Renewable Energy 35 (2010) 2689–2697

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Framework for analysis of solar energy systems in the built environment from an exergy perspective

H. Torío*, D. Schmidt

Department of Energy Systems, Fraunhofer Institute for Building Physics, Gottschalkstrasse 28a, D-34127 Kassel, Germany

ARTICLE INFO

Article history:
Received 14 October 2009
Accepted 18 April 2010
Available online 14 May 2010

Keywords:
Exergy/energy analysis
Direct-solar systems
Primary energy sources
Building systems
Solar thermal systems
Photovoltaic systems

ABSTRACT

Exergy analysis is a more powerful tool than mere energy analysis for showing the improvement potential of energy systems. Direct use of solar radiation instead of degrading other high quality energy resources found in nature is advantageous. Yet, due to physical inconsistencies present in the exergy analysis framework for assessing direct-solar systems commonly found in literature, high exergy losses arise in the conversion process of solar radiation in direct-solar systems. However, these losses are disregarded in indirect-solar systems.

In this paper, contradictions and physical inconsistencies which result from including the conversion of solar radiation only for direct-solar systems are shown. An evaluation framework physically coherent for systems making direct and indirect use of solar radiation is derived and its physical correctness is thoroughly discussed. Results from case studies using the proposed framework are presented and compared with the conventional approach, enabling their direct comparison and better understanding of the benefits and correctness of the proposed method. The new method allows recognizing clearly the suitability of direct-solar systems, being appropriate for highlighting more sustainable energy supply systems.

Although this paper focuses on building systems, the framework might be used for exergy analysis of direct-solar systems in the context of other energy uses.

1. Introduction

Exergy is a thermodynamic property of a system, defined as the maximum theoretical work obtainable as the system is brought into equilibrium with its environment [1], i.e. it represents the useful part of an energy flow which could be transformed into any other energy form. A detailed description and derivation of the exergy concept can be found in [1]. Exergy analysis is a more powerful tool than mere energy analysis for the determination of the improvement potential and suitability of using an energy source for supplying a certain use, since it joints both the concepts of used energy quantity (1st law analysis) and energy quality or potential (2nd law analysis) [2,3]. Therefore, this paper focuses on the analysis of building systems making a direct use of solar radiation from an exergy perspective.

It is a scientific fact that solar radiation represents a high quality energy flow, i.e. has high exergy content. Consequently, its degradation to low quality energy forms is possible, enabling hereby many of the energy processes and interactions on earth [2,4,5]. Natural exergy losses connected with the natural degradation of solar radiation are one of the main causes of many energy processes on earth [2,6]. Following, in this paper energy systems are classified into (i) direct-solar systems, which make a direct use of solar radiation (e.g. solar thermal, photovoltaic systems or windows in the building envelope) and (ii) systems making an indirect use of solar radiation (e.g. heat pumps, wind turbines, etc.), in the following referred to as indirect-solar systems.

Environmental impact can be reduced by taking advantage of the openness of the earth as energy system and maximising the direct use of solar radiation instead of degrading other high quality resources found in nature [7], since the degradation of high quality solar radiation into low-temperature heat happens naturally. Yet, due to the physical inconsistencies found in the exergy analysis framework used in the literature for evaluating direct-solar systems, high exergy losses seem to occur only in the conversion process from solar radiation to other energy forms in direct-solar systems. These losses are disregarded for indirect-solar systems. In consequence, direct-solar energy use may seem unsuitable or disadvantageous from an exergy perspective when compared to other energy systems (e.g. fossil fuelled boiler), as it will be shown in Section 6.

* Corresponding author. Tel.: +49 561 804 1871; fax: +49 561 804 3187.
E-mail address: herena.torio@ibp.fraunhofer.de (H. Torío).

0960-1481/$ – see front matter
doi:10.1016/j.renene.2010.04.015

Nomenclature

A	Area, m^2
$\dot{En}$	Energy flow, *W*
$\dot{Ex}$	Exergy flow, W
I	Irradiance per unit tilted area, W/m^2
T	Temperature, K

Acronyms

ACH	Air changes per hour
CEC	Cumulative exergy consumption
COP	Coefficient of performance
DIN	Deutsches Institut für Normung
DHW	Domestic hot water
ECBCS	Energy Conservation in Buildings and Community Systems
ECEC	Ecological cumulative exergy consumption
EEA	Extended exergy analysis
EFH	Single family house (from German)
ELCA	Exergy life cycle analysis
GSHP	Ground-source heat pump
ICEC	Industrial cumulative exergy consumption
IEA	International Energy Agency
PV	Photovoltaic
SDHW	Solar domestic hot water system

Subscripts

0	Reference
coll	Collector
in	Inlet
out	Outlet
phys	Physical (boundary)
tech	Technical (boundary)
s	Sun
sol	Solar

In Section 2 of this paper the relationship between primary energy and direct-solar energy use as found in current building standards is introduced. The role of exergy in currently available building regulations is also presented here. A review of developed boundaries and methodologies for exergy analysis is presented in Section 3. In Section 4 contradictions and physical inconsistencies existing in the exergy analysis framework found commonly in the literature for analysis of direct-solar systems are highlighted. Based on the inconsistencies found, an evaluation framework physically coherent for systems making direct and indirect use of solar radiation is derived and presented in Section 5. Its physical correctness is thoroughly discussed in Sections 5 and 6. In addition, in Section 6 the conventional approach and the method proposed here are applied to four different building systems as case studies, enabling a direct comparison of both approaches and a better understanding of the benefits and correctness of the proposed method.

The proposed framework allows evaluating all energy systems, direct- and indirect-solar systems, on a common basis and makes exergy losses in their conversion processes comparable. The importance and benefits of using direct-solar systems can be clearly recognised with the proposed approach, being a suitable method for highlighting more sustainable and suitable energy supply systems.

