface. Generalized ϕ-charts have been constructed by Liu and Jordan which relate ϕ to the critical radiation intensity ratio, and K_T, the ratio of monthly average total horizontal to extraterrestrial radiation. Klein [7] and Rabl et al. [8] have further extended and simplified the utilizability concept so that a wide variety of collector types of arbitrary orientation can be handled.

"Semi-empirical" methods are those which rely on correlations of results from detailed simulation programs. Klein's F-Chart method [9,10] and the Balcomb et al. solar to load ratio methods [11,12] are examples. In these methods the monthly performance of "standard" systems is determined from monthly climate statistics and system parameters.

"Approximate Simulation Methods" retain the flexibility of the system specification inherent in the detailed simulation codes, but reduce computation time by making simplifying approximations. One possible technique is to represent the weather by simple analytical expressions so that closed solutions for daily performance can be obtained. In the SOLCOST method [13], performance is simulated for a typical sunny day and a typical overcast day each month. Percent possible sunshine is then used to weight these contributions for the monthly results. Bruno et al. [14] proposed a method in which daily loads and meteorological data were represented by the first term of a Fourier series. The approach of Anand et al. [15] and Haslett and Monaghan [16,17] is to compress monthly weather data into probability density matrixes and use them to weight the results of simulations using simple analytic data to get the results for each month.

"Hybrid Methods", in the classification scheme of Hughes et al., are those which include elements of the three other approaches. Klein's $\bar{\phi}$-FChart method [18] combines the utilizability method with the empirical approach of F-Chart. Lunde [19,20] has developed simple methods which are both semi-empirical and probabilistic.

Bruno and Kersten [4] identify only two classes of simplified methods: 1) "quasi-stationary, semi-empirical methods which use functional forms to describe system ... and performance parameters over longer time spans (e.g., a month or year)" and 2) "dynamic methods which exactly solve a set of differential equations over longer time periods (e.g., a day or month)."

For the purpose of disseminating information to the U.S. public on the availability and capability of U.S. solar heating and cooling (SHAC) analysis methods, the Solar Energy Research Institute (SERI) has consolidated the results of the aforementioned surveys [1,2] and published them in [3]. There, the methods are separated into two groups: "manual methods" that can be done by hand or with a programmable calculator and "computer methods" that require a computer to run. It should be noted that this is a somewhat confusing and arbitrary classification scheme since some of the "computer methods" are simplified methods by consensus of [1] and [4], while others are detailed hourly simulation programs. It can safely be said that all of the "manual methods" as well as all the "computer methods" that have a monthly "computation interval" are simplified methods. The summary tables from [3] are reproduced in the following pages.

2.2 Selected Methods Used in the IEA Participating Countries

No comprehensive survey has been made of simplified solar thermal analysis methods used throughout the world. However, the participants in this IEA solar system optimization subtask have in many cases been directly involved with the development of solar design tools in their respective countries. A brief review of this sampling of simplified analysis tools follows.

SHAC Manual Design Methods Summary

The following table describes solar heating and cooling manual design methods. This table does not give all of the design methods applicable to SHAC analysis, but it does contain the most currently used and best known methods. These methods do not require access to a computer although some (e.g., F-CHART) have been implemented on computers. They vary in degree of sophistication from the simple, almost rule-of-thumb type to methods requiring programmable calculators. Some of the latter type methods are available from the source indicated as prerecorded programs on magnetic cards.

Description	Author	Availability			Application				Col. Type		System Type		Tools Required				Basis of Method			Output		
		Cost ($)	Date	Reference/Source	Space Heat	Domestic Hot Water	Space Cooling	Economic Analysis	Liquid	Air	Active	Passive	Graphs/ Tables	4 Function Calculator	Scientific Calculator	Programmable Calculator	Detailed Simulation	F-Chart Correlation	Other Correlation	Solar Fraction	Optimum Area	Other
A Simplified Method for Calculating Solar Collector Array Size for Space Heating	J.D. Balcomb and J.C. Hedstrom		1976	Sharing the Sun: Solar Technology in the Seventies. Vol. 4, American Section, International Solar Energy Society, 1976, pp. 281-284.	●	●			●	●	●		●	●					●		●	
Passive Solar Design Handbook	J.D. Balcomb and Bruce Anderson		Early 1980	Will be available from NTIS. 5285 Port Royal Road Springfield, VA 22161	●							●	●	●					●	●		
Optimal Sizing of Solar Collectors by the Method of Relative Areas	C.D. Barley and C.B. Winn		1978	Solar Energy, Vol. 21, No. 4, 1978, pp. 279-289.	●	●		●	●	●	●		●		●			●			●	
MESH	Dr. John Clark		1978	Dr. John Clark Central Solar Energy Research Corp. 1200 6th Street, Room 328 Detroit, MI 48226	●			●	●	●	●				●				●	●	●	
Predicting the Performance of Solar Energy Systems	U.S. Army Construction Engineering Research Lab		1977	Rept. No. AD-A035 608/9 ST (NTIS)	●	●	●	●	●	●	●		●	●					●	●	●	
Copper Brass Bronze Design Handbook—Solar Energy Systems	Copper Development Association	3	1976	Copper Development Association, Inc 1011 High Ridge Road Stamford, CN 06905	●	●			●	●	●		●	●					●	●		
PEGFIX and PEGFLOAT	W. Glennie	75 both	1978	Princeton Energy Group 729 Alexander Road Princeton, NJ 08540	●							●				●	●					●
Solarcon Programs ST355 and ST365	R.W. Graeff	239 both 142 each 15 weather data	1977	Solarcon, Inc. 607 Church Street Ann Arbor, MI 48104	●	●		●	●	●	●					●		●		●		
Solarcon Program ST33	R.W. Graeff	138	1979	Solarcon, Inc.	●							●				●	●			●		
Solar Heating Systems Design Manual	ITT Corporation Fluid Handling Division	2.50	1977	Bulletin TESE-576, Rev. 1 ITT Training & Education Dept. Fluid Handling Division Morton Grove, IL 60053	●	●			●	●	●		●	●			●			●		
A General Design Method for Closed-Loop Solar Energy Systems	S.A. Klein and W.A. Beckman		1977	Proceedings of the 1977 Annual Meeting, Vol. 1 American Section, International Solar Energy Society, 1977, pp. 8.1-8.5.			●		●		●		●		●			●		●		
Solar Heating Design by the F-Chart Method	S.A. Klein, W.A. Beckman, and J.A. Duffie	10	1977	John Wiley and Sons, New York, N.Y., 1977 (Publisher)	●	●		●	●	●	●		●	●				●		●		
A Design Procedure for Solar Heating Systems	S.A. Klein, W.A. Beckman, and J.A. Duffie		1976	Solar Energy, Vol. 18, No. 2, 1976, pp. 113-127.	●	●			●				●		●				●	●		
TEANET	J.T. Kohler and P.W. Sullivan	95	1978	Total Environmental Action, Inc. Church Hill Harrisville, NH 04350	●							●				●	●					●

The GFL Method for Sizing Solar Energy Space and Water Heating Systems	G.F. Lameiro and P. Bendt		1978	Rept. No. SERI-30 Solar Energy Research Institute 1617 Cole Boulevard Golden, CO 80401	●				●	●	●		●		●			●		●		
A Design Handbook for Direct Heat Transfer Passive Solar Systems	R.M. Lebens	10	1978	Northeast Solar Energy Association P.O. Box 541, 22 High Street Brattleboro, VT 05301	●			●				●	●			●	●			●		
A Rational Procedure for Predicting the Long-Term Average Performance of Flat-Plate Solar Energy Collectors	B.Y.H. Liu and R.C. Jordan		1963	Solar Energy, Vol. 7, No. 2, 1963, pp. 53-70.	●	●			●	●	●		●		●		●			●		
Pacific Regional Solar Heating Handbook	Los Alamos Scientific Lab		1976	Rept. No. TID-27630 (NTIS)	●	●			●	●	●		●		●				●	●		
Prediction of the Monthly and Annual Performance of Solar Heating Systems	P.J. Lunde		1977	Solar Energy, Vol. 20, No. 3, 1977, pp. 283-287.	●	●			●		●		●	●					●	●		
SCOTCH Program	R. McClintock	195 Thermal alone, 175; econ. anal. alone, 75	1977	SCOTCH Programs P.O. Box 430734 Miami, FL 33143	●	●		●	●	●	●					●		●		●	●	
Solar Heating of Buildings and Domestic Hot Water	Naval Facilities Engineering Com. E.J. Beck, Jr. and R.L. Field		1976	Rept. No. AD-A021 862/8ST (NTIS)	●	●		●	●	●	●		●		●			●		●	●	
PCTS	J. Schoenfelder	F-Chart Therm. 35; F-Chart Econ. 35	1978	Central States Research Corp. P.O. Box 2623 Iowa City, IA 52240	●	●		●	●	●	●					●		●		●	●	
Domestic Hot Water Manual Using Sunearth Solar Collector Systems	Sunearth Corp.	3	1976	Sunearth Solar Products Corp. Technical Services R.D. 1 P.O. Box 337 Green Lane, PA 18054		●			●		●		●					●		●		
An Averaging Technique for Predicting the Performance of a Solar Energy Collector System	G.H. Stickford		1976	Sharing the Sun, Vol. 4, 1976, pp. 295-315.	●	●			●	●	●	●	●		●		●			●		
Calculation of Long-Term Solar Collector Heating System Performance	S.R. Swanson and R.F. Boem		1977	Solar Energy, Vol. 19, No. 2, 1977, pp. 129-138.	●				●	●	●		●		●			●		●		
Minimum Cost Sizing of Solar Heating Systems	J.C Ward		1976	Sharing the Sun, Vol. 4, 1976, pp. 336-348.	●			●	●	●			●		●			●		●	●	
Designing and Building a Solar House; Your Place in the Sun	D. Watson	9	1977	Garden Way Publishing Charlotte, VT 05445	●	●		●	●	●	●		●	●			●			●		
SEEC I — Heat Load, Monthly Solar Fraction, Economics	C.B. Winn	125	1976	Solar Environmental Engineering Co., Inc. 2524 East Vine Drive Fort Collins, CO 80522	●	●		●	●	●	●					●		●		●		
SEEC II — Collector Optimization, Annual Solar Fraction, Economics	C.B. Winn, D. Barley, G. Johnson, J. Leflar	95	1978	Solar Environmental Engineering Co., Inc.	●	●	●	●	●	●	●					●		●			●	
SEEC III — SEEC II Plus Insulation Optimization	C.B. Winn, D. Barley, G. Johnson, J. Leflar	125	1978	Solar Environmental Engineering Co., Inc.	●	●		●	●	●	●					●		●			●	
SEEC VI — Passive Solar Heating	C.B. Winn, D. Barley, G. Johnson, J. Leflar	125	1978	Solar Environmental Engineering Co., Inc.	●			●				●				●			●	●		
Sunshine Power Programs for Modeling Solar Energy Components and Systems	G. Shramek	30-60	1977	Sunshine Power Co. 1018 Lancer Drive San Jose, CA 95129	●	●		●	●	●	●	●				●	●	●	●	●		●
Mazria Design Patterns (Rule-of-Thumb) in The Passive Solar Energy Book	Edward Mazria	11	1979	Rodale Press, Emmaus, PA 18049	●				●	●		●	●				●			●	●	●

SHAC Computer Methods Summary

The following summary table and text describe the most frequently used and currently available solar analysis computer methods. The information was obtained largely from a program author survey conducted by Arthur D. Little, Inc. for the Electric Power Research Institute and primarily reflects the opinions of each program author.

Most summary table categories are self-explanatory; however, the intended user category needs emphasis. Programs suitable for use by builders were limited to the interactive type program that interrogates the user by a question and answer methodology. Architects/engineers use mainly design-oriented computer programs and generally restrict their analysis to standard input/output options of the program. The research engineer generally has hands-on access to the program and is very familiar with both the operation and assumptions of the program and the details of the system being analyzed.

