Thermal Performance of Transparent Insulation in Exterior Envelopes of Buildings

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ABSTRACT

Task X of the IEA Solar Heating and Cooling Program was initiated to carry out cooperative activities that support the research and development of new and existing materials that have the potential to improve the performance and durability of materials used in solar systems. Part of this research addresses the establishment of performance criteria for "transparent insulation materials in buildings," especially for dwellings.

The principal results of the research are, first, a means of material selection for various solar applications and locations and, second, a methodology to estimate the energy benefits resulting from such selections.

A step-by-step guide for material selection was developed using climatic data, system operating and boundary conditions, simulation programs, and relevant material properties. A data base of important material properties for the applications of solar energy was compiled to assist designers and manufacturers in selecting materials. The results respond to the need to design systems that operate more efficiently with respect to energy conversion, material conservation, and environmental quality preservation.

INTRODUCTION

The objective of this IEA task was to investigate and improve the energy performance and durability of materials used in solar buildings and solar heating systems. The following scope was identified for Subtask A, in which researchers from Canada, Denmark, Germany, Italy, the Netherlands, and the United States participated:

- investigate how new materials or assemblies of materials can improve system efficiency and expand the application of solar systems to a wider variety of needs,
- estimate and evaluate the energy benefits of using new materials, and
- determine the necessary and quantitative criteria for the properties of advanced materials that can yield greater system and component performance.

To accomplish those objectives, some participants in Subtask A (1) developed a means of material selection for various locations and solar applications and (2) provided a methodology to estimate the energy benefits of transparent insulation in passive solar dwellings in particular.

The research is illustrated with a case study that was conducted on the energy benefits. The material requirements and energy impacts for transparent insulation in buildings (dwellings) were investigated by researchers through modeling of a reference "shoebox" house for several locations and orientations.

An additional Task 10 report was prepared to document Subtask C (research) of the IEA Task X on characterization of new window glazing.

LOCATIONS AND CLIMATIC FACTORS

The description of selection criteria and performance levels for materials can be simplified by taking into account only a selected number of climatic areas, accurately representing most regions on earth. The recognition of differences and similarities between climatic types has prompted climatologists to identify and classify them according to their particular properties. Because of its relative simplicity and usefulness, Trewartha's classification is used here as a basis for this part of the IEA study (Trewartha 1961). The criteria for classifying climatic types for research on solar energy applications emphasize ambient temperature and solar radiation. These variables have the primary effects on system performance.

Because of the application category considered in this part of the IEA research (solar heating), the temperate continental climate is very important with regard to promising prospects of transparent insulation.

Climatic data were received from 10 locations. Table 1 presents the annual totals of several important variables for these climates. The climatic data were compiled in a consistent tabular format and presented graphically. Also considered are the heating degree-days. Important with respect to the durability of materials are pollution in industrial and urban areas, ultraviolet radiation, high temperature exposure, and precipitation (rain, snow, hail). They are discussed in a general way (Brouwer 1992a).

SOLAR ENERGY APPLICATIONS AND SYSTEMS

The realization of a solar energy system occurs within a context of technical, legal, and institutional requirements that increase in scope from the application (e.g., building)

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TABLE 1
Annual Totals of Climatic Data

Climate locations		Yearly, averaged climate data		
		average temperature °C	total horizontal solar radiation Wh/m2.day	total heating degree-days (below 18-19 °C) K.d
Canada	Toronto	8.9	3617	3646
Canada	Edmonton	2.4	3451	5713
Denmark	Copenhagen	7.6	2782	2918
F. R. Germany	Freiburg	10.4	3033	3123
Italy	Messina	18.4	4753	327
the Netherlands	de Bilt	9.3	2591	3131
Switzerland	Rapperswil	10.1	2625	3848
U. S. A.	Denver	10.1	5316	3343
U. S. A.	Madison	7.3	3749	4294
Spain	Huelva	17.0	4884	1202

for which the system is designed, to the site, to the region and its climate, up to the goals of national energy policy. Regional climatic conditions may exert a strong influence on thermal performance, the choice of components and systems, and even on material selection.