2. Primary energy and exergy in the standards

Primary energy has been defined as the energy from natural resources which is used to supply a certain end-energy demand including extraction, transformation and distribution losses of the energy carrier [8,9]. Solar energy is also regarded as primary energy, i.e. as an available natural resource, equivalent to wind and superficial ground-source heat. The German standard DIN V 18599-1 [8] foresees the calculation of primary energy flows by multiplying the given end-energy flows by so-called primary energy factors. These primary energy factors intend to account for the energy used in the extraction, transport and process of a given end-energy flow and are defined separately for renewable and fossil energy flows [8]. However, in order to recognize the environmental benefits of using renewable energy sources in terms of CO_2 emissions, only primary energy factors associated to fossil energy sources shall be used in final assessment of primary energy input into a building. In consequence, renewable energy flows are excluded from the balance. Only auxiliary energy required to operate the renewable energy systems considered is included in the assessment. In this way, penalization of solar energy is avoided. A similar approach can be found in EN 15603 [10], where primary energy factors are defined separately for renewable and not renewable sources. This Standard [10] defines “not renewable primary energy balances” (based on assessment of fossil energy flows) and “total primary energy balances”. Energy flows from renewable sources are regarded only as part of the total primary energy balance.

The International Energy Agency (IEA), in turn, includes energy from renewable energy sources such as superficial ground heat and solar energy in the energy supply and, thus, on the efficiency of energy supply in a country [11].

Exergy allows comparing all energy sources, renewable and not renewable on a common and scientifically anchored basis [12], therefore being a suitable additional parameter for measuring the efficiency of the energy supply in a building, regional or national scale. This allows characterising the quality levels of different energy supply sources in addition to their quantity. In [13] an attempt to include exergy efficiency in energy regulations for buildings can be found.

The methodology proposed in the present paper could be applied to evaluate different direct uses of solar energy for supplying a given exergy demand (e.g. space heating demands on a national scale) on the basis of their achieved exergy output (instead of accounting for the total solar radiation required as input). Different exergy levels would need to be defined, thus, for direct-solar thermal (low exergy) and photovoltaic (high exergy) technologies. Following, beyond decreasing CO_2 emissions, direct use of solar energy, e.g. for substituting fossil fuels in the production of low-temperature heat (e.g. for space heating), would significantly contribute to increase the exergy efficiency of the energy supply on a country or system level.

3. Review of boundaries for exergy analysis

Exergy analysis is used to detect and quantify the improvement potential of energy systems [2], and makes possible to find suitable energy sources for a certain energy use by matching the quality levels of supply and demand [14]. However, if the whole production chain or the interaction with natural ecosystems is excluded, the advantage of exergy analysis for environmentally conscious decision making is greatly reduced. To overcome this barrier, several thermodynamic methods have been developed to analyse systems on scales larger than individual equipment or single processes. Cumulative exergy consumption (CEC) [2] and industrial cumulative exergy consumption (ICEC) [15] consider exergy consumed in every conversion step of industrial processes starting from natural resources. However, exergy required for the production of those natural resources (conversion process from column 1 to column 2 in Fig. 1) is excluded from the analysis. In turn, ecological cumulative exergy consumption (ECEC) includes the exergy consumption occurring in the production of those natural resources in ecological systems. Exergy of solar radiation, tidal energy and geothermal energy are regarded as inputs for the ecological systems [15]. Moreover, extended exergy analysis (EEA) and the so-called emergy method, include the contribution of labour to the production chain in the analysis framework [16]. Exergetic life cycle analysis (ELCA) regards, in addition to the supply chain, the exergy consumption in the disposal and use of the products [17].

3.1. Review of boundaries for exergy analysis of direct-solar systems

Most of the papers devoted to exergy analysis of direct-solar systems found in the literature include the conversion process of solar radiation into other energy forms. Bejan [18] derives the optimum operation temperature for maximising the exergy extraction from a solar thermal collector under varying environmental conditions. Bejan concludes that the exergy obtained is maximised when the outlet temperature from the collector is maximised as a function of the incident radiation. In [19–23] energy and exergy analyses of a solar thermal collector, solar thermal power system, solar absorption cooling system, and solar domestic hot water (SDHW) systems are presented. These studies regard exergy of solar radiation as input into the direct-solar system assessed, i.e. the conversion of solar radiation into heat or electricity is taken into account. Following, all authors above conclude that the greatest exergy losses in the system (on the range of 90% of the total losses in the system) occur in the collector field. These exergy losses, due to the conversion of high quality solar radiation into low-temperature heat, are also present in the production of other so-called "primary energy sources" (column 2 in Fig. 1), but they are usually disregarded in the analysis, as shown in the following section.

In turn, Meir [24] obviates solar radiation as an input for direct-solar systems. Sandnes [25] also takes this approach for analysing control strategies and operational modes for solar combi-systems. The use of this approach leads Sandnes to conclude that control strategies of solar thermal systems should try to adapt the collector outlet temperatures in order to provide the minimum temperature required to supply the given energy demand. However, in [24] and [25] neither a discussion on the physical consistency nor a comparison of their approach with the conventional method can be found. In turn, in this paper a thorough discussion on the

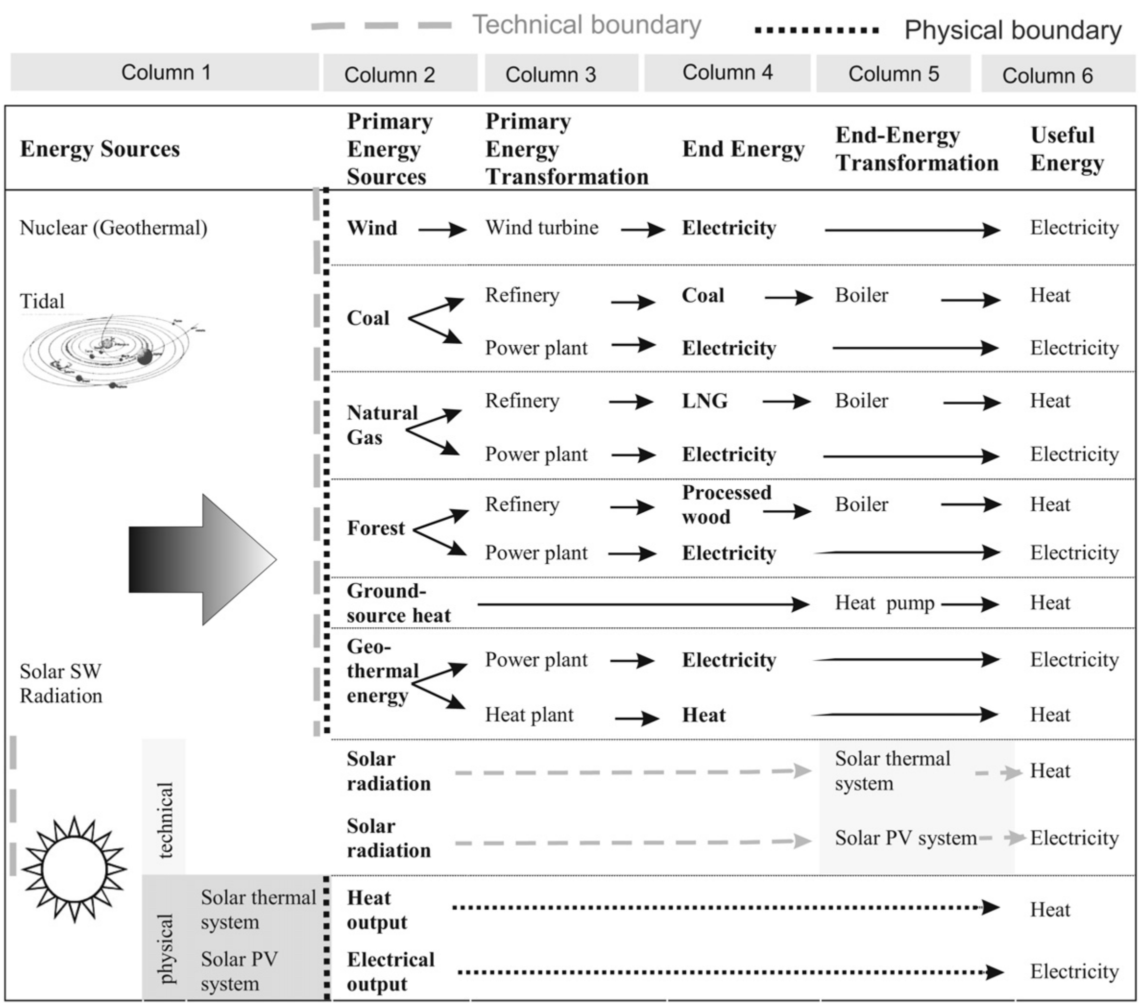

Fig. 1. Energy chain for 12 energy systems, from "sources" to final uses, including direct-solar systems. The dashed light grey line represents the "technical boundary" typically used for the analysis of energy systems. The dotted dark grey line represents the "physical boundary" proposed in this paper.

physical correctness of this framework is presented and the main differences in the achievable conclusions from such analysis are presented.

4. Boundary based on technical viewpoint

In Fig. 1, a schematic view of the energy conversion chain, from energy sources (column 1) to final uses (column 6), is shown for 12 energy systems. Energy sources regarded in column 1 of Fig. 1 are in accordance to those shown in [5] and [26]. Solar energy is one of the very first energy inputs (besides tidal and nuclear energy, as it is shown in column 1 of Fig. 1) from which all other energy sources available are derived (e.g. wind and superficial ground-source heat). Thus, in the present paper, solar energy is regarded as an "energy source" (column 1) and not as "primary energy source" as it is done in the regulations presented in Section 2. "Primary energy sources" (column 2 in Fig. 1), in turn, are regarded here as those natural energy resources present on the earth ecosystem and derived from the very first energy inputs (i.e. "energy sources"). Two different boundaries are shown by the dotted line (physical) and by the dashed line (technical).

When analysing the energy conversion chain of any certain appliance or usage, the conversion process from the energy inputs into the earth as energy system ("energy sources", column 1 in Fig. 1) into "primary energy sources" (column 2) is often left out of consideration. In other words, the efficiency of the conversion from solar radiation into the kinetic energy in the wind, chemical energy in wood or low-temperature heat in the earth surface (i.e. ground-source heat) is disregarded: the energy content of these "primary energy sources" is considered as existing within the earth-system and ready to be used. Thus, "primary energy sources" are regarded as the first energy input in the primary energy transformation system (column 3).

As an example, in an energy or exergy analysis of a building with a ground-source heat pump (GSHP), electrical energy required for the operation of the heat pump, and thermal energy extracted from the ground are considered as inputs for the system. This approach can be found in [27,28]. Accordingly, taking outdoor air temperature as reference, the quality factor for the energy coming from the ground would be very small, for it is energy at a low-temperature level, i.e. with low exergy content. The fact that low-temperature ground heat stored comes to a large extent from the solar radiation absorbed and stored in the ground, is left out of consideration. Detailed distributions of the incident solar radiation absorbed by the oceans, atmosphere and ground surface can be found in [26].

This boundary is then drawn from a "technical" point of view (dashed line): the boundary that encloses the system to be studied begins at the step where some form of technical or artificial input (human intervention) is required to convert and make use of the available energy. The reason behind is that by these means, those energy conversion processes where human intervention takes place are analysed and so the efficiency of human-made devices can easily be studied and improved. This boundary (in the following referred to as "technical boundary") is usually kept also for the analysis of systems making direct use of solar radiation (light grey dashed line in the penultimate row in Fig. 1), e.g. solar thermal, and photovoltaic (PV) systems. In consequence, for these systems, the conversion of solar radiation as high quality energy into low-temperature heat or electricity is considered, since solar energy is the direct naturally available input in these systems and its conversion happens through an artificial human-made device whose efficiency needs to be assessed and improved. Most of the studies mentioned in Section 3.1 follow this framework.

However, from a physical point of view, an inconsistency arises from this analysis framework: the efficiency of the conversion from solar radiation into other energy forms is included in the analysis of direct-solar systems and left out in the rest (i.e. indirect-solar systems). In consequence, efficiencies as well as total energy and exergy losses of indirect- and direct-solar systems are not comparable, since in direct-solar systems a further energy conversion process is being regarded. Therefore, this boundary might be used for comparing different direct-solar systems among themselves but not for comparing direct- and indirect-solar systems.

5. Boundary based on physical viewpoint

In order to withdraw a physically consistent boundary for direct-solar systems, the conversion process from solar radiation into heat or electricity should be disregarded, similarly as it is done for the rest of energy systems. Thus, thermal energy output of a solar collector field at its corresponding temperature level or electricity output of a PV system should be regarded as primary energy sources, as shown graphically in the last row of Fig. 1 (dotted dark grey line). In Fig. 1 the dotted dark grey line represents graphically this analysis boundary, which in the following will be referred to as "physical boundary".

