Recommended Standard for the Characterization and Monitoring of PV/Thermal Systems

A Report of IEA SHC - Task 35

PV/Thermal Solar Systems

Report DB2

November 13, 2009

Mike Collins
Herbert Zondag

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

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A technical report of Subtask B
Report DB2

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IEA Solar Heating and Cooling Programme

The *International Energy Agency* (IEA) is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) based in Paris. Established in 1974 after the first “oil shock,” the IEA is committed to carrying out a comprehensive program of energy cooperation among its members and the Commission of the European Communities.

The IEA provides a legal framework, through IEA Implementing Agreements such as the *Solar Heating and Cooling Agreement*, for international collaboration in energy technology research and development (R&D) and deployment. This IEA experience has proved that such collaboration contributes significantly to faster technological progress, while reducing costs; to eliminating technological risks and duplication of efforts; and to creating numerous other benefits, such as swifter expansion of the knowledge base and easier harmonization of standards.

The *Solar Heating and Cooling Programme* was one of the first IEA Implementing Agreements to be established. Since 1977, its members have been collaborating to advance active solar and passive solar and their application in buildings and other areas, such as agriculture and industry. Current members are:

Australia
Austria
Belgium
Canada
Denmark
European Commission
Germany
Finland
France
Italy
Mexico
Netherlands
New Zealand
Norway
Portugal
Spain
Sweden
Switzerland
United States

A total of 44 Tasks have been initiated, 33 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition to the Task work, a number of special activities—Memorandum of Understanding with solar thermal trade organizations, statistics collection and analysis, conferences and workshops—have been undertaken.

To find Solar Heating and Cooling Programme publications and learn more about the Programme visit
www.iea-shc.org or contact the SHC Executive Secretary, Pamela Murphy, e-mail: pmurphy@kmgrp.net.

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The Tasks of the IEA Solar Heating and Cooling Programme, both underway and completed are as follows:

Current Tasks & Working Group:

Task 35	*PV/Thermal Solar Systems*
Task 36	*Solar Resource Knowledge Management*
Task 37	*Advanced Housing Renovation with Solar & Conservation*
Task 38	*Solar Thermal Cooling and Air Conditioning*
Task 39	*Polymeric Materials for Solar Thermal Applications*
Task 40	*Net Zero Energy Solar Buildings*
Task 42	*Compact Solar Thermal Energy Storage*
Working Group	*Daylight Research Group*

Completed Tasks:

Task 1	*Investigation of the Performance of Solar Heating and Cooling Systems*
Task 2	*Coordination of Solar Heating and Cooling R&D*
Task 3	*Performance Testing of Solar Collectors*
Task 4	*Development of an Insolation Handbook and Instrument Package*
Task 5	*Use of Existing Meteorological Information for Solar Energy Application*
Task 6	*Performance of Solar Systems Using Evacuated Collectors*
Task 7	*Central Solar Heating Plants with Seasonal Storage*
Task 8	*Passive and Hybrid Solar Low Energy Buildings*
Task 9	*Solar Radiation and Pyranometry Studies*
Task 10	*Solar Materials R&D*
Task 11	*Passive and Hybrid Solar Commercial Buildings*
Task 12	*Building Energy Analysis and Design Tools for Solar Applications*
Task 13	*Advance Solar Low Energy Buildings*
Task 14	*Advance Active Solar Energy Systems*
Task 16	*Photovoltaics in Buildings*
Task 17	*Measuring and Modeling Spectral Radiation*
Task 18	*Advanced Glazing and Associated Materials for Solar and Building Applications*
Task 19	*Solar Air Systems*
Task 20	*Solar Energy in Building Renovation*
Task 21	*Daylight in Buildings*
Task 23	*Optimization of Solar Energy Use in Large Buildings*
Task 22	*Building Energy Analysis Tools*
Task 24	*Solar Procurement*
Task 25	*Solar Assisted Air Conditioning of Buildings*
Task 26	*Solar Combisystems*
Task 28	*Solar Sustainable Housing*
Task 27	*Performance of Solar Facade Components*
Task 29	*Solar Crop Drying*
Task 31	*Daylighting Buildings in the 21st Century*
Task 32	*Advanced Storage Concepts for Solar and Low Energy Buildings*
Task 33	*Solar Heat for Industrial Processes*
Task 34	*Testing and Validation of Building Energy Simulation Tools*

Completed Working Groups:

CSHPSS, ISOLDE, Materials in Solar Thermal Collectors, and the Evaluation of Task 13 Houses

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IEA SHC Task 35 PV/Thermal Solar Systems

Objective

The objectives of the Task are to catalyze the development and market introduction of high quality and commercial competitive PV/Thermal Solar Systems and to increase general understanding and contribute to internationally accepted standards on performance, testing, monitoring and commercial characteristics of PV/Thermal Solar Systems in the building sector.

The Task is organized in 5 subtasks:

- Subtask A: Market and Commercialization of PV/T
- Subtask B: Energy Analysis and Modeling
- Subtask C: Product and System Development, Tests and Evaluation
- Subtask D: Demonstration Projects
- Subtask E: Dissemination

Organisation

IEA SHC Task 35 "PV/Thermal Solar Systems" is a three year Task initiated by the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme in January 2005.
The Danish Energy Authority, acting through Mr. Henrik Sørensen, Esbensen Consulting Engineers A/S, Denmark, is designated as Operating Agent for the Task.

Task 35 is a so-called "minimum-level" collaboration task with IEA PVPS (Photovoltaic Power Systems Programme). At this level, experts selected by the PVPS Executive Committee participate in experts meetings of the Task managed by the SHC Executive Committee. The Task is fully defined and managed by the SHC Executive Committee with appropriate input from the PVPS Executive Committee. In this project Israel participated as a PVPS country member.

The official participants in the Task are listed in the table below:

Country	Organization	Person
Canada	Dept. of Mechanical Engineering, University of Waterloo, Waterloo, Ontario, Canada	Mike Collins
Denmark	Esbensen Consulting Engineers A/S	Henrik Sørensen
	Solar Energy Center, Danish Technological Institute	Ivan Katic
Israel	Millennium Electric	Ami Elazari
Sweden	Lund Technical University	Björn Karlsson Johan Nilsson Bengt Perers
The Netherlands	ECN (Energy Research Centre of the Netherlands)	Wim van Helden Herbert Zondag Marco Bakker

Apart from the above mentioned a number of manufacturers, universities, and research institutes from the countries Germany, Greece, Hong Kong, Italy, South Korea, Thailand, and Spain have been involved in the work.

Visit the Task 35 website: http://www.iea-shc.org/task35 for more details on activities and results.