In passive solar systems, the greatest significance is often attached to glazing materials for windows and walls (transparent insulation). Ultimately, thermal performance and economic feasibility determine whether a specific application is justified or not. The annual local climatic conditions (solar radiation), the specific annual heat or cooling demand, and the governmental rules and codes (health, safety, fire resistance) restrict a specific solar energy application and are fundamental criteria that must be satisfied before considering components and materials in a more technical way.

A general scheme for the analysis of passive solar systems in which some of the techniques of passive solar heating are incorporated is presented in Figure 1. However, the research in the report focuses on the glazing materials (especially transparent insulation materials). The application category is space heating for dwellings.

The occurrence of so many types of solar energy applications and solar systems with different solar loads and solar fractions means components and materials have to match in an extensive set of operating conditions.

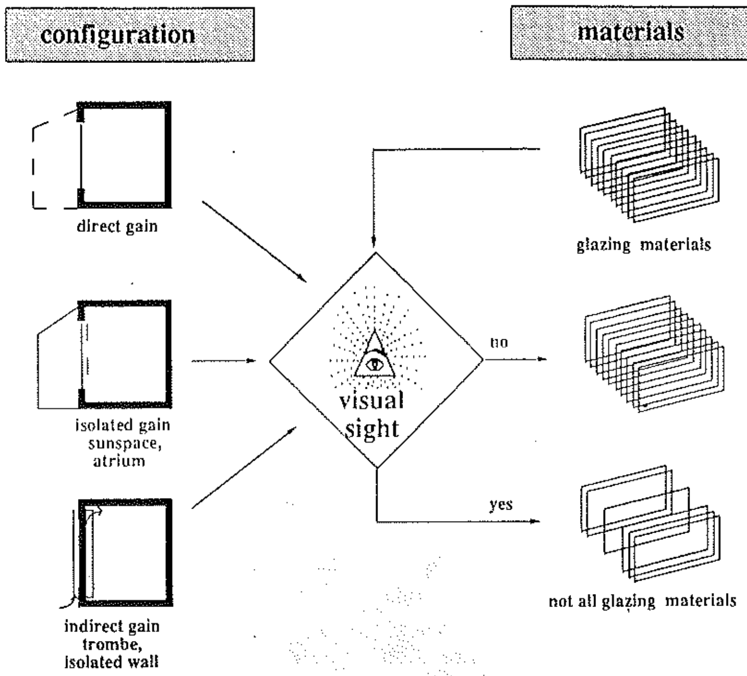
COMPONENT AND SYSTEM MODELING

From a number of frequently used computer programs the simulation program SIMHAUS was selected (Platzer 1990). This program is used for calculation of the thermal performance of transparent insulation materials in buildings and considers building effects.

MATERIALS AND SELECTION

Climatic and operating conditions for different applications affect the materials in a very complex way, restricting the choice of products. The search for more promising and improved materials and the increasing level of performance and quality requirements reinforce the need for accurate knowledge of solar materials. A data base on material properties, containing the most recent data, was prepared. To organize the materials and their specifications, a classification scheme was needed. It is shown in Figure 2. The specification of the materials presented in the working document, "Data Base Solar Materials," deals

a. First selection glazing material



Glazing materials

1. One or more layers glass or polymer
2. Large area chromogenics
3. Transparent, wavelength selective coatings
4. High performance glazings and collector covers gas filled, translucent, angle selective
5. Concentrator collector and light guide materials

b. Second selection glazing material

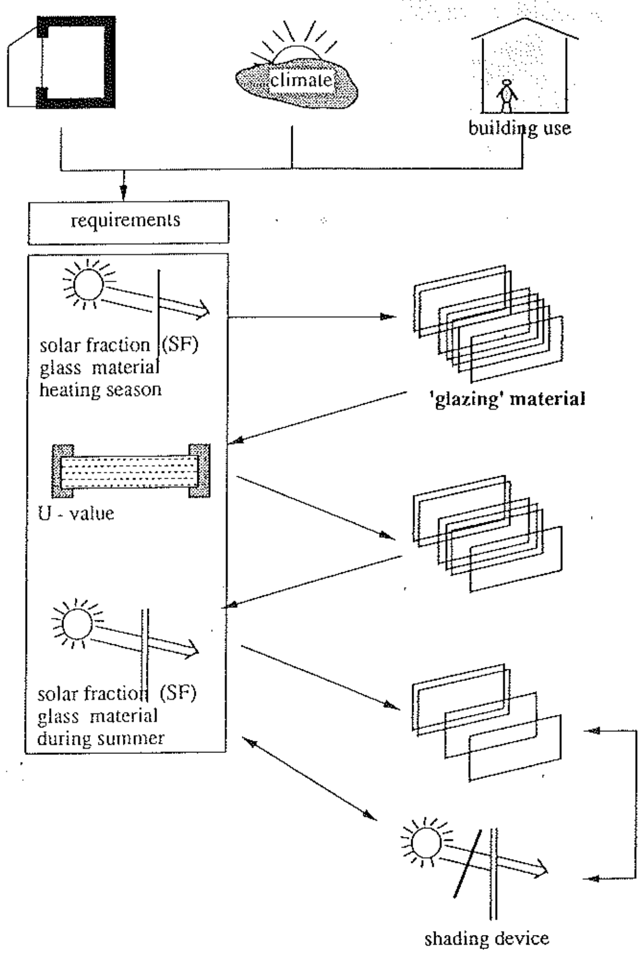


Figure 1 ***Selection of glazing materials.***

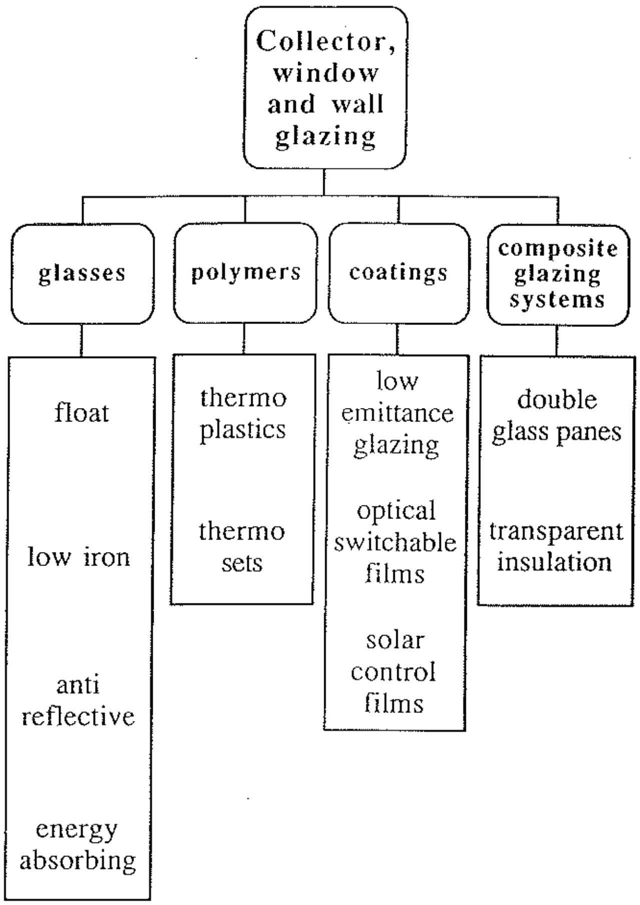


Figure 2 *Classification scheme of materials.*

with the following classes: physical background, optical and thermal properties, mechanical properties, and durability (Brouwer 1992b).

The selection of glazing materials is made primarily on the properties of solar transmittance and heat loss coefficient (U-value). Figure 3 illustrates the relationship between this critical material property pair for transparent insulation. Evacuated aerogel, honeycomb, and capillary constructions are very promising devices because of their high solar transmittance and low heat loss coefficient.

A guide for material selection for various solar applications throughout the world follows this sequence: define climatic data and criteria, select the application and device of interest, select a simulation tool or calculation method for analysis, establish the operating conditions, consult the data base of solar materials, establish the system's energy performance and overheating, and estimate the effects of degradation of materials. The evaluation criteria for material selection are presented in Table 2.

IMPACT OF MATERIAL PROPERTIES ON THERMAL PERFORMANCE

The estimation of the energy benefits of new materials in solar energy applications is restricted here to *transparent insulation materials* for space heating (passive) dwellings using solar radiated masonry walls covered with transparent insulation (controlled air ventilation) in temperate continental climates. Approaches and relationships for differing climates, systems, and applications are presented in the case study.