Program Name	Latest Version	Availability				Application							Intended Users			Computation Interval		Computer Versions Available	Economic Analysis	Sponsor
		Purchase ($)	Time Share	Special Arrangements	Comments	User Manual	Service Hot Water	Space Heating	Space Cooling	Process Heat	Active System	Passive System	Research Engineers	Architect/Engineers	Builders	Hour	Month			
ACCESS*	1978	10,000		●	No cost to EEI members	●	●	●	●	●	●		●	●		●		IBM	●	Edison Electric Institute (EEI)
BLAST*	1978	300	●		Training available	●	●	●	●		●		●	●		●		CDC	●	USAF, USA, GSA
DEROB	1979	Nom.				●		●	●			●	●	●		●		CDC		NSF, ERDA, DOE
DOE-2*	1979	400	●			●	●	●	●		●	●	●	●		●		CDC	●	LASL, DOE
EMPSS	1978	500		●	Consulting with ADL	●	●	●	●		●		●	●		●		IBM	●	EPRI
F-CHART	1978	100	●		Training available	●	●	●			●			●	●		●	CDC, IBM UNIVAC	●	DOE
FREHEAT	1979	150			Limited documentation			●				●	●			●		CDC	●	DOE
HISPER	1978	Avail. on request			Limited documentation		●	●	●		●		●			●		UNIVAC		NASA, MSFC
HUD-RSVP/2	1979	175	●		Based on F-CHART	●	●	●			●	△		●	●		●	CDC UNIVAC	●	HUD
SHASP	1978	Avail. on request				●	●	●	●		●		●			●		UNIVAC	●	DOE
SIMSHAC	1973	300					●	●			●		●			●		CDC	●	NSF
SOLAR-5	1979		●					●	●			●		●	●	●	●	CDC		UCLA, DOE
SOLCOST	1979	300	●			●	●	●			●			●	●		●	CDC, IBM UNIVAC	●	DOE
SOLOPT	1978	20				●	●	●			●		●				●	AMDAHL	●	Texas A&M Univ.
SOLTES	1979				Available Argonne Fall 1979	●		●		●	●		●			●		CDC		Sandia
SUNCAT	1979	Nom.			Limited documentation	●		●				●	●	●		●		Data General Eclipse	●	NCAT
SUNSYM®	1979		●	●		●	●	●	●		●			●		●		IBM	●	Sunworks Comp. Systems
SYRSOL	1978	Nom.			Avail. but not actively marketed		●	●	●			●	●	●	●	●		IBM	●	ERDA, NSF, DOE
TRACE SOLAR*	1979		●	●		●	●	●	●	●	●		●	●		●	●	IBM	●	The Trane Co.
TRNSYS	1979	200	●		Training required	●	●	●	●		●	△	●			●		CDC, IBM UNIVAC		DOE
TWO ZONE	1977			●		●		●	●			●	●			●		CDC	●	LRL
UWENSOL	1978	200				●		●				●	●			●		CDC		State of Wesh.
WATSUN II	1978	200				●	●	●			●		●			●		IBM	●	Nat'l Research Center of Can.

*Programs are primarily developed for large-scale, multi-zone applications
△ Being added

Belgium. The SYS2 program [21] is a simplified design method developed between 1975-1978 as part of the Belgian National Energy Research and Development Program. SYS2 is based on a modular approach wherein solar collection, storage, load and auxiliary are represented by a distinct subsystem models. Hourly simulations are performed with a detailed collection model which is used to generate a matrix of daily performance data for different operating conditions. Storage is represented as a fully mixed water storage tank whose capacity is assumed large enough so that tank temperature will not change more than a few degrees per day.

A daily space heating load is calculated using the degree day method. Load energy distribution is calculated daily and is rate limited by the load heat exchanger. Auxiliary is modeled as a "parallel" supplement to the solar or as a "series" heat pump which uses the tank as the heat source. In the latter case, a daily COP is defined as a function of source temperature.

A daily energy balance is written on the storage tank and daily simulations are performed. Using the weather data for Belgium and fixed collector design it is found that the annual performance (i.e., auxiliary energy use) is a unique function of three variables: the thermal load per unit collector area, the storage capacity per unit load, and the storage tank time constant. "Optimizations" are performed by iteratively selecting and running various collector sizes and types, and plotting the auxiliary to load fraction as a function of these groups.

Denmark. The Thermal Insulation Laboratory of the Technical University of Denmark has developed a simplified solar heating dimensioning method based on detailed, half-hour timestep simulations of space and dhw heating systems using a Danish reference meteorological year. The simulations have been performed for both one- and two-cover flat plate collectors, fully mixed storage tanks, and standard residences incorporating three different levels of insulation. For the dhw system, the collector area, the storage volume per unit collector area, and the daily hot water load per unit collector area were varied over typical ranges. Regression analyses were used to express the solar heating fraction as a unique function of the daily hot water load per unit collector area and the storage volume per unit collector area, for both one- and two-cover collectors.

Similarly, simulations were performed for the space heating systems. The solar fraction was regressed as a unique function of collector area, the total space and dhw load, the storage volume per unit collector area, and the ratio of the space heating load to the total load, for both one- and two-cover collectors.

Finally, the secondary parameters like collector orientation, tank insulation, heat exchanger size, etc., were varied one at a time for several base cases to illustrate the approximate effects of other "non-standard" designs.

Germany. Several models of solar thermal systems have been developed by Philips Research Laboratory [4] under German federal sponsorship. At least two of these are termed simplified methods by their authors. The "lumped circuit" method uses the hourly, component based system simulation approach, but simplifies the model by assuming a very simple "lumped" model for each flow loop. Meteorological and load data are assumed constant and simple analytical solutions are obtained over each hour. Run times are very short for an hour-by-hour code, but still too long for most optimization work.

The second method is a "dynamic simplified model" in which each flow loop is defined by a first order differential equation, similiar to that used in the lumped circuit, hourly simulation described above. The weather and load data are approximated by simple integrable daily functional forms. The first term of a Fourier series is used to represent solar insolation, ambient temperature, and wind velocity. Space heating and cooling loads are represented as constants over three daily time intervals while dhw loads are represented as point demands at three instants each day.

Daily simulations can be run for several different operating modes which include air and water systems, dhw, space heating, space cooling, and any combination of these.

United Kingdom. Many simulation programs have been developed in the United Kingdom for the predicton of the performance of solar energy systems. A survey for the Department of Energy has identified 25 programs written for water heating systems alone. Programs have been validated by comparison of predicted performance with measurements on real systems [28] and then used to explore the sensitivity of performance to variations in the main system parameters and operational factors [29,30].

It was recognized that models needed to be simplified so that many variations could be studied without excessive use of computer time. Compound variables were identified, and it was shown that for given climatic conditions, the performance of water heating systems could be expressed adequately in terms of two ratios: the collector area per unit daily hot water demand and the storage volume per unit demand [30,31]. This was the basis of the simplified method of performance prediction incorporated into the British Standard Code of Practice for Solar DHW Systems [32,33]. Subsequent developments led to the introduction of economic factors into the models and to the use of automatic routines for optimization [34]. It has been found that simple routines for multivariate optimization are well suited to use with full hour-by-hour simulations, though simplifications may be necessary to reduce computing time. It has been shown that optima obtained with a condensed year of 60 averaged days are satisfactorily close to those obtained with a full 365-day year.

United States. The F-Chart method [9,10] was developed at the University of Wisconsin in 1976 under U.S. Department of Energy (DOE) funding. The original method is a correlation of results from detailed hourly simulations of standard air and liquid based system designs. Monthly solar heating fraction has been correlated with two dimensionless groups (the ratio of available solar energy to the load and the ratio of a reference collector heat loss to the load). In the version of the F-Chart computer program now available (version 4.0) weather data for 266 U.S. cities are built into the program as well as a monthly "tilted" surface radiation model. The high temperature system capabilities of the Ø-FChart method are programmed into version 4.0 as well as recently developed simplified techniques for "parallel" and "series" solar heat pump systems, and certain kinds of passive systems.

The F-Chart interactive program is very flexible, and easy to use. It is the most widely used design tool in the U.S. for active systems. The F-Chart correlations form the basis for a number of other computerized and manual analysis methods involving graphical, programmable calculator, and small computer techniques as evident from the SERI summary table presented earlier.

2.3 Summary

Each of the simplified methods discussed above has its own strengths and weaknesses, which are often inherent in the approach employed in the development of the simplified method. These strengths and weaknesses can be summarized in terms of four highly interrelated areas; 1) the ability to account for solar system dynamic behavior, 2) the range of systems and parameters for which the method is applicable, 3) the accuracy and reliability of the method, and 4) the general ease of use of the method.

The issue of greatest controversy within the IEA Task 1 group was probably the first of these. The dynamic interaction between a solar system and a residential dhw or space heating or cooling load is potentially very important. For real houses, especially those built to be very energy efficient, the dynamic effect of the loads on a solar system often cannot be represented or are systematically misrepresented by some simplified methods.

As an example, it has been shown by one Task 1 participant that two houses with identical solar systems in the same climate can have the same monthly heating loads and yet have radically different solar fractions. Why? One house might be a small, poorly insulated, low mass building while the other might be a larger, well-insulated "passively" designed house with large south windows and high internal heat capacity. On cold sunny days, the first house will have a much higher heating load. The active solar system will be much more highly loaded, and therefore more efficient in the first case.

The importance of this dynamic interaction clearly varies widely from system to system. It increases as the thermal capacitance of the dwelling increases and that of the active solar system decreases. It increases in climates with highly variable weather, and for houses which are significantly passively heated, etc.

It is probably safe to say that only the "approximate simulation methods" identified by Hughes et al [1] or the "dynamic methods" identified by Bruno and Kersten [4] are capable of handling this effect in any general sense. It is very difficult to envision a general empirical technique that could account for the dynamic interaction of a solar system with its load. The fact that FChart and many other semi-empirical methods are insensitive to hourly and daily load profiles, and hence to the dynamics of the solar-load interaction, is perhaps their greatest weakness. Still, there is a broad range of practical cases where this limitation is not critical.

In terms of the range of applicability of the methods to systems and parameters, it is generally true that the empirical methods are inherently the most limited. Because they are developed from correlations of performance results of particular system types, they are generally applicable to a fairly restricted set of cases. "Approximate simulation" and "dynamic" methods do not inherently have this limitation although the specific systems handled by individual methods vary considerably. "Utilizability" methods have been generalized for a very broad range of collection system types, geometries, and orientations, however, they are not concerned with modeling the energy delivery system. Incorporation of the utilizability concept into a more complete "system" model has been accomplished in the $\bar{\phi}$-FChart method. This method, however, has many of the system and dynamic limitations inherent in F-Chart.

The question of the accuracy and reliability of simplified methods is very closely related to the first two issues. Often the absolute accuracy is of secondary importance to the mutual consistency of results obtained for different systems or parameter values. When this is the case, it is of very questionable value to use a mix of simplified techniques to model different generic systems for inter-comparison. One classic problem is when an optimization of active, passive, and conservation features is sought, but no simplified method can be found to handle all three (much less to account for the interactions of the three). Great caution must be exercised when two or more methods are used to analyze the options since a variety of inconsistent assumptions may be involved.

In general, the empirical methods like FChart are fairly accurate representations of the limited systems (with their inherent assumptions) and the limited parameter spaces, for which they were designed. When used for systems or parameters outside of these limits, the reliability of the methods is generally unknown but must be presumed to be unacceptable. The reliability of the various approximate simulation methods varies widely but is potentially better for a wider range of systems particularly if "dynamic effects" are very important. In practice, however, due to the large number of simplifying assumptions employed, it is doubtful that most of these methods are more accurate than empirical methods when applied within their parameter space.

The ease of use of the methods is of course highly dependent upon the final form of implementation of the method (hand calculations, graphs and tables, programmable calculator, computer, etc.), and the effort expended in providing a user interface. FChart, for example, is available in all of the forms mentioned above. Although many simplified methods can be implemented and used effectively in a variety of ways, there are a number of restrictions. Since empirical (and utilizability) methods are based upon relatively simple correlations they are easily implemented with graphical and hand methods. Virtually any dynamic, approximate simulation approach on the other hand requires the use of at least a small computer.

The nature and format of the meteorological data required by the methods varies considerably. Most empirical methods use the most widely available types of weather data, namely simple monthly totals and averages of key weather variables. Approximate simulation methods have been devised that require a variety of pre-processed weather data including Fourier representations of key forcing functions, hourly data for particular days, probability density matrices, and various forms of "synthetic" data. The data base needed to generate this data does not exist for many locations and the required forms may be very cumbersome to generate and handle.

3.0 OVERVIEW OF ECONOMIC ANALYSIS METHODS

As mentioned earlier, the process of optimization is usually separated into two distinct parts: a thermal analysis and an economic analysis. The former yields the purchased energy requirement or savings in terms of GJ/year or similar, and the latter translates the corresponding energy cost savings and the costs of system installation and operation into money savings. As noted earlier, there is a great amount of uncertainty concerning which of these methods should be used for the optimization of solar systems. This section is not meant to advocate any of these methods, but to illustrate by an example some of the drawbacks and advantages of the standard economic analysis methods, to point out similarities and differences, and to show what effect they can have on the result of an optimization study.

