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ENERGY RESOURCE REQUIREMENTS OF A SOLAR HEATING SYSTEM

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Abstract—The methods of energy analysis have been applied to a liquid-based, short-term storage solar space and water heating system suitable for a single family dwelling in Toronto. This system, which in many respects represents a worst case for solar heating, takes 1.0–3.5 years of operation to conserve the energy resources required to build, operate and maintain the system. Alternatively, over the twenty year lifetime of the system, the energy resources used indirectly by the solar heating system amount to between 6 and 24% of the direct energy resources conserved by the system. These considerations do not significantly alter the energy-conservation characteristics of the solar heating system unless thermally-generated electricity is used as backup for a 50% solar heating system which replaces oil or gas heating; in this case, only 4–9% of the energy resources are conserved by the solar system. A factor of three variation in energy resource use in collector materials was found in a sample of 7 flat-plate collectors with steel-based collectors using the least. The total energy embodied in the collector was about double that found in the materials alone. The collectors and annual operating energy for the pumps were found to be the two most significant factors in the analysis. An appendix summarizes the energy resource requirements embodied in the materials used for collectors.

1. INTRODUCTION

Solar energy is normally viewed as a renewable energy resource. This view ignores the fossil fuels which are used to construct and operate a solar system. A more useful way to think of solar energy systems is to consider them as a method of using scarce fossil fuel resources to provide energy. Given this view, a question which arises is: "Are solar systems more efficient users of non-renewable resources than traditional systems or other suggested new technologies?" Some authors have suggested that solar heating is not very efficient.[1,2] If this were true, much of the current effort to induce the use of solar energy would be misguided.

This paper addresses the question of the total energy resource use of a solar hot water and space heating system compared to the traditional oil, gas and electric heating options. One way of looking at the problem is to ask: "How long does it take for a solar heating system to produce the same amount of heating energy as would have been supplied by a traditional system using the fuels required to produce, install and operate the solar system, i.e. what is the energy payback time?"

To give the present results some general value, this paper will deal with a specific example of solar heating which, from many points of view, is a worst case. Also, worst case results are used where problems of methodology occur. Hence, if the energy resource use in this system is efficient, then it is reasonable to conclude that all "well designed" solar-heating systems are energy-efficient.

2. ENERGY ANALYSIS

The act of following the energy flows in a system is known as energy analysis. After an initial flurry over net energy ratios, most energy analysts today attempt to evaluate the energy resources consumed by various alternative methods for meeting a given end use. This is of interest since hopefully it will help to pinpoint how to use scarce energy resources most effectively.

Unfortunately, there are limitations to energy analysis. The most serious of these is the question of boundaries concerning how and what should be included as inputs (see e.g. Ref. 3). Various groups use widely differing conventions. One must have a clear idea of how boundary questions are handled in any particular study if the results are to be meaningfully interpreted. The following summarizes the major premises used in this study. Imports of energy are treated as if of local origin. Labour is assigned no energy content because the energy of direct human work is negligible and to include the energy content of items purchased by labour would leave the system with no net output. Wood is not considered as a fuel and other fuels are associated with their heat of combustion. Results from the 1971 Statistics Canada input–output (I/O) energy model[4] are used and they have electricity rated at about 10,000 Btu/kWh. Electricity use buried in materials energy coefficients is likely to be at about this same conversion factor since 10,000 Btu/kWh represents electricity generated from thermal sources. Only those fuels at the mine mouth or well head are accounted for, although keeping track of total resources affected would be a desirable goal if the data were available. No energy is associated with the use of environmental factors.

One final general remark concerning energy analysis is that, in the solar energy case, the conclusion that resources are saved follows immediately if one assumes solar energy systems are economic and prices per joule for various forms of energy are equivalent. This result follows because the economic benefits of solar energy all accrue by avoiding direct energy costs. It follows that if a system is economic, then the cost of the system, which includes the costs of the energy used to build the system, must be less than the value of the saved energy and hence the system must conserve energy resources.

In view of these remarks, why has this study been done? Firstly, it seeks a quantitative estimate of how much energy is conserved by a solar heating system. Secondly, an energy analysis is necessary because the prices paid per joule of energy vary by a factor of nearly ten in Canada,[4] thus negating one of the essential assumptions in the above argument. It is also possible that solar heating systems could be adopted for non-economic reasons such as defense security or energy self-reliance. An energy analysis would provide an important input to such a decision. Finally, an energy analysis provides information on the temporal aspects of energy-resource use by various resource systems.

3. PREVIEW OF RESULTS

There are a wide variety of approximations made in this study. In order to make it clear in advance which of these makes a significant difference to the final result, Table 1 summarizes the results for a "typical" solar heating system serving a single family dwelling in Toronto (defined in Appendix B). Determining the energy resources needed for the collectors and operations are clearly the most important parts of this study.

Table 1. Summary of energy costs for a 50% solar system providing 59 GJ/yr to a house in Toronto. Note it takes 122 GJ/yr to supply the same energy with oil or gas.

Component	Total Embodied Energy GJ	Annualized Energy Cost (over 20 yrs) GJ/year
Collectors		
Hardware	144-324	7.2-16.2
Installation	14	0.7
Fixed Costs	31	1.5
Storage	15	0.8
Total initial energy costs	204-384	10-19
Maintenance		2.3
Operating		11[a]
Total annual energy cost		24-33

a) This value includes electricity as if it were thermally generated.

4. ENERGY ANALYSIS OF A SOLAR HEATING SYSTEM

4.1 *Collectors*

Appendix A presents estimates of the energy embodied in the *materials* of seven different solar collectors. There is a wide variation of embodied energies ranging from 1.8 to 5.6 GJ/m^2 with an average of 3.7 GJ/m^2. The steel-based collectors are on average 45% less energy intensive than the other collectors.

The energy embodied in the collector materials is not the energy embodied in the collector when it arrives at the house site. There are many other direct and indirect energy inputs involved in getting the collector there. These further inputs are difficult to estimate for a non-existent industry and it is at this point that many energy analysts adopt different methodologies.

Some have argued that assembly involves very little energy. However a mature industry is assumed here and hence all the standard industrial overheads exist (e.g. assembly line energy use, factory heating, transportation, energy for advertizing firms, banks and insurance agents, wholesale and retail energy consumption, etc.). Three different approaches have been used to estimate the energy embodied in the delivered collectors. None of these methods is very convincing on its own, but in conjunction with each other they lead to a fair degree of confidence in the resulting range of values, especially in view of the variation observed in the material requirements of the collectors themselves.

4.1.1 *The typical product assumption.* This method makes the assumption that a mature solar panel industry will be much like many other manufacturing industries in its overall use of energy. Studies have shown that for two widely varying products (wooden casement windows[5] and cars[6]) the energy embodied in the materials amounts to about one-half the energy in the final delivered products. If it is assumed that this ratio also applies for solar panel manufacturing, then based on the results in Appendix A, there are on average 7.4 GJ/m^2 of energy resources embodied in solar collectors delivered to the house site with a range of 3.6–11.2 GJ/m^2.

4.1.2 *A hybrid process-I/O analysis.* As discussed in Appendix B, it is assumed that the price of solar collectors is \$86/m^2 or \$140/m^2 and that 40% of this price is wholesale and retail margins. For the collectors specified in Appendix A the cost of materials is at least \$14/m^2. This means that the value added by the solar panel manufacturers is at most \$38 or \$70, depending on which selling price is assumed.

From a study of the Canadian 1974 census of manufacturers, the IBI Group produced a table of direct energy use per 1974\$ of value added for various industries.[6] For light manufacturing industries they found a range of values which, after correcting for inflation, was 9–16 MJ per 1976\$ of value added. Thus 342–1120 MJ/m^2 of direct energy is used to manufacture solar collectors.

In addition to this energy, there is the energy associated with wholesaling and retailing the collectors. At 40% of the price, this amounts to \$34 or \$56/m^2. According to Statistics Canada's input–output (I/O) energy model,[4] the wholesaling and retailing sectors added 31 MJ/1976\$†. Wholesaling and retailing therefore adds 1.1 or 1.7 GJ/m^2 to the energy embodied in the collectors.

In the "typical" case, transportation costs of \$11/m^2 have been assumed. Truck transport energy intensity coefficients from the Statistics Canada I/O model imply that this corresponds to 0.7 GJ/m^2 of energy embodied in the collectors due to their transportation to the job site. On the other hand, the IBI study of transport energy costs[6] has estimated that 3250 J/kg-km are used for truck transport. In the present case, 1 m^2 of collector weighs about 36 kg; we assume a 320 km delivery distance. Then the energy embodied in delivering the collectors is only 0.04 JG/m^2. This discrepancy in estimates is not understood but the higher value will be used.

Adding up these contributions, the total embodied energy is: $3.7+(0.34$ or $1.1)+(1.1$ or $1.7)+0.7=5.8$ or 7.2 GJ/m^2 (depending on costs) for the average collector delivered to the job site. These numbers do not include any estimate of indirect energy use for industrial overheads, which were about 10% in the casement window example given in Ref. 5. Adding this extra 10% gives a final range of 6.4 or 7.9 GJ/m^2 for the energy embodied in the average collector delivered to the site. Taking into account the range of materials in the collectors, the total range of values is 4.3–10.0 GJ/m^2.

4.1.3 *Pure I/O analysis.* A third approach to finding the energy embodied in the collectors is to define collectors as one of the industrial commodities covered by the Statistics Canada I/O model. This will not be too inaccurate because the energy-intensity coefficients do not vary

†The I/O model deals with 1971\$ and cost estimates are given in 1976\$. Throughout this study, costs have been converted to 1971\$ using the Statistics Canada Industry Selling Price Index (a factor of 1.62 from 1976 to 1971).

drastically for many industries producing metal based products. Using a value of 57 MJ/76$ and the 1976 price estimates of $86 or $140/m^2$ implies an embodied energy of 4.9 or 8.0 GJ/m^2 for the collectors.

