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The role of solar energy in the future energy scenario

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Abstract. The future energy scenario of each country needs to be developed based on key issues that are outlined and examples of innovative solutions for implementing solar energy conversion systems in the built environment are presented. Additionally, sustainability features of the implemented systems are presented and the emergent solar energy conversion processes – as photocatalysis – are discussed.

Keywords. Energy scenario, solar energy conversion systems in the built environment, sustainability of the renewable energy systems, photocatalytic processes in the built environment.

1. The future energy scenario

The trends registered in the humankind evolution show during the last century a significant evolution that has to be considered for the future development scenarios; one major trend is related to the increasing population number, that has as consequences an increasing in the global energy demand both for direct use and for various industrial processes.

The World population was lower than one billion in 1800 with a growth rate always lower than 1%; the industrial revolution marked an increase in the living and health standards and a turning point in the number of inhabitants could be registered, with a growth rate peaking 2.1% in 1962.

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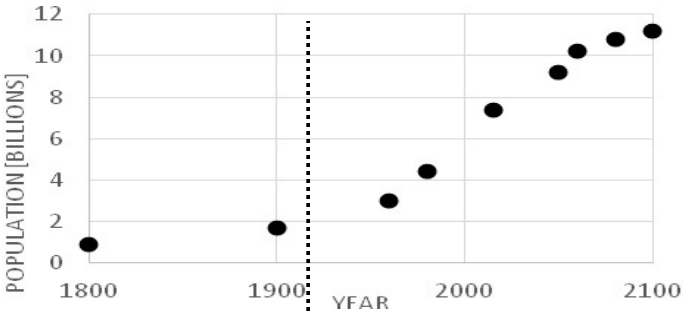


Fig. 1. Evolution of the World population.

Since then, the growth rate slowly decreased and the trend will continue being expected a growth rate of 0.1% in 2100. The dynamic of the World population is presented in Fig. 1 for the 1800 – 2018 period along with the predictions made up to 2100. The World population is currently of 7.6 billion peoples, out of which more than half are living in urban areas, according to the data delivered by the Population Reference Bureau.

This population is consuming energy, negativelly influencing the environment quality, as the largest share of the energy sources is based on carbon and the energy production pattern relyes on burning fossil fuels (coal, oil and gas) with CO_2 and other greenhouse gases (GHG) released in an increasing trend.

Following the conclusions of the Report on Climate Change, [1], a global target was proposed for reducing the GHG emissions down to 450 ppm, [2], to reach a limit of maximum 2°C for the global heating relative to the pre-industrial levels, [1]. This reduction involves the efficient use of the fossil fules (thus cutting the losses during the energy production and reducing the wasted energy) and novel carbon capture, use and storage (CCUS) technologies, along with the extended implementation of renewable energy systems for decarbonizing the electrical and thermal energy production.

The World Energy Council (WEC) developed two scenarios for the sustainable electrical energy production, [3]. One scenario is focused on increasing the energy efficiency of the energy produced based on fossil fuels (the Jazz scenario) while the second one (the Symphony scenario) relies on increasing the share of renewables (mainly solar and biomass) with a large share of investment in solar, wind and hydro systems, about 60% of which is in PV systems. The electrification degree will significantly increase (up to 30% as compared to 17% in 2010) and the population without access to electrical energy will decrease, from 1.267 billion in 2010 to 319…530 million in 2050, mainly in the sub-Saharan Africa, South and Central Asia, South-East Asia and Pacific. Here the economic growth will have the most significant increase and so will also have the total energy consumption, as for example in Asia the total primary energy consumption will raise from 40% (in 2010) to 45…48% in 2050, while Europe and North America will represent about 30% (in 2050) as compared to 44% in 2010, [3]. A significant reduction in the GHG emissions is only possible based on global agreements including the "emissions trading" system, which – if implemented - can lead to a 40% GHG emissions decrease in 2050 as compared to 2010, based on the Symphony scenario. The costs per ton of CO_2 estimated in the scenarios range between 23…75 USD/t_{CO2} in 2050, East Asia being the major emitter now (in 2018) and in 2050. The CCUS amount of CO_2 can and has to be seriously considered starting with 2030 and it will amount between 1.3 (Jazz) and 6.9 (Symphony) Gt_{CO2}/year.