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INTRODUCTION

This document has been prepared in support of IEA Task 35: Combined Photovoltaic and Solar Thermal (PV/Thermal) Systems – Subtask B: Energy Analysis and Modelling. Specifically, it reports on the proposed practice to characterize and monitor PV/Thermal systems, and identifies and addresses the gaps that currently exist in characterization and monitoring activities.

The present document details those schemes for flat-plate style thermal collectors. Omitted at this time are PV/Thermal systems based on concentrating collectors.

RATING SCHEMES

PV/Thermal modules produce both electrical and thermal output, and it is important to represent these outputs in a uniform way as to facilitate inter-comparison between PV/Thermal collectors. Furthermore, since PV/Thermal systems represent only a very small market volume, it is important to follow as closely as possible the conventions established for both PV and solar thermal systems.

The required level of detail in the representation of the output depends on the type of user and/or the purpose. On technical expert level, a different type of presentation is required than on the policy level. As such, the following discussion will focus on each of three PV/Thermal characterization schemes.

- The *design* scheme contains the most significant level of detail, and is also the most complex. It is not well suited to adaptation to in-situ measurements outside of a research laboratory setting. The real value of this approach is as a research tool for individuals well versed in PV/Thermal system design, testing, and operation.
- The *rating* scheme is a practical approach that will allow for convenient comparison of systems and good approximations of annual electrical and thermal system output. The method is also easily adapted to test facilities.
- The *marketing* scheme will simply be a comparative analysis of systems intended for policy and marketing documents. It is intended to show comparative indices such as peak output, and yearly thermal and electrical production values.

'DESIGN' SCHEME:

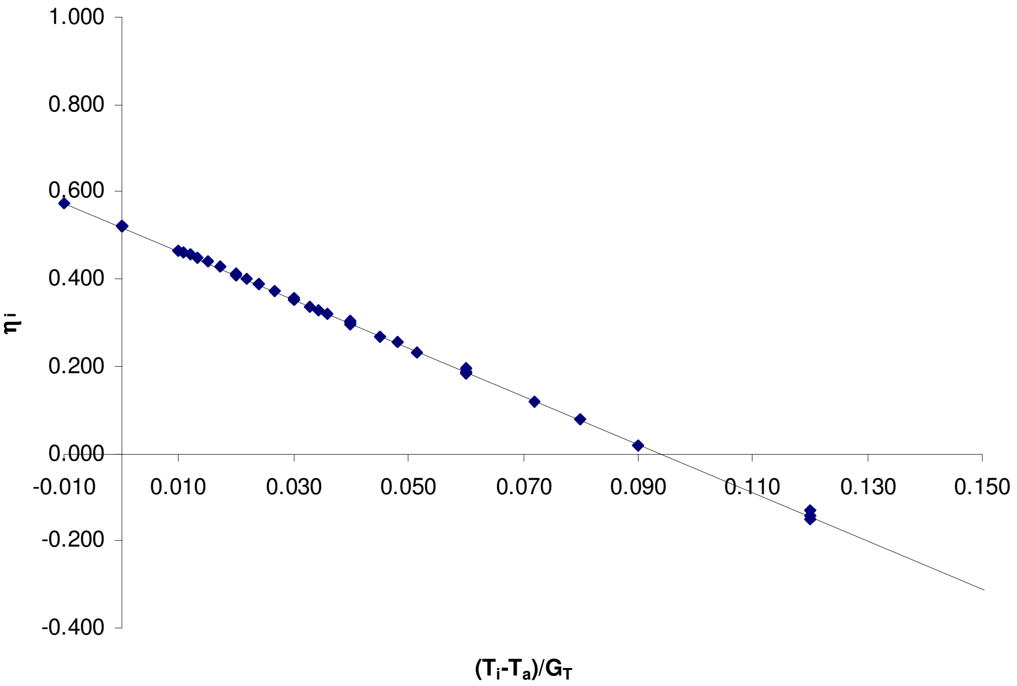
The information presented in this section is not the recommended approach to analyzing PV/Thermal systems. The intention in presenting this material is to educate the reader as to how these systems react in different situations, and to provide a suitable high-level methodology for researchers and designers.

The *design* scheme is derived from the standard rating scheme used to assess the performance of solar-thermal systems. The model, derived from an energy balance on the collector [1], is

$$\eta_i = \frac{Q_u}{G_T A_c} = F_R \tau\alpha - F_R U_L \frac{(T_i - T_a)}{G_T}$$

where η_i = Collector efficiency (dim)
Q_u = Thermal energy collected where $Q_u = \dot{m} C_p (T_i - T_o)$ (W)
G_T = Total solar irradiance on the plane of the panel (W/m^2)
A_c = Collector absorber area (m^2)
F_R = Collector heat removal factor (dim)
$\tau\alpha$ = Tau-alpha product of the collector (dim)
U_L = Collector loss transfer coefficient (W/m^{2}K) ($U_L = U_t + U_b + U_e$)
T_i = Fluid inlet temperature (^{o}C)
T_a = Ambient air temperature (^{o}C)
$\dot{m}$ = Mass flow rate of the collector fluid (kg/s)
C_p = Specific heat of the collector fluid (J/kgK)

The equation shown is linear. A performance plot of the collector can be produced from experimental or modeled data, such as that shown in the following figure.



It is noted that that an equivalent procedure is often employed that uses the average fluid temperature instead of the inlet fluid temperature. For this discussion, we will use the above derivation. Expansion to the average fluid temperature case would be a simple exercise.

When the system includes photovoltaic cells, the energy balance changes to

$$\eta_i = \frac{Q_u}{G_T A_c} = F_R \tau\alpha - F_R U_L \frac{(T_i - T_a)}{G_T} - \eta_{PV}$$

where η_{PV} = Photovoltaic efficiency

$$\eta_{PV} = Q_E/G_T A_c = \tau_c \eta_{PV,ref} pF(1 - C(T_{cm} - T_{ref})) \text{ (dim)}$$

Q_E = Electrical output of the cells (W)
τ_c = Transmissivity of the glass covers (dim)
$\eta_{PV,ref}$ = Photovoltaic efficiency at T_{ref} (dim)
C = Temperature coefficient of PV cells based on power (K^{-1})
T_{cm} = Mean PV temperature (°C)
T_{ref} = Reference temperature for cell efficiency (°C)
pF = PV packing factor ($pF = A_{PV}/A_c$)
A_{PV} = PV area (m^2)

With the addition of photovoltaic cells, the performance indicators of a solar thermal panel will change to due to changes in surface absorptance and emittance, and absorber heat transfer efficiency (i.e., F_R, $\tau\alpha$, and U_L terms will change). The same characteristic performance that is shown in the above figure, however, will still be observed. Furthermore, depending on the amount of electricity extracted, the curve shown should shift downward (i.e., the thermal performance is lowered).