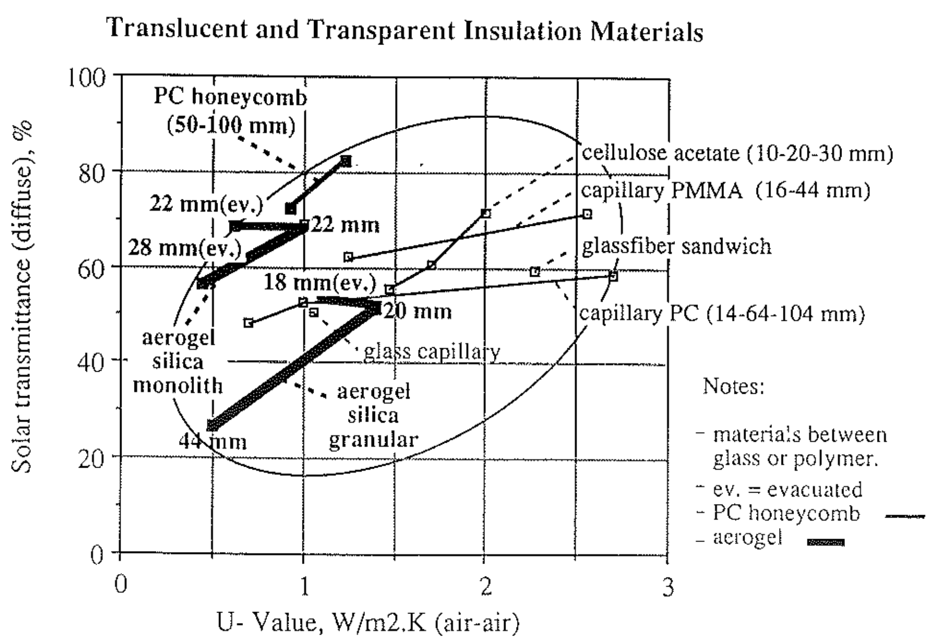


Figure 3 *Pair of thermal properties of transparent insulation.*

TABLE 2
Evaluation Criteria for Material Selection

Evaluation Criteria for Material Selection			RESULT:
NON TECHNICAL CRITERIA:			
	Intended application		
	- local climate	- macroclimate	
		- microclimate	- location (climate)
	- energy demand	- total requirement	- application
		- simultaneous occurrency	- system
		- temporal distribution	- material classification
		- temperature conditions	
		- solar system	
	- governmental rules, standards	- building codes	
		- siting	
TECHNICAL CRITERIA:			
	Operational and extreme conditions		
	- thermal performance	- solar radiation	
		- solar spectral distribution	
		- ambient temperature	
		- service operating temperature of material	
		- service stagnation temperature of material	material:
		- thermal spectral distribution	- thermal conditions
	- degradation (Subtasks B and C)	- solar UV radiation UVB radiation	- durability
		- air impurities, SO_2, NO_2	- failure
		- high temperature exposure	
		- temperature cycling	
		- temperature shock	
		- relative humidity ambient air	
		- time of wetness of material	
		- life time	
	- failure	- structural exposure, hail, wind, snow	
MATERIAL CRITERIA:			
	Material properties		
	- optical and thermal	- transmission	
		- absorption	
		- reflection	
		- temperatures	material:
	- mechanical	- strength	- selection
		- expansion	
	- durability	- degradation	
		- weatherability	
	- environment	- kind of material	
ENERGY CRITERIA:			
	Thermal performance		
		- selected solar systems and locations	material:
		- other system parameters and locations	- performance
	Light performance		
ECONOMIC CRITERIA:			
	Material and device	- material cost	material:
		- device costs	- feasibility
		- others	