The focus on electrical energy in the WEC scenarios is justified by the extensive future use of electricity in industrial and residential processes, as the thermal energy directly obtianed using renewables raises significant problems reated to the lack of simultaneity of the optimal production conditions and the thermal energy demand. One obvious example is the need for heating which is at its peak during the cold season, when e.g. the amount of solar energy is the lowest (because of the shorter days in winter, and becasue of the cloudness).

Modelling and simulation studies further outlined that the future can be tailored according to two extreme scenarios: high economic growth, that supports energy produced using affordable solutions or higher energy prices (more expensive energy) but with a much lower environmental impact. These two paths has to be considered in developing long-term scenarios, based on a stable development strategy (up to 2050 and beyond), with a predictable financial cost, accepted and implemented at regional level.

2. The role of solar energy conversion systems at community level

Solar energy can be converted in the built environment to obtain electricity, using photovoltaic (PV) systems, or heat using solar-thermal systems (STS). Currently, there already are installed PV and STS systems but the share of energy provided into the overall system is rather low. For a broad scale implementation, covering a large share of the energy demand, progress is required to face the lack of simultaneity between the energy demand and the available solar energy.

The total global primary energy consumption rose, during 1990 – 2010, by about 45% [3]. This trend is expected to continue but at a slower rate and for

2050 the two scenarios developed by the World Energy Council estimate an increase between 27% to 61%. There is not a general solution able to fully meet the energy demand, all over the world, thus the goals of sustainable, affordable and secure energy supply need to be met based on specific solutions for each component (e.g. industry, household, etc.).

As already outlined, the built environment represents an energy consumer that, in the temperate climate, may account for up to 40% of the global energy consumption. This is why the specific issues to be solved and the optimization of the specific solutions already implemented represent significant investigation topics.

The WEC estimated that in 2050 the share of renewables in electricity generation will range between 31….48%, meaning in absolute terms a 4…5 time increase as compared to 2010. Out of this, by 2050, the amount of electrical energy produced using PV systems will equal that produced using coal as result of an 230 times increase in the PVs production in 2050 as compared to 2010, [3].

The share of solar heat in meeting the thermal energy demand was also modelled and the results show that in Germany, this varies from 2 to 5% in 2030 up to 7…17% in 2050. Additionally, the share in district heating can reach 20% in 2050, representing about 40% of the heat produced by solar-thermal systems, thus reducing the pressure on different other resources as biomass, [4].

The electrical and thermal energy demand has to be predicted as accurately as possible at building and community levels. However, it will never be 100% accurate as there is a certain fluctuation in the regular behavior of the inhabitants. This is the reason why it is preferable to make prediction calculations at community and not at building's level as it is highly unlikely that all the community buildings will drift away in the same direction of energy (lack of) consumption.

Obviously, it is not only the energy demand at building/community level that is important but also the climatic conditions. The seasonal variation of the thermal energy demand significantly depends on the geographical location and on the building's insulation.

The geographical location supports the estimation of the maximum available solar energy, based on the geographical coordinates of the location (latitude, longitude, altitude). However, the momentary fluctuations in the solar energy amount reaching the Earth in a particular location, at a particular moment of the day, month, year cannot be accurately predicted within a timeframe covering days and this brings several restrictions in developing a 100% solar energy community. Such a community asks for certain energy storage solutions or for the use of energy mixes where, besides the solar energy convertors other renewable energy systems, with more predictable output, are part. Energy storage represents one of the major uncertainties in the (electrical) energy production by 2050 along with the carbon capture, utilization and storage (CCUS). As Asia is the major source of energy consumption it will also has the highest potential for implementing CCUS technologies, to mitigate the environmental impact. This will increase the complexity of the energy system by 2050.