A model of the system was built in the TRNSYS platform and examined. The modelled collector had the following input parameters and units[1].

Collector	**Photovoltaics**	**Other**
$A_c = 1\ m^2$	$C = -0.004\ K^{-1}$	$V_w = 0.5$ m/s
$F' = 0.80$	$T_{ref} = 25\ ^oC$	$G_{b,T}$ is variable (KJ/hrm^2)
$KL = 0.06$	$\eta_{E.ref} = 0.15$	$G_{d,T} = 0$ kJ/hrm^2
$U_b + U_e = 10$ kJ/hrm^{2}K	$Pf = 0.9$	$\theta = 0^o$
$C_p = 4.19$ kJ/kgK	$\varepsilon = 0.80$	T_a is variable
$T_i = 30\ ^oC$	$\alpha = 0.90$	
$\dot{m}/A_c = 108$ kg/hrm^2		
#covers=1		
$\beta = 45^o$		

---

[1] A number of the variables and units included in the table do not correspond with the previously shown nomenclature. The differences will be explained in the Section 'Experiments versus Model Inputs'.

here F' = Collector efficiency factor
KL = Extinction coefficient thickness product
U_b, U_e =Loss coefficients for bottom and edges
#covers = Number of glass covers
β = Collector tilt
ε = Cell emissivity
α = Cell absorptivity
V_w = Wind speed
$G_{b,T}$ = Incident beam irradiation
$G_{d,T}$ = Incident diffuse irradiation
θ = Incident angle of beam irradiation

The variables given in the previous table are those needed for the Type250 model in the TRNSYS platform. This is a variation of the standard Type50d model, which includes a number of corrections[2] and simplifications. While these variables are not the same as those used to develop the theory of the rating procedure, the two methods are in fact the same. Differences essentially lie in the units, and intermediate variables used in the calculation. For example, F_R is calculated using F', $\dot{m}$, C_p, U_L and A_c.

It is apparent, that a 3-plot system consisting of η_i vs $(T_i-T_a)/G_T$, $(T_{cm}-T_a)/G_T$ vs $(T_i-T_a)/G_T$, and $(T_{cm}-T_a)/G_T$ vs η_E, may be the easiest approach. Alternatively, the $(T_{cm}-T_a)/G_T$ vs $(T_i-T_a)/G_T$, and $(T_{cm}-T_a)/G_T$ vs η_E, can be removed and a plot of η_E vs $(T_{cm}-T_a)/G_T$ added. Offsetting the x-axis could account for the missing information.

Example:
For the collector shown in the plots, what is the thermal and electrical output, and the mean cell temperature when $G_T = 800$ W/m^2 and $T_a = 10$ °C.

$$(T_i - T_a)/G_T = (30 - 10)/800 = 0.025 \text{ m}^2\text{K/W}$$

From the 1st plot, we see that the thermal efficiency is approximately 0.38, and the thermal output is

$$\eta_i G_T A_c = 0.38 \text{ x } 800 \text{ x } 1 = 304 \text{ W}$$

Extending the vertical line down, we see that the parameter $(T_{cm}-T_a)/G_T$ is approximately 0.04

$$T_{cm} = 0.04\ G_T + T_a = 0.04 \text{ x } 800 + 15 = 42\ ^{\circ}\text{C}$$

Extending the last line horizontally to $T_a = 10$ °C, we see $\eta_E = 0.108$, and the electrical output is

$$\eta_E G_T A_c = 0.108 \text{ x } 800 \text{ x } 1 = 86.4 \text{ W}$$

It is an easy extension to see how this can be done with the second set of plots.