In this approach energy efficiency of the conversion from solar radiation by direct-solar systems is implicitly considered, for it determines the available energy and exergy output from the systems. However, a common goal of solar energy engineering is to assess and improve the efficiency of different direct-solar systems. For this aim, the efficiency of the systems must be explicitly stated in the analysis. Energy efficiency in the solar conversion process can be explicitly included in this approach by an additional parameter, namely the total required area to be installed. In direct-solar systems the efficiency of the energy conversion in the solar system determines the required area to be used for supplying a requested given output. Characterising direct-solar systems in terms of their required installed area and exergy output allows comparing on one hand the efficiency of the solar energy conversion, since improvements in the energy efficiency of the solar energy conversion would reduce the required area, while the same exergy output would be maintained. On the other hand, for a given final energy use (i.e. exergy demand) the exergy output of direct-solar systems allows evaluating the suitability (efficiency) of different systems to provide the requested demand. This is shown in Figs. 4 and 6, in the following section, where exergy losses are shown for a solar thermal and photovoltaic system used to provide space heating (low exergy) demands. The suitability of solar thermal systems for this particular application can be clearly recognised from the figures.

Furthermore, a comparison between different kinds of direct-solar systems (PV, collectors, hybrid PV-thermal, solar thermal power plants) aiming at assessing the best use of solar exergy would also be possible following this approach. The best use of solar radiation would mean, then, to maximise the exergy output. For a given available area, or available solar resource (radiation), the system with the greatest exergy output would be the best performing one.

Alternatively to the "physical boundary", which is the approach proposed in this paper, the boundary for analysis could also be drawn at the beginning of column 1 for all energy systems. This would lead to include the conversion of the energy sources (column 1) into primary energy sources (column 2) for all energy systems. This evaluation framework would be analogous to that of the ecological cumulative exergy consumption (ECEC) [15], extended exergy analysis (EEA) and the emergy approach [16]. However, translating all energy processes to the ultimate and actual energy sources (column 1 of Fig. 1) implies increasing the level of inaccuracy in the assessment. This is one of the main criticisms from Sciubba to the emergy method in [16] and it is identified as one

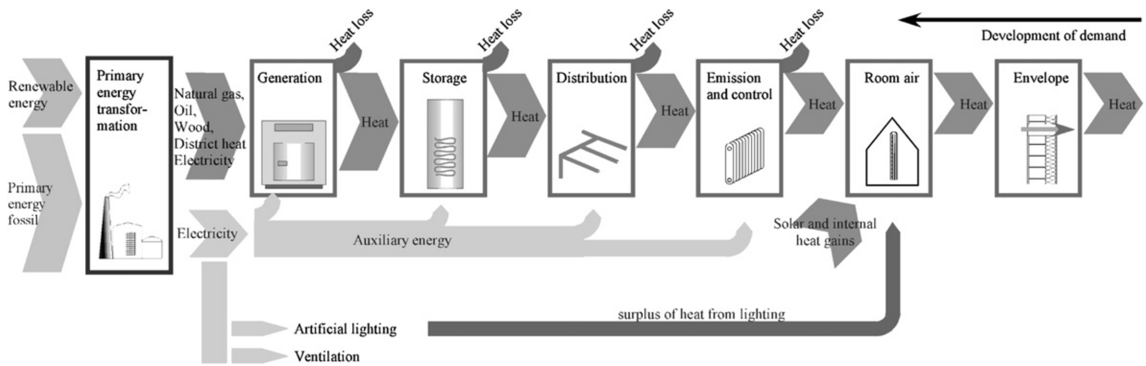

Fig. 2. Subsystems and energy flows considered for the case studies analysed. Energy flows and subsystems, from source to sink, correspond to the modular method for analysing building's energy supply chain developed by Schmidt (2004).

challenge to be solved by Ukidwe and Bakshi [15]. The analysis of such long term and global scale processes implies assumptions regarding the energy balances and flows on the earth ecosystem. In his analysis for global energy flows, Sørensen [26] also explicitly mentions these inaccuracies in energy terms.

In turn, the framework proposed here, which leaves the ecological formation of energy sources out of consideration, is not affected by these inaccuracies and represents a solid analysis method, upon which holistic methods, such as EEA or ECEC, could be implemented straightforwardly and with relative ease.

6. Case studies using both boundaries

In order to provide a clearer picture on the difference between the "technical" and "physical" boundaries for evaluating direct-solar systems, both approaches have been applied to several theoretical case studies. Steady-state calculations for direct-solar systems (solar thermal and PV systems) have been carried out. Results for these systems are presented and compared with other building systems typically used for space heating, namely a condensing boiler and a ground-source heat pump. Steady-state calculations are performed for typical operating conditions of the systems studied stated in Tables 2 and 3. For a detailed assessment and comparison of the yearly energy and exergy performance of the systems dynamic analysis would be necessary. However, the focus of this paper is to compare the approaches for exergy analysis presented in Sections 4 and 5 and for this aim steady-state analysis is a suitable approach. Results for the energy and exergy flows estimated represent steady-state values for the conditions assumed (see Tables 2 and 3) and are not yearly energy or exergy demands for the studied building.

Steady-state energy and exergy analyses have been performed with an Excel tool based on that developed within the framework of IEA ECBCS Annex 37 [14]. The tool and calculation approach follows the method developed by Schmidt [29], which divides all processes involved in energy supply in buildings into several blocks or subsystems, from the primary energy conversion to the final heat transfer through the building envelope, as shown in Fig. 2 (left to right). Energy processes within and between the blocks are assessed following an input–output approach. This modular approach aids in developing a better understanding of the processes involved in each subsystem and makes easier to compare results obtained for different building systems under analysis.

A single family house has been chosen as case study. The building geometry and insulation standard have been defined according to the German residential building typology study (type EFH_I) developed by IWU [30]. The net heat transmission coefficient[1], H'_T, following the German regulation [31], amounts 0.44 W/m^2 K. The air exchange rate due to the opening of windows and air leakages in the building envelope has been regarded as 0.6 ACH[2], and no domestic hot water (DHW) consumption has been considered. Only the space heating demand and the auxiliary energy required to provide it have been evaluated here. Specific power for lighting (2 W/m^2), appliances (2.05 W/m^2) and 2.05 occupants (80 W/occupant), directly contributing to internal gains in the building, have been assumed. Table 1 shows the case studies analysed. All cases consist of the same building and only the space heating supply system (so-called "generation" subsystem in Fig. 2) has been varied. In all cases, a floor heating system with supply and return temperatures of 28/22 °C has been considered. Main parameters defining the operation of the subsystems in the case studies analysed are shown in Table 2. Relevant temperatures for energy and exergy analysis are shown in Table 3. Outdoor air temperature is regarded as reference temperature for exergy analysis.