The building insulation represents another key point; for a feasible installation of renewables in/on a building, that building has to be energy efficient thus the energy consumption should be as low as possible. The new buildings can be designed and built considering the up-to-date construction materials that are well insulating and reducing the energy losses; however, for the existing buildings it is not always easy to implement the refurbishment solutions aiming at cutting the losses and the smart use of the technical installations implemented in buildings. Thus, the following three retrofitting directions are mainly recommended, [5], as being the most feasible energy saving solutions:

- Lighting retrofits, by replacing the old lighting with those currently considered to be the best options: LED [6]; an initial investment slightly higher is compensated through significant energy saving during their lifetime.
- Window retrofits, aiming at cutting the losses through a better sealing and through an optimized air gap for double (or multiple) glazed windows.
- Building insulation on the façades and on the rooftop. This should be designed considering the efficient insulation during cold and during very warm periods and is recommended to be done using traditional materials (mineral wool for the walls and glass wool, rock wool, sheep's wool, cellulose fibers for the roof and the attic) or novel, performant materials (polystyrene, polyurethane for floors).

Afterwards, the energy demand has to be covered in a significant share, by using renewables. If the costs are too high or the potential solutions are too complicated, a limited amount of the energy demand can be covered by the traditional fossil fuels as efficiently as possible, thus using performant technical installations, with reduced losses during the energy production, transportation and use, [5].

Specific plans were developed for high (up to 100%) energy demand covered by renewables in well-known cities, [1], as:

- Barcelona: Towards energy self-sufficiency by 2050
- Frankfurt: a German pioneer with a "100% renewable" roadmap

- Geneva: preparing 100% renewable energy in municipal buildings
- Malmö: from an industrial to a renewable capital

Planning involves in a large extent solar energy conversion and specific legislation was already developed for supporting the set targets as e.g. in Barcelona, where the municipality adopted in 1999 a solar-thermal ordinance that asks for the use of at least 60% of solar energy to cover the hot water needs in new and retrofitted buildings, [7]. The choice of this particular application is wise as the domestic hot water demand is rather constant all over the year and the climatic profile of the city supports a rather high solar energy potential.

For communities that have a more limited solar energy potential and with a rather uneven distribution over the year, the use of solar energy for heating and cooling can be done in energy mixes with heat pumps. The heat pump must be chosen with a high coefficient of performance (e.g. COP = 4, means that the heat pump delivers four times more energy as it consumes). Only a very small share of the energy should be obtained using gas / fossil fuels in extremely cold periods when the heat pump – solar-thermal energy mix cannot fully cover the energy demand. To calculate the optimal size of the components in this energy mix, a technical and site analysis needs to be developed, as the heat pumps need to be sized according to the specific thermal energy demand of a given building. Further on, as the heat pumps are powered by electricity, their overall output needs to be well managed and planned, [3]. Sustainability scenarios were developed aiming at decarbonizing heat in UK where the current usage of gas is 40% for residential heating. If the 2050 targets are to be met in time to decarbonize the UK economy, heating needs to move away from gas and towards low carbon sources and this need to rapidly occur. Thus, the use of gas boilers will considerably decline by 2050 and will be overtaken by heat pumps, supported by improved heat retention in the house, [8]. Heat pumps proved to be the best and the most feasible alternatives to the gas boilers.

In the extremely cold periods of the year, the energy mix can include burning gas or biomass boilers, [5]. However, the use of solar-thermal systems is recommended mostly for DHW preparation at community level, thus avoiding complex issues related to (long term) thermal energy storage, as large amounts of heat can be produced and stored during the warm season and are required to be used (e.g. for heating) during the cold and very cold periods of the year.

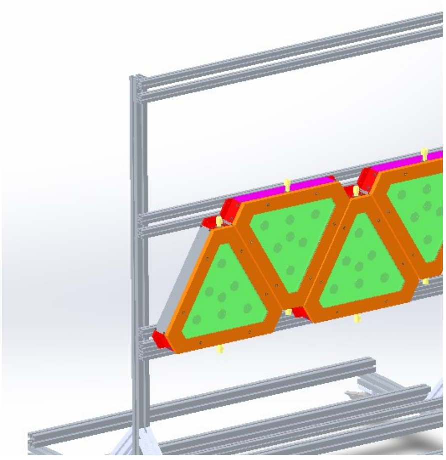
The use of solar-thermal systems implemented in solar-thermal plants developed at the community border represents a more feasible solution for district heating as compared with individual solar-thermal systems installed for each residence. The largest heat savings correspond to district heating systems (close to 12%), with 3…4% higher than for individual buildings. If 50% of the users are connected to a solar-thermal plant, the solar energy potential can be much better used, as when only 20% of the users are connected, [9]. Moreover, the costs of district systems is lower than for individual houses in all investigated countries (Italy, Denmark, Austria and Germany), because extreme cost reductions are required for implementing solar-thermal systems on individual houses as compared with other thermal energy resources (geothermal, excess industrial heat, heat pumps). A significant benefit of solar-thermal systems is related to the reduction of bio-fuels consumption, thus the solar-based technology should replace biomass boilers (especially when no other technologies are available) making biomass available for other uses (transportation or industrial sectors), [9].

