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Solar energy under cold climatic conditions: A review☆

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ABSTRACT

Solar energy has seen tremendous development in recent years towards fulfilling the energy requirements of our planet. This paper presents an extensive review of solar-energy-based technologies and research work conducted under cold climatic conditions. These conditions include mountainous, continental, cold oceanic and polar climates and in general, all climates where below Zero temperatures are common during the winter.

This article describes the use of solar energy under cold conditions from various aspects: greenhouses, buildings and housing, heat pumps, heat storage, PV panels, solar thermal and PV/T, high-latitude issues, cooling, and policies.

Both environmental and economic aspects are considered in this paper, and the zones covered more or less intensively are Central and Northern Europe, North America, Turkey, Iran, China, Japan, the Andes and Antarctica.

This analysis shows that, for most cold climatic conditions, it is worth implementing solar energy technologies for certain uses. However, many parameters need to be carefully considered before concluding on the relevance of a given technology.

1. Introduction

Energy issues will dominate the world situation during the 21th century. The increase in the CO_2 concentration in the atmosphere and the consequences in terms of climate change are expected to be dramatic.

International agreements, such as the Conference of Parties 21 (COP21) may limit the consequences of climate change and will facilitate the development of sustainable energy [1]. The development of solar energy will thus be a key instrument in ensuring a sustainable future for the planet.

Solar energy use can be grouped into three categories: electricity production (mainly by solar PV panels), solar thermal energy and passive solar energy.

The three aspects of solar energy have been significantly developed worldwide both in terms of research and infrastructure. Understandably, solar energy has been developed under hot and sunny conditions in hot desert areas such as Northern Africa [2], the Middle East [3], the USA, China [4,5] and Australia [6,7], and in more humid climates such as Sub-Saharan Africa [8], South America [5] and southern Asia [7].

Other important solar energy developments can be found in southern Europe [9] as well.

Under cold climates, renewable energies can cover a large number of energy needs [10], but the share and impact of solar energy can be legitimately questioned. If its feasibility is real, then several parameters most likely need to be considered before optimizing such systems.

For example, it is theoretically possible to adapt any household to optimize solar energy use even in cold climates [11]; however, all installations are different, and small details (the shadow from a tree or a mountain, for example) can negate the investment and the energetic balance of an installation.

Concerning passive and thermal solar energy: By definition, the needs for heating under cold climates are important; however, buildings in such regions are in general well-designed to address the cold. The benefit of developing solar energy can be discussed considering the conditions.

Concerning the benefits for agriculture: Climate change may drastically disturb the production of fruits and vegetables. Climate-smart agriculture is a key concept for limiting the impact of climate change on food production [12] in accordance with other parameters [13], so developing concepts to adapt agriculture to cold climates can be part of the solution.

Concerning the solar photovoltaic (PV) cells: They have better efficiency at cold temperatures [14]; therefore, this property can be exploited in cold climates.

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This review details the recent developments in solar energy under cold climatic conditions. The research projects are grouped depending on the aspects that they cover to afford greater readability.

2. Solar energy use under cold conditions: review

This review covers separately the different aspects of solar energy use under cold climatic conditions.

2.1. Solar passive energy

2.1.1. Building optimization

A simple way of using solar energy is by optimizing buildings. Indeed, the changes can be limited and efficient as there is no need to rebuild everything.

2.1.1.1. Historical buildings. The most delicate situation is for buildings with historical or architectural considerations. Room for improvement is limited in these situations.

For example, in Drammen, Norway, the renovation of a historical building involved solar control glass [15]. It helped to reduce the thermal losses and thus the electricity bill and improved the thermal comfort as well.

This illustrates that improvements are possible despite the huge aesthetical and legal constraints when modifying a historical building.

2.1.1.2. Influence of the absorptivity and/or the color of the walls and roof. When there is greater freedom for adaptation, the absorption of solar energy through or at the wall can be optimized, so the aesthetics of the building can also be considered. Indeed, the color strongly influences the absorptivity of a wall or roof and then directly impacts the absorbed or reflected energy. Furthermore, their emissivity can be considered to optimize the energy flux calculation.

Chwieduk [16] studied the influence of paint absorptivity on the energy balance of housing. Taking two extreme cases (absorptivities of 0.1 and 0.9), Chwieduk demonstrated that an influence exists, but it is not very significant, especially if the wall is well insulated. However, a recommendation for a variable absorptivity during the year was provided. Using phase-change materials (PCMs) on the inside of the wall was recommended to obtain greater thermal inertia as well.