4.1.4 *Summary of collector estimates.* Considering materials alone, a sample of 7 collectors showed a factor of 3 variation in energy intensity. The methodology also leaves something to be desired but, in view of the real variations in industrial technique involved, a more refined analysis would be overkill. The uncertainty in price also leads to substantial variation in the final estimated energy intensities.

Table 2 summarizes the results of the previous three sections. From these results, it appears safe to say only that most current flat-plate collectors require somewhere between 4 and 9 GJ/m^2 of energy resources for their manufacture and delivery to the job site.

Table 2. Summary of energy embodied in liquid-based flat-plate solar collectors.

Method of Estimate	Embodied Energy in GJ/m^2 Price $140/$m^2$	$86/$m^2$
Typical Industry	3.6 to 11.2 ave 7.4	3.6 to 11.2 ave 7.4
Hybrid	5.8 to 10.0 ave 7.9	4.3 to 8.5 ave 6.4
Pure I/O	8.0	4.9

4.2 *Storage*

Table 1 shows that the storage tank embodies 5% or less of the energy resources of the total system. However, in other studies it has represented from 10 to 50%. Several comments are worth making. The first is that in Canada a properly sized short-term storage tank has about 0.09 m^3 of storage for every m^2 of collectors[7] (the ratio is 0.075 in the US[8]). The second comment is that this storage should be insulated to R30 against the inside of the house or R50 against an exterior heat sink (these values are needed to satisfy the criteria used in most simulation and system sizing algorithms[11]).

The differences between our results and others arise because previous studies have used overly large storage systems and/or grossly overdesigned storage. Several estimates have been made for various systems, all sized to give 3.2 m^2 of storage insulated to R30. A prefabricated concrete tank would require about 10 GJ of energy resources; a concrete tank built at the time of construction would require 10–15 GJ; and steel storage (in fuel oil containers) would require 14–32 GJ of energy resources.

A value of 15 GJ has been adopted as the energy resources embodied in the storage system since this is the maximum estimate for a concrete based system and a reasonable estimate for a well designed steel-based system.

4.3 *Other energy costs*

The estimate of Hollands and Orgill of $43/$m^2$ for the installation of the solar collectors appears to be a conservative estimate of the installation costs.[12] Estimating the energy involved in installation is somewhat tricky since I/O model coefficients for construction sectors include the energy embodied in the materials used and the costs needed for use with the energy intensity coefficients refer to the total job cost (including materials). In this case, the energy embodied in the main components has been analysed separately and the costs for solar collectors are not typical of other construction industry building materials. However, the CAC estimate[5] of 10% of construction energy being direct energy use implies 3 MJ/1976$ of total construction costs. This gives a conservative estimate of 0.4 GJ/m^2 for the energy embodied in the collector-installation process.

The fixed costs for plumbing, circulating pumps, heat exchangers, etc. were estimated by

Hollands and Orgill to be \$750. No single commodity in the Statistics Canada model applies directly but, taking into account the relevant commodities, a value of 41 MJ/\$ has been used as a conservative estimate. This value implies that the fixed costs embody an energy resource requirement of 31 GJ.

Hollands and Orgill have estimated the annual maintenance costs to be \$75. This is in reasonable agreement with the experience reported by the CSU solar house over a 20 year period, for which the annual maintenance costs were found to be about 1% of capital costs.[13] In general, this figure will be too low for systems representing a new technology, but it is not an unreasonable estimate for collectors built by the "mature" collector industry assumed here. Once again there is considerable ambiguity as to which I/O commodity to associate with this maintenance and a conservative figure of 2.3 GJ/yr has been adopted (Statistics Canada commodity 587).

4.4 *Operating energy*

Most solar systems require electrical energy to operate a pump which circulates the fluid through the collectors and back to storage and usually another pump circulates the stored hot water to a heat exchanger if there is forced air heating.

The question of how to treat this operating energy is difficult. To the extent that the pumps heat the water, the energy is put to use meeting the heating load. To the extent that they heat the air, they reduce the heating load of the house. However, even if all of the energy used by the pumps helps to meet the heating load, the indirect energy used outside the house to supply the electricity must be taken into account.

Furthermore, it is difficult to estimate the actual amount of energy used by the pumps because it depends on the construction of the collector and the amount of pressure needed to maintain the proper flow rate. The typical system today uses a 1/4 hp pump to circulate the water through the collectors and another to send water to the heat exchanger (both are likely much larger than needed). Making the very conservative estimate that both pumps use a full 1/4 hp and using simulation results for how long the pumps run each year, one finds that 3.1 GJ/yr of electricity (= 11 GJ of energy resources) are needed. In this analysis, 3.1 GJ/yr is added to the system output and the annual operating energy requirement is taken as 11 GJ. This is a singificant factor although much of it comes from treating electricity as thermally generated.