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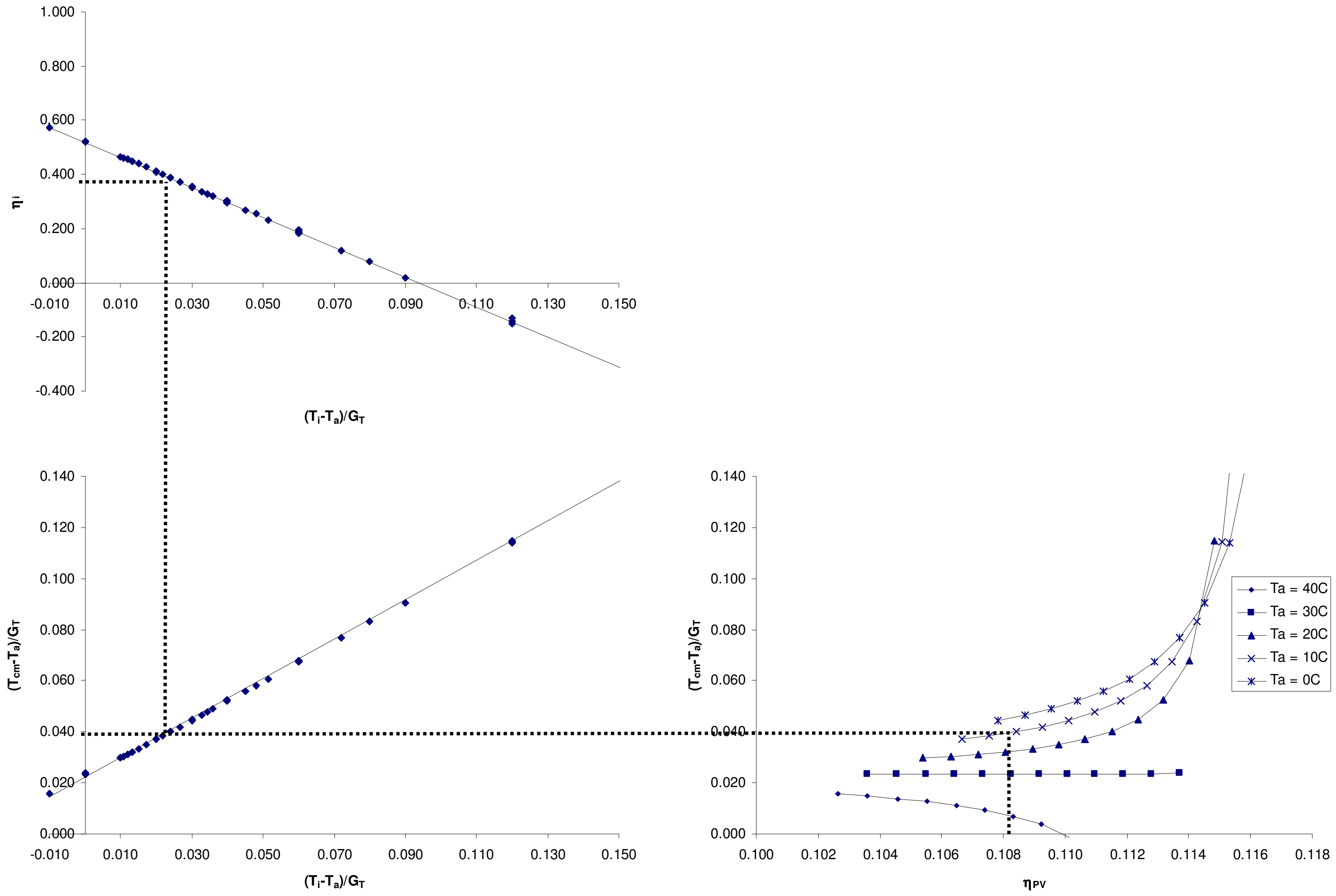
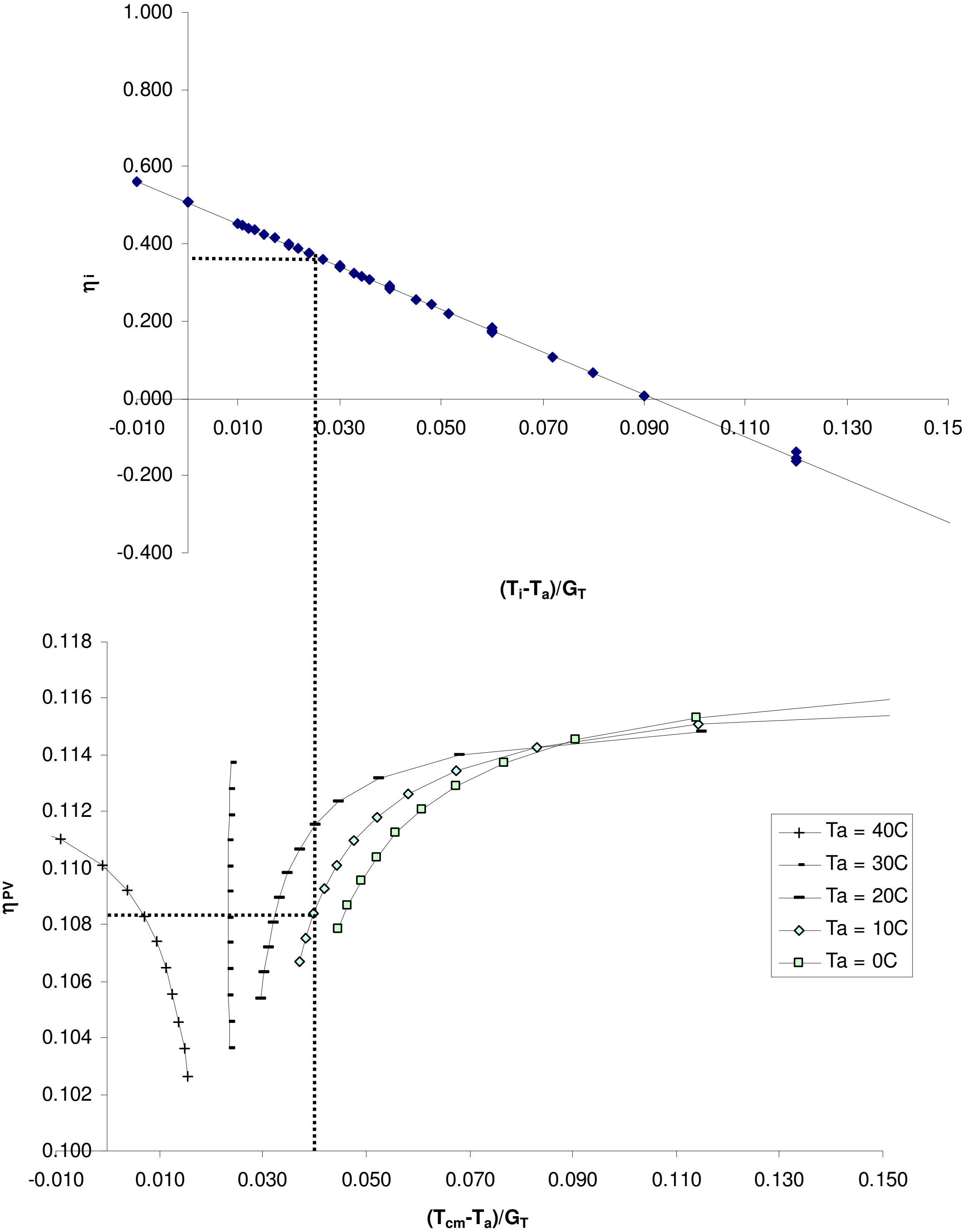
[2] TRNSYS requires that the unit be K, but the value must be in °C. i.e., an entry of 20 K means 20 °C. This has been corrected for the Type250 version of the model. Further, the constant C defaults to a negative value. This results in cells that become more efficient as they increase in temperature. A positive value is required.


1.000
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
η^i
-0.010
0.010
0.030
0.050
0.070
0.090
0.110
0.130
0.150
$(T_i-T_a)/G_T$
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
$(T_{cm}-T_a)/G_T$
-0.010
0.010
0.030
0.050
0.070
0.090
0.110
0.130
0.150
$(T_i-T_a)/G_T$
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
$(T_{cm}-T_a)/G_T$
0.100
0.102
0.104
0.106
0.108
0.110
0.112
0.114
0.116
0.118
η_{PV}
Ta = 40C
Ta = 30C
Ta = 20C
Ta = 10C
Ta = 0C


1.000
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
ηi
-0.010
0.010
0.030
0.050
0.070
0.090
0.110
0.130
0.150
(Ti-Ta)/GT
0.118
0.116
0.114
0.112
0.110
0.108
0.106
0.104
0.102
0.100
ηPV
Ta = 40C
Ta = 30C
Ta = 20C
Ta = 10C
Ta = 0C
-0.010
0.010
0.030
0.050
0.070
0.090
0.110
0.130
0.150
(Tcm-Ta)/GT

Experimental Production of Plots:

The η_i vs $(T_i-T_a)/G_T$, and $(T_{cm}-T_a)/G_T$ vs $(T_i-T_a)/G_T$, can be easily produced for a given collector using the same number of tests required to examine an equivalent thermal-only system. Unfortunately, this may leave insufficient data from which the $(T_{cm}-T_a)/G_T$ vs η_E plot can be produced. Further, to properly populate the 3rd plot, a variety of ambient temperatures are required, which may prove to be an impractical requirement.

It is suggested that the standard tests be run, and the 3rd plot extrapolated empirically.

Static Parameters: A_c, F', C_p, α, #covers, ε, U_b, U_e, β, KL, C, T_{ref}, $\eta_{E.ref}$, Pf

1. A_c, #covers, β: recorded at test time.
2. F': may be estimated based on tube spacing, U_L, absorber thickness, and absorber conductivity. The last parameter must be the apparent conductivity of the PV-absorber laminate. A better option is to determine F_R from collected data (F_RU_L = - slope of the previously shown plot). F' can then be found using
$$F' = -\frac{\dot{m}C_p}{A_cU_L} ln\left[1 - \frac{F_RA_cU_L}{\dot{m}C_p}\right]$$
F' is constant for a given collector at a specific fluid flow rate.
3. C_p: can be determined from fluid type.
4. α, ε: obtained from PV manufacturer specifications, measured, or taken from published values.
5. U_b: recorded at test time. $U_b = k_b/t_b$ for the backing insulation.
6. U_e: recorded at test time. $U_e = k_eA_e/t_eA_c$ of the edge insulation.
7. KL: recorded at test time. K for glass is 16.2 m^{-1}. L is the thickness of the glass.
8. C, T_{ref}, $\eta_{E.ref}$: obtained from PV manufacturer specifications. Typical values are given in the following table for $T_{ref} = 25^oC$.
9. Pf: obtained from PV manufacturer specifications or measured.

Monitored Parameters: T_i, $\dot{m}$, V_w, $G_{b,T}$, $G_{d,T}$, T_a, θ

1. T_i, $\dot{m}$, V_w, T_a: recorded during test
2. $G_{b,T}$, $G_{d,T}$, θ: can be recorded at time of test. May be replaced by G_T measured in the plane of the collector.

Type of Cell[3]	$\eta_{PV,ref}$	**C (based on power)**
multicrystalline Si	11-15%	0.0040 to 0.0050 K^{-1}
monocrystalline Si	10-17%	0.0040 to 0.0050 K^{-1}
HIT Cells	16-17%	
ribbon & EFG cells	12-13%	
a-Si (single j)	4-6%	0.0020 K^{-1}
a-Si (multi j)	5-7%	0.0020 K^{-1}
CIS	9-11%	0.0036 K^{-1}
CdTe	6-9%	0.0025 K^{-1}

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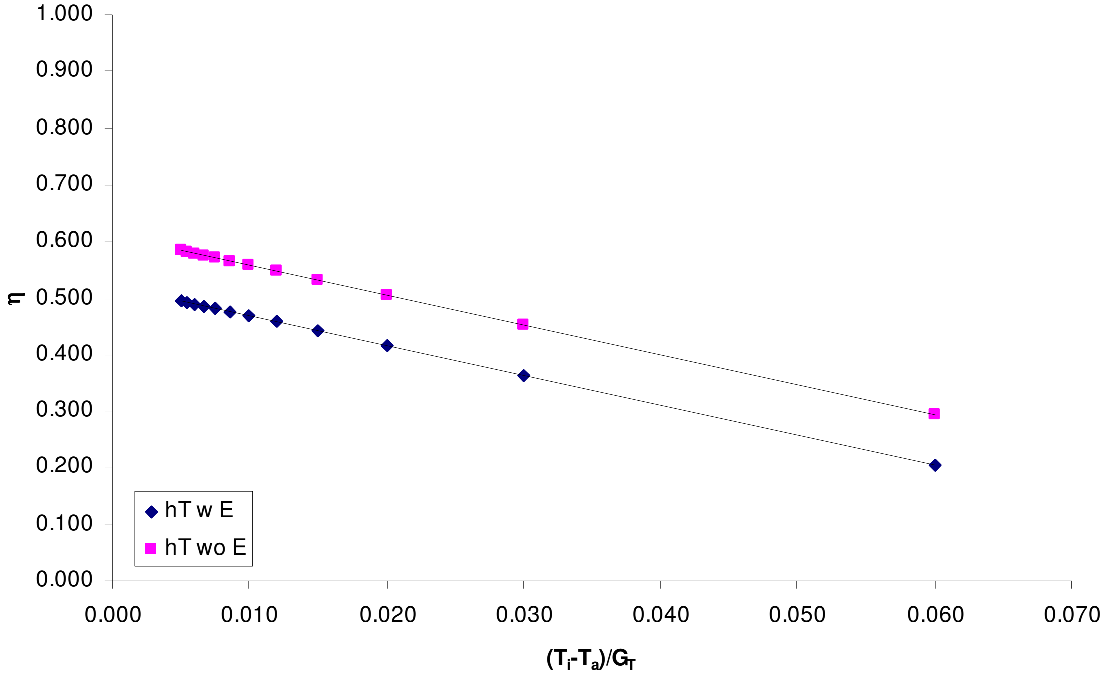
[3] Data from this table have been taken from [2]

'RATING' SCHEME:

With respect to module test reports, it is important to follow as closely as possible the existing ways of characterization as adopted for PV (IEC 61215) and solar thermal (EN 12975 for modules or 12976 for systems). A guideline for testing PV/Thermal modules in accordance with IEA 61215 and EN 12975 is presented in the report ‘PV/T performance measurement guidelines’ [3], which was a deliverable of the EU project PV-Catapult [3] (the report is downloadable from www.pvtforum.org).

