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Solar Air Heating and Ventilation in Buildings: A Key Component in the Forthcoming Renewable Energy Mix

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This article is dedicated to Antonio Tombolini, eminent scholar and entrepreneur at StreetLib (Loreto, Italy), for all he has done to grow the digital publishing industry.

The achievements of the last two decades in using solar energy for naturally ventilating and heating buildings of any size and scope across the world are remarkable, though comprising a niche market and being generally poorly known to this point. Air quality, thermal and hygrometric comfort, and reduced energy costs are some of the benefits provided by solar ventilated spaces. We identify the remaining hurdles to be addressed prior to forthcoming widespread adoption of this technology in the building environment across the world, well beyond the cold-climate countries.

1. Introduction

Since its first applications in the late 1980s thousands of buildings of various sizes and scopes (e.g., homes, schools, offices, hospitals, as well as sport, commercial, recreational, industrial, and agricultural buildings) have been integrated with solar air heating collectors, which have provided significant economic savings and greatly improved the health conditions within the building environment.[1] As energy usage for indoor space heating and ventilation is by far the largest part of energy utilization in buildings and buildings account for over one third of the total final energy consumption,[2] one would expect to see millions of buildings across the world integrated with solar air collectors, in a similar way to how solar photovoltaic (PV) modules have developed.[3]

However, today only a few buildings around the world, mostly located in North America and Europe, use solar ventilation.[4] Similarly, only a few companies use solar-heated air collectors for processing purposes, even though the outcomes observed in applications such as drying crops or garments have been truly significant, with energy savings exceeding 50 % (as described below). For comparison, in 2008 solar air heating collectors had only 0.8 % of the nominal installed capacity in the solar heating and cooling market,[5] whereas the solar–thermal technology to heat water for domestic or industrial purposes grew dramatically; the capacity in operation worldwide grew from 127.8 GW_{th} (corresponding to 182.5 million m^2 collector area) in 2006 to 410.2 GW_{th} (586 million m^2) by early 2015.[6]

Reflecting the limited market acceptance, the scholarly interest for the technology has remained limited. As of late 2016, for example, a simple "any time" search on a scholar database using the query "solar air heating" returned only 1960 hits (Google Scholar; excluding patents and citations). For comparison, the analogous search of "solar photovoltaics" returned 55 000 hits. In the following we identify the reasons that have limited the adoption of the technology, suggesting avenues on how to tackle the remaining hurdles prior to its widespread adoption in buildings across the world.

2. Technology Applications in the Building Environment

Relying on wind and thermal buoyancy as driving forces, natural ventilation in buildings is experiencing a global renaissance,[7] as it provides an effective alternative to the mechanical ventilation and air conditioning widely used to control and adjust our indoor climate, and which very often do *not* deliver the desired indoor climate.[8]

Buildings of all types commonly suffer from the effects of condensation and mold growth, especially when airtight windows and doors to conserve energy are used in poorly thermally insulated buildings.[9] In brief, during winter the temperature of the building's internal surfaces gets close to the dew point of indoor air. Rapid condensation of the moist air trapped within the building occurs, which thereby creates the humid surface as a necessary condition for mold growth.[10] Adding to the mold spores, the organic and inorganic air pollutants released by furniture, concrete, garments, and the daily activities of the occupants create unhealthy indoor air

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pollution, which is among the main environmental risk factors for public health (symptoms collectively known as “sick building syndrome”).[11]

Solar air heating solves this problem by delivering low-temperature heat as an air flow of optimal relative humidity, transporting away undesired contaminants and preventing the formation of mold. Solar air heating collectors, both glazed and unglazed, have been used for the past 30 years for a variety of applications, from agricultural and manufacturing process drying to providing warm fresh air to a wide variety of residential, commercial, industrial, educational, and recreational buildings, which directly translates into enhanced i) comfort, ii) health conditions, and iii) protection of the building and its contents against dampness. All of this is achieved without the freezing, boiling, or corrosion problems associated with solar–thermal technology to heat water and requires little maintenance, limited to changing the air filters once or twice per year.

The very low heat capacity of air in comparison with water ($0.0003\,\mathrm{kWh\,m^{-3}\,K^{-1}}$ for air vs. $1.16\,\mathrm{kWh\,m^{-3}\,K^{-1}}$ for water) means that a large quantity of air needs to be supplied to a building to raise the temperature inside, which in turn results in excellent ventilation of the indoor space. For example, installed in 2013 as part of an expansion to the existing school buiding in Lachine, Quebec, a 400 $\mathrm{m^2}$ transpired solar collector wall now preheats 34000 cubic meters per hour of fresh air, which yields an estimated 235000 kWh in yearly energy savings and a reduction of 65 tons in CO_2 emissions.[12]

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2.1 Glazed collectors

Flat-plate, glazed collectors are extensively used because they are simple to build and operate.[13] These solar panels are generally composed of a blackened absorber surface parallel to which a glazing cover made of glass or polycarbonate works as a heat trap for the radiation re-emitted from the absorber surface, which protects the absorber from dust deposition, rain, snow, and wind. One (or two) small photovoltaic module(s) that are integrated to the collector produce the voltage needed to power a fan, which crucially improves the heat transfer between the absorber plate and the air flow, and ventilates the warm, dehumified air inside the building through a suitable perforation on the wall (or through the roof, Figure 1). As such, the system generates all of the energy required to its function using the sun.

Figure 1. An home along Sicily’s west coast using solar air heating to heat and ventilate the indoor space. The weather in the region has very high humidity levels thoughout the year.

A well-designed glazed collector includes a roughened absorