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Solar energy utilisation

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Solar energy can be used by man in a planned direct way. There are two fundamental methods of solar energy conversion: photothermal and photoelectric. The paper is dealing with the analysis of photothermal conversion in the high latitude countries. Different types of solar active and passive systems are considered. The more reliable the solar system and the higher the temperature requirements, the required technology is more modern and sophisticated, and the construction of the system, together with the automatic control, is more complicated. The degree of complexity depends on the function of the system and required mode of its operation. In the case of solar space heating in high latitude countries, it is evident that thermal performance of solar source is not coherent with the heat demand. Therefore the use of solar energy requires a special upgrading, e.g. in a form of a heat pump or seasonal storage. However, the best idea for efficient use of solar energy is to design a building in a proper way, including the passive systems. The architecture is crucial for the energy balance of a building and it should assure proper use of environment, improving solar energy gains in winter and protecting inside of the building against solar overheating in summer.

Keywords: photothermal conversion of solar radiation, solar active heating systems, heat pumps, solar passive systems, solar architecture, availability of solar radiation, isorads.

1. Planned direct methods of utilization of solar energy

Solar energy can be used by man in a planned direct or indirect way. In the case of indirect utilization of solar energy we consider the use of renewable energies which are secondary effects of solar energy [1,2], i.e., wind energy, hydro energy, ocean energy, and secondary energy from photosynthetic process that is mostly connected with the use of biomass and biofuels. Using solar energy in the direct way we can apply two fundamental methods of energy conversion:

- photothermal conversion of energy of solar radiation;
- photoelectric conversion of energy of solar radiation.

Applying a photothermal conversion of solar radiation energy [3] we consider usually the following systems:

- Active low temperature solar water and air heating or cooling systems, which includes;
  - solar water heating systems with flat plate or vacuum solar collectors,
  - solar air heaters, including crop driers,
  - solar space cooling systems coupled with sorption refrigerator,
  - solar ponds, which are solar collectors and heat stores at the same time. They comprise several layers of salty water. With the increase of depth the salinity (density) increases, convection is suppressed, and the bottom layer is the hottest,
  - solar stills for distilling water.
- Passive low temperature solar heating (cooling) systems, which constitute solar architecture [4,5];
- High temperature solar systems with solar concentrators, in which a working fluid can drive a conventional heat engine to produce mechanical work and if necessary electricity (in this case we consider electric power systems as described below);
- Electric power systems. They utilize collectors with concentrators, which achieve temperature high enough to operate a heat engine to generate electricity. These systems include:
  - electric power system with the distributed concentrating collectors. The collectors transfer the gained solar heat to a working fluid, then the working fluid circulating through an every collector is gathered at the central power station. If the working fluid is steam, it is used directly in a steam turbine. The working fluid could be also a thermochemical storage medium, e.g., dissociated ammonia. Under the solar heat, the ammonia gas (at high pressure) is dissociated into hydrogen and nitrogen, then in the central plant hydrogen and nitrogen are recombined (partially) in the synthesis chamber, the obtained heat can be used to drive the engine,
  - power tower. This system constitutes a large field of sun-tracing plane mirrors, which focus solar rays (beam radiation) on to a large central receiver at the top of a tower.

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Solar radiation can cause photovoltaic generation of a power by separating positive and negative charge carriers in the absorbing material. In a presence of an electric field, the charge carriers can produce a current. Photoelectric devices are electrical current sources driven by a flux of solar radiation. However, solar cells are not the subject of this paper.

When concerned with the effective use of solar energy and other renewables we consider the following characteristic features:

- availability and power of a source,
- coherency between a source and an user,
- capacity of a source,
- low cost of energy extraction/conversion and transmission,
- steady and as high as possible performance of a source,
- energy use/extraction ought not to disturb natural energy balance of the source/environment,
- ecological issues.

The features mentioned above together with geographical location, climate, and local conditions are the most important factors that determine the possibilities of applying solar energy and other renewables and methods of energy conversion. Due to these factors some methods of energy conversion and some types of the system are preferable, and some are limited or even ineffective in the given conditions. In the case of solar energy, the use of high temperature systems with concentrators, electric power system with distributed concentrating collectors or centralised power tower systems, is restricted to special geographical regions characterised by high irradiation with high proportion of beam radiation, and high clearness sky index. Therefore in the high latitude countries it is not viable to apply these systems (even at the present state of a solar technology).

The paper analyses only these solar systems that utilise the photothermal conversion of solar radiation and can operate in effective way in the high latitude countries. These systems are the typical and most popular option for modern low temperature heating systems and particularly they are the active solar water heating systems with flat plate solar collectors and passive solar space heating systems. Nowadays, the applied active and passive solar technologies are mature and start to compete with traditional water and space heating systems.