The aim of passive solar design is to minimize the amount of auxiliary heating without impairing comfort or convenience. The solar savings is the extent to which the solar design has reduced the auxiliary heat requirement of the solar building relative to a building without this solar device. The IEA study describes the effect of these materials on the energy benefits when used in dwellings. For a rough first estimate of the energy benefits of glazing for heating purposes, without taking into account building effects and overheating, this basic formula can be used:

$$\eta \text{ solar} = g - U_{TIM} \times (T_i - T_{amb})/S$$
$$= (\text{ solar gain factor})$$

where

g = fraction of incident solar radiation (at the average angle of incidence) that is directly transmitted by the glazing and indirectly absorbed within the glazing and conducted into the building,

U_{TIM} = thermal transmittance coefficient of the transparent insulation (W/m2·K),

T_i = average indoor temperature (°C),

T_{amb} = average ambient temperature (°C),

S = average solar radiation (incident) (W/m^2).

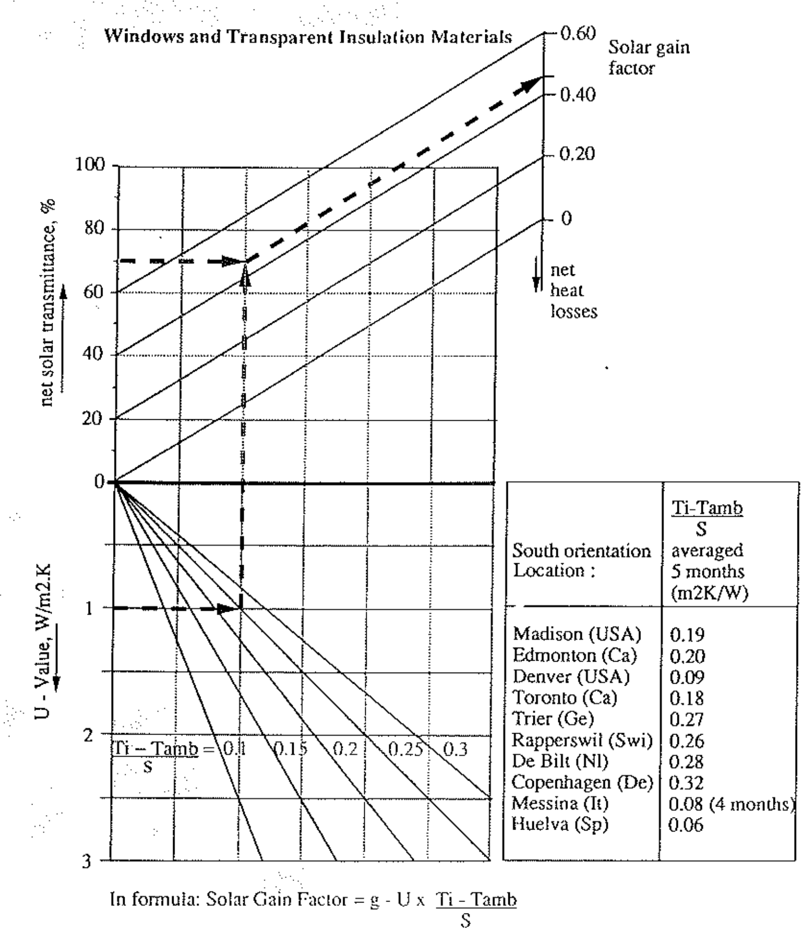
Considering averaged weather data of ambient temperatures (T_{amb}) and solar radiation (S) for the five winter months (from November to March), the solar gain factor can be derived for an arbitrary location, e.g., Rapperswil, Switzerland, with a temperate continental climate $(T_i - T_{amb})/S = 0.26$. Then,

$$\eta \text{ solar} = g - U_{TIM} \times 0.26$$

(see example in Figure 4). A comparison of materials and a description of how the combinations of solar transmittance and U-value of transparent insulation materials act in different locations is also indicated in Figure 4.

Using this rough approach, the energy benefits per square meter of south-oriented solar wall area in dwellings in western European localities amount to 30% to 40% of those for Denver with equivalent design criteria. Energy benefits for solar walls in Madison are about 50% those of Denver.

Consideration of the building effects was implied in a case study (Platzer 1990) using a new simulation code.