Before we consider any of the more or less standard methods of economic analysis, it is important to recognize the limitations of all of them as a class. These approaches are necessarily at a micro-economic level, that is, from the point of view of the single, private owner, looking for the best way of spending his money. Caution is needed for two, interrelated reasons:

a. The values of the economic parameters needed to perform the analyses are quite unpredictable, particularly for periods of greater than a few years.

b. All of the societal benefits and costs associated with the different energy choices cannot be directly accounted for.

The reasons why solar energy utilization is so attractive are well known: it is available everywhere at no cost, it is non-depletable, it can be used through "soft" technologies, and it is environmentally benign. All these advantages have high societal value: reduction of fossil fuel imports, and therefore, greater national independence and stability, more job opportunities with less capital investment, greater social control over energy uses, and a cleaner, healthier environment. The importance of these social aspects of solar energy is lost when adopting a micro-economic approach.

To a certain extent social values can be put into the analysis by adjustment of economic parameters. For example, tax incentives are the result of a political/social decision, and reflect, in quantitative terms, how much a society is willing to spend for the indirect benefits of a certain technology. On the other hand, these incentives are often quite arbitrary and may not lead to solar energy systems which are near optimum from society's point of view.

3.1 Standard Economic Methods

Five economic methods commonly used in connection with optimization of solar energy systems (and other energy conservation measures) are as follows:

1. First year savings (FYS) is the sum of interest and principal repayment of the initial investment, and operating costs in the first year, divided by the first year energy savings and expressed in many ways (e.g., \$ per gallons of saved oil or \$ per GJ of saved energy).
2. Simple pay back period (SPB) is the initial investment divided by the net money savings in the first year, expressed as a number of years. It is a simple measure of the time required to recoup the initial investment cost.
3. Exact (discounted) pay back period (EPB) is a more sophisticated measure of the time required to recover the initial investment. It takes into account the "time value of money" by "discounting" future costs into "present value". It also accounts for inflation of system operating costs, particularly for fuel. It is also expressed as a number of years.
4. Present day value (PDV), also known as the life cycle cost (LCC) method, expresses all future costs of owning and operating a system over its lifetime by discounting these costs back to a present day value, and is expressed in terms of any currency.
5. Internal discount rate (IDR), also known as internal rate of return or "return on investment", is the discount rate that makes the present day value of net solar savings zero and is expressed in %.

These methods are explained in more detail in Appendix 1.

3.2 Sample Economic Analyses of a Typical Domestic Hot Water System

To illustrate the drawbacks and advantages of these methods and to show the relative effects of choosing any one of them, all five economic quantities have been calculated for different sizes of collectors in a typical domestic hot water system. The following table lists the nomenclature and values of constant parameters used here.

Table 3.1 Nomenclature and Parameter Values

A = collector area, m^2

Y_m = parameter for yield function = 1.5 GJ/m^2

L = yearly load = 20 GJ (equivalent to 325 liters/day, heated 40°C)

L_a = yearly load per unit area, GJ/m^2

Y_a = yearly solar energy yield as a function of L_a
= $Y_m \cdot (1 - \exp(- L_a/Y_m))$, GJ/m^2

Y = yearly energy yield of solar system = $A \cdot Y_a$, GJ

S_o = yearly oil savings, liters

C_o = yearly operating costs = 0 Dcrs

C_f = present cost of conventional fuel = 100 Dcrs/GJ
(oil burner efficiency of 0.7 assumed)

S = first year net savings = $S_o \cdot C_f - C_o$, Dcrs

C_e = constant solar system costs (pump, valves, etc.) = 2000 Dcrs

C_a = collector area dependent costs = 2000 $Dcrs/m^2$

I_o = total system investment = $C_e + A \cdot C_a$

a_1 = yearly interest + repayment on loan = 20.54%

a = yearly costs of loan = a_1 - tax deduction = 8.54%

t = tax deduction rate = 60%

C_y = yearly costs of solar system, Dcrs

i_n = inflation rate = 10%

i = market interest rate = 20%

d = real discount rate = $i \bullet (1 - t) - i_n = -2\%$

e = annual rate of rise of oil prices above inflation = 5%

g = annual rate of rise of operating costs, %

N = period of economic analysis = 20 years

n_p = simple pay back period, years

n = exact pay back period (discounted), years

i_r = internal discount rate

f = solar fraction, %

A simple solar energy yield function [22] is used to estimate the energy savings of the system as a function of the load per unit collector area:

$$Y_a = Y_m (1 - \exp(- L_a/Y_m)) \qquad GJ/m^2$$

Two resulting well known curves of solar fraction and yearly energy output per unit collector area as a function of the area-load ratio are presented in Figure 3.1.

Based on the solar contribution of Figure 3.1, and the costs of the solar system and the necessary remaining economic parameters, the five economic quantities have been calculated as a function of A and A/L. These functions have been plotted in Figure 3.2.

In Figure 3.2 it is seen that the curves of FYS (C_y/S_o) and SPB (n_p) are nearly parallel. Depending on the exact definitions of these terms, these two criteria are essentially identical, that is, they yield the same optimal collector area. (It can be shown by differentiating the expressions in Appendix 1 for SPB and FYS with respect to collector area, and setting the results equal to 0, that the same optimal area will result as long as the non-fuel related operating costs, C_o, are negligible.)

It should also be mentioned that another suggested economic criteria, first year energy savings per unit of original investment, is essentially equivalent to the SPB and FYS methods. It is simply the reciprocal of SPB divided by the cost of fuel. Hence, the system size which minimizes the

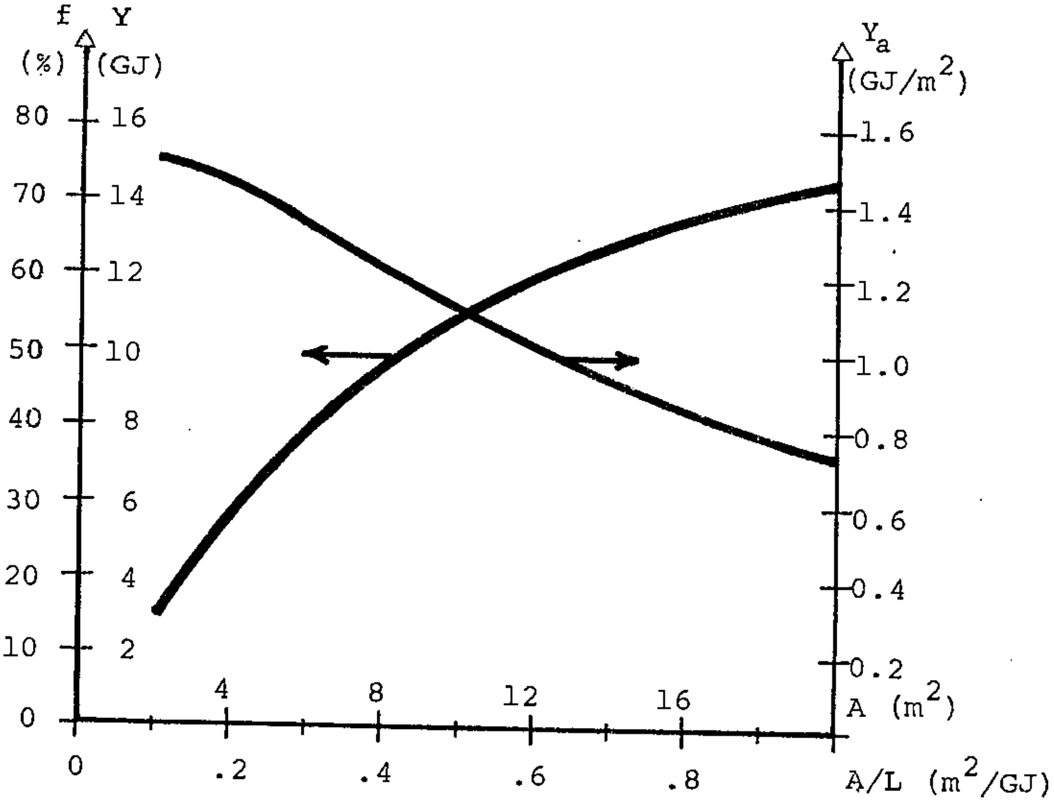

Fig. 3.1 Solar fraction and yearly yield

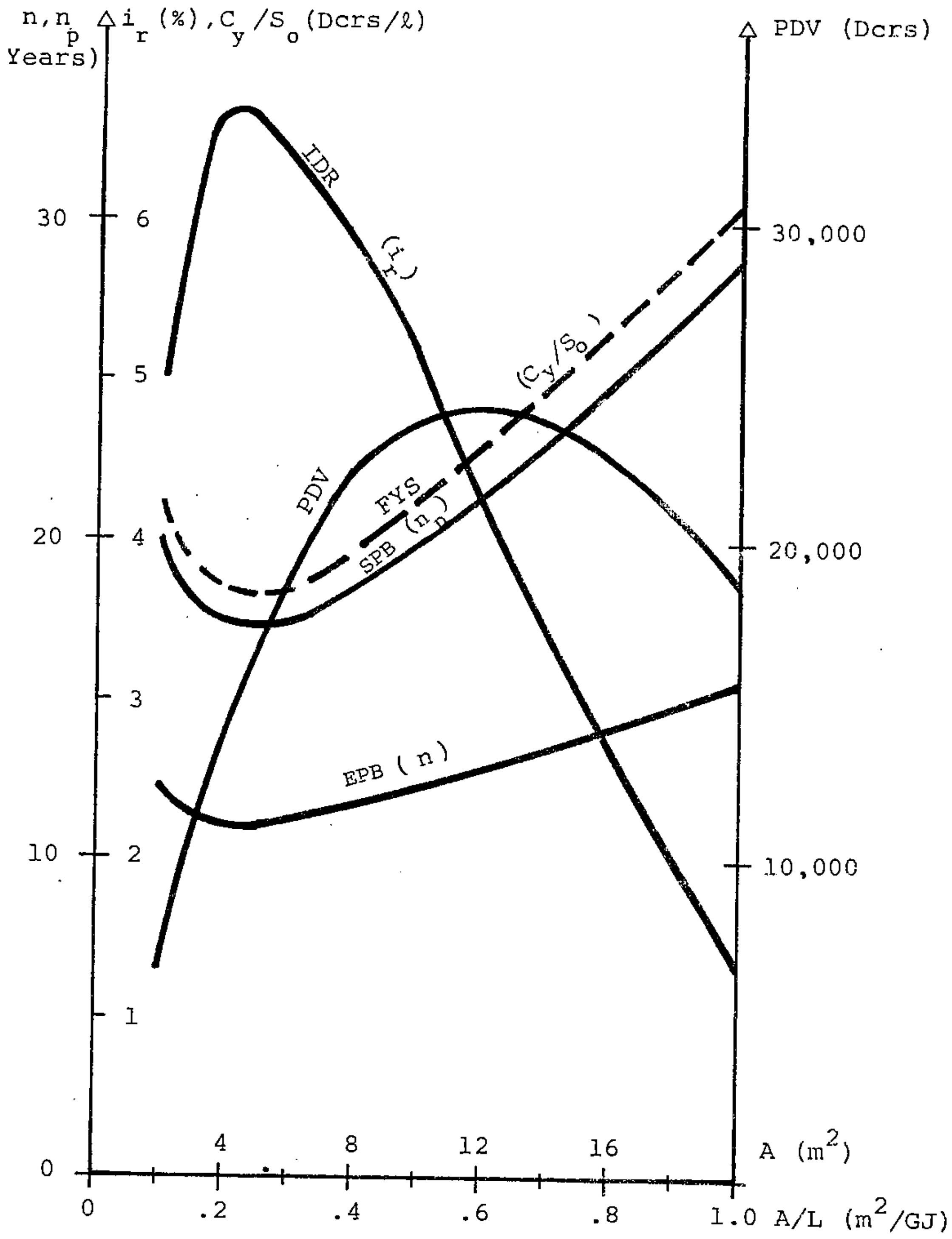

Figure 3.2 The five economic quantities as a function of area-load ratio.

simple payback period will maximize the energy savings per year per unit money invested.

The main difference between these methods and the remaining three is that the former do not account for future escalation of energy prices, for the present day value of future costs and savings, or for the useful lifetime of the system. This does not mean that the later three methods are equivalent, however. As seen from Figure 3.2 the optimum values (minimum EPB, and maximum IDR and PDV) do not all coincide. The optimum EPB and IDR system sizes occur at about $4m^2$ of collector while the optimum PDV system occurs at about $12m^2$.

It can be shown by differentiating the expressions in Appendix 1 for EPB, PDV, and IDR with respect to collector area and setting the results equal to zero, that identical expressions are obtained for optimum collector area for both the EPB and IDR criteria. Whats more, these optima are dependent only on the initial investment for the solar system, the initial cost of fuel and operating costs, and the systems' thermal performance. The optimum for the PDV criteria involves these variables as well as the fuel inflation rate, the market discount rate, and the "lifetime" of the equipment.

3.3 Summary

The FYS-SPB method is easy to calculate and understand and does not require guessing future rises in oil prices and the discount rate. But the method is often misleading if the pay back period and system lifetime are more than a few years (unless the discount rate and the assumed rate of energy price escalation are the same, which is not very often the case).

Economic evaluation techniques such as payback period or first-year energy savings are useful for sizing purposes where a collector type has been selected but the collector size (or the number of panels) must be determined. For an analysis of this sort the life of the system need not be a part of the optimization. If, however, the consumer is trying to select an optimum collector type as well as a collector size, life expectancy must be considered and a criterion such as life cycle cost would be more appropriate.

The inclusion of the fuel price escalation and discount rate effects in the EBP, PDV and IDR methods makes them more rigorous theoretically, but at the same time much more dependent on guesswork. (This is why the most important section of this report explores the sensitivity to the choice of different economic parameters in the PDV method.)

The principle difference between the PDV criteria and the EPB and IDR methods is that the latter two optimize the <u>marginal</u> economic benefit while the former maximizes the total economic benefit. Though the "payback times" and the "internal discount rates" are highly dependent on fuel inflation rates, an important result is that the optimal system size is not affected by it. As shown in Chapter 5, however, the optimal PDV system is highly dependent on fuel cost inflation.

When using SPB, EPB or IDR another criterion can be used, namely that IDR should exceed a certain value, say 4 percent (or that SPB and EPB should be less than 22 and 13 years, respectively) with maximum energy savings. In this example this would lead to the same result as given by the PDV method.

Because IDR is expressed as a financial rate of return there is a temptation to compare it with other rates such as the rate of bank loans or obligations. This cannot be done directly, however, since the IDR is an expression of the investment rate of return, over inflation and with no taxes exposed to it.

In summary, it is evident that when optimizing a solar energy system, or any other investment with an expected lifetime of more than 5-10 years, care must be taken in the selection of both the economic method and the economic parameters. The selection of both the method and the parameters is highly dependent on the financial perspective and goals of the investor and should be done with an understanding of how they will bias the conclusion. Even then, limited confidence can be advised in any result involving more than 5-7 years of analysis. This leads to the conclusion that the optimization process should not result in a single answer, but rather define a band of opportunities which are likely to be financially relevant and attractive.

4.0 COMPARISON OF THE THERMAL PERFORMANCE PREDICTED BY F-CHART AND THE DETAILED SIMULATION PROGRAMS

The purpose of this chapter is to compare the thermal performance predictions of a selected simplified method to that of the detailed simulation programs used in subtask A of this IEA task [23] for typical liquid and air based residential solar heating systems defined in [23]. The Hamburg, Santa Maria, and Madison liquid systems and the Madison air system have been evaluated with storage sizes of both 336 kJ/C-m^2 and 168 kJ/C-m^2 with version 3.0 of the FCHART interactive computer program. These systems are of the "standard" configuration handled by FChart. Input to the program is very straightforward; however, the following two points should be noted:

1. The radiation incident on the collector plane and the space heating loads have been input to FCHART from the TRNSYS monthly summaries presented in [23].

2. The effects of pipe and duct losses were accounted for by modifying $F_R U_L$ and $F_R \tau\alpha$ using the method described in [24]. (Because collector pipe and duct losses occur to 20°C rather than ambient, a small modification was made to the average ambient temperatures as well).

All FCHART program outputs are presented on the following pages. In Table 4.1 the results obtained from the detailed simulation programs in [23] are compared to the results predicted by the F-Chart method.

Very good agreement is achieved in Madison and Santa Maria but only fair agreement is achieved in Hamburg. This result is consistent with the relatively poor agreement obtained between FCHART and TRNSYS in highly cloudy U.S. cities. The "utilizability" (or the insolation above the critical level needed to produce useful energy gain) becomes increasingly important in climates with highly intermittent sunshine. Also, in cloudy climates second order climate statistics like "persistence" and "co-variance" of insolation and temperature are of increased importance. These effects are not accounted for in the F-Chart space and domestic hot water heating correlations.

No attempt has been made here to determine the absolute accuracy or the limits of applicability of this simplified method. Many efforts have been made to "validate" FCHART and other simplified methods by using results from both detailed simulation codes and measurements from actual systems, with varying degrees of success and conclusiveness. It is generally agreed, at

HAMBURG LIQUID SYSTEM

```
 CODE            VARIABLE DESCRIPTION                                VALUE UNITS

     1 AIR SH+WH=1,LIQ SH+WH=2,AIR OR LIQ WH ONLY=3.                  2.00
     2 IF 1,WHAT IS (FLOW RATE/COL.AREA)(SPEC.HEAT)?                 12.23 W/C-M2
     3 IF 2,WHAT IS (EPSILON)(CMIN)/(UA)?...........                  2.00
     4 COLLECTOR AREA...............................                 50.00 M2
     5 FRPRIME-TAU-ALPHA PRODUCT(NORMAL INCIDENCE)..                   .63
     6 FRPRIME-UL PRODUCT...........................                  3.68 W/C-M2
     7 INCIDENCE ANGLE MODIFIER (ZERO IF NOT AVAIL.)                  0.00
     8 NUMBER OF TRANSPARENT COVERS.................                  2.00
     9 COLLECTOR SLOPE..............................                 63.50 DEGREES
    10 AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90)........                  0.00 DEGREES
    11 STORAGE CAPACITY.............................                336.00 KJ/C-M2
    12 EFFECTIVE BUILDING UA........................                  0.00 KJ/C-DAY
    13 CONSTANT DAILY BLDG HEAT GENERATION..........                  0.00 KJ/DAY
    14 HOT WATER USAGE..............................                350.00 L/DAY
    15 WATER SET TEMP.(TO VARY BY MONTH,INPUT NEG.")                 50.00 C
    16 WATER MAIN TEMP(TO VARY BY MONTH,INPUT NEG.")                 10.00 C
    17 CITY CALL NUMBER.............................                269.00
    18 THERMAL PRINT OUT BY MONTH=1, BY YEAR=2......                  1.00
    19 ECONOMIC ANALYSIS ? YES=1, NO=2..............                  2.00
 TYPE IN CODE NUMBER AND NEW VALUE
 ? R
 USER SUPPLIED DATA    54.00
```

LARGE STORAGE

```
****THERMAL ANALYSIS****
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
        SOLAR    SOLAR    LOAD   LOAD   DAYS    TEMP
                  (GJ)    (GJ)   (GJ)  (C-DAY)  (C)
 JAN     0.0      2.80    8.06   1.82     0.    2.8
 FEB     7.9      5.66    7.20   1.64     0.    2.9
 MAR    60.1     14.53    4.83   1.82     0.    6.2
 APR    70.5     16.20    4.09   1.76     0.    6.2
 MAY    99.9     21.48    1.45   1.82     0.   12.6
 JUN   100.0     25.07    0.00   1.76     0.   16.4
 JUL   100.0     20.84    0.00   1.82     0.   17.8
 AUG   100.0     26.10    0.00   1.82     0.   16.9
 SEP    96.5     16.71    1.18   1.76     0.   14.1
 OCT    49.8     10.68    3.52   1.82     0.    8.3
 NOV    24.6      8.37    6.48   1.76     0.    5.1
 DEC     3.5      5.30    8.49   1.82     0.    2.8
 YR     38.0    173.74   45.30  21.41     0.
```

SMALL STORAGE

```
****THERMAL ANALYSIS****
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
        SOLAR    SOLAR    LOAD   LOAD   DAYS    TEMP
                  (GJ)    (GJ)   (GJ)  (C-DAY)  (C)
 JAN     0.0      2.80    8.06   1.82     0.    2.8
 FEB     3.7      5.66    7.20   1.64     0.    2.9
 MAR    55.1     14.53    4.83   1.82     0.    6.2
 APR    65.5     16.20    4.09   1.76     0.    6.2
 MAY    97.3     21.48    1.45   1.82     0.   12.6
 JUN   100.0     25.07    0.00   1.76     0.   16.4
 JUL   100.0     20.84    0.00   1.82     0.   17.8
 AUG   100.0     26.10    0.00   1.82     0.   16.9
 SEP    93.5     16.71    1.18   1.76     0.   14.1
 OCT    44.7     10.68    3.52   1.82     0.    8.3
 NOV    20.1      8.37    6.48   1.76     0.    5.1
 DEC     0.0      5.30    8.49   1.82     0.    2.8
 YR     34.8    173.74   45.30  21.41     0.
```

SANTA MARIA LIQUID SYSTEM

```
CODE          VARIABLE DESCRIPTION                          VALUE UNITS

  1 AIR SH+WH=1,LIQ SH+WH=2,AIR OR LIQ WH ONLY=3.          2.00
  2 IF 1,WHAT IS (FLOW RATE/COL.AREA)(SPEC.HEAT)?         12.23 W/C-M2
  3 IF 2,WHAT IS (EPSILON)(CMIN)/(UA)?..........           2.00
  4 COLLECTOR AREA..............................          20.00 M2
  5 FRPRIME-TAU-ALPHA PRODUCT(NORMAL INCIDENCE)..           .63
  6 FRPRIME-UL PRODUCT..........................           3.68 W/C-M2
  7 INCIDENCE ANGLE MODIFIER (ZERO IF NOT AVAIL.)          0.00
  8 NUMBER OF TRANSPARENT COVERS................           2.00
  9 COLLECTOR SLOPE.............................          44.00 DEGREES
 10 AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90)........          0.00 DEGREES
 11 STORAGE CAPACITY............................         336.00 KJ/C-M2
 12 EFFECTIVE BUILDING UA.......................           0.00 KJ/C-DAY
 13 CONSTANT DAILY BLDG HEAT GENERATION.........           0.00 KJ/DAY
 14 HOT WATER USAGE.............................         350.00 L/DAY
 15 WATER SET TEMP.(TO VARY BY MONTH,INPUT NEG.")         50.00 C
 16 WATER MAIN TEMP(TO VARY BY MONTH,INPUT NEG.")         10.00 C
 17 CITY CALL NUMBER............................         270.00
 18 THERMAL PRINT OUT BY MONTH=1, BY YEAR=2......          1.00
 19 ECONOMIC ANALYSIS ? YES=1, NO=2.............           2.00
TYPE IN CODE NUMBER AND NEW VALUE
? R
USER SUPPLIED DATA   34.00

****THERMAL ANALYSIS****       LARGE STORAGE
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
        SOLAR    SOLAR    LOAD   LOAD  DAYS    TEMP
                 (GJ)     (GJ)   (GJ) (C-DAY)  (C)
 JAN   82.0     11.36     3.07   1.82      0.   8.3
 FEB  100.0     12.91     2.29   1.64      0.   9.3
 MAR  100.0     15.79     1.73   1.82      0.  11.7
 APR  100.0     15.09     1.78   1.76      0.  10.7
 MAY  100.0     13.12     1.17   1.82      0.  12.7
 JUN  100.0     13.29      .89   1.76      0.  13.6
 JUL  100.0     15.73      .80   1.82      0.  14.0
 AUG  100.0     15.50      .59   1.82      0.  15.2
 SEP  100.0     15.15      .74   1.76      0.  15.0
 OCT  100.0     13.82      .92   1.82      0.  14.6
 NOV   93.7     12.07     1.72   1.76      0.  12.8
 DEC   72.9      7.79     1.66   1.82      0.  12.0
 YR    94.7    161.62    17.37  21.41      0.

****THERMAL ANALYSIS****       SMALL STORAGE
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
        SOLAR    SOLAR    LOAD   LOAD  DAYS    TEMP
                 (GJ)     (GJ)   (GJ) (C-DAY)  (C)
 JAN   78.6     11.36     3.07   1.82      0.   8.3
 FEB   98.8     12.91     2.29   1.64      0.   9.3
 MAR  100.0     15.79     1.73   1.82      0.  11.7
 APR  100.0     15.09     1.78   1.76      0.  10.7
 MAY  100.0     13.12     1.17   1.82      0.  12.7
 JUN  100.0     13.29      .89   1.76      0.  13.6
 JUL  100.0     15.73      .80   1.82      0.  14.0
 AUG  100.0     15.50      .59   1.82      0.  15.2
 SEP  100.0     15.15      .74   1.76      0.  15.0
 OCT  100.0     13.82      .92   1.82      0.  14.6
 NOV   89.7     12.07     1.72   1.76      0.  12.8
 DEC   68.7      7.79     1.66   1.82      0.  12.0
 YR    93.5    161.62    17.37  21.41      0.
```