2. Active solar water heating systems with flat plate solar collectors

2.1. Hot water heating

The main element of an active solar water heating system is a flat plate solar collector. A solar collector, according to its name, is a device to collect solar radiation. Solar energy is absorbed by an absorber, the most important part of the solar collector, and is transferred to a working fluid, which is usually a liquid (antifreeze mixture or water) circulating in pipes connected to the absorber surface. The flow is forced by a pump. A typical flat plate solar collector is shown in Fig. 1. Flat plate solar collectors absorb the beam and diffuse radiation, and in a case of a tilted collectors, as is typical, also the reflected radiation. Even if the sky is cloudy, they can operate efficiently. Solar collectors are heat exchangers and they operate in accordance to the rules of heat and mass transfer that govern this type of a device.

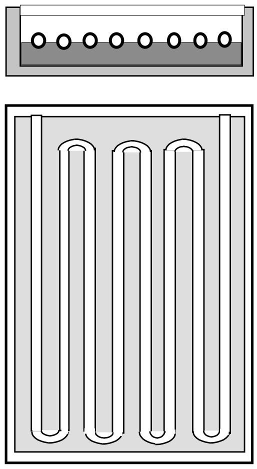

Fig. 1. The cross section and view through the simplified model of a flat plate solar collector.

The main task of a solar collector is to absorb as much solar energy as it is possible and to lose as little as possible. According to the needs of an end (heat) user, the requirements of quantity and quality (expressed in term of a temperature) of heat can be different. In consequence, the construction and technology of a solar collector can vary. The more reliable solar system and higher temperature requirements, the technology required is more modern and sophisticated, and the construction of the solar collector and the whole system, together with the control system, are more complicated. The degree of complexity depends on the system function and the required mode of its operation. Figures 2–12 show a review of solar active heating systems, beginning with the simplest system that heats a flowing water, through the domestic hot water (DHW) systems which contain water storage tanks and auxiliary conventional heaters, to most advanced DHW solar and space heating systems coupled with a heat pump.

Figure 2 presents an open direct solar heating system which can be used for very simple applications in agriculture or summer resorts. Figure 3 shows a closed indirect swimming pool system which is usually used for outdoor summer swimming pools. Figure 4 presents a solar DHW system with a closed solar collector loop, heat storage tank with an embodied heat exchanger between a collector loop and end-user, and an auxiliary heater.

Because of the stochastic nature of solar radiation and due to its periodical availability, when heating of water is required for domestic or public use, the storage of the solar energy is necessary. The storage has a short-term character, i.e., it is assumed to be sufficient for one to two days of a hot water supply. The auxiliary heater is required because the stand-alone solar heating system cannot provide all the required heat. Figure 5 presents a DHW system with a storage tank coupled with an auxiliary heater in one unit. This system gives a very good stratification effect in a tank that can be advantageous for efficient storage of energy, but can be also disadvantageous for operation of a solar collector because of the influence on its efficiency. Figure 6 shows a thermosyphon DHW system which is a natural passive system. It does not require any mechanical device to drive the flow in the collector loop. The liquid (usually water) circulation is forced by the density difference between hot and cold water.

The technology of the active solar systems is well developed and can assure the reliable and long life operation of the system with a high efficiency. Nowadays, the solar active heating systems are applied in small, medium, and large-scale applications. These systems are very effective, even in a high latitude climate, during spring and summer (especially from June to the end of August) when there is a coherency between solar energy availability and heat demand. In the case of a small-scale, we usually consider DHW systems for single-family houses (a few square meters of solar collectors) that can provide, even in the high latitude countries, about 60% of heating requirements annually (nearly 100% in summer). In the case of a medium-scale, the hot water systems can be used for residential purposes (in multifamily apartment buildings), public buildings, schools, hospitals, offices, stores, recreation and leisure centres, etc. with annual efficiency usually about 40–50% (several hundreds square meters of solar collectors, the efficiency could be higher, but because of typical circumstances like limited area for installation of solar collectors and limited funds – high investment costs, the size of the solar system is usually also limited). In the case of large-scale, the flat plate solar collectors are used in a form of large solar collectors fields (a few thousands square meters) as a preheating system for a large heating plant providing heat through a centralised heating system to the cities (however, the solar rate is equal to only a few percent).

The use of a solar energy in agriculture is also a very promoting application. In most of agriculture applications, low temperature sources of energy are needed. The time and peak values of a solar energy are very often in quite good accordance with the time and peak values of the heat demand, e.g., in some sectors of agriculture production, domestic hot water heating, and solar drying.

2.2. Space heating

Some limitations of solar energy applications exist mainly due to variation of solar radiation over one day and over a year. When we consider availability of solar energy and its use to provide heat for space heating, it is evident that thermal performance of the solar source is not in phase with the heating requirements, especially in high latitude countries. In these countries the winter season is characterised by low insolation level, short duration of this insolation and consequently, cold climate with high heat demand. When energy is needed for space heating purposes, time and peak values of heat demand are quite opposite to time and peak values of available solar radiation. Therefore the standard solar space heating, which is shown in Fig. 7, cannot meet the high space heating requirements. To support the solar heat source it is necessary to involve other heat sources. Figure 8 shows the DHW and space heating solar system coupled with an extra boiler (fired, e.g., by gas or biomass) and an auxiliary heater (e.g., electrical). Heating is accomplished in three stages: solar – preliminary heating, boiler – main heating, and auxiliary – peak heating.

To improve the efficiency of the solar system, a heat pump can be used that allows application of solar energy in more effective way. The general principle of a heat pump is to extract heat from a low temperature heat source and to give it off at a higher temperature level. Of course, additional energy is needed to assure this "unnatural" heat transfer from a low temperature source to a high temperature energy sink. This operating energy can be mechanical energy (e.g. compression heat pumps) or thermal energy (e.g., absorption heat pumps). A main task of a heat pump is to upgrade heat, therefore so often it is so-called "heat transformer". The useful energy output is significantly greater than additional energy required to drive a heat pump. Thus, a heat pump is very important in energy conservation activities. Energy extracted from the solar heat source is converted into an useful heat in the low temperature range. This low temperature useful heat can be applied with a good efficiency for space heating in buildings. Solar systems coupled with heat pumps are shown in Figs. 9–12. Figures 9–11 present different configuration of series Solar Assisted Heat Pump systems for space heating and for DHW and space heating. In the systems presented in Fig. 9 and Fig. 10, the solar energy stored in a storage tank is used as a heat source for a heat pump evaporator. Heat from the heat pump condenser is used to provide heat for space heating of a building. It is also possible to use solar energy directly from the storage tank to the space heating system in a building. Figure 11 shows a solar heat pump space heating system. A solar collector is connected directly to an evaporator of a heat pump. If a solar heat pump cannot provide a required heat, the auxiliary heater is operating in a parallel way. A double source SAHP system is presented in Fig. 12. Solar energy is absorbed by solar collectors and is accumulated in a storage tank. A heat pump is coupled with a solar storage tank and ground vertical heat exchangers. The energy from ground or solar energy can be used as heat sources for the heat pump that is equipped with two evaporators. Solar or ground heat is used depending on which source gives higher coefficient of performance of the heat pump [6].

Apart from upgrading the solar heat by using a heat pump to utilize solar energy for space heating there are other possible solutions. One of them is to apply seasonal storage of solar energy [7,8].

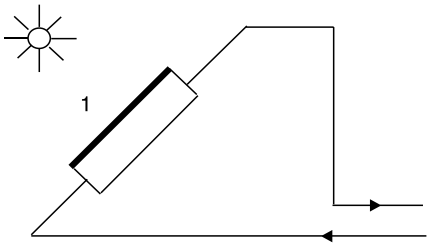

Fig. 2. Open direct flow system.

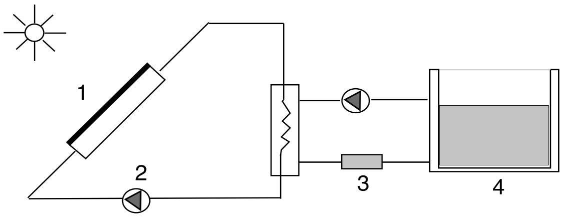

Fig. 3. Close indirect swimming pool system.

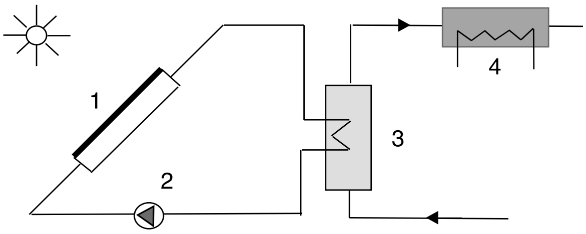

Fig. 4. DHW system with an auxiliary heater.

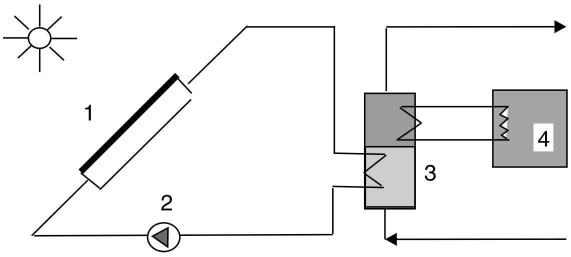

Fig. 5. DHW system with storage coupled with a heater.