South orientation Location :	Ti-Tamb / S averaged 5 months (m2K/W)
Madison (USA)	0.19
Edmonton (Ca)	0.20
Denver (USA)	0.09
Toronto (Ca)	0.18
Trier (Ge)	0.27
Rapperswil (Swi)	0.26
De Bilt (Nl)	0.28
Copenhagen (De)	0.32
Messina (It)	0.08 (4 months)
Huelva (Sp)	0.06

Figure 4 *Solar gain factor of windows and transparent insulation for solar heating as a function of net solar transmittance, U-value, and climate; overheating is not taken into account (only for comparison purposes).*

From the results of a number of situations, a correlation equation was derived relating solar gain utilization to solar load ratio, which gives excellent agreement with calculated monthly gains.

The gain utilization factor ($\Phi_{TIM\text{-}wall}$) amounts to

$$\Phi_{TIM-wall} = 1 - e^{\left(-1.31/(SLR+0.177)\right)}$$

where SLR = solar-load ratio (solar gain through the TIM-wall divided by the remaining heat load).

By combining the correlation equation and the solar gain factor, the energy benefits of using solar walls in dwellings can be easily calculated. It shows that the reduction of heating load due to solar gains is highest for sunny climates with moderate temperatures (Denver), as well as for less sunny but cold climates (Edmonton). The calculation procedure and an example of a calculation are presented in Appendix A.

RESULTS AND RECOMMENDATIONS

Results

- Regarding the methodology for estimating performance enhancement due to transparent insulation materials in dwellings:
  - A correlation equation was developed to express "gain utilization versus solar load ratio" with an excellent correspondence with calculated monthly gains. For the purpose of IEA Task X, this utilization function is satisfactory as a general approach to calculation of the impact of transparent insulation on the heating demand in dwellings (Platzer 1990).
  - A guideline to estimate and to compare the energy benefits of transparent insulation on the south wall of dwellings is presented.
- Regarding material selection and evaluation criteria:
  - A means of material selection for various solar applications throughout the world is provided (Brouwer 1992a).
  - A data base on material properties with the most recent data (including the results of other subtasks of IEA Task X) was developed and presented in a working document (Brouwer 1992b).

Recommendations

- Regarding material properties:
  - Material properties and application requirements should be specified with respect to spectral energy distribution.
  - Research on the application possibilities and the energy benefits of polymers should be continued.
  - Tentative guidelines for applying materials in solar technology with respect to optimum energy conservation and minimum environmental damage are needed.
- Regarding thermal performance:
  - Research and development should concentrate not only on material development but also on reliable methods to assess the performance and the long-term stability of materials.
  - Since the overheating problem is a dominant obstacle to the economical use of transparent insulation, the most important research and development may be on cheap and reliable shading concepts.
- General:
  - Based on the experience in Task X, much more attention should be paid to the usefulness of research results in applications (product manufacturing and project design).

ACKNOWLEDGMENTS

The methodology presented for the estimation of the energy benefits of transparent insulation was developed in cooperation with the Fraunhofer Institute, Germany, and the TNO-Bouw Institute, the Netherlands.

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APPENDIX A

CALCULATION METHOD AND EXAMPLE

The seasonal (five months) performance of transparent insulation materials on a south facade was calculated and presented in Figure 4. The calculation is independent of the optimal dimensioning of the solar area for the building and does not take into account summer overheating. The solar gain factor was derived for different property data (from Figure 3) of the transparent insulation materials and for different locations or climates (from Table 1).

In the graph of Figure 4, the gain factor is the ratio of the net (inward-outward) energy transmitted by the solar area and conducted into the building to the incident solar radiation (at the average angle of incidence). The parameter in the lower quadrant is the ratio of the seasonal average indoor-outdoor temperature difference and the seasonal average incident insolation. This graph can be used as a first approach for selecting south-oriented window and wall glazings for the many climates and materials presented in the single graph. Either seasonal or monthly performance estimates can be performed with this plot. Similar graphs can be derived for other orientations.

CALCULATION OF HEAT DEMAND (Q_{HD}) AND EXCESS TEMPERATURE (ΔT)

Inputs:

- heating load, including direct solar and internal gains and the heat transmission through the transparent insulation, Q_L' in MWh;
- total and mean solar radiation on a wall with transparent insulation (TIM), G in MWh and S in W/m^2, respectively;
- averaged ambient temperature, T_{amb} in °C;
- averaged indoor temperature, T_i in °C;
- properties of transparent insulation material, g_{TIM}, U_{TIM}, in W/m^2·K and wall, U_{wall}, in W/m^2·K.