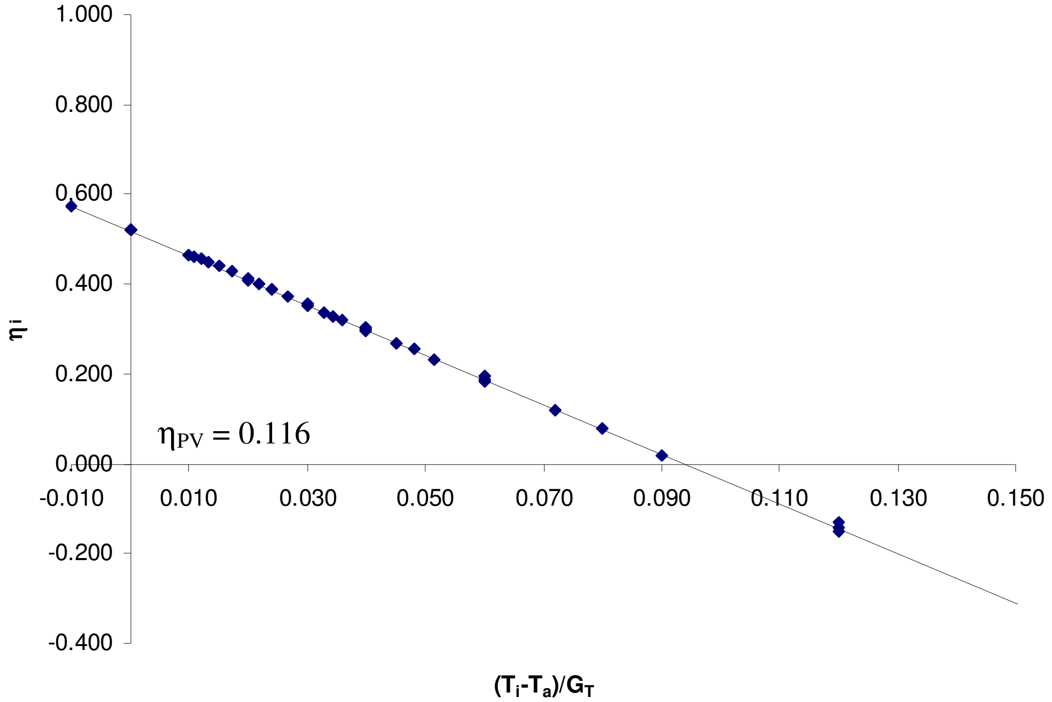
That method originally dictated that the collector be tested with and without electricity production (see Figure). The thermal performance is lowered when electrical energy simultaneously produced. Therefore, a lower and upper performance curve can be obtained. The electricity is obtained at the maximum power-point (MPP).



Some modifications to this procedure were proposed because of issues specific to the testing of PV/Thermal systems. Since it is expected that the normal mode of operation is with electrical generation, and to avoid an increase in the required testing period (which is for normal solar thermal collectors already quite long), it was decided only to measure the instantaneous efficiency curve in the same way as normal solar thermal collectors, except with simultaneous production of electricity.

The electrical output is presented in a power matrix. Electrical output is determined under STC (Standard Test Conditions, defined by an irradiance of 1000 W/m^2 irradiance and a temperature of 25 C) as well as under different module temperatures and irradiance levels. Important here is that the power matrix is based on module temperature and not ambient temperature; this is due to the fact that the PV temperature is strongly influenced by the collector inflow temperature.

A plot like the one presented below can be produced for a collector to determine thermal output, and the product of cell efficiency irradiation, area, and packing factor can be used to determine electrical output. As a result, given ambient conditions and inflow temperature, both thermal and electrical yields of the PV/Thermal system can be determined in a standardized way. The PV Catapult group has produced excellent documentation of this procedure [3], including a procedure to calculate the PV temperature from ambient conditions and inflow temperature.



T_{cell} G_i	0-5 °C	5-10 °C	10-15 °C	etc
0-100W/m^2				
100-200W/m^2				
200-300W/m^2				
etc				

For technical experts, the efficiency curve will be the preferred way of presentation of the thermal yield. For marketing purposes, however, manufacturers often prefer to present these same data in the form of a collector yield for a certain climate given a certain inflow temperature. In this situation, it is recommended to use certain reference temperatures and reference climates (as defined in the EN 12976) at inflow temperatures of 25 C, 50 C and 75 C to facilitate comparisons. The yield under these conditions should be calculated from the efficiency curve in combination with n incidence angle modifier.

With respect to what area the efficiency should be based upon, it is good to realize that for PV/Thermal systems, the following areas may be relevant; (a) absorber area, (b) aperture area, (c) collector gross area, (d) PV area. **Fejl! Henvisningskilde ikke fundet.**The figure below shows a situation in which there is a large difference between these areas.

PV/Thermal prototype by with PV on part of the absorber [4].

For PV/Thermal systems, it is recommended to base thermal efficiencies and thermal output on the collector aperture area, since this is conventionally done for solar collectors. For the electrical output, a rating of the entire PV/Thermal module in Wp is given (not per unit area). Unlike the electrical output, the electrical efficiency is not a prescribed characteristic for the PV/Thermal module, but if one would want to give an electrical efficiency after all, it is likewise recommended to base these on the collector aperture area, since it would be confusing to base the thermal and electrical efficiencies on two different areas. For PV/Thermal collectors in which only a small part of the absorber is covered with PV, this will lead to low electrical efficiency, even if the actual PV cell efficiency would be high, which is nevertheless seen as appropriate for the representation of the PV/Thermal module efficiency as a whole. Therefore, the PV efficiency quoted should include the aperture area, PV area (possibly including the packing factor) and cover system transmittance ($\eta_{PV} = A_{PV}\tau_c\eta_{PV,ref}pF/A_C$). In the example system, therefore, $\eta_{PV} = 1 \text{ x } 0.86 \text{ x } 0.15 \text{ x } 0.9 / 1 = 0.116$.

As a final note, one should realise that technical collector ratings, as carried out in test institutes, is part of an overall collector assessment that also includes reliability and safety of the collector. For PV/Thermal systems, specific reliability and safety issues exist, (e.g. stagnation temperature resistance of the PV encapsulation material), but presently still insufficient experience is available to assess these issues properly. A first overview of possible specific PV/Thermal issues and possible methods to assess these is suggested in the appendix of the abovementioned report ‘PVT performance measurement guidelines’ [3], but much more field experience is required to evaluate these suggestions and to arrive at sound testing standards for reliability and safety aspects.

Example:

Using the procedure put forward by the PV Catapult project, the predicted electrical output would have been

$$\eta_{PV} G_T A_c = 0.116 \text{ x } 800 \text{ x } 1 = 92.8 \text{ W}$$

The thermal output would be the same as the previous prediction of 304W.

Using the second procedure

$$(T_i - T_a)/G_T = (30 - 10)/800 = 0.025 \text{ m}^2\text{K/W}$$

$\eta_{wo/PV} = 0.50$ and $\eta_{w/PV} = 0.38$. The second number gives us the same predicted thermal output of 304W. The PV output can be predicted by

$$(\eta_{wo/PV} - \eta_{w/PV}) G_T A_c = (0.50\text{-}0.38)800\text{x}1 = 96\text{W}$$

'Market' Scheme:

System Performance Presentation

Recently, efforts have been carried out within the scope of the EPBD (European Building performance directive), to standardize also the calculation of the annual performance of solar thermal systems (EN 15316-4) and PV systems (EN 15316-6). These calculations include various system losses such as piping heat loss, storage heat loss and inverter electrical loss.