For evaluating the exergy of solar radiation, the approach from Jeter [32] has been used, i.e. exergy of solar radiation is regarded as the availability of a heat flow at the sun temperature, considered here as 5727 °C [26]. This is a simplified approach where the exergy of solar radiation is not treated as a radiative transfer but as the heat available from direct contact with the sun surface.

The exergy of solar radiation onto the collector surface estimated with equation (1) represents the exergy input into the generation subsystem when the technical boundary is applied. With this approach, the quality factor associated to solar radiation is 0.95. In equation (1) the exergy of solar radiation is expressed as a function of the incident irradiance on a unitary area of tilted collector plane, I_s (in W/m^2), collector surface, A_{coll} (in m^2), sun temperature, T_s (in K), and the reference temperature, T_0 (in K).

In turn, equation (2) shows the expression for calculating the exergy output from a solar thermal collector, which is the input into the generation subsystem (Fig. 2) when the "physical boundary" is applied. The conversion of solar radiation into heat is disregarded, and exergy output from the collector is in the form of low-temperature heat. Therefore, the exergy output from solar collector field is expressed as a function of the respective collector inlet, T_{in},

[1] H'_T represents the value of the heat transmission coefficient of all surfaces of the building envelope, including thermal bridges, weighted according to the area of each envelope element and with factors for accounting adjacent zones to the building at different temperature levels others than outside air.

[2] ACH stands for air changes per hour and represents the number of times that the total building net volume is replaced in 1 h. Its unit is h^{-1}.

Table 1
Cases analysed.

Cases
1 EFH_I with liquefied natural gas (LNG) condensing boiler
2 EFH_I with solar thermal system (covering 100% of space heating demand)
3 EFH_I with PV powered electrical boiler (covering 100% of space heating demand)
4 EFH_I with PV powered (borehole) GSHP (water/glycol)

Table 3
Main relevant temperatures for energy and exergy analysis of the cases studied.

Main relevant temperatures	Temperature [°C]
Outdoor air temperature	0
Indoor comfort temperature	21
Sun temperature	5727
Outlet/inlet temperature solar collector	80/40
Ground temperature	10

and outlet, T_{out}, temperatures, the reference temperature, T_0 , and the energy output from the collector field, $\dot{E}n_{coll}$ (in W).

$$\dot{E}x_{sol,tech} = I_s \cdot A_{coll} \cdot \left[1 - \frac{T_0}{T_s}\right] \quad (1)$$

$$\dot{E}x_{sol,\ phys} = \frac{\dot{E}n_{coll}}{(T_{out} - T_{in})} \cdot \left[(T_{out} - T_{in}) - T_0 \cdot \ln\left(\frac{T_{out}}{T_{in}}\right)\right] \quad (2)$$

As stated in Section 5, a complete comparison of direct-solar systems can be done in terms of their exergy output and required area. The necessary installed area can be calculated according to equation (3). The parameter η_{sol} represents the efficiency of the direct-solar energy converter, i.e. solar thermal collector or PV modules. Values assumed here for the efficiency of solar converters are shown in Table 2. For estimating the area of all direct-solar systems considered here an incident solar radiation of 800 W/m^2 per unitary area of tilted solar field has been regarded.

$$A_{sol} = \frac{\dot{E}n_{coll}}{\eta_{sol} \cdot I_s} \quad (3)$$

In Figs. 4–6 energy and exergy flows through the supply chain for space heating in the building regarded are shown following the methodology in [29]. Steady-state analysis for a single timestep has been performed. Thus, results are presented in terms of power, i.e. energy and exergy flows.

In the abscissa, the different subsystems in the energy supply chain are represented, following those shown in Fig. 2. On the ordinate, energy and exergy flows in terms of instantaneous power input and output for each subsystem are shown, according to the assumptions mentioned in Tables 2 and 3. Following, energy and exergy losses are the difference between the respective input and output in each subsystem and can be seen graphically for each subsystem as directly proportional to the slope of the curves. In all cases, energy flows after the building envelope turn zero, for all energy supplied is dissipated to the surrounding environment and, thus, regarded as “lost” from the point of view of the building as energy system. Similarly, exergy is always zero after the building envelope, for it represents the exergy of an energy flow at outdoor (reference) temperature. Thus, total exergy and energy losses over the subsystems are equal to the primary exergy and energy supplied (input in the “primary energy transformation” subsystem). Auxiliary electrical energy for the operation of the building systems is included in the corresponding subsystem. Energy and exergy losses from the electricity production process are regarded in the “primary energy transformation” step. An efficiency of 40.6% has been assumed for conventional electricity generation (it does not apply for electricity from the PV system).

In Fig. 3, energy and exergy flows using the technical boundary for the analysis are presented for case 1 (condensing boiler) and case 2 (solar thermal system). From both an energy and exergy perspective, the condensing boiler seems advantageous for supplying the space heating demand as compared to the solar thermal system. Using this assessment approach (technical boundary), exergy losses from converting directly solar radiation into heat in the collector field are even greater than those occurring when high quality fossil fuels are burned to produce low-temperature heat. The reason for this is that the conversion of solar radiation into liquefied natural gas (LNG) is not included in the analysis of the condensing boiler (case 1). This is shown graphically by the position of the white sun outside the diagram field, leaving this conversion step before the primary energy transformation. Yet, the

Table 2
Main relevant parameters assumed for the operation of the systems under analysis. Energy efficiencies of the solar thermal and photovoltaic systems are only relevant if the technical boundary is applied to the analysis.

Parameters	Energy efficiency [−]	Auxiliary energy [W/kW$_{heat}$]
Condensing boiler	0.95	1.80[a]
Borehole heat pump, COP[b]	3.28	2.00
Electric boiler	0.98	0.02
Solar thermal collector	0.70	10.00
Photovoltaic modules	0.15	–
Storage system	0.95	2.00
Distribution system	0.86	8.26
Emission system (floor heating 28/22 °C)	0.99	2.00

[a] In addition to the demand-dependent auxiliary energy demand, a constant auxiliary power consumption of 20W was assumed for the condensing boiler.
[b] COP stands for coefficient of performance.