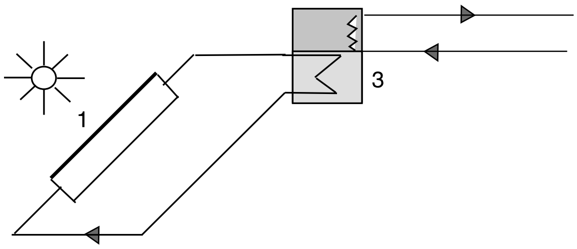

Fig. 6. Thermosyphon DHW system.

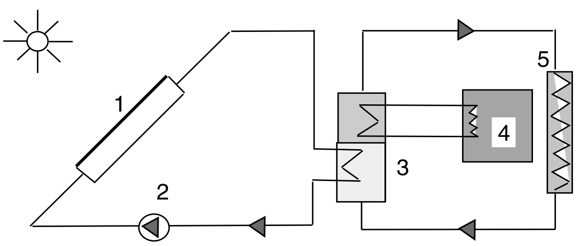

Fig. 7. Space heating with storage coupled with a heater.

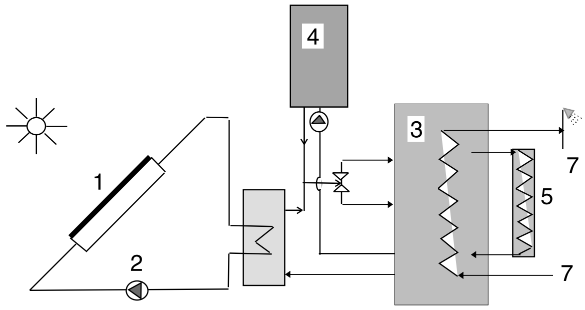

Fig. 8. DHW & space heating with an extra boiler and auxiliary heater.

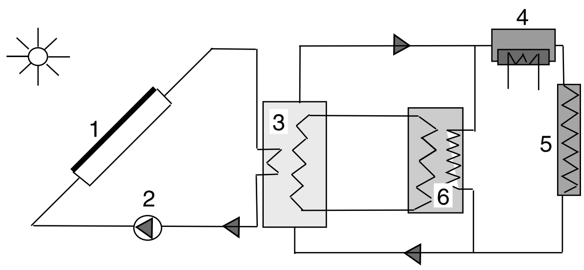

Fig. 9. Series solar-heat pump space heating system.

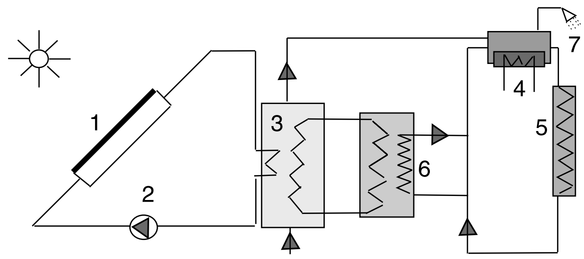

Fig. 10. Series solar-heat pump DHW & space heating.

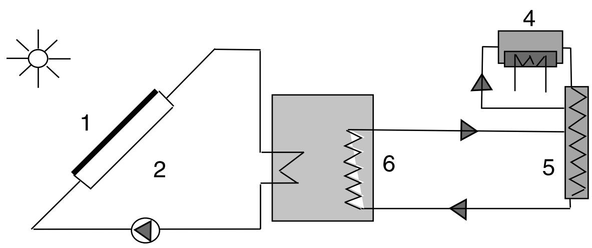

Fig. 11. Parallel solar heat pump space heating system.

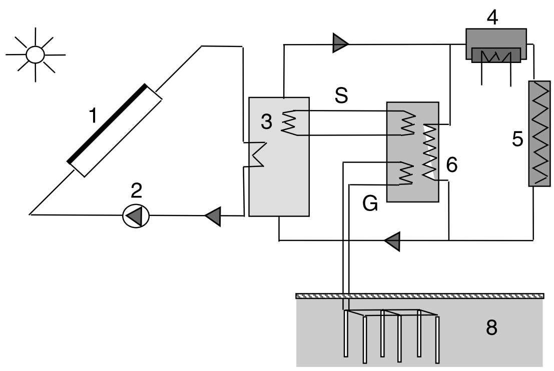

Fig. 12. Double source solar-ground heat pump space heating system.

Legend: 1 – solar collector, 2 – pump, 3 – storage tank, 4 -auxiliary heater, 5 – space heating system, 6 – heat pump, 7 – hot water, 8 – ground heat exchanger.