MADISON LIQUID SYSTEM

```
 CODE          VARIABLE DESCRIPTION                                      VALUE UNITS

    1 AIR SH+WH=1,LIQ SH+WH=2,AIR OR LIQ WH ONLY=3.                       2.00
    2 IF 1,WHAT IS (FLOW RATE/COL.AREA)(SPEC.HEAT)?                      12.23 W/C-M2
    3 IF 2,WHAT IS (EPSILON)(CMIN)/(UA)?...........                       2.00
    4 COLLECTOR AREA...............................                      50.00 M2
    5 FRPRIME-TAU-ALPHA PRODUCT(NORMAL INCIDENCE)..                        .63
    6 FRPRIME-UL PRODUCT...........................                       3.68 W/C-M2
    7 INCIDENCE ANGLE MODIFIER (ZERO IF NOT AVAIL.)                       0.00
    8 NUMBER OF TRANSPARENT COVERS.................                       2.00
    9 COLLECTOR SLOPE..............................                      53.00 DEGREES
   10 AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90)........                       0.00 DEGREES
   11 STORAGE CAPACITY.............................                     336.00 KJ/C-M2
   12 EFFECTIVE BUILDING UA........................                       0.00 KJ/C-DAY
   13 CONSTANT DAILY BLDG HEAT GENERATION..........                       0.00 KJ/DAY
   14 HOT WATER USAGE..............................                     350.00 L/DAY
   15 WATER SET TEMP.(TO VARY BY MONTH,INPUT NEG.")                      50.00 C
   16 WATER MAIN TEMP(TO VARY BY MONTH,INPUT NEG.")                      10.00 C
   17 CITY CALL NUMBER.............................                     268.00
   18 THERMAL PRINT OUT BY MONTH=1, BY YEAR=2......                       1.00
   19 ECONOMIC ANALYSIS ? YES=1, NO=2..............                       2.00
TYPE IN CODE NUMBER AND NEW VALUE
? R
USER SUPPLIED DATA   43.00

****THERMAL ANALYSIS****    LARGE STORAGE
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
        SOLAR     SOLAR    LOAD   LOAD  DAYS    TEMP
                  (GJ)     (GJ)   (GJ) (C-DAY)  (C)
 JAN    41.8     17.53    12.95   1.82     0.  -4.9
 FEB    58.3     20.08    10.54   1.64     0.  -4.0
 MAR    84.2     26.83     7.98   1.82     0.   1.0
 APR    98.3     25.44     4.31   1.76     0.   7.2
 MAY   100.0     26.54     1.40   1.82     0.  15.0
 JUN   100.0     29.70     0.00   1.76     0.  21.9
 JUL   100.0     27.79     0.00   1.82     0.  22.5
 AUG   100.0     28.62     0.00   1.82     0.  20.4
 SEP   100.0     27.83     1.25   1.76     0.  15.0
 OCT    98.4     20.84     2.58   1.82     0.  11.5
 NOV    57.4     15.88     6.99   1.76     0.   4.1
 DEC    40.1     15.57    11.33   1.82     0.  -1.8
 YR     66.6    282.65    59.33  21.41     0.

****THERMAL ANALYSIS****    SMALL STORAGE
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
        SOLAR     SOLAR    LOAD   LOAD  DAYS    TEMP
                  (GJ)     (GJ)   (GJ) (C-DAY)  (C)
 JAN    38.4     17.53    12.95   1.82     0.  -4.9
 FEB    54.7     20.08    10.54   1.64     0.  -4.0
 MAR    79.9     26.83     7.98   1.82     0.   1.0
 APR    93.3     25.44     4.31   1.76     0.   7.2
 MAY   100.0     26.54     1.40   1.82     0.  15.0
 JUN   100.0     29.70     0.00   1.76     0.  21.9
 JUL   100.0     27.79     0.00   1.82     0.  22.5
 AUG   100.0     28.62     0.00   1.82     0.  20.4
 SEP   100.0     27.83     1.25   1.76     0.  15.0
 OCT    93.4     20.84     2.58   1.82     0.  11.5
 NOV    53.1     15.88     6.99   1.76     0.   4.1
 DEC    36.4     15.57    11.33   1.82     0.  -1.8
 YR     63.2    282.65    59.33  21.41     0.
```

MADISON AIR SYSTEM

```
CODE         VARIABLE DESCRIPTION                                   VALUE UNITS

   1 AIR SH+WH=1,LIQ SH+WH=2,AIR OR LIQ WH ONLY=3.                   1.00
   2 IF 1,WHAT IS (FLOW RATE/COL.AREA)(SPEC.HEAT)?                   12.23 W/C-M2
   3 IF 2,WHAT IS (EPSILON)(CMIN)/(UA)?..........                    2.00
   4 COLLECTOR AREA..............................                    50.00 M2
   5 FRPRIME-TAU-ALPHA PRODUCT(NORMAL INCIDENCE)..                    .46
   6 FRPRIME-UL PRODUCT..........................                    2.67 W/C-M2
   7 INCIDENCE ANGLE MODIFIER (ZERO IF NOT AVAIL.)                    0.00
   8 NUMBER OF TRANSPARENT COVERS................                    2.00
   9 COLLECTOR SLOPE.............................                   53.00 DEGREES
  10 AZIMUTH ANGLE (E.G. SOUTH=0, WEST=90)........                   0.00 DEGREES
  11 STORAGE CAPACITY............................                  336.00 KJ/C-M2
  12 EFFECTIVE BUILDING UA.......................                    0.00 KJ/C-DAY
  13 CONSTANT DAILY BLDG HEAT GENERATION..........                   0.00 KJ/DAY
  14 HOT WATER USAGE.............................                  350.00 L/DAY
  15 WATER SET TEMP.(TO VARY BY MONTH,INPUT NEG.")                  50.00 C
  16 WATER MAIN TEMP(TO VARY BY MONTH,INPUT NEG.")                  10.00 C
  17 CITY CALL NUMBER............................                  268.00
  18 THERMAL PRINT OUT BY MONTH=1, BY YEAR=2......                   1.00
  19 ECONOMIC ANALYSIS ? YES=1, NO=2.............                    2.00
TYPE IN CODE NUMBER AND NEW VALUE
? R
USER SUPPLIED DATA   43.00
```

```
****THERMAL ANALYSIS****   LARGE STORAGE
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
       SOLAR     SOLAR    LOAD  LOAD  DAYS    TEMP
                 (GJ)     (GJ)  (GJ) (C-DAY)  (C)
 JAN   34.7      17.53   12.95  1.82     0.  -4.9
 FEB   49.9      20.08   10.54  1.64     0.  -4.0
 MAR   77.1      26.83    7.98  1.82     0.   1.0
 APR   96.2      25.44    4.31  1.76     0.   7.2
 MAY  100.0      26.54    1.40  1.82     0.  15.0
 JUN  100.0      29.70    0.00  1.76     0.  21.9
 JUL  100.0      27.79    0.00  1.82     0.  22.5
 AUG  100.0      28.62    0.00  1.82     0.  20.4
 SEP  100.0      27.83    1.25  1.76     0.  15.0
 OCT   96.6      20.84    2.58  1.82     0.  11.5
 NOV   49.9      15.88    6.99  1.76     0.   4.1
 DEC   33.3      15.57   11.33  1.82     0.  -1.8
 YR    60.9     282.65   59.33 21.41     0.
```

```
****THERMAL ANALYSIS****   SMALL STORAGE
 TIME PERCENT INCIDENT HEATING WATER DEGREE AMBIENT
       SOLAR     SOLAR    LOAD  LOAD  DAYS    TEMP
                 (GJ)     (GJ)  (GJ) (C-DAY)  (C)
 JAN   31.6      17.53   12.95  1.82     0.  -4.9
 FEB   46.6      20.08   10.54  1.64     0.  -4.0
 MAR   73.1      26.83    7.98  1.82     0.   1.0
 APR   91.3      25.44    4.31  1.76     0.   7.2
 MAY  100.0      26.54    1.40  1.82     0.  15.0
 JUN  100.0      29.70    0.00  1.76     0.  21.9
 JUL  100.0      27.79    0.00  1.82     0.  22.5
 AUG  100.0      28.62    0.00  1.82     0.  20.4
 SEP  100.0      27.83    1.25  1.76     0.  15.0
 OCT   92.5      20.84    2.58  1.82     0.  11.5
 NOV   45.8      15.88    6.99  1.76     0.   4.1
 DEC   30.0      15.57   11.33  1.82     0.  -1.8
 YR    57.8     282.65   59.33 21.41     0.
```

LONG TERM PERCENT SOLAR HEATING PREDICTIONS

SIMULATION PROGRAMS	HAMBURG LIQUID		SANTA MARIA LIQUID	MADISON LIQUID	MADISON AIR
	LARGE STORAGE	SMALL STORAGE	LARGE STORAGE	LARGE STORAGE	LARGE STORAGE
US - TRNSYS	44.5	43.0	95.5	68.5	63.9
US - LASL	44.2	41.7	96.1	67.3	63.4
JAPAN	43.3	41.5	96.7	70.7	63.5
DENMARK	45.5	44.2	96.4	70.1	63.5
GERMANY	46.9	45.0	96.8	70.2	--
GREAT BRITAIN	41.2	--	97.7	67.2	--
ITALY	50.0	--	--	68.6	--
BELGIUM	47.1	--	97.9	74.5	--
AVERAGE	45.3	43.1	96.7	68.6	63.6
FCHART	38.0	34.8	94.7	66.6	60.9

*NOTE: LARGE STORAGE = 336 KJ/ ^{o}C-M^{2} (80 L/M^{2} liquid storage or 0.25 M^{3}/M^{2} rock storage)
SMALL STORAGE = 168 KJ/ ^{o}C-M^{2} (40 L/M^{2} liquid storage)

TABLE 4.1

least in the U.S., that the FChart method is sufficiently accurate and general to be used confidently in a broad range of typical residential active solar heating systems. Due to the difficulties imposed by many "non-standard" design features, uncertainties in equipment characteristics, occupant or user interactions, accurate long-term performance data acquisition etc., it is practically impossible to establish confidence intervals on any solar thermal analysis technique, much less, simplified techniques.

Experience seems to indicate, however, that the percentage of a space or hot water load met by solar can be predicted by FChart and other widely used methods to within about ±10 percentage points with little difficulty, particularly if the actual weather data from which the measurements were made is used in the analysis. Compared to the uncertainties introduced into the optimization process by the economic method and parameters, this can be viewed as an acceptable accuracy.

5.0 SOLAR HEATING ECONOMIC SENSITIVITY

As pointed out in Chapter 3, the present day value, or life cycle cost, method of economic analysis is a widely accepted means of assessing the relative cost effectiveness of investment alternatives [25]. It is used extensively in solar system optimization work despite the fact that many economic parameters must be estimated as far as 20 years into the future. The purpose of this chapter is to determine the sensitivity of the life cycle cost optimum solar system to the key economic parameters. A simple graphical method of determining the life cycle cost optimum collector size in a manner consistent in the following method of analysis is presented in Appendix 1.

5.1 Life Cycle Cost Analysis with P_1 and P_2 *

References [26] and [27] introduce the concept of the economic functions, P_1 and P_2, to facilitate the use of life cycle cost methods in a compact and flexible form. Any cost which is proportional to either the first-year fuel cost or the initial investment can be included. These factors allow for variation of annual expenses with time (e.g. inflation) and they reflect the time value of money by discounting future expenses to present values. Depending on the desired economic complexity, the factors, P_1 and P_2 can include loan costs, maintenance and insurance costs, income and property tax adjustments, commercial tax deduction of operating expenses, fuel expenses, and system salvage value. The explicit evaluation of P_1 and P_2 depends on the significance and applicability of each of these contributing costs. The life cycle savings of a solar heating system over a conventional heating system can then be expressed as the difference between a reduction in fuel costs and an increase in expenses incurred as a result of the additional investment for the solar system as:

$$SAV = P_1 C_F L\,F - P_2(C_A A + C_E) \tag{5.1}$$

---

*The following section is paraphrased from M.J. Brandemuehl [26] and Brandemuehl and Beckman [27].

Where:

SAV = life cycle savings of a solar heating system over a conventional heating system [\$].

C_F = unit cost of delivered conventional energy (including furnace efficiency) for the first year of analysis [\$/GJ].

L = average annual combined space and water heating load [GJ].

F = annual load fraction supplied by solar energy.

C_A = solar energy system investment costs which are directly proportional to collector area [\$/m^2].

A = collector area [m^2].

C_E = solar energy system investment costs which are independent of collector area [\$].

P_1 = factor relating life cycle fuel cost savings to first year fuel cost savings.

P_2 = factor relating life cycle expenditures incurred by additional capital investment to the initial investment.

It is assumed that the costs of components which are common to both conventional and solar heating systems (e.g., the furnace, ductwork, blowers, thermostat), and the maintenance costs of this equipment, are identical. As a result, all references to solar heating system costs, or conventional system costs, refer to the cost increment above the common costs.

To illustrate the evaluation of P_1 and P_2, consider a very simple economic situation in which the only significant costs are fuel and system equipment costs. Assume that fuel costs inflate at a constant annual rate, and the owner pays cash for the system at the beginning of the analysis (as may be the case for a water heating system). Here, P_1 accounts for fuel inflation and the discounting of future fuel payments. The factor P_2 accounts for investment related expenses which, in this case, consist only of the initial investment. Since the investment is already expressed in current dollars, P_2 is unity for this example. The factors P_1 and P_2 are then:

$$P_1 = f(N_E, e, d) \tag{5.2}$$

$$P_2 = 1 \tag{5.3}$$

where:

d = annual market discount rate.

e = annual market rate of fuel price inflation.

N_E = years of economic analysis.

and the function $f(N_E, e, d)$ is defined as:

$$f(N_E, e, d) = \frac{1}{d - e}\left[1 - \left(\frac{1 + e}{1 + d}\right)^{N_E}\right] \qquad (5.4)$$

The function $f(N_E, e, d)$ is a discount-inflation factor. When multiplied by a first period cost (which is inflated at a rate, e, and discounted at a rate, d, over N_E periods), the resulting value is the life cycle cost. When the inflation rate is zero, $f(N_E, 0, d)$ is the familiar series-payment present-worth factor, and $[f(N_E, 0, d)]^{-1}$ is the capital recovery factor.

A more complex analysis may be formulated to include miscellaneous costs (maintenance, insurance, etc.), property tax, income tax deductions for interest and property tax, and commercial deductions for fuel expenses, miscellaneous expenses, and depreciation*. Under these conditions, P_1 and P_2 take the following forms:

$$P_1 = (1 - C\bar{t})f(N_E, e, d) \qquad (5.5)$$

$$\begin{aligned} P_2 = {} & D + (1 - D)\frac{f(N_1, 0, d)}{f(N_L, 0, i)} \\ & - (1 - D)\bar{t}\left[f(N_1, i, d)\left(i - \frac{1}{f(N_L, 0, i)}\right) + \frac{f(N_1, 0, d)}{f(N_L, 0, i)}\right] \\ & + (1 - C\bar{t})Mf(N_E, g, d) + t(1 - \bar{t})Vf(N_E, g, d) \\ & - \frac{C\bar{t}}{N_D} f(N_2, 0, d) \end{aligned} \qquad (5.6)$$

where: C = commercial or non-commercial flag (1 or 0, respectively).

i = annual mortgage interest rate.

g = general inflation rate.

---

*Straight line depreciation is used in the example. It can also be shown that, for N_2=N_D, double declining balance or sum-of-digits may be used as follows:

$$DB = C\bar{t} + \frac{2C\bar{t}}{N_D}\left[f(N_D - 1, {}^{-2}/N_D, d) - \frac{f(N_D - 1, {}^{-2}/N_D, 0)}{(1 + d)^{N_D}}\right]$$

$$SOD = \frac{2\bar{t}}{N_D(N_D + 1)}\left[f(N_D, 0, d) + \frac{N_D - 1 - f(N_D - 1, 0, d)}{d}\right]$$

N_E = term of economic analysis.

N_L = term of loan.

N_1 = $\min(N_E, N_L)$.

N_D = depreciation lifetime in years.

N_2 = $\min(N_E, N_D)$.

$\bar{t}$ = effective income tax rate.

t = property tax rate based on assessed value.

D = ratio of down payment to initial investment.

M = ratio of first year miscellaneous costs to initial investment.

V = ratio of assessed value in first year to initial investment.

All other terms are as previously defined.

In the expression for P_2 of Equation 5.6, the first term represents the down payment; the second term represents the life cycle cost of the mortgage principal and interest; the third, income tax deductions of the interest; the fourth, miscellaneous costs; the fifth, net property tax costs; the sixth, straight line depreciation tax deduction. These and other terms may be added to or deleted from an analysis, allowing a range of economic complexity.

[The preceding discussion was based on the assumption that all costs which change with time do so at constant annual rates. This is not required by the definition of P_1 and P_2 in Equation 5.1. These two factors can be used to accommodate arbitrary time variations of any costs which are either proportional to the initial investment or to the first-year fuel cost (e.g. periodic cover replacement).]

5.2 Qualitative Sensitivity

The values of some economic variables will be fixed by the conditions surrounding the individual owner's situation. There is little uncertainty surrounding loan cost variables, since the down payment, interest rate, and term of the mortgage are determined by the loan contract. However, knowledge of their effects is still useful.

The loan interest rate can have a significant effect on the value of P_2. Clearly, a 5 percent loan interest rate will make a noticeable change in P_2 over a 12 percent interest rate. The effect of a small change in the interest rate, though, is generally not very significant. This is especially true if the discount rate is approximately equal to the loan interest rate. If the difference between the interest and discount rates is large, and the income tax rate is large, the sensitivity to the interest rate increases.

The operating costs of both a solar and conventional heating system are among the most difficult costs to evaluate. Unfortunately, the results of a life cycle cost analysis are strongly influenced by, and highly sensitive to the economic variables which determine these costs. The rate of inflation of conventional and auxiliary heating system fuel costs will depend on a host of uncontrollable and often unpredictable factors. An error in estimating this fuel cost inflation rate as small as 1 percent can easily result in an 8-10 percent error in the value of P_1 for a 20 year analysis. This error can, in turn, cause huge errors in the life cycle savings. If the results of a life cycle cost analysis are to be viewed objectively, this uncertainty must not be overlooked. It must also be realized that the error caused by this uncertainty will overshadow those caused by many other economic variables. This situation often makes results from very sophisticated models no more accurate than those from very simple models.

Miscellaneous costs often seem insignificant when considering the error introduced by fuel inflation uncertainty. Neglecting them, however, can result in errors as large as those caused by fuel inflation uncertainties. For example, consider a 20 year analysis with 6 percent general inflation rate, an 8 percent discount rate, and an $8,000 solar system investment. The difference in life cycle savings between an analysis which neglects miscellaneous costs and one which assumes a first-year miscellaneous cost of 1 percent of the initial investment is $1,248. This sensitivity is further complicated by ignorance about the magnitude and future variations of the miscellaneous costs.

Property tax life cycle cost contributions and their uncertainties can also be significant, especially if the property tax rate is high and the income tax rate is low. If the building is located in a state or country which taxes solar systems, the significance of this contribution will depend largely on the owner's tax situation. One of the main sources of uncertainty in the U.S. is that many states that now tax solar systems may exempt them from property taxes in the near future.

It is often assumed that miscellaneous costs and property taxes rise with the general inflation rate. This assumption is based more on its convenience than its validity. Maintenance costs will probably be irregular, and property taxes will eventually decrease near the end of the system lifetime. In spite of these uncertainties, increases in miscellaneous costs and property taxes at the general inflation rate still seem a reasonable assumption. Accepting this, the general inflation rate is a relatively uncontroversial variable, since there is little sensitivity to errors in its estimation*.

In an effort to simplify the life cycle cost model, miscellaneous costs and taxes are often omitted on grounds that they will cancel each in the final analysis. In many cases, this can be a very good assumption. Depending on the individual situation, though, it is often better to assume that either property taxes or miscellaneous costs will cancel income taxes, since it is usually unlikely that income taxes will offset both.

Like property taxes, income taxes can also be significant, depending on the loan terms. Both the sensitivity and the significance of income taxes will be greater for loans with low down payments, high interest rates, and long mortgage terms assuming interest payments are deductions from taxable income. However, the main uncertainty is the possible variation of the income tax rate, especially if the owner is young and the duration of the analysis is long.

When considering commercial buildings, the effect of income taxes can be tremendous. This increased effect is accompanied by a dramatic increase in life cycle cost sensitivity to the value of the income tax rate (an increase in sensitivity by a factor of 5 is not uncommon). Fortunately, it is usually known at the beginning of the analysis whether the building will qualify for commercial tax deductions. However, if this eligibility is changed at some time in the future, it can strongly influence the analysis results.

---

*It should be noted however, that the market discount rate is directly related to the inflation rate and that the discount rate _is_ critical in a life cycle cost analysis.

The salvage value is another variable that is difficult to quantify. For short analyses, its value and sensitivity can be significant and must be recognized. For longer analyses, its value and sensitivity will probably be small, due to discounting to present value. The salvage value is often omitted from longer analyses to yield a slightly conservative life cycle savings.

The discount rate has a major effect in tempering the uncertainty of many economic variables. While costs incurred far in the future are the most uncertain, the discounting of future costs will reduce the significance of these uncertainties. However, the broad influence of the discount rate makes the life cycle cost analysis results rather sensitive to its value. Similarly, the duration of the analysis has a strong and obvious influence on the life cycle cost analysis. Like the discount rate, the magnitude of the sensitivity is determined by the value of almost every economic variable. The best way to recognize these sensitivities is to use several values of the discount rate and period of analysis.

The down payment has little effect on the value of P_2. The effect it does have is determined by the interest rate, discount rate, mortgage term, and income tax rate. If the discount rate is greater than the interest rate, an increase in the down payment will increase the value of P_2. If the discount rate is less than the interest rate, the effect on P_2 will depend on the income tax rate. Since the interest is deductible from income taxes, it has the effect of lowering the interest rate. In most cases, it remains beneficial to have a small down payment and long mortgage term.

5.3 Economic Sensitivity of the IEA Liquid System in Madison

As an example of the use of the concepts discussed above, a fairly complete economic sensitivity study of the IEA liquid system in Madison will be illustrated. This analysis will show both the effects on the economics of a given size (i.e. collector area) solar system <u>and</u> the shift in the optimum size as the important economic parameters are varied. To simplify the analysis it is assumed that the period of the economic analysis is identical to the term of the mortgage and the effects of both income and property taxes are neglected.

The starting point is a graph of the system thermal performance as a function of system size (Figure 5.1). This graph has been obtained from the F-Chart method but any suitable method of estimating thermal performance can be used. The life cycle savings of the solar system over a conventional furnace system is given in equation 5.1. The graphical analysis is further simplified if it can be assumed that the "fixed" capital costs can be lumped into collector area costs (i.e. $C_E = 0$). Then, when equation 5.1 is divided through by the load one has:

$$S/L = (P_1C_F)F - P_2C_C(A/L) \qquad (5.7)$$

$$= \text{Fuel Savings} - \text{Capital Costs}$$

$$= \Gamma_1 - \Gamma_2$$

Now life cycle savings is in terms of two economic parameters, P_1C_F and P_2C_C, and two thermal parameters, F and A/L. Γ_1 and Γ_2 can be plotted as functions of A/L for a wide range of P_1C_F and P_2C_C since F as a function of A/L is known. S/L can then be found by subtraction.

To illustrate, assume the set of economic parameters given in Table 5.1 represents the base economic case. In Table 5.2 the parameters have been varied one by one through a wide range of values while the other parameters have been held constant at their base values. Also shown in Table 5.2 are the corresponding values of P_1 and P_2 calculated from equations 5.5 and 5.6.

The total heating load in Madison is L = 80.74 GJ. F(A) and F(A/L) are shown in Figure 5.1. Figure 5.2 shows $\Gamma_1(A/L) = (P_1C_F) \times F(A/L)$ for a range of P_2C_C from 50 to 500. Figure 5.3 shows $\Gamma_2(A/L) = (P_2C_C) \times (A/L)$ for a range of P_2C_C from 50 to 500.

Figure 5.4 shows the life cycle savings per unit load for the base case of Table 5.1. It is found by locating $P_1C_F = 20.03 \times 8. = 160$ (dashed line in Figure 5.2) and $P_2C_C = 1.08 \times 200 = 216$ (dashed line in Figure 5.3) and subtracting the two.