A similar study on the coating of external walls has been conducted on a laboratory bench test in an outdoor environment [17]. They found that a reflective insulated coating lowers the temperature of the wall insulation by approximately 0.73 °C; the benefit during the summer (and on a yearly basis) is small but real. However, the benefit is less significant in winter; the extra insulation helps, but the high reflectivity doesn't.

In Harbin, China, winter experiments proved that the color of a solar air heating system affects its efficiency [18]. However, a certain panel of colors remains sufficiently competitive; the aesthetic of the housing can then be improved. Furthermore, with the unglazed transpired collector tested there, the efficiency increased, but the air temperature decreased with the air mass flow rate. The system must be carefully designed depending on the given requirements.

The roof itself can be optimized considering solar energy needs or activity. Hosseini and Akbari [19] studied the influence of cool roofs on energy savings under cold northern American climates. A cool roof typically has a high reflectivity and emissivity. The interest is obvious under hot climatic conditions. However, such interest exists as well for cold climates. During the winter, the snow accumulated on a roof neutralizes the cooling effect of this roof, and even without the snow, the benefit during the summer is sufficiently high to compensate for the scarce losses during winter.

The influence of the absorptivity and/or the color of the walls and roof can then be significant. Several issues need to be considered: the balance between absorbing energy during the winter versus reflecting it during the summer; the aesthetic issues, and the natural benefits (typically snow during winter or shadow during summer). All of these can influence the optimization of the system. Typically, dark colors are more advantageous under cold conditions and clear colors during hot ones due to their different absorptivity. However, the emissivity can be of a concern as well, so an appropriate balance between all the parameters discussed above (and different for all cases) must be found before determining an optimal option.

2.1.1.3. Façade. Improving the entire façade is an interesting option to investigate. The façade is obviously widely exposed to the surroundings and optimizing the heat flux at its level is a necessary step. Since the façade is part of the envelope, its relationship with solar energy is fundamental. Furthermore, optimizing façades can be done at an industrial scale, which reduces the costs.

In Helsinki, Finland and Moscow, Russia [20], most buildings are several decades old. Prefabricated façade products can simplify the renovation process and drastically increase the energy savings in both locations. However, heating systems in Russia are centralized; therefore, changes in this direction should be politically supported and at a large scale to facilitate the acceptance of the innovations.

Shi and Zhang [21] conducted a computer simulation for different climates to measure the influence of the solar reflectance of the envelopes of the buildings. The simulation showed that low solar reflectance and emissivity (for example, dark ceramic tiles) make the buildings more energy efficient on a yearly basis under mountain or frigid climates (unlike hot climates).

Thalfeldt et al. [22] studied the influence of different parameters of a façade on energy consumption. Utilizing triple-glazed (or more) windows, reducing their size while maintaining sufficient daylight, and installing low-emissivity glass and external shading proved to be efficient for cold climates for reducing either heat losses in winter or cooling needs during the summer.

In central China (hot summer, cold climate), a study described the influence of different façade parameters under such conditions [23]. The optimal window coverage of 40% of the south wall, and use of high transmittance glass is preferable. Notice that the light transmittance has a greater impact than the heat transfer coefficient or the shading and should thus be considered as a priority. A more advanced study under the same condition detailed the impact of each season at the scale of the building [24]. Generally, shading and the window-to-wall ratio have the largest influence during the summer (cooling time). In winter, the heat transfer coefficient and the shape of the building are prevalent. The absorbance of the walls and roof are important over the course of a year. However, the parameters depend on each other and on the location.

To summarize, the improvement of the facades influences different aspects under cold climates. A high absorptivity and low emissivity will optimize the heat exchange. The area and orientation of the windows, as well as the quality of the windows can have an impact: the energy from the sun can then heat the building through the windows during cold and sunny days. However, each case requires careful planning due to the climatic (huge differences between summer and winter, cloudy vs. sunny cold winter) as well as the local environment (shading from trees or other buildings).

2.1.1.4. Addition of infrastructures to existing buildings. Adding new infrastructures to the façade limits the changes and thus the costs, and facilitates the acceptance as well. It can be possible to slightly improve many different infrastructures rather than drastically improve a limited number of installations.