The implementation of the solar-thermal systems at community level asks for novel solar-thermal collectors with good conversion efficiency and increased architectural acceptance. The latest pre-requisite implies avoiding the monotony of the collectors' shape and colour and this makes the current commercial collectors not fully suited for implementation on the visible parts of the buildings. If the collectors will be installed on the roofs or terraces, the shape and the aspect of the collector are not so important, but if the implementation targets the façades, this becomes a very important issue. Additioanlly, façades implementation is recomended as it adds insulation features to the suitably oriented façade.

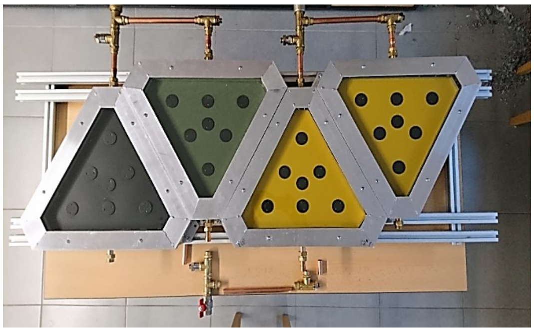
Following this concept, our research group developed two types of collectors with unconventional shapes, particularly suited for façades implementation. These two types of collectors have trapeze and trainagle shapes that allows a better coverage of the façade's geometry. The demo trapeze collectors are implemented on the façade of the testing building in the R&D Centre Renewable Energy Systems and Recycling, Fig. 2:

Fig. 2**.** Solar-thermal array with trapeze flat plate solar-thermal collectors for architectural integration.

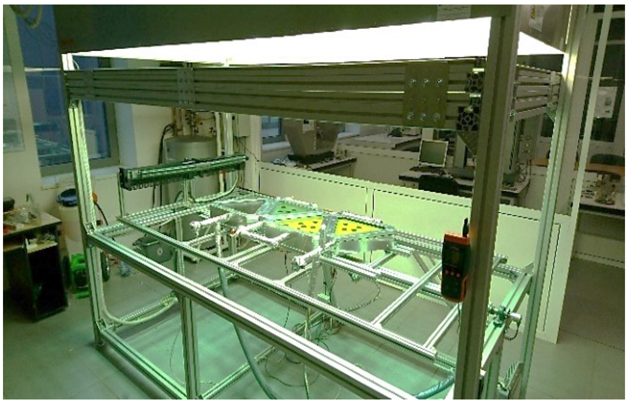
The conversion efficiency ranges for the trapeze collectors between 38....62% registered during mixed (sunny – cloudy) and sunny days, [10]. Triangle solar-thermal collectors are currently under final optimization as they involve specific solutions to mittigate the shape's effect and the collector's size. The solar – thermal array consisting of four triangle collectors, Fig. 3, was tested on the indoor testing rig (Fig. 3c) and the tightness was porved along with the conversion efficiency values of 55....58%. Considering the rather high value of the ratio between the collector's perimeter and area, this efficiency values can be considered very good.



(a)



(b)



(c)

Fig. 3. Triangle solar-thermal collector array: (a) sketch; (b) demonstrator solar-thermal array with four solar-thermal collectors serially connected; (c) testing the demo array on the indoor solar simulator

Architectural acceptance for façade's integration can be futher reached by developing variously coloured collectors, as the demonstrator in Fig. 3b shows.

3. The sustainability of the solar-energy conversion systems implemented at community level

It is important now not only to develop a built environment with low energy consumption but also with a well-controlled and reduced amount of energy spent for developing that specific environment.