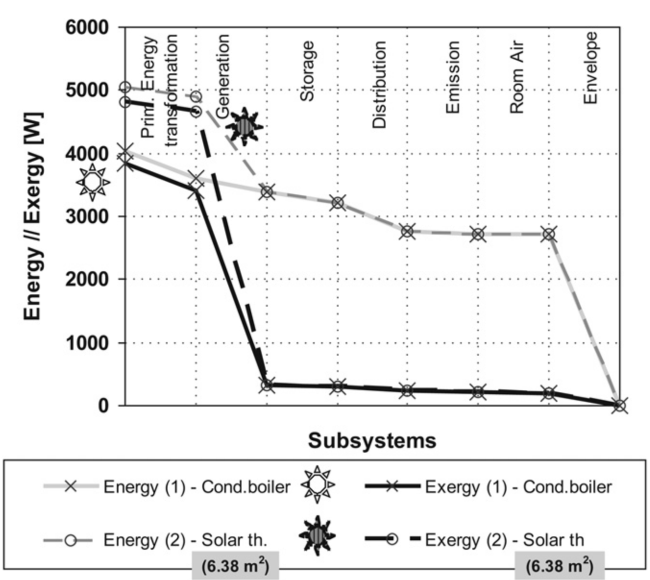

Fig. 3. Energy and exergy flows for cases 1(LNG condensing boiler) and 2 (solar thermal system) following the “technical boundary” for the direct conversion of solar radiation. The position of the sun indicates in which step of the energy supply chain the conversion of solar radiation has been regarded: for case 1 (white sun) this conversion process has been disregarded and therefore it is out of the diagram field; for case 2 (grey sun) this process has been regarded in the generation step (solar radiation is transformed into low-temperature heat). Required installed area of solar thermal collectors in case 2 is indicated.

conversion of solar radiation is indeed included in the generation step in case of the solar collector field (case 2). This is shown graphically by the position of the grey sun in the generation subsystem. Energy losses for case 2 in the generation subsystem amount 30% (a collector efficiency of 70% was assumed, see Table 2). Exergy losses associated to the direct conversion of solar radiation into low-temperature heat in this step for case 2 amount, in turn, 93%.

A similar situation occurs when comparing direct-solar systems with ground heat, wind or wood-based systems. If exergy losses throughout the century-long process of the formation of LNG were depicted, exergy losses for case 1 would be much greater than for case 2 and physical consistency would be ensured. This would be similar to the ECEC or emergy approaches, as mentioned in Sections 3 and 5.

Furthermore, regarding the conversion of solar radiation into heat or electricity in direct-solar systems is inconsistent with the evaluation of passive solar gains through the glazed surfaces in the building envelope. Passive gains are directly evaluated as heat at room temperature made available by the solar radiation passing through the windows [29]. The conversion of solar radiation into indoor heat, and the subsequently high exergy losses related to it, is not regarded.

For completeness, the required solar thermal collector area for providing this demand has been calculated according to equation (3) and is shown in Fig. 3.

In turn, in Fig. 4, results using the boundary proposed in this paper (physical boundary) are shown for cases 1 and 2. The conversion of solar radiation is not regarded, either into LNG or into low-temperature heat, i.e. in both cases this process is left out of the diagram (as shown graphically by the position of the grey and white sun at the left of the "primary energy transformation" subsystem outside the diagram field). In consequence, low-temperature solar heat from the collector field is considered as a primary energy source (column 2 in Fig. 1), just as LNG. Following, the solar collector system is able to supply the space heating demand with much lower exergy level.

Lower primary exergy input means that lower exergy losses through the supply process occur, and, thereby, indicates a more appropriate system to provide the required demand. In other words, lower primary exergy input indicates better matching between quality levels of energy supplied and demanded. Total exergy input in case 2 (818 W), which is equal to the exergy losses over the whole supply process, is significantly lower than that in case 1 (3843 W). Hereby, the suitability of a direct use of solar radiation instead of using fossil fuels to supply low-temperature heat for space heating applications is shown.

For completeness, cases 1 and 2 have also been compared with the rest of energy supply systems proposed in Table 1. Figs. 5 and 6 show results for the energy and exergy flows using the boundary proposed in this paper (physical boundary). Since the same storage, distribution and emission subsystems have been regarded in all cases, energy and exergy output from the generation subsystem, required to provide the given energy and exergy demands, are the same in all cases. Additionally, since all energy flows, renewable and fossil are depicted in Fig. 5, energy inputs into generation subsystems required by all systems are very similar.

In turn, in Fig. 6 renewable and fossil energy flows are evaluated in exergy terms and significant differences can be seen among the four cases. Since the building is the same for all cases analysed, energy and exergy demand required to keep indoor air at 21 °C amount 2729 W and 194 W, respectively, in all cases. An ideal system would be able to provide that energy demand with exactly that exergy level (194 W). In turn, total exergy input amounts 3843 W and 3443 W in cases 1 and 3, respectively. On the contrary, if a solar thermal system is used (case 2) total exergy input amounts only 818 W, showing that a better matching can be achieved by means of the solar thermal system, and greatly reducing exergy losses through the energy supply chain. Similarly, if the PV system is used to power a GSHP (case 4) a great amount of low-temperature heat from the ground is made available to supply the low exergy space heating demand. Thus, total exergy input and losses

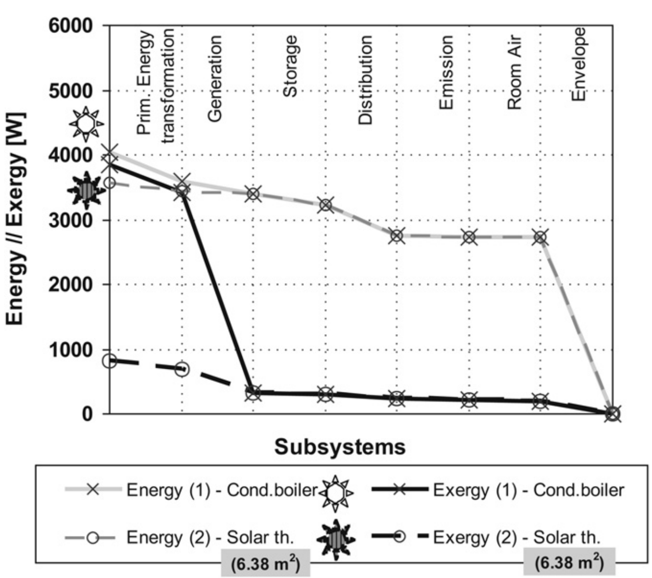

Fig. 4. Energy and exergy flows for cases 1 (LNG condensing boiler) and 2 (solar thermal system) following the "physical boundary" for the direct conversion of solar radiation. The position of the sun indicates in which step of the energy supply chain the conversion of solar radiation has been regarded: neither for case 1 (white sun) nor for case 2 (grey sun) this conversion process has been regarded and therefore it is out of the diagram field, occurring previously to the primary energy transformation step. Required installed area of solar thermal collectors in case 2 is indicated.

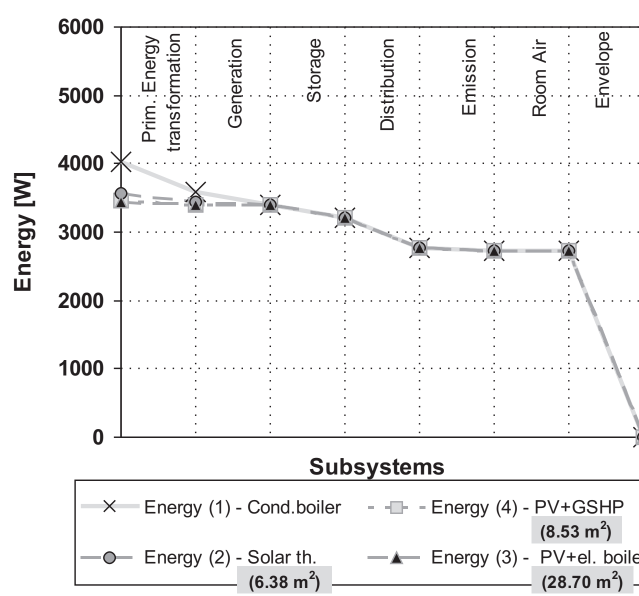

Fig. 5. Energy flows for cases 1 (LNG condensing boiler), 2 (solar thermal system), 3 (solar PV system with electric boiler) and 4 (PV system with GSHP), following the boundary proposed in this paper ("physical boundary") for the direct conversion of solar radiation. Required installed area of solar thermal or PV systems in cases 2, 3 and 4, respectively, is indicated.

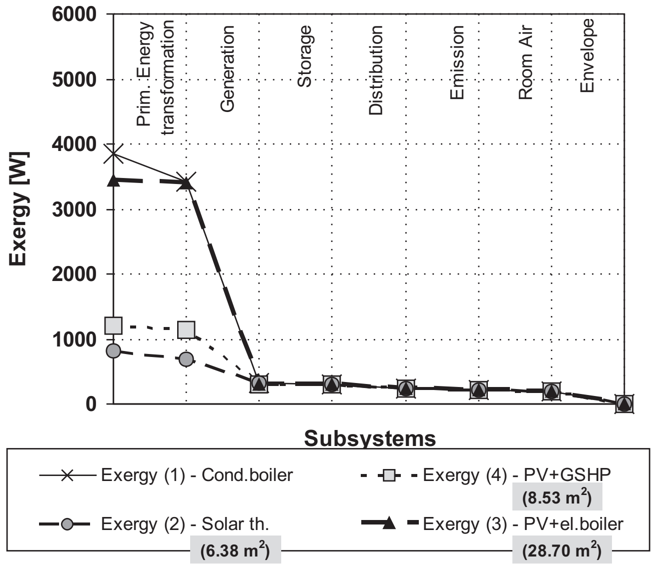

Fig. 6. Exergy flows for cases 1 (LNG condensing boiler), 2 (solar thermal system), 3 (solar PV system with electric boiler) and 4 (PV system with GSHP), following the "physical boundary" for the direct conversion of solar radiation. Required installed area of solar thermal or PV systems in cases 2, 3 and 4, respectively, is indicated.

through the supply chain are drastically lowered (1207 W), representing about one-third of those in cases 1 and 3, therefore being a more suitable and optimal energy system to provide the given demands.

Exergy losses in the generation subsystem for cases 1 (condensing boiler) and 3 (electric boiler powered by a PV system) amount 3342 W and 3316 W, respectively. In both cases high quality energy in the form of LNG (case 1) or electricity (case 3) is being transformed into low-temperature heat by the condensing and electric boilers in the generation subsystem.

This comparison makes obvious that making direct use of solar radiation does not guarantee a thermodynamically optimised system. The unsuitability of using directly electricity for heating (case 3), even if it is produced by direct conversion of solar radiation in PV cells, can be clearly recognised in Fig. 6.

In Figs. 5 and 6 the required area of solar collector field (calculated with equation (3)) for the different direct-solar systems is also shown. Efficiencies for the PV modules and solar thermal collectors are shown in Table 2. PV powered systems here would represent grid-connected systems (for only thermal storage has been regarded, i.e. without electric storage in batteries) producing as much electric energy as they require. For the assumptions made, results from a comparison of the required area are in accordance with conclusions from exergy analysis, being the solar thermal system the most efficient option, followed by the PV powered GSHP and the PV powered electric boiler. However, this might not always be the case. If the energy efficiency of the PV modules or GSHP increases, these systems (cases 3 and 4) might require less area than solar thermal systems (case 2) for providing the given demand. The decision should, then, be made depending on the design criteria: if the goal is to make the best use of solar radiation, the area needs to be minimised. If the goal is to choose a suitable system for providing a given demand, exergy losses need to be minimised.

7. Conclusions

In the physical boundary presented in this paper for the evaluation of direct-solar energy systems the same processes as those considered for energy systems making an indirect use of solar radiation are regarded. With this approach, the conversion of solar radiation into low-temperature heat or electricity is obviated from exergy analysis, in the same way as it is done for other energy sources. Hereby, the proposed framework is equivalent for direct- and indirect-solar systems, and physically consistent. Thus, it allows a proper comparison of their exergy flows on a common basis, as shown in Figs. 4 and 6.

In the technical boundary a further conversion process is regarded exclusively for direct-solar systems, namely conversion of solar radiation into their energy output (heat or electricity). Thus, results from this approach for direct- and indirect-solar systems are not comparable, as shown in Fig. 3.

The boundary defined in this paper is based on physical considerations, and it provides conclusions on the optimisation and suitable use being made of different energy sources, but it does not provide hints on the renewability, environmental impact or depletion of energy sources. By expressing the total solar, tidal or relict-exergy required for the generation of a specific energy source, similarly as proposed in the ECEC, EEA, ELCA and emergy approaches, conclusions on the total exergy losses from source to final useful energy could be withdrawn, giving direct insight into the deterioration of global ecological resources and the environmental impact of certain energy systems. However, this holistic analysis requires the definition of factors which have to be determined on a global scale and for long periods of time, and are subsequently linked to considerable uncertainties. In turn, the proposed framework is system and site-specific, just as common engineering methods for energy systems analysis, and has the same accuracy as such widely used analysis approaches. Yet, to obtain a global picture, holistic analyses could be easily added to the proposed framework.