In summer solar energy collected by an active solar system can be stored in the ground by means of vertical heat exchangers. In winter, heat stored in the ground can be extracted from the ground and used for space heating via a heat pump. Underground thermal energy storage system (UTES) can be designed to operate in a monovalent mode, that is, the total space heating is accomplished by a ground heat pump system. The consumption of energy is equal to electric energy needed to drive a compressor of the heat pump. The other possibility is to use passive solar systems, as is it described in the next section.

3. Solar passive systems – solar architecture

To reduce winter heat demand for space heating we can do a lot through the proper design of the building, including building materials, structure of the building and heating installations. We also can assure the rational use of the heat supplied to the building. Reduction of energy consumption in buildings can be also achieved by applying the solar passive systems. The proper design of the building, including passive systems, can assure significant reduction in energy requirements [4,9]. The idea of such buildings is to be suitable to climatic and environmental conditions. The idea of solar passive architecture is to use the building itself either to gain as much solar energy as it is possible, or to protect from the sun, depending on a season of a year and climatic condition. Such changes have an influence on the building architecture. Architects must be aware, that proper passive solutions can improve the energy balance of the building, as well as its exterior and aesthetic impression of an observer.

For a purpose of proper building construction we can choose proper building materials and technology, for proper thermal energy balance we can apply solar passive design. We should try to “open” the buildings to the sun to make them utilize solar energy when it is needed and to “close” them to protect from negative influence of surrounding, when it is necessary. It can be achieved by introducing solar passive systems at south part of the building coupled with appropriate shading devices and applying “super” insulation at north walls. Typical options of concepts of passive heating systems are shown in Figs. 13–20.

Figure 13 presents a direct solar gain passive system which constitute a window and a building itself. Solar radiation is transmitted through the window (the rate of solar radiation entering the interior of the building depends on optical properties of windows, which are connected with the materials used for glazing and construction of windows) and then is accumulated in building construction elements: walls, floors, and other elements inside, e.g., furniture. Windows are very important for transmission of solar radiation, in consequence in gaining solar energy. However, in summer overhangs, wingwalls and other architectural devices should be used to shade a window and not allow too much solar radiation to enter the building.

Figures 14–16 present indirect solar gain passive systems, where the part of a main facade contains different types of a solar collector – storage walls. Collector – storage walls (Fig. 14,15) combine the function of collection and storage of solar energy, when a collector wall (Fig. 16) acts as a solar collector and the internal elements of building construction have a storage function. A collector – storage wall is covered by single or double glazing, next there is a massive wall of masonry material painted black to act as solar absorber. From the storage wall to the room, heat is transferred by radiation and convection. In a case of a ventilated collector – storage wall (Fig. 15) room air can enter the space between glazing and storage wall through vents in the bottom of the wall and come back to the room through the vents at the top. The heat transfer takes place through a natural convection, i.e., due to the difference in the temperature at the bottom and at the top natural air circulation takes place. In a case of poor insolation conditions (low irradiation, high share of diffuse radiation), heat and mass transfer process have to be forced by a mechanical device like an air fan. The ceiling and roof can be also the part of a storage unit. Collector – storage walls are preferable for warm climate, for moderate and cold one the passive systems with sunspaces (buffer zones) are better.

Figures 17–20 present different types of sunspaces, so called buffer zones because they constitute a buffer between the interior – living space of the building and outdoor of the building – environment. Buffer zones allow the use of solar energy and protect the building against extreme weather conditions, i.e., too cold or too hot. Sunspaces are attachments to buildings, which can be used as solar collectors, with storage in walls, floors or in special designed storage spaces like pebble beds. Sunspaces are similar in their structure and function to greenhouses. In high latitude countries in winter, the energy losses can easily exceed the solar energy gains, therefore careful design of such systems is needed, and double sunspaces (Fig. 19–20) are much better than standard single ones (Fig. 17–18).

4. Availability of solar radiation

Analysing a possible application of solar energy, usually we do not consider horizontal surfaces. The main components of active systems, i.e., solar collectors, have to be tilted to a horizontal surface. In the passive systems, most of elements of a building shell are vertical or tilted. The surfaces of walls, windows, and elements of sun glass spaces, buffer zones, atria, roofs are not also horizontal. For active solar systems, it is essential to maximise solar gains. However, for passive systems more careful analysis is needed. This allows a compromise between the needs of high heat gains in winter with the necessity of protection against too much solar radiation in summer. To perform the analysis of the influence of surface inclination and orientation on the amount of energy incident on this surface, it is very useful to present solar radiation data in a very clear and comprehensive way. One of the options for such presentation is a graphical interpretation of solar radiation in

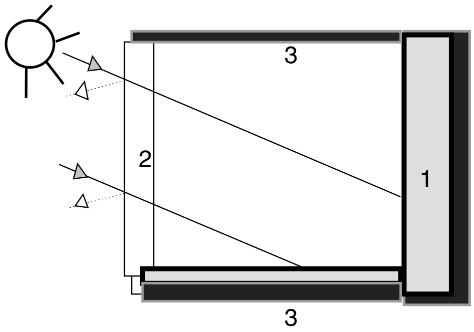

Fig. 13. Direct – gain passive system.

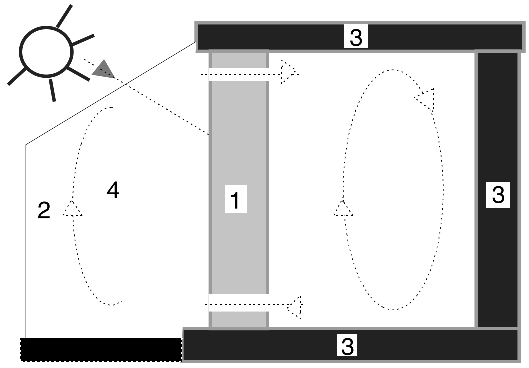

Fig. 17. Sun space coupled with a storage wall.

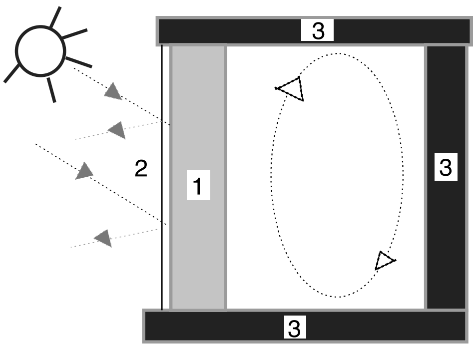

Fig. 14. Indirect – gain system. Solar collector – storage full wall.

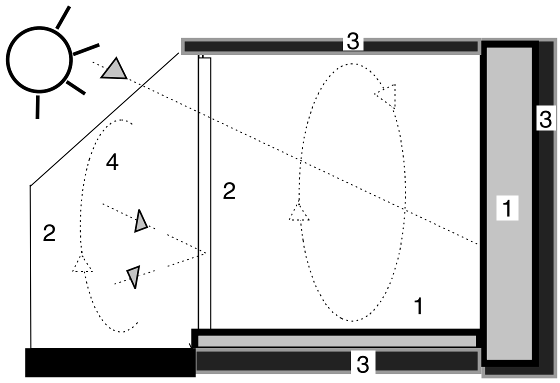

Fig. 18. Sun space.

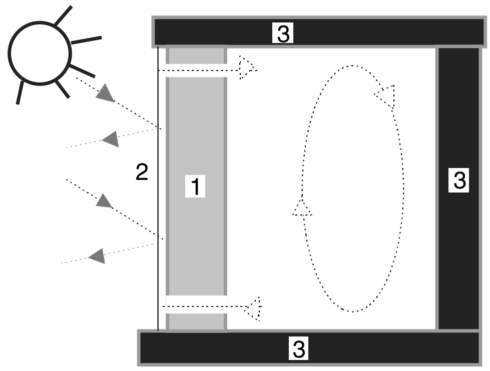

Fig. 15. Indirect – gain system. Ventilated solar collector – storage wall.

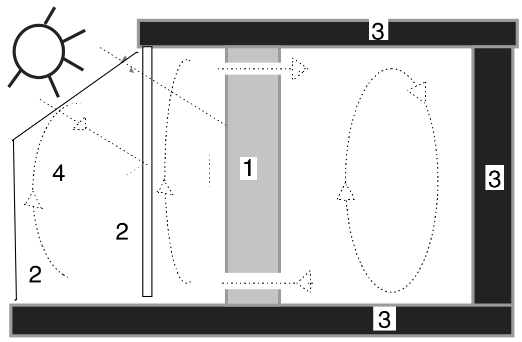

Fig. 19. Double sun space coupled with a storage wall.

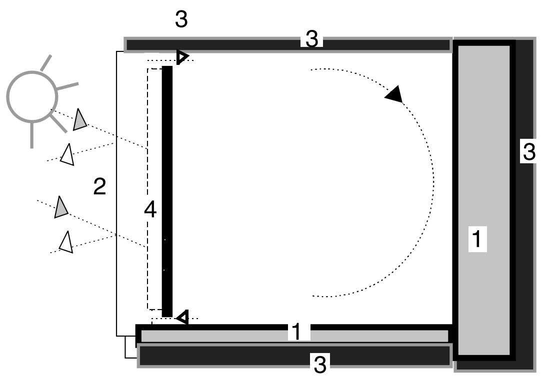

Fig. 16. Indirect – gain system. Standard solar collector wall.