1. For the PV annual system performance, the calculation is directly in line with EN 15316-6. In this norm, the PV output is calculated from the following formula $Q_{PV} = H_i P_0 R_p / G_{ref}$, in which H_i is the actual annual solar in-plane irradiance (in W/m^2), G_{ref} is the reference irradiance under STC (1000 W/m^2), P_0 is the rated PV module power under STC (in W) and R_p is a value related to the PV temperature. For R_p, the norm gives a value of 0.7 for unvented modules, 0.75 for moderately vented modules and 0.8 for strongly vented modules. It is not clear how representative these values are for PVT. It is recommended, however, to follow this convention and use 0.7 for glazed and 0.8 for unglazed PV/Thermal systems.

2. For the solar thermal annual performance, EN 15316-4 gives a procedure using the efficiency curve. This procedure is recommended here for PV/Thermal systems as well, assuming that the efficiency curve is determined following the PV/Thermal system performance measurement guidelines.

Nominal Power Rating

For PV, module power measured and rated in Watt peak. For solar thermal collectors, a power rating in Watt peak is also used, but for different purposes; it is purely a nominal value that is used in policy documents to facilitate the comparison of installed collectors to the energy production by other renewable techniques (PV, wind). For solar thermal systems, this is a nominal value of 700 Wp/m^2 that is applied to glazed and unglazed collectors irrespective of their actual efficiency and location. This means that differences in irradiance are also not taken into account. This is not a way of characterizing individual solar thermal collectors, but rather solar thermal collectors as a class.

Following this reasoning, it is logical to have one value for PV/Thermal systems as well. Since the idea for solar thermal was to have one number for simple comparison, one should not be concerned with the difference between PV/Thermal systems and conventional solar collectors. Although it can be argued that the peak yield of PV/Thermal systems will generally be less than the peak yield of solar thermal systems, it is recommended to still use the value for solar thermal. While the small market size of PV/Thermal systems does not warrant a separate rating convention Therefore, the same nominal value of 700 Wp/m^2 that is used for conventional collectors should be used for PVT.

If the nominal contribution of PV/Thermal systems is assessed, the system should be evaluated as giving both a thermal installed capacity of 700 Wp/m^2 and an electrical installed capacity corresponding to the measured electrical STC performance in Watt peak.

Combined Thermal and Electrical Output

In some special cases, it may be desirable to give an overall output for the PV/Thermal systems that includes both thermal and electrical yield. A nice overview of the different ways of comparing electrical and thermal energy is presented by Coventry et al. [5]. In that work, it is argued that electrical and thermal energy can be compared in different ways:

- final energy,
- primary energy savings (taking into account the conversion efficiencies of conventional power stations whose output is displaced by the PV/Thermal system)
- exergy (the amount of work that can be done with the output)
- open market energy cost (based on utility prices for gas and electricity, as well as possible savings in fixed cost due to displacement of the conventional heating installation)
- renewable energy market energy cost (same as the above, but including feed-in tariffs, subsidies, tax benefits etc)
- displaced greenhouse gas emissions (comparing the emissions for conversion of fossil fuel to electricity and to heat)
- life cycle greenhouse gas emissions (same as above, but including also emissions resulting from the production of the device over the entire production chain).

Within this publication, the following figure is shown to indicate the comparative value of electrical and thermal energy based on the above metrics.

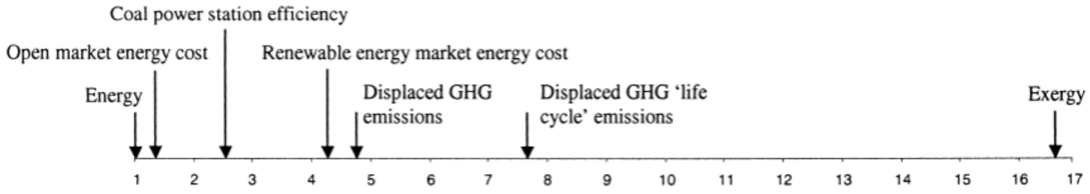


Fig. 3. Summary of sample electrical-to-thermal ratios developed in this paper.

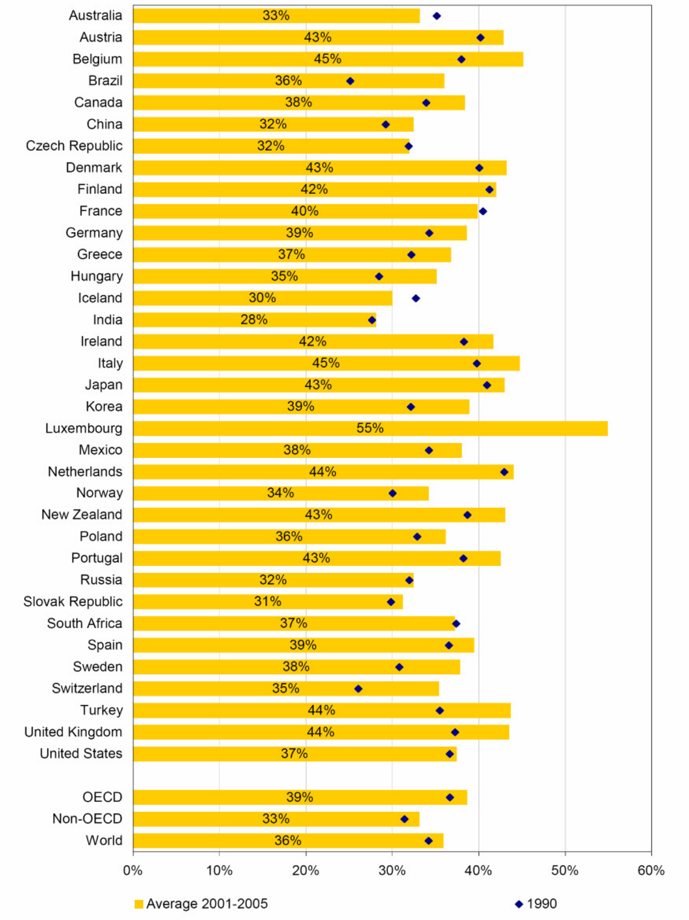
Comparison of electrical and thermal output [5].

If a combined number is necessary, within IEA SHC task 35 it is recommended to use primary energy. Primary energy is the best indicator of the amount of fossil fuel saved, which is basic goal of renewable energy systems.

Comparing electrical output to thermal output by means of exergy is strongly discouraged. It underrates the actual profit from the thermal yield and is not a relevant criterion for this application. In the words of Coventry (2003), '*the significance of an exergy comparison is not clear if electrical or mechanical work is not the only desired output from the system, such as when the thermal output is hot water used directly for showers and washing.*'

It is felt that the remaining criteria based on cost or displaced greenhouse gas emissions are less useful since they are not related directly to the energy production of the PV/Thermal system. In addition, the criterion of energy cost savings is risky since it changes over time depending on developments in the costs of electricity and fossil fuels, and is therefore only valid for short-term comparisons.