Given that all energy sources are limited, there is an undisputable need for their rational and careful use, which implicitly means using existing resources in an appropriate and efficient way. This can be accomplished by matching the quality level of the energy supply, to that of the energy demand: for instance, electricity from a PV system could be better used to power appliances or a heat pump than for direct heating purposes (e.g. via an electrical boiler), for which other low quality sources are available and able to meet the (low) exergy demands (e.g. low-temperature ground heat harvested by a GSHP or solar thermal heat). The required area to be installed for different direct-solar thermal systems also needs to be regarded, for it gives an idea of how efficiently the solar resource available is being used.

Furthermore, the proposed boundary could be applied to other energy uses where direct-solar energy use is involved apart from space-heating/cooling, such as day-lighting and lighting demand on buildings, or surplus electricity generation with building integrated PV systems.

Acknowledgments

The authors warmly thank the Deutsche Bundesstiftung Umwelt (DBU) and German Ministry of Economy and Technology for their financial support, and the colleagues from the working group of IEA ECBCS Annex 49 for the lively discussions.

References

[1] Moran MJ, Shapiro HN. Fundamentals of engineering thermodynamics. 3rd ed. New York, USA: John Wiley & Sons; 1998.
[2] Szargut J. The exergy method – technical and ecological applications. Renewable Wiley Interscience; 2005.
[3] Dincer I, Rosen M. Exergy – energy environment and sustainable development. 1st ed. Elsevier Science Publications; 2007. pp. 11–34.
[4] Shukuya M, Komuro D. Exergy-entropy process of passive solar heating and global environmental systems. Solar Energy 1996;58(1–3):25–32.

[5] Szargut J. Anthropogenic and natural exergy losses (exergy balance of the earth's surface and atmosphere). Energy 2003;28(11):1047–54.
[6] Dincer I, Cengel YA. Energy, entropy and exergy concepts and their roles in thermal engineering. Entropy 2001;3:116–49.
[7] Rosen MA. Assessing energy technologies and environmental impacts with the principles of thermodynamics. Applied Energy 2002;72:427–41.
[8] DIN V 18599-1:2007-02. Energy efficiency of buildings – calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting – part 1: general balancing procedures, terms and definitions, zoning and evaluation of energy sources. German National Standard. Berlin: Deutsches Institut für Normung e.V; 2007
[9] Sartori I, Hestnes AG. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy and Buildings 2007;39:249–57.
[10] EN 15603:2008–07. Energy performance of buildings – Overall energy use and definition of energy ratings, European Comittee for Standardization, CEN, Brussels. 2008.
[11] IEA. Key world energy statistics – 2008. International Energy Agency Publications, www.iea.org; 2008.
[12] Schmidt D, Torio H, Kühler D. In: Perspectives of a more efficient energy use in buildings and communities through the use of the exergy concept. Ulm: DKV Tagungsbericht/Deutsche Kälte-Klima-Tagung; 2008.
[13] Favrat D, Marechal F, Epelly O. The challenge of introducing an exergy indicator in a local law on energy. Energy 2008;33:130–6.
[14] IEA ECBCS Annex 37. International Energy Agency – Low Exergy Heating and Cooling of Buildings – Annex 37, 2003. See also: http://www.lowex.net.
[15] Ukidwe NU, Bakshi BR. Industrial and ecological cumulative exergy consumption of the United States via the 1997 input-output benchmark model. Energy 2007;32:1560–92.
[16] Sciubba E, Ulgiati S. Emergy and exergy analyses: complementary methods or irreducible ideological options? Energy 2005;30:1953–88.
[17] Cornelissen RL. Thermodynamics and sustainable development – the use of exergy analysis and the reduction of irreversibility. Doctoral Thesis, Technical University Twente, ISBN 903651053, Enschede, the Netherlands; 1997.
[18] Bejan A. Extraction from exergy from solar collectors under time-varying conditions. International Journal of Heat and Fluid Flow 1982;3(2):67–72.
[19] Luminosu I, Fara L. Determination of the optimal operation mode of a flat solar collector by exergetic analysis and numerical simulation. Energy 2005;30:731–47.
[20] Koroneos C, Spachos T, Moussiopoulos N. Exergy analysis of renewable energy sources. Renewable Energy 2003;28:295–310.
[21] Izquierdo-Millán M, Hernández F, Martín E. Available solar exergy in absorption cooling process. Solar Energy 1996;56(6):505–11.
[22] Gunerhan H, Hepbasli A. Exergetic modelling and performance evaluation of solar water heating systems for building applications. Energy and Buildings 2007;39(5):509–16.
[23] Xiaowu W, Ben H. Exergy analysis of domestic-scale solar water heaters. Renewable and Sustainable Energy Reviews 2005;9:638–45.
[24] Meir M. On creating thermal comfort without energy use. Doctoral Thesis, University of Oslo, Norway; 2002.
[25] Sandnes B. Energy efficient production, storage and distribution of solar energy. Doctoral thesis, University of Oslo, Norway; 2003.
[26] Sørensen B. Renewable energy: its physics, engineering, use, environmental impacts, economy and planning aspects. 3rd ed. USA: Elsevier Academic Press Inc.; 2004.
[27] Essen H, Inalli M, Esen M, Pihtili K. Energy and exergy analysis of a ground-coupled heat pump system with two horizontal ground heat exchangers. Building and Environment 2007;42:3606–15.
[28] Hepbasli A. Exergetic modelling and assessment of solar assisted domestic hot water tank integrated ground-source heat pump systems for residences. Energy and Buildings 2007;39:1211–7.
[29] Schmidt D. Design of low exergy buildings – method and pre-design tool. Bd.3. The International Journal of Low Energy and Sustainable Buildings; 2004:1–47.
[30]. IWU, editor. Deutsche Gebäudetypologie – Systematik und Datensätze. Darmstadt: IWU; December 2003.
[31] EnEV. 2007. Verordnung über energiesparende Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Enegieeinsparverordnung – EnEV); 24 July, 2007.
[32] Jeter SJ. Maximum conversion efficiency for the utilization of direct-solar radiation. Solar Energy 1981;26:231–6.