Other energy analyses of solar energy have produced widely varying estimates of the operating energies.[1,14,15] However, the variation in these values is quite reasonable if considered on a per meter squared of collector basis; an exception is Ref. 15, where a considerably lower value is given.

5. ENERGY RESOURCE REQUIREMENTS OF TRADITIONAL HEATING SYSTEMS

This study is concerned with the use of solar heating in a fuel-saver mode which provides 50% of the house heat. This means a traditional home-heating system must be in place to handle the other 50% of the heating load. Since the furnace and ductwork would be necessary whether or not the solar system were employed, the energy embodied in these components does not enter into the analysis (it is interesting to note that the 15 GJ embodied in a furnace[5] amount to less than 1% of the energy consumed by the furnace over a 20 year period).

To do a comparison with the solar case, the total energy-resource requirements of oil, gas and electrical sources of energy must be known (see columns 1 and 2 of Table 3). Solar heating in the "typical" system supplied 48 GJ of space heat and 7.7 GJ of hot water heating plus an extra 3.1 GJ due to pump energy. If the hot water had been heated by electricity, then the 7.7 GJ of heating would have required 28 GJ of energy resources. The space heat could have been delivered by oil, gas or electric systems and Table 3 summarizes the energy-resource requirements of these systems.

6. COMPARISON OF ENERGY REQUIREMENTS OF TRADITIONAL VS SOLAR SYSTEMS

In Section 4, it was shown that the "typical" solar heating system has between 204 and 384 GJ of energy resources tied up in its capital equipment and it requires about 13 GJ of energy

Table 3. Energy-resource requirements of traditional systems to supply 51 GJ of space heating and 7.7 GJ of hot water heating per year.

System	Total Resources to deliver 100 MJ to end use[a)]	End Use Efficiency	Space Heating GJ	Water Heating GJ[b)]	Total GJ
Gas	112	61%[d)]	94	28	122
Oil	112	61%	94	28	122
Electric	368[c)]	100%	188	28	216

a) Taken from appendix E of ref. 10.

b) Assumed to be electric heating.

c) Assumes thermal generation with 32% efficiency, distribution losses of 9% and self-use losses of 8%.

d) Overall efficiency compared to a static furnace efficiency of 70 to 80% (ref. 5).

resources per year to operate and maintain. On an annualized basis, this system uses 24–33 GJ of energy resources (assuming a 20 year lifetime) to supply 59 GJ of the house heating load.

The relative efficiency of the traditional vs solar options can now be discussed and the solar system payback time can be defined. In keeping with the energy analysis (as opposed to net energy analysis) approach of comparing the energy-resource requirements of alternative systems serving the same end use, payback time is defined as the length of time the solar heating system must operate before it has produced more heat than the conventional systems would have produced using the energy resources embodied in the solar system capital and operating requirements; i.e. the payback time T is defined as

$$T = \frac{K_s}{F_c - O_s},$$

where K_s is the energy embodied in the solar systems equipment; F_c is the annual energy resource requirement of the conventional system to provide the same heat as generated by the solar system; and O_s the annual energy resource requirement for operating and maintaining the solar system.

This definition is dependent on which conventional solar system is adopted as the reference system but not on the choice of backup; it is somewhat different from the various definitions of payback time is which only consider the actual heat output of the system (see e.g. Table 6).

For the "typical" system studied here, the payback times are summarized in Table 4 which shows that, even in the worst case, solar heating saves energy resources after a payback period which is short compared to the expected lifetime of the system.

However, the payback time only tells part of the story. To discuss the relative overall efficiency of a solar vs a conventional system, one must add up the total energy use of each system over the assumed lifetime as is done in Table 5. A solar heating system sized to provide 50% of the heat to a house will save 38–42% of the energy resources needed to heat the house when a conventional oil or gas system is used. Similarly, a solar/electric system will save 45–47% of the energy resources needed for an all-electric system. In short, the results of this study show that the energy resource savings associated with the "typical" solar heating system are reduced from 50% to between 38% and 47% if indirect energy consumption is considered, i.e., the energy savings are reduced by 6–24%.

The results of Table 5 also show that if thermally generated electric heating is used as the back-up in a solar heating system which is replacing what would have been an oil- or gas-heating system, then overall energy resource use is only reduced from 4700 GJ to between 4300 and 4500 GJ, i.e. by 4–9% rather than the 50% expected.

Table 4. Payback times for the "typical" solar system heating a moderately insulated, single family dwelling in Toronto.

Reference System	Payback Time (years) K_S = 204 GJ	K_S = 384 GJ
Gas/Oil	1.9	3.5
Electricity (resistance)	1.0	1.9

Table 5. Total energy resource use by 50% solar and conventional home heating systems over a 20-year period.