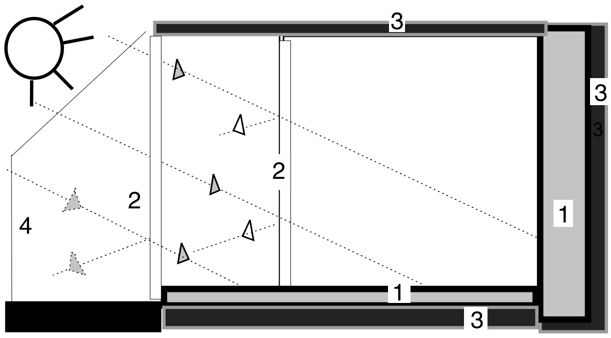

Fig. 20. Double sun space.

Legend: 1 – storage element, 2 – glazing, 3 – insulation element, 4 – glazing of buffer zone.

the form of isorads – curves that show the areas of equal irradiation of a given surface for a determined period of time (day, month, season, year). Analysis of the distribution of isorads through the whole year give recommendation for the architectural concept of the building, and design of passive and active systems. Isorads can be used in evaluation of the energy balance of buildings. The selected set of isorads for the Polish conditions [10] is presented in Figs. 21–24. They show the effects of slope and azimuth angle on energy received on a surface located in Warsaw on a monthly (actually it is an averaged day of the month) and annual basis.

Analysis of the distribution of isorads for Warsaw apart from some specific conclusions for Central Poland can lead to some general remarks for the building concept and utilization of active solar systems in high latitude countries. In early spring, late autumn and especially in winter, the orientation of the surface is very important. In summer, the slope of the surface is a dominant factor. It is suggested to expose the main part of a building envelope to south, the living area, sun glass spaces, buffer zones should be situated at that side. The passive elements should be tilted at angles bigger than the local latitude. Horizontal surfaces and glass surfaces tilted at small angles are not recommended, since they give a high positive solar gain effect in summer and high heat losses in winter. In summer the overheating of living spaces situated at the south part (and west part in Polish conditions) of the building can happen very often and so the use of shading devices and natural environment shading is required.

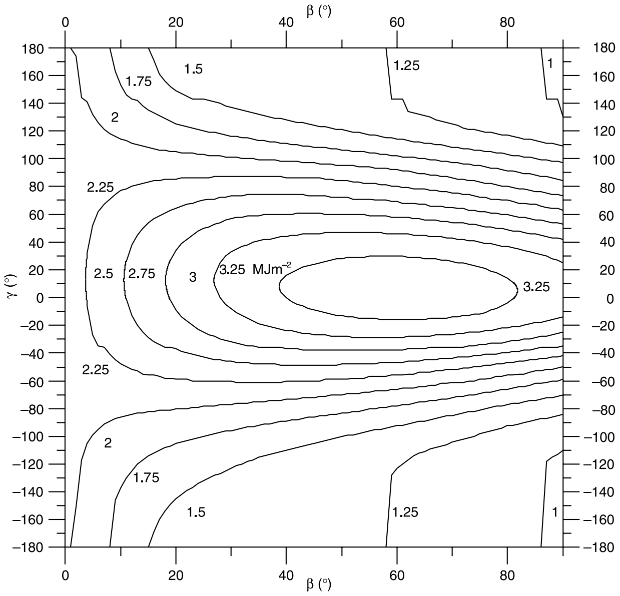

Fig. 21. Distribution of isorads in January in Warsaw.

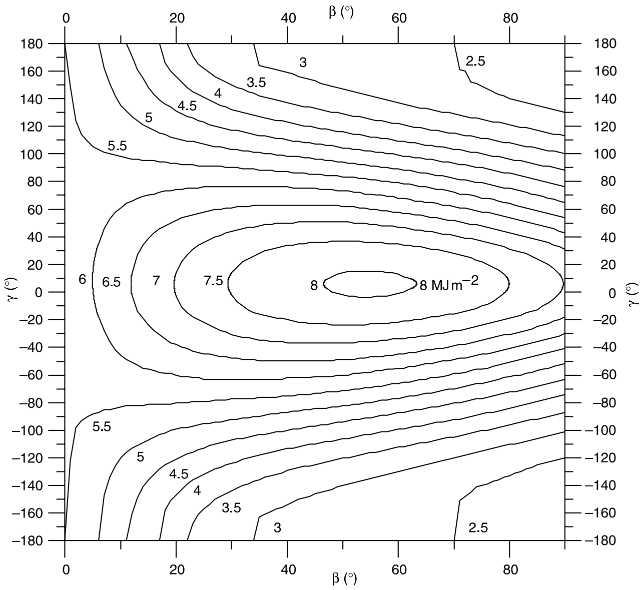

Fig. 23. Distribution of isorads in October in Warsaw.