This asks for a certain balance considering the energy consumption for obtaining the novel building materials and the energy saved through their use, therefore the ratio between the windows/glazed part and the opaque part of the building needs to be carefully analyzed; in this energy analysis it should also be included the energy required for the demolition. Thus the lifecycle analysis of a building (considered for a lifetime of 70 years), [11] should consider accurate values of the following indicators:

- The energy embedded in the building (considering each component and the energy costs for each component transport from the manufacturing place to the implementation location);
- Energy used for the building's maintenance and refurbishment of the components or technical installations;
- Energy used for building's operation;
- Energy required for the building's demolition also considering that there are recyclable materials (glazing, steel, aluminum);
- Energy required for wastes disposal and reuse or for their storage at the land field.

This type of calculations are required also when developing energy efficient buildings and especially when scaling up this solution at community level.

In a next step, implementing renewable energy systems has to consider the overall energy balance, i.e. the energy provided using the renewable energy source(s) and the energy required for building up the conversion system. This is particularly important for solar energy conversion systems that have an average lifetime of 20…25 years, much shorter than, e.g the lifetime of a hydro-system estimated at over 50 years, and if well maintained it can reach 100 years.

One typical example is related to the PV systems where reducing the energy costs for the PV system production should be an explicit goal of the technology development. The major energy consumption in crystalline silicon PVs is related to the ingot and wafer manufacturing (36%, [12]). The lower energy value corresponding to thin films PVs means a less energy intensive product, thus a more sustainable solution for e.g. CdTe or CIGS PVs.

Similarly, the energy payback time can also be estimated for solar-thermal systems. The focus is on the development of more cost-effective materials and processes, [13]. Following these prerequisites, the trapeze and the triangle collectors are obtained using common deposition techniques as Spray Pyrolysis Deposition or the deposition of dispersions obtained through sol-gel synthesis. These techniques run at normal pressure and temperatures of 300…450^{o}C. These conditions are mild in terms of energy consumption, thus acceptable. Further, the use of plastic materials to manufacture the collectors was also considered but this option should be carefully evaluated considering the expected lifetime of the polymeric materials under thermal stress.

4. Emergent solar energy conversion processes in the built environment

During the past decade another use of solar energy was intensivelly investigated: the photcatalytic processes that convert light/solar energy into chemical energy.

In the built environment the photocatalytic conversion has two major applications:

- Advanced water or wastewater treatment to remove, thorugh oxidation, oragnic or microbiological pollutants bringing the water at the required standards for use, re-use or discharge;
- Self-cleaning surfaces on the buildings' façades.

Although there are many photocatalytic materials investigated and optimized, industrial processes relying on photocatalysis are not scaled up because of several issues that need to be further solved, as the optimum system set-up using VIS-active photocatalyst materials, that can be also indoor used and activated in a much more cost-effective way.

The main steps of a photocatalytic process involve: the pollutant's adsorption on the solid-state photocatalyst followed by irradiation of the photocatalytic material with the optimal radiation type (UV if the photocatalyst is a wide band gap semiconductor and VIS if the photocatalyst is a VIS-active tandem or a diode type system) when the electron-hole pair is produced and separated to further interact with the oxygen or hydroxid ion in water to form oxidation species as the superoxide anion radical ($^{\bullet}O_2^-$), or the hydroxyl radical ($HO^{\cdot}$). Further on, these species will oxidize the

pollutant(s) up to mineralization. Following this description, it is obvious that resaerch is focused on insuring the optimal conditions for:
(a) developing VIS-active photocatalytic structures, as powders or thin films, stable in aqueous media
(b) increasing the pollutant's adsorption on the photocatalyst
(c) avoiding the electron-hole recombination.
The photocatalytic coatings applied on the building's walls and façades represents another photctalaytic application of the solar-active materials. These coatings can protect the buildings (that is important especially for built heritage) as it is the case of TiO_2 – lime based coatings, [14] or can function as self – cleaning coatings for façades exposed to urban and industrial environments, that may cause soiling phenomena that raise durability and aesthetic concerns, [15]. In these applications mostly TiO_2 is the key component, alone or associated with VIS-sensitizers as CZTS [16], CIS [17], graphene oxide, etc.