The calculation of primary energy depends on the efficiency of the production of electricity and heat from conventional installations. Worldwide, substantial variation exists in this efficiency. In the IEA publication ‘Energy efficiency indicators for public electricity production from fossil fuels’ [6], the following average values are presented: world 36%, OECD countries 39%, non-OECD countries 33% (see figure) [6]. It is recommended here to use a value of 40% for the conversion, which implies that the PV/Thermal system electrical output should be multiplied by 2½ to determine the primary energy saved. For the thermal system efficiency, widely varying efficiencies are found, depending on type of heater and type of use. Typical efficiencies would be 55-80% for tap water heating and 90-100% for space heating. In the Dutch protocol on renewable energy monitoring [7], a value of 65% is used for tap water heating and 95% for space heating (based on lower heating value), and it is recommended here to use these values also for other countries in which gas is used for heating. This would imply that the thermal output for tap water would have to be multiplied with 1/0.65 and the thermal output for space heating with 1/0.95 to obtain the corresponding primary energy yield. The energy mix used for heating, however, strongly varies over Europe (see figure) [7]. If electricity is used for heating, these conversion efficiencies for heating should be lowered to also include the conversion efficiencies from primary fuel to electricity. It is suggested that a conversion efficiency of 28% be used for electrical tap water heating and 40% conversion efficiency for electrical room heating (see figure) [8]. If primary energy yield is presented, it is recommended to also present the values for thermal and electrical yield separately, and to indicate the conversion efficiencies that have been used to calculate primary energy, so that the reader may convert the data to values that correspond better to the specific energy carrier and conversion efficiency typical for domestic heating in his country.



Source: IEA analysis.
Note: According to IEA statistics Luxembourg does not have any public electricity generation from fossil fuelled-fired plants in 1990.

Average plant efficiency [6].

Type		**efficiency**
Boiler	electrical	28%
	Improved efficiency burner with central heating boiler	45%
	Condensing gasburner with central heating boiler	55%
	Cogeneration / heat pump	60%
	Steam	40%
Combi-boiler	Improved efficiency combi boiler	60%
	Condensing combi boiler	65%
Throughflow heater	Geyser	55%
	Cogeneration / heat pump	70%
	Steam	45%
	Electrical	33%

Nominal conversion efficiency for various types of heating installations [7]. The values presented here are a policy choice by the Dutch ministries of VROM and Economic Affairs.

Zone and country	Solid fuels	Oil	Gas	Electri-city	Heat	Renewable energy sources	Number of households	Share of zone
	%	%	%	%	%	%	Mio.	%
Zone 1	**0.7**	**32.6**	**36.8**	**11.8**	**0.1**	**17.9**		
Malta	0.0	55.0	0.0	44.7	0.0	0.0	0.13	0.1
Cyprus	0.0	23.0	0.0	52.2	0.0	24.4	0.30	0.3
Portugal	0.0	25.3	3.3	22.2	0.0	49.1	5.30	6.0
Greece	0.1	74.0	0.0	5.4	0.8	19.9	5.50	6.2
Spain	1.2	35.5	22.2	23.4	0.0	17.6	20.90	23.7
Italy	0.0	24.7	67.2	3.0	0.0	5.0	26.50	30.1
France	1.3	31.4	33.1	10.4	0.0	23.8	29.50	33.5
Zone 2	**4.7**	**17.0**	**51.3**	**5.1**	**14.9**	**6.9**		
Belgium	1.7	39.9	40.7	15.3	0.4	2.1	4.80	4.5
The Netherlands	0.1	0.8	92.9	0.5	2.8	2.9	6.80	6.4
Ireland	16.6	41.8	21.8	18.1	0.0	1.7	1.60	1.5
Hungary	4.0	4.4	65.4	0.7	15.9	9.5	4.10	3.8
Slovenia	0.0	40.5	6.2	7.8	16.2	29.3	0.80	0.7
Luxembourg	0.0	47.8	43.7	0.0	5.9	2.6	0.20	0.2
Germany	1.1	27.8	44.5	3.0	15.6	7.9	38.90	36.4
United Kingdom	2.7	7.5	79.7	9.5	0.0	0.6	25.60	24.0
Slovakia	4.3	0.2	57.2	0.0	36.7	1.3	1.90	1.8
Denmark	0.0	14.2	14.5	1.1	59.3	10.8	2.60	2.4
Czech Republic	9.5	1.0	38.9	10.4	31.7	8.4	4.40	4.1
Austria	2.3	29.6	24.1	6.1	11.0	26.8	3.30	3.1
Poland	23.9	6.6	13.6	0.3	41.6	14.0	11.80	11.0
Zone 3	**0.6**	**6.8**	**1.0**	**25.5**	**50.7**	**15.4**		
Lithuania	2.4	4.3	4.0	2.2	57.7	29.0	1.30	13.1
Latvia	1.2	3.8	2.9	0.3	46.5	45.1	1.00	10.1
Estonia	1.4	13.0	0.0	12.1	56.7	17.3	0.60	6.1
Sweden	0.0	2.4	0.2	43.2	51.3	2.8	4.40	44.4
Finland	0.3	15.0	0.5	20.0	46.4	17.8	2.60	26.3

Heating energy carrier mix for EU-25 [8].

REFERENCES

[1] J. Duffie and W. Beckman, "Solar Engineering of Thermal Processes, 3rd Ed.", Wiley Publishing.

[2] PVT Roadmap; A European Guide for the Development and Market Introduction of PV-Thermal Technology. www.pvtforum.org

[3] PVCatapult, "D8-6: PVT Performance Measurement Guidelines", Contract No 502775(SES6), 2005. www.pvtforum.org

[4] **Chow et al, 2006 ???**

[5] Coventry, J. S., Lovegrove, K., Development of an approach to compare the 'value' of electrical and thermal output from a domestic PV/thermal system, Solar Energy, 75, 63-72, 2003.

[6] Taylor et al.(??), , Energy Efficiency indicators for Public Electricity Production from fossil fuels - IEA Information paper, 2008.

[7] Bosselaar, L., Gerlagh, T. (2006), Protocol monitoring renewable energy – update 2006, publication number 2DEN0611 (in Dutch).

[8] Cijfers en Tabelen, Novem publication, 2006.

[9] Nemry, F., Uihlein, A., Environmental Improvement Potentials of Residential Buildings (IMPRO-Building), JRC report (ftp.jrc.es/EURdoc/JRC46667.pdf), 2008