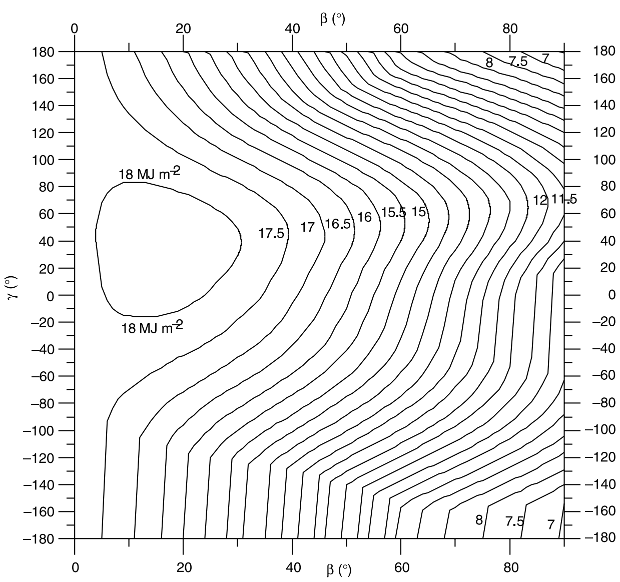

Fig. 22. Distribution of isorads in July in Warsaw.

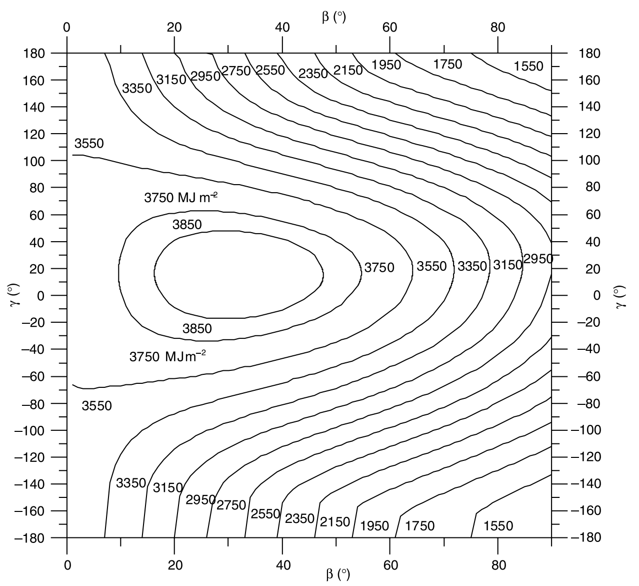

Fig. 24. Distribution of annual isorads in Warsaw.

Shading analysis is very important for a proper design of a building envelope. The sun charts [3,4,11] present the angular position of the sun, i.e., the solar altitude angle in a function of solar azimuth angle (both parameters are function of declination and solar hour angle), depending on time expressed on the plots by dates and times (in hours). The sun charts can be used to determine the shading of buildings by near-by natural or artificial obstructions, or by specially designed shading devices of the building envelope, like wingwalls and overhangs which angular position can be entered on the same plots. Apart from applying the sun charts, other analytical and numerical methods can be used to determine the shading of a given object [12].

5. Conclusions

Nowadays, utilisation of solar energy has a very wide spectrum and is a complex problem. The type of applied solar technology depends not only on the climate. Social and environmental considerations also determine the method of solar energy conversion and its use. The tradition of working with and using the environment in a benign way has become modern again. Modern technologies and innovative materials allow application of old proven energy ideas in a new very efficient way. Modern solar energy utilisation does not only mean applying solar devices and installations. It also entails treating energy and environment in a more global and sustainable way. Utilisation of solar energy treats the problem of energy supply and energy use in the same way, that is to say that energy conservation starts with extraction of energy (fuel) and finishes with its recuperation.

Modern solar energy utilisation is nowadays strictly concerned with the building as a whole. Every building is affected by the solar radiation. Therefore buildings should be designed and constructed in a way that assures proper use of the energy existing in environment what means the planned efficient use of solar energy and secondary effects of solar radiation. Solar architecture is beneficial to the energy balance of buildings and indoor living conditions, it links energy conservation with the environment and it also allows the building to be "human friendly" as well as environmen friendly.

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Solar energy is radiant light and heat from the Sun that is harnessed using a range of ever-evolving technologies such as solar heating, photovoltaics, solar thermal energy, solar architecture, molten salt power plants and artificial photosynthesis. It is an important source of renewable energy and its technologies are broadly characterized as either passive solar or active solar depending on how they capture and distribute solar energy or convert it into solar power. Active solar techniques include