System	Energy Resource Use in GJ K_S = 204 GJ	K_S = 384 GJ
Solar/oil or gas	2700	2900
Solar/electric	4300[a]	4500[a]
100% oil/gas	4700	
100% electric	8200[a]	

[a] Value assumes thermal generation of electricity.

7. DISCUSSION OF PREVIOUS RESULTS

There are several previous studies which address the question of the energy embodied in solar heating systems.[1,2,14–17] It is very hard to compare their specific results to ours on account of the variety of systems analysed. However, it is instructive to review their results to see if the apparently large discrepancies can be reconciled.

The systems are summarized in Table 6. Several general comments are in order. There is clearly a large variation in the actual materials used in the collectors. Many of the other studies did not estimate the assembly and overheads involved in collector construction. Those that did estimate these energy costs got considerably smaller estimates than are obtained here. In view of the similarity of the results for the three methods used in Section 4 to estimate this factor, it seems likely that our lower estimates are at least lower bounds on this component of the energy resources required.

It is instructive to observe the variety of definitions of "payback time" used in the previous studies. This variety is the primary cause of the large discrepancies in reported results, as may be seen by the reduced variation obtained when a common definition (ours) is applied to all of the results. However, the "agreement" is almost completely fortuitous in at least three cases, as can be seen from the significant differences in individual components in the analysis. In three studies,[1,14,16] there are some distinct differences, but the overall results are in broad agreement with those presented here, expecially considering the variation in the systems being studied. In the following paragraphs, we examine briefly the main features of each of these previous studies.

Ashton and Robinson[17] analysed a particular system which appears to have a very low energy output and an oversized, energy-intensive storage tank. This was compensated for by ignoring all energy costs in the collector, except for the materials and by the fact that the particular collector studied was very light (20 kg/m^2) and used a relatively small amount of energy per unit area. Operating energies and fixed costs were not accounted for.

The overall method used by Baron[1] is similar to ours although his approach and hence his conclusions are much more negative. His specific results show solar energy in a worse light than our results because he has analysed a particularly energy-intensive collector (collector B-3, Appendix A). Using our materials energy intensity coefficients, Baron's collectors are 66% more energy-intensive than the average of the other 6 collectors studied here and using his

Table 6. Comparison of present results with those of previous studies.

	Present	Lenchek ref.15	Payne&Doyle ref.2	Ashton & Robinson ref.15	Baron ref.1	Sherwood ref.14	W&F-DSI ref.16
Collector area m^2	36	71	46	117	48	24	46$^{q)}$
Location	Toronto	Colorado	Wash DC	Shediac NB	Wash DC	Santa Fe	Wash DC
Collector Energy Materials GJ/m^2	3.7 (2-4.5)	3.6	5.3 (4.0-6.4)$^{d)}$	1.4	7.1$^{g)}$	5.3$^{k)}$	4.5$^{p)}$
Assembly,margins GJ/m^2	3.1 (1.4-3.9)	0	1.4$^{c)}$	0		0	0
Installation,GJ/m^2	0.4	0	1.6$^{c)}$	0	1.7$^{f)}$	0	0
Transport GJ/m^2	0.6	1.5%	0.2	0		0	0
TOTAL FOR COLLECTORS GJ	144-324	256	391	167	422	129	205
Energy in labour?	no	no	yes 0.46 GJ/hr	no	no	no	no
Industrial Overhead?	yes	no	no	no	no$^{f)}$	no	no
Storage material	concrete	steel	fiberglass	steel	steel	plastic	concrete
volume m^3	3.2	4.7	11.4	18	2.5	1.9	7.6
energy embodied GJ	15	83	73	123		51	25
Fixed Costs (plumbing etc) GJ	31	313 $^{a)}$	1.4	2.1 $^{e)}$	97	69 $^{m)}$	49 $^{r)}$
K, TOTAL CAPITAL ENERGY COSTS, GJ	204-384	664	465	293	519	249	279
Maintenance GJ/yr	2.3	0	11.5 $^{c)}$	0	0	0	1.9
O, Operating GJ/yr	11	0.7	0	0	16	7.5	11
Conventional efficiency considered?	yes	no	no	no	yes	yes	yes
Q_s, Annual Heat Output GJ	58	94	55	77	73	45	66
Payback Def'n Used	$\frac{K}{F-O}$	$\frac{K}{Q}$	$\frac{K}{Q-O}$	$\frac{K}{Q}$	$\frac{K+20*O^{h)}}{F}$	(n)	(n)
Payback:their def'n	-	7	10.6	4	7	-	-
Payback:present def'n $^{b)}$	1.9-3.5	3.8	5.2	2.1	4.4	3.3	2.6

a) There was an error in Lenchek's pipe coefficient ; its value should be no more than 78 GJ and likely only 17 GJ.
b) An overall efficiency of 1.84 is assumed for the conventional system (see Section 5).
c) Based on labour content estimates.
d) B-1, B-4, B-5 in appendix A.
e) Most components were ignored.
f) Possibly some assembly is included via the materials coefficients.
g) 5.6 GJ/m^2 using our energy intensity coefficients, see f.
h) This differs from our payback definition by 39%.
k) Assembly was assumed zero, some margins were included.
m) Estimated cost was $725(1978).
n) These studies only compared systems, no payback was defined.
p) This includes some margins.
q) System sized for air conditioning also.
r) Costs were $1375 but this possibly included some of the air conditioning costs.