Note: g_{TIM} presents the net solar transmittance (including additional heat from the device). If not known, use transmission diffuse (τ_d) as a rather conservative number.

Equations:

$$Q_{HD} = Q_L' - \Phi_{TIM\text{-}wall} \times QS_{CW} \text{ (MWh)} \quad (1)$$

$$\Delta T = (1 - \Phi_{TIM\text{-}wall}) \times SLR \times (T_i - T_{amb}) \text{ (°C)} \quad (2)$$

$$U_{tot} = 1/(1/U_{wall} + 1/U_{TIM}) \quad (3)$$

$$g_{tot} = g_{TIM}\,(U_{tot}/U_{TIM}) \quad (4)$$

T_i = average indoor temperature (°C)

T_{amb} = average ambient temperature (°C)

$$QS_{CW} = g_{tot}\,G \text{ (MWh)} \quad (5)$$

$$SLR = QS_{CW}/Q_L', \text{ solar load ratio} \quad (6)$$

$\Phi_{TIM\text{-}wall}$ = gain utilization factor for TIM-wall in specific standardized dwellings for monthly calculations (7)

$$= 1 - e^{(-K/(SLR - D))}$$

Correlation factors from case study, $K = 1.31$ and $D = -0.177$.

The monthly solar gain factor can be used for comparison of the thermal performance of different TIMs and different locations, as illustrated in Figure 4.

$$\text{Solar gain factor} = g - U\,(T_i - T_{amb})/S \quad (8)$$

where

$g = g_{TIM}$ for TIM glazing only, g_{tot} for complete wall,
$U = U_{TIM}$ for TIM glazing only, U_{tot} for complete wall.

Example: (tentative approach for seasonal energy performance using monthly correlation formula).

Main input data:

- Transparent insulation on south-facing wall of a well-insulated dwelling; location: De Bilt, the Netherlands.

Solar wall area	10 m^2
Seasonal heating load (five months)	6.6 MWh
Solar radiation (five months)	2.08 MWh (= averaged 58 W/m^2)
Indoor temperature	20°C
Average ambient temperature	3.5°C
Insulation	16 mm aerogel + 2 x glass (low iron) evacuated
Solar transmittance TIM	0.74
Heat transfer coefficient TIM	0.6 W/m^2·K
Heat transfer coefficient wall behind TIM	5 W/m^2·K

Calculation :

$U_{tot} = 1/(1/5 + 1/0.6) = 0.54$ W/m^2·K,
$g_{tot} = 0.74 \times 0.54/0.6 = 0.67$,
solar gain through collector wall $= 0.67 \times 2.08 = 1.40$,
solar load ratio $= 1.40/6.6 = 0.21$,

gain utilization factor $= 1 - e^{(-1.31/(0.21 + 0.177)} = 0.97$,
heat demand $= 6.6 - 0.97 \times 1.40 = 5.2$ MWh,
mean temperature increase $= (1 - 0.97) \times 0.21 \times (20 - 3.5) = 0.10°C$,
utilized heat gain, solar wall $= (6.6 - 5.2)/10 = 0.14$ MWh/m^2 $= 140$ kWh/m^2

For comparison to 50-mm honeycomb with single glass (low iron):

Solar transmittance TIM 0.81,
Heat transfer coefficient TIM 1.3 W/m^2·K,

$U_{tot} = 1/(1/5 + 1/1.3) = 1.03$ W/m^2·K,
$g_{tot} = 0.81 \times 1.03/1.3 = 0.64$,
$(T_i - T_{amb})/S = (20 - 3.5)/58 = 0.28$ m^2·K/W,
aerogel: seasonal solar gain factor

$= 0.67 - 0.54 \times 0.28 = 0.52$,

honeycomb: seasonal solar gain factor

$= 0.64 - 1.03 \times 0.28 = 0.35$,

utilized heat gain solar wall (honeycomb) $= 0.35/0.52 \times 140 = 94$ kWh/m^2