5. Conclusions

The development of the future energy scenario depends on the current and future needs, on the available resources and on the financial support; thus, these scenarios will be different for each country, region, and community and have to support the sustainable development of each entity.
The key directions involve energy efficiency and implementing renewabble energy systems but, for these to become the core strategy, plenty of coherent work has to be developed, to gather and give use to all the findings that were, scattered, obtained in the past two decades. Based on an aggregated energy scenario, the beneficiaries have to choose their own future, giving use to the energy obtained according to the new strategies. Education is part of this scenario and has to be explicitelly implemented from the early stages, for developing generations that are able to siginificantly contribute to the development and implementation of the future energy scenario(s)

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References

[1] United Nations Framework Convention on Climate Change Report of the Conference of the Parties on its Sixteenth Session, held in Cancun from 29 November to 10 December 2010 (FCCC/CP/2010/7/Add.1, United Nations, 2011).
[2] Rogeli J., Hare W., van Vuuren D.P., Riahi K., Metthews B., Hanoka T., Jiang K., Meinshausen M., Emission pathways consistent with a 2 °C global temperature limit, Nature Climate Change volume 1, 2011, p. 413–418.
[3] Wolrd Energy Council, World energy scenarios, Composing energy futures to 2050, 2013
[4] Palzer A., Solar Heat and Energy Economics in Urban Environments, Task 52, IEA, available at: http://task52.iea-shc.org/Data/Sites/1/publications/IEA_SHC-Task52-Highlights-2017.pdf
[5] Sundaram S., Design of a net-zero energy community: Waalwijk, Master of Science Thesis GI-2013-069MSC EKV963, The Netherlands
[6] Khan N., Abbas N., Comparative study of energy saving light sources, Renewable and Sustainable Energy Reviews, vol. 15, 2011, p. 296-309.
[7] Anne Bringault, Miriam Eisermann and Sylvie Lacassagne), Cities heading towards 100% renewable energy. Food for though and action, 2016, available at: http://www.energy-cities.eu/IMG/pdf/publi_100pourcent_final-web_en.pdf)
[8] Stewart M., Future energy scenarios, Energy Insights, National Grid, 2017.
[9] Mathiesen B. V., Fellow K., Is Solar-thermal a Viable Solution for a Future Renewable Energy System?, Task 52, IEA.
[10] Visa I., Duta A., Comsit M., Moldovan M., Ciobanu D., Saulescu R., Burduhos B., Design and experimental optimization of a novel flat plate solar thermal collector with trapezoidal shape for façades integration. Applied Thermal Engineering, **90**, 2015, p. 432-443.
[11] Cellura M., Guarion F., Longo S., Mistretta M., Energy life-cycle approach in Net zero energy buildings balance: Operation and embodied energy of an Italian case study, Energy and Buildings, **72**, 2014, p. 371-381.
[12] Dale M., The Energy Balance of the Photovoltaic (PV) Industry: Is the PV industry a net electricity producer?, GCEP Symposium, 2012.
[13] Davidson J.H., Low-Temperature Solar Thermal Systems: An Untapped Energy Resource in the United States, *Journal of Solar Energy Engineering,* **127**(3), 2005, p. 305-306.
[14] Nuno M., Photocatalytic coatings in the built environment, doctoral thesis, 2015 available at https://researchportal.bath.ac.uk/en/publications/photocatalytic-coatings-in-the-built-environment
[15] Andaloro A., Mazzuchelli E.S., Lucchini A., Pedeferri M.P., Photocatalytic self-cleaning coatings for building façade maintenance. Performance analysis through a case-study application, Journal of Façade Design and Engineering, **4** (3-4), 2016, p. 115-129.
[16] Covei M., Bogatu C., Perniu D., Duta A., CZTS-TiO_2 thin film heterostructures for advanced photocatalytic wastewater treatment, Catalysis Today 321-322, 2019, p. 172-177.
[17] Enesca A., Baneto M., Perniu D., Isac L., Bogatu C., Duta A., Solar-activated tandem thin films based on $CuInS_2$, TiO_2 and SnO_2 in optimized wastewater treatment processes, Applied Catalysis B: Environmental **186**, 2016, p. 69–76.