energy-intensity coefficients they are 110% more energy intensive. Baron also presents his results in a manner which gives the impression that energy characteristics of the solar option are worse than they really are. In particular, his unusual definition of solar payback time gives an unduly pessimistic view. It is over 50% greater than the value obtained using his figures and our definition (or 160% greater using another definition given in his paper). In short, Baron views the question of solar energy efficiency in far too pessimistic a light because he has analysed a particular system which uses an unusually large amount of energy and because he presents his results with a definition of payback time which is somewhat misleading.

Lenchek[15] first evaluates the total energy-resource use of a particular solar heating and cooling system and then proposes design changes which use less energy-intensive materials.

Starting from a collector which has a materials energy intensity near the average of our other 6 collectors (collector B-6, Appendix A), Lenchek's design changes reduced the collector energy use by a factor of three. This result clearly demonstrates the scope for improvement which is possible. However, Lenchek's study suffers from several faults: it does not account for assembly, margins, industrial overheads or maintenance energy; piping accounts for nearly 50% of the systems energy costs but there is a large error in the energy-intensity coefficient used for cast iron pipe (Ref. 5 gives a value which is 25% of the value used by Lenchek; Sherwood[14] gives a value for copper pipe which is 5% of Lenchek's value); his steel storage tank is over three times heavier than need be; and his payback time does not consider the conventional fuel savings, only the system output.

Payne and Doyle's study[2] also begins by showing how much energy is needed to put together a solar heating system and then presents a series of suggestions for drastically reducing this requirement. The major difference between our studies is that Payne and Doyle have explicitly considered the energy content of the labour involved in constructing the solar heating system. Payne and Doyle did not take into account assembly, margins or installation energy costs except via this labour input which more than compensates for the omission. Their calculated payback time also ignores the inefficiencies of conventional fuel use, thus overestimating payback time by a factor of two. The important aspect of their paper, as with Lenchek's, was the degree of energy conservation shown to be possible in constructing the solar system.

Sherwood[14] has compared the energy resource use of 6 New Mexico home-heating systems ranging from electric heating to passive and active solar. While there are some variations in approach (he did not consider assembly, installation or maintenance costs), our results are in good agreement, given the differences in the systems being analysed. The important result of Sherwood's study was that passive solar heating was nearly twice as energy efficient as active solar heating for a 90% solar heating system.

The Development Sciences Inc. study reported by Wilcocks and Frabetti[16] is part of a major energy-analysis undertaking which compares the energy resource use of many different energy-supply options. Our results are broadly similar although their study ignored assembly, installation and industrial overhead costs and they used an overly large storage tank. A more detailed comparison is somewhat difficult because they have analysed a combined heating and cooling system.

8. CONCLUSIONS

The primary purpose of this study was to find out whether or not the indirect use of energy resources in building a solar space-heating system was so large as to make solar heating a futile exercies in terms of energy conservation. The conclusions are as follows:

(1) The indirect use of energy resources does not have a major impact on the overall energy conservation characteristics of the solar heating system studied here (which, in many respects, is a worst case).

(2) It takes as little as one year and no more than 3.5 years of operation for a solar system to save more fuel resources than were used in building the system. This represents less than 20% of the assumed 20-year lifetime of the system.

(3) A solar heating system sized to provide 50% of the heating requirement to a house uses between 53 and 62% as many energy resources over twenty years as a conventional system heating the same house (rather than the 50% expected if indirect energy resource use was ignored).

(4) The energy resource-conservation qualities of solar energy could be completely negated by the use of *thermally* generated electricity as backup in a 50% solar heating system which replaces an oil or gas heating system.

(5) The operating energy required by a solar heating system to run its pumps is clearly an important energy input. It would seem worthwhile to incorporate the effects of these pumps (heating the water and the surrounding air) into various simulation codes since they obviously can play a significant role. It would also be worthwhile to design solar systems to minimize the energy used by pumps since the pumps used are often much larger than necessary.

(6) In comparing our results with other studies, it became clear that all energy-analysis pa-

pers must be very carefully evaluated before using the results. This conclusion follows because there are different methodologies which give substantially different results (e.g. including the energy costs of labour), and because the methods presenting results can be very misleading (e.g. the various definitions of payback times lead to vastly different impressions about the viability of solar energy as an energy-conserving option). It also became clear that a range of collector designs must be considered in view of the great variety of designs currently in use.

The present results and all previous studies have dealt with liquid-based systems with short-term storage since this is currently the most economically attractive option. Air-based systems or annual storage systems could produce substantially different results. Air-based collectors can be substantially less efficient per unit area than the liquid-based collectors studied here (the air-based collector of Hollands and Orgill would require 30% more area for the same output) and the operating energy required to drive fans is considerably greater. Until the costs and design of annual storage systems are more clearly defined, it is hard to make an estimate of the indirect energy effects in these systems.

The underlying theme of this study has been that "renewable energy resources" require energy inputs. Even if society eventually switches entirely to annual storage solar heating systems, it is clear that will always be a significant amount of energy resources required to manufacture the systems. This result implies that the need for conservation of these resources is critical to our long term needs.

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REFERENCES

1. S. Baron, *Public Utilities Fortnightly* **102**(7), 31 (1978).
2. P. R. Payne and D. W. Doyle, "The Fossil Fuel Cost of Solar Heating". Paper presented at *13th Annual Intersociety Energy Conversion Engineering Conf.* San Diego, California (Aug. 1978).
3. G.Winstanley, "Energy Analysis, Methods, Uses and Implications", Office of Energy Conservation, EMR Canada, *Research Series*, No. 11, Ottawa (Feb. 1976).
4. J. M. Deachman and K. E. Hamilton, "Energy Availability, Detailed Disposition and Industrial Demand Coefficients for Canada, 1971", *Working Paper* 78–08–01, Structural Analysis Division, Statistics Canada, Ottawa (Aug. 1978); K. E. Hamilton, private communication; "User's Guide to Statistic Canada Structural Economic Models", *Statistics Canada Rep.* Ottawa (Feb. 1976); B. C. McInnis and K. E. Hamilton, "Gross Energy Requirements for the Production of Goods, an I/O Baseline", *Working Paper* 75-06-01, Structural Analysis Division, Statistics Canada, Ottawa (June 1975).
5. B. M. Hannon, R. G. Stein, B. Z. Segal, P. F. Diebert, M. Buckley, and D. Nathan, "Energy Use for Building Construction", Vol. 1 and 2, University of Illinois Center for Advanced Computation Documents 228 and 228A (NTIS COO-2791-3), Urbana, Illinois (Feb. and Oct. 1977).
6. "Indirect Energy in Transportation", a report prepared by the IBI group for Transport Canada, Ottawa (March 1978).
7. K. G. T. Hollands and J. F. Orgill, "Potential for Solar Heating in Canada", *University of Waterloo Rep.* 77–01 (Feb. 1977); and addendum, report 77-02 Waterloo, Ontario (Aug. 1977).
8. W. A. Beckman, A. K. Klein and J. A. Duffie, *Solar Heating Design by the f-CHART Method.* Wiley, New York (1977).
9. S. A. Klein, W. A. Beckman and J. A. Duffie, *Solar Energy* **18**, 113 (1976).
10. D. W. O. Rogers, "Energy Resource Requirements of a Solar Heating System", *NRC Energy Project Rep. EPO*-79-1, Ottawa (Feb. 1979).
11. Wm. Carscallen, NRC Division of Building Research, Private communication (1978).
12. M. K. Berkowitz, "Implementing Solar Energy Technology in Canada, The Costs, Benefits and Role of Government", *EMR Canada, Rep. EI*77-7, Ottawa (1977).
13. J. C. Ward, G. O. G. Lof and L. N. Hadley, "Maintenance Costs of Solar Air Heating Systems", *NTIS Rep. No. COO*/2830-1 (May 1977).
14. L. Sherwood, "Total Energy Use of Home Heating Systems". In *Proc. of IGT Symp. on Energy Modeling and Net Energy Analysis*, Colorado Springs; IGT Chicago, 1978.
15. T. E. Lenchek, *Alternative Sources of Energy* **21**, p. 13 (June 1976).
16. D. K. Wilcock and A. J. Frabetti, *Solar Age*, p. 32 (Jan. 1978).
17. Wm. Ashton and J. E. Robinson, "Energy Analysis of an Aluminium Solar Collector", contribution 1-1-4 to *SESCI Conf.* London Ontario (1978).

APPENDIX A

Energy resource requirements for solar collector materials

To determine the energy resource requirements of the materials in solar collectors requires knowledge of (a) the materials needed for solar collectors and (b) the energy intensities of these materials. Table A presents data on 7 flat-plate collectors. The materials breakdowns for collectors B-1 and B-2 were obtained from manufacturer's brochures and the other five from reports. The material's energy-intensity coefficients have been adopted as "reasonable" values after considering values from many studies (the range of values found is also shown in Table A and a complete set of references is given in Ref. 10). These values represent energy requirements to produce the products starting from raw materials. There

Table A. Energy resource requirements of materials in a selection of water-based, flat-plate solar collectors.

Material	MJ/kg Used[a)]	MJ/kg Range Found	MJ/m² B-1	B-2	B-3	B-4	B-5	B-6	B-7
Copper plate	90	49-140	207	-	-	-	-	-	-
Copper tube	145	145-170	406	-	348	1560	559	-	276
Glass	30	20-110	510	540	-	510	492	510	267[h)]
Aluminium	250	130-300[b)]	3000	153	4100	-	3325	2750	252
Steel plate	50	28-58	-	1450	-	1500	-	-	975
Insulation	15[c)]	15-79	78	78	-	78	78	132	23
Other			-	-	1150[e)]	-	-	33[g)]	40
Total GJ/m²									
present work			4.2	2.2	5.6	3.6	4.4	3.5	1.8
other work			4.1[d)]	-	7.1[f)]	3.3[d)]	4.9[d)]	3.6[j)]	-
Weight kg/m²			36	49	24	62	37	29	25

a) Adopted value from range found
b) 11 MJ/kg for pure scrap
c) R11 is 78 MJ/m²
d) Ref (2)
e) Acrylic cover plus 5% misc.
f) Ref (1), includes some assembly
g) Paint
h) Single glazed
j) Ref (15)

is obviously considerable uncertainty in these values but the effects of the variation in collector materials outweighs the effects of the uncertainty in the coefficients. This can be seen from the good agreement obtained in the comparisons with the previous author's values for the total energy resources embodied in the materials despite the use of various coefficients for the individual materials.

APPENDIX B

A typical solar heating system

It is impossible to define a "typical" solar heating system because of the rapidly changing technology, the variety of possible purposes and the effects of geography, time and economics on the design. One cannot meaningfully talk of the energy delivered by a collector unless all these factors are considered and the entire system design is specified. A "typical" system shall nonetheless be defined. It is one of those specified and analysed by Hollands and Orgill[7] in a study which used the simulation code WATSUN to optimize the various system parameters for a series of solar heating configurations for use in Canada. We analyse their system to provide 50% of the space and hot water heating for a moderate to poorly insulated single family dwelling in Toronto (150 m² floor area; heat loss 297 W/°K; kept at 21°C; internal gains 1.2 kW continuous for 16 hr per day; total space heating load 98 GJ/yr; hot water demand of 0.73 kW for 16 hr per day = 15.5 GJ/yr). Auxiliary space heat is supplied by oil, gas or electricity and the hot water heating is augmented by electrical resistance heaters. To provide this much solar energy with liquid-based flat-plate collectors requires 36 m² of solar collector and 3.2 m³ (i.e. two days worth) of water storage.

The collectors are traditional, liquid-based, flat-plate collectors with double glazing and an efficiency that is typical of that obtained by well engineered collectors on the market today. The system lifetime is taken as 20 years. No account is taken of possible collector-efficiency deterioration over time nor of variations in the efficiency of the particular collectors studied. In addition to specifying the system, it is assumed that the entire system is produced by a standard manufacturing operation and installed by regular construction contractors.

*B.*1 *Sensivity to assumptions.* To check the validity of this system design, it has been compared with the results from the widely used program *f*-CHART[8,9]. This code predicts a solar fraction of 43% which delivers 49 GJ to load rather than the 56 GJ predicted by WATSUN. This result may be considered to show good agreement considering the variations in the weather data used.

Table B. Cost estimates of Hollands and Orgill (1976$) for the "typical" solar system.

Component	$/m²	$/sq.ft.	Total cost for system defined in text
Collectors			
Hardware	140	13	5040
installation	43	4	1550
transport	11	1	400
Fixed Costs (pipes, heat exchangers, etc)			750
Storage	$110/m³	$0.50/gal	350
		Total Capital Costs	$8090
Annual Maintenance			$ 75

Using f-CHART, it is also possible to estimate the solar output of this "typical" system if sited at other locations. Values range from 40 to 76 GJ for 8 major cities in North America. Thus, although this system may be far from optimal for these other locations, the fact that it produces nearly as much or more output eleswhere means that the output per unit materials input obtained in Toronto is, if anything, rather low because of cloudy conditions.

It is also worth noting that the results are not overly sensitive to the level of house insulation. If the house were well insulated (building loss coefficient of 112 W/K), then the total heat load would be much less (52 GJ instead of 113 GJ[7]). However, the collector area required to provide 50% of the heat in this well insulated house decreases even more rapidly than the output produced. This result follows primarily because the hot water supply is a much larger fraction of the load in the well insulated house (30% vs 14%) and hence more effective use is made of the collectors in the summer.

Thus, the "typical" solar heating system does not appear to have any unusual characteristics which would overly restrict the qualitative conclusions of the study.

B.2 Typical costs. In order to apply several of the methods of energy analysis, cost estimates for the solar heating system are needed. Hollands and Orgill gave the cost estimates shown in Table B for the various components in their system[7]. Significant cost savings are thought to be possible for the collectors and hence a cost of \$86/m^2 (\$8/sq.ft) is used in the study to demonstrate the sensitivity of the results to the assumed collector costs.