Figure 5.5 shows the effects of the variation of the discount rate on life cycle savings from Table 5.2, Cases 1-8.

Figure 5.6 shows the effects of the fuel inflation rate from Cases 13-17 and Figure 5.7 shows the effect of mortgage interest rate from Cases 18-22.

The effects of the other economic parameters can be visualized by noting their effect on P_1 or P_2 and by subtracting the appropriate curves from Figures 5.3 and 5.4.

The initial year fuel cost and collector costs do not affect P_1 or P_2 but figure into life cycle savings in accordance with equation 5.7.

Table 5.1
BASE ECONOMIC PARAMETER VALUES

symbol	description	value
N	Term of mortgage	20 yrs
d	Market discount rate	9 %
i	Annual mortgage interest rate	8 %
e	Annual market inflation rate of fuel	10 %
g	General inflation rate	6 %
D	Ratio of down payments to intial investment	.1
M	Ratio of 1st year misc. costs to initial investment	.01
C_F	Initial cost of conventional fuel	\$8/GJ
C_C	Collector Area Dependent Costs	\$200/m^2
C_E	Constant Solar Costs	\$1000

TABLE 5.2
P_1 and P_2 Under Various Economic Conditions

Case NO.	Base Case (Except as noted)	P_1	P_2
1	d = 0%	57.27	2.28
2	d = 3	38.93	1.72
3	d = 6	27.44	1.34
4	d = 9 (BASE)	20.03	1.08
5	d = 12	15.13	.90
6	d = 15	11.78	.76
7	d = 18	9.43	.66
8	d = 21	7.74	.59
9	N = 10 yr	9.56	1.04
10	N = 20 (BASE)	20.03	1.08
11	N = 30	31.52	1.11
12	N = 40	44.09	1.14
13	e = 0%	9.12	
14	e = 5	13.16	
15	e = 10 (BASE)	20.03	1.08
16	e = 15	32.00	
17	e = 15	53.10	
18	i = 4%	↑	.85
19	i = 6		.96
20	i = 8 (BASE)	20.03	1.08
21	i = 10	↓	1.21
22	i = 12		1.34
23	D = 0	20.03	1.07
24	D = .10 (BASE)	↓	1.08
25	D = .20		1.09
26	D = .50		1.11
27	D = 1.00		1.14
28	M = 0	20.03	.94
29	M = .01 (BASE)	↓	1.08
30	M = .02		1.22
31	M = .05		1.65

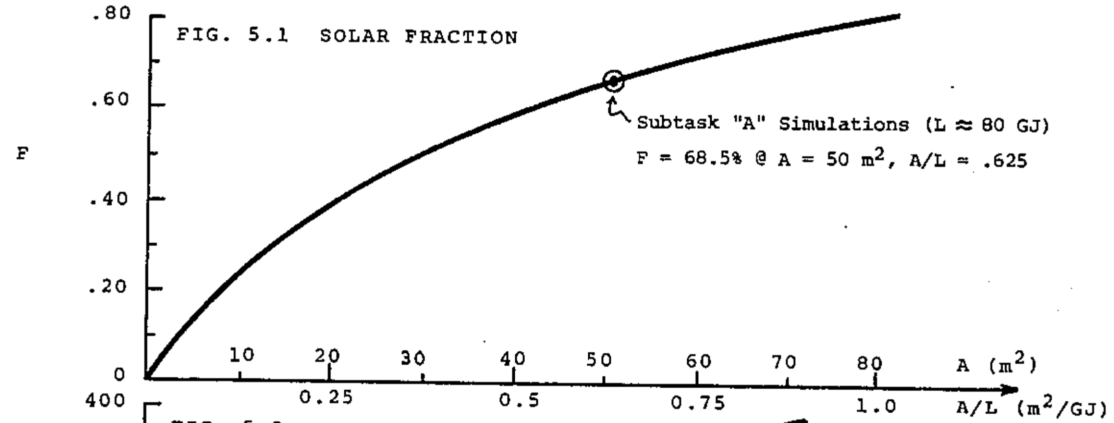

FIG. 5.1 SOLAR FRACTION

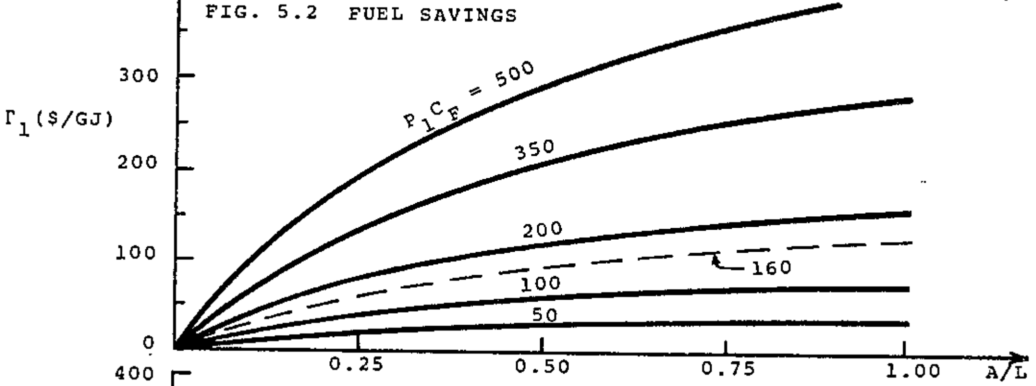

FIG. 5.2 FUEL SAVINGS

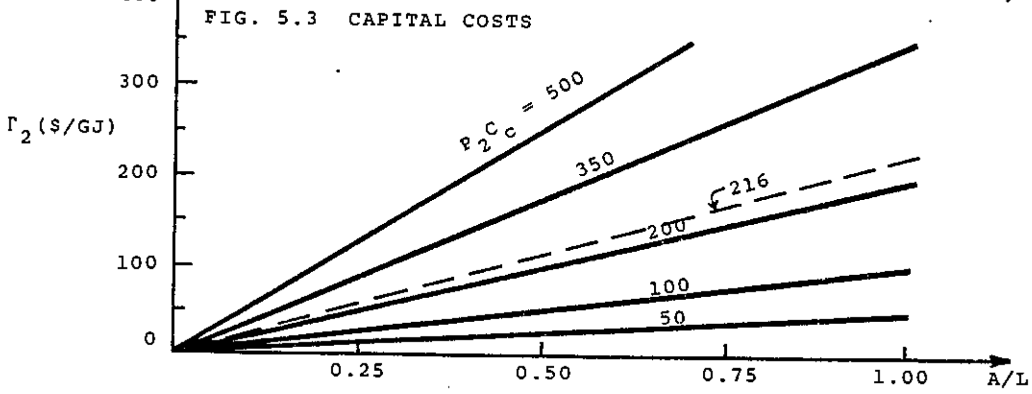

FIG. 5.3 CAPITAL COSTS

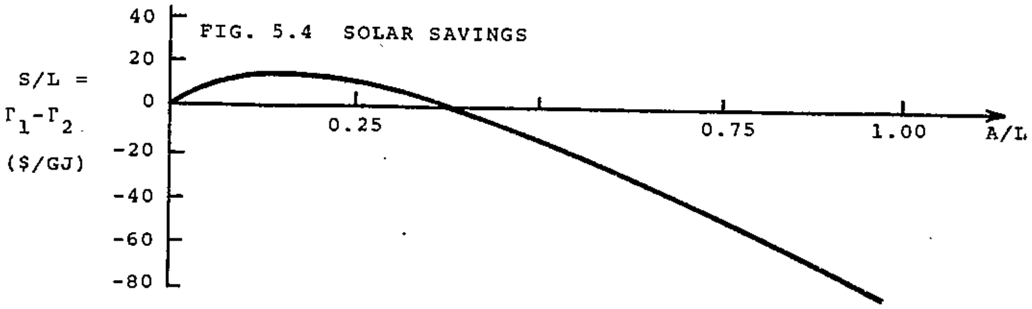

FIG. 5.4 SOLAR SAVINGS

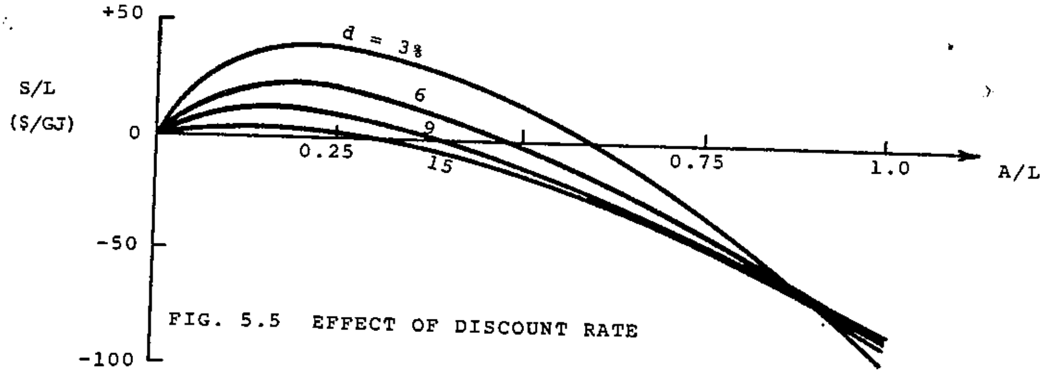

FIG. 5.5 EFFECT OF DISCOUNT RATE

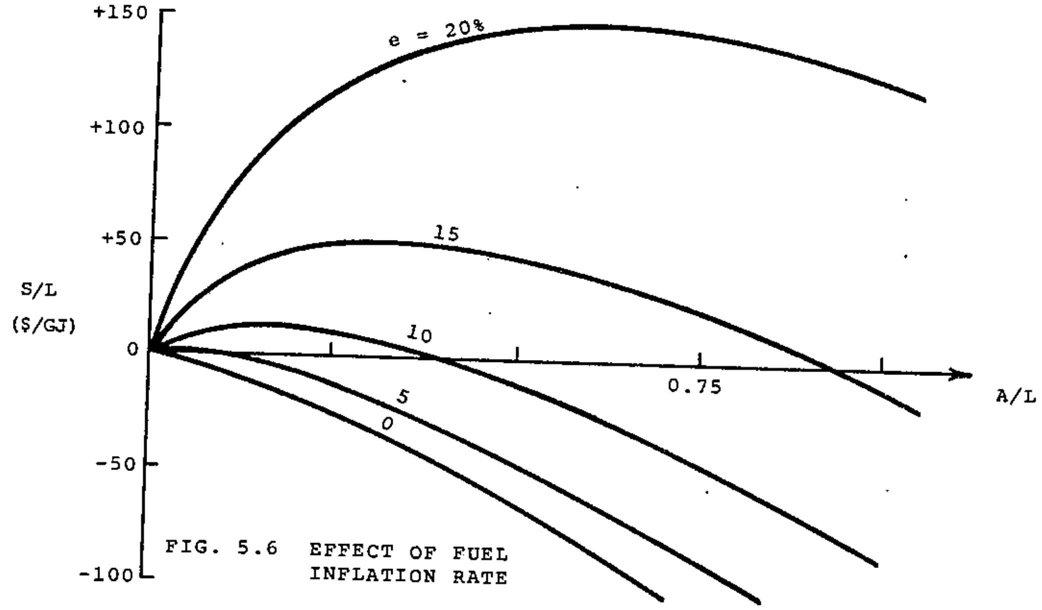

FIG. 5.6 EFFECT OF FUEL INFLATION RATE

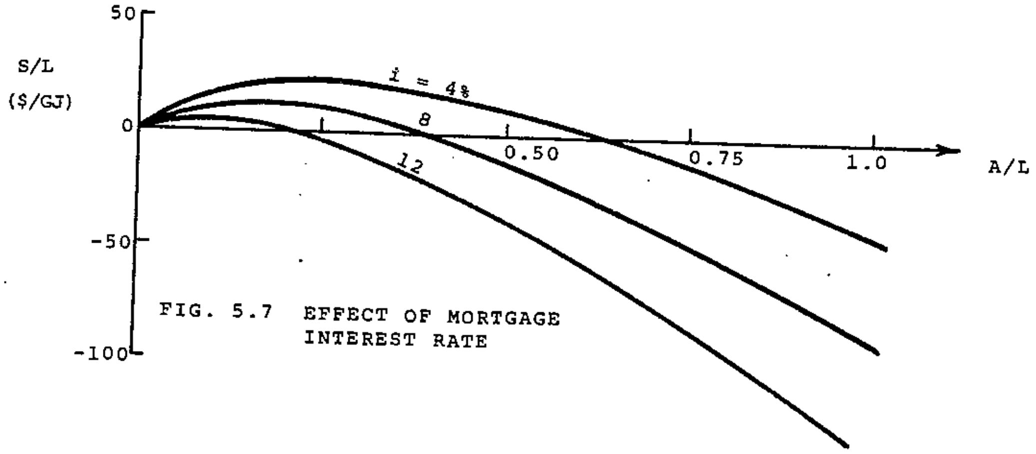

FIG. 5.7 EFFECT OF MORTGAGE INTEREST RATE

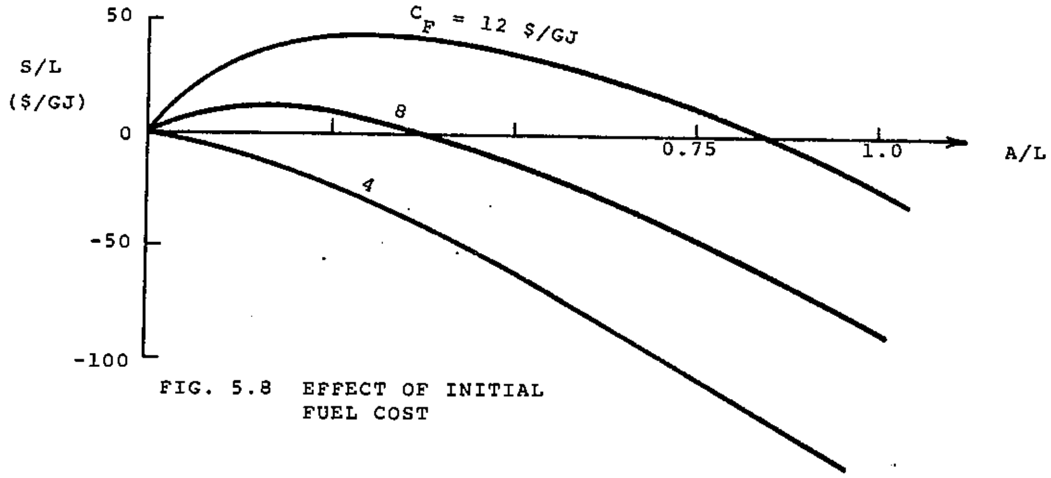

FIG. 5.8 EFFECT OF INITIAL FUEL COST

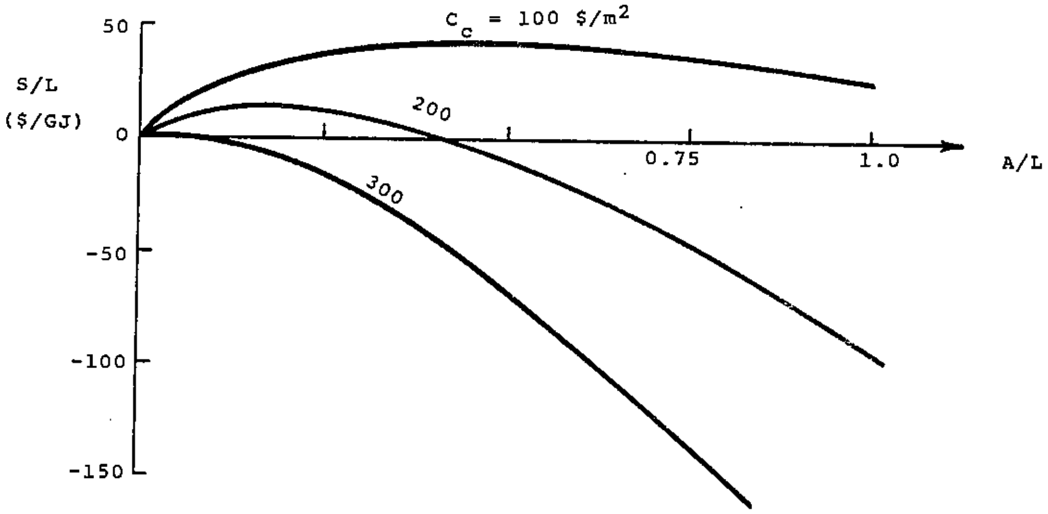

FIG. 5.9 EFFECT OF COLLECTOR AREA DEPENDENT COSTS

The optimum system size for any set of economic parameters is simply the maximum of the appropriate S/L curve. Although these results are for a particular system design in a particular climate, the sensitivity trends, summarized in Table 5.3, are typical of those predicted by the life cycle cost approach for other systems and climates In general it can be seen from the savings curves that any economic parameter change that increases life cycle savings also increases the optimum solar system size.

Table 5.3 Summary of Economic Sensitivity Analysis

Economic Parameter	Range	Effect on Optimal Size as Parameter is Increased
Discount Rate	3-15%	decreases from 16 to 8m^2
Fuel Inflation Rate	0-20%	increases from 0 to 48m^2
Mortgage Interest Rate	4-12%	decreases from 16 to 8m^2
Initial Fuel Cost	$4-12/GJ	increases from 0 to 24m^2
Collector Area Dependent Costs	$100-300/m^2	decreases from 40 to 0m^2

The greatest life cycle savings variations result from the rate of fuel inflation. It is very important to note that this is <u>the</u> single important economic parameter about which the least is known at the time a system is designed and installed. In practice, the enormous importance and uncertainty of fuel cost inflation in the optimization process far outweigh most of the differences inherent in both the thermal and economic methods.

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APPENDIX 1 DETAILS OF SEVERAL ECONOMIC ANALYSIS METHODS

(See Chapter 3 for nomenclature)

1. First Year Savings (FYS) method

The sum of interest and repayment is found by the expression:

$$\frac{a_1}{100} = \frac{\frac{i}{100}\left(1 + \frac{i}{100}\right)^N}{\left(1 + \frac{i}{100}\right)^N - 1}$$

The tax deduction on interest is subtracted:

$a = a_1 - i \bullet t$

The first year cost is then:

$C_Y = I_o \bullet a + C_o$

First year savings can be expressed in different ways:

C_Y/S_o (Dcrs/ℓ) or C_Y/Y (Dcrs/GJ) or C_Y/S (Dcrs/Dcrs)

2. Simple Pay Back (SPB) method

The simple pay back period is simply:

$n_p = I_o/S$ (years)

3. Exact Pay Back (EPB) method

When $R = \dfrac{1 + e/100}{1 + d/100}$

the present day value of the fuel savings is given as:

$$PDV = SR(1 + R + R^2 + \dots R^{N-1}) = \frac{SR(R^N - 1)}{(R - 1)}$$

and because the present day value of the savings accumulated over the exact pay back period (n) should equal the initial investment, we have:

$$\frac{PDV}{S} = n_p$$

$$n_p = \frac{R(R^n - 1)}{(R - 1)}$$

(Note that a difference between the inflation rates of oil prices and operating costs is not taken into account in this method.)

Present Day Value (PDV) or Life Cycle Cost method

The accumulated present day value of future savings and costs is given by the following expression:

$$PDV = \sum_{t=1}^{N} \left(\frac{1 + e/100}{1 + d/100}\right)^t \bullet S_o C_f - \sum_{t=1}^{N} \left(\frac{1 + g/100}{1 + d/100}\right)^t C_o - I_o$$

The easiest way to calculate this expression is to look at it as two quotient series where:

$$R = \left(\frac{1 + e/100}{1 + d/100}\right) \quad \text{and} \quad Q = \left(\frac{1 + g/100}{1 + d/100}\right)$$

then

$$PDV = S_o \; C_f \bullet R \, \frac{(R^N - 1)}{R - 1} - C_o \bullet Q \, \frac{(Q^N - 1)}{Q - 1} - I_o$$

which reduces to:

$$PDV = S \, \frac{R(R^N - 1)}{R - 1} - I_o$$

when $g = e$, which is not unreasonable since a considerable part of the operating cost is energy cost (electricity for pumps or fans).

Internal Discount Rate (IDR) method

i_r is the choice of d making:

$PDV = 0$ (see present day value method)

Appendix 2 A SIMPLE GRAPHICAL OPTIMIZATION TECHNIQUE*

Introduction

Presented here is a simple graphical optimization technique that is an extension of the economic analysis method discussed in Chapter 5. Given a specific collector type, the main solar heating system design parameter is the collector area. For very small collector areas, the load fraction supplied by solar energy is close to zero, and fixed costs force the solar system life cycle savings over a conventional heating system to be negative. For very large collector areas, the solar energy load fraction approaches unity, but the excessive system costs due to large collector area result in negative savings. At some intermediate collector area, fuel savings and system expenses combine to yield maximum savings. For a given set of economic conditions, collector type, location, and heating load, it is desirable to optimize the system by determining the collector area at which maximum savings can be achieved. When the optimum occurs at zero area, or at a finite area but with negative savings, the conventional system is the best choice from an economic viewpoint. If the optimum is associated with a positive life cycle savings, the solar system is the economic choice.

Discussion of Method

Optimum solar system size can be found graphically with the method illustrated in Chapter 5. The drawback is that the life cycle savings must be plotted for a wide range of collector areas (or area/load values) until the maximum is found. An alternative method is suggested by the fact that the derivative of life cycle savings with respect to collector area is equal to zero at the optimum.

$$\frac{\partial\ SAV}{\partial A} = 0 = P_1 C_F \frac{\partial F}{\partial (A/L)} - P_2 C_A \qquad \text{A2-1}$$

hence, at the optimum, $$\frac{\partial F}{\partial (A/L)} = \frac{P_2 C_A}{P_1 C_F} \qquad \text{A2-2}$$

Thus, if the solar fraction, F, is known as a function of the collector area to load ratio, A/L, the function $\partial F/\partial (A/L)$ can be found by graphically differentiating the F curve (or by analytically differentiating F if an expression is available). The optimum is then simply found by evaluating P_2C_A/P_1C_F with the aid of the expressions for P_1 and P_2 given in Chapter 5, and locating the value of A/L that satisfies equation A2-2 as shown in Figure A2-1. This method is equivalent in terms of the result to the graphical maxima search used in Chapter 5 and to the iterative search used in the FCHART computer program.

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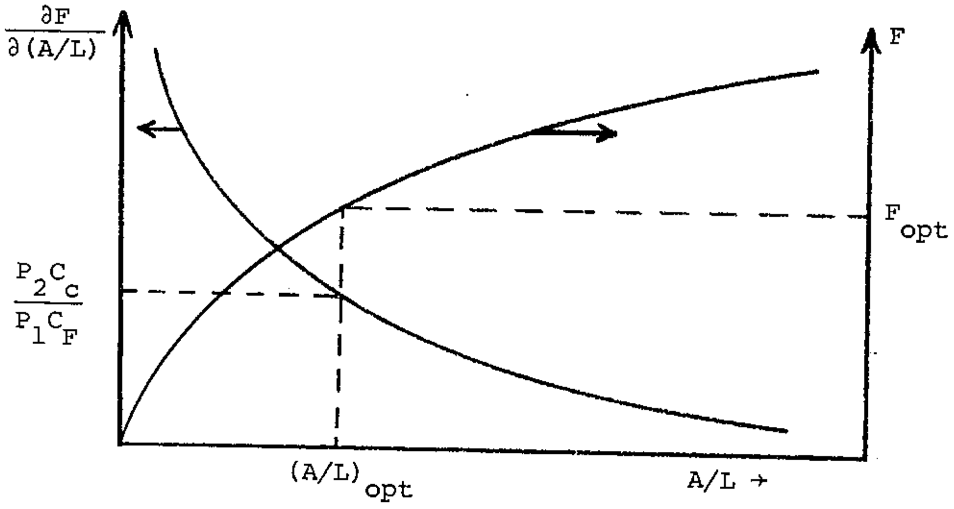
*from Brandemuehl, M.J. and W.A. Beckman [27]



GRAPHICAL OPTIMIZATION PROCEDURE

FIG. A2-1

ABSTRACT

A review of general techniques and specific methods useful in the optimization of solar heating and cooling systems is undertaken. A discussion of the state of the art and the principal problems in both the simplified thermal performance analysis and economic analysis portions of the optimization problem are presented. Sample economic analyses are performed using several widely used economic criteria. The predicted thermal results of one typical, widely used simplified method is compared to detailed simulation results. A methodology for and the results of a sensitivity study of key economic parameters in the life cycle cost method are presented. Finally, a simple graphical optimization technique based on the life cycle cost method is proposed.

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Task I: Investigation of the Performance
of Solar Heating and Cooling Systems
Subtask D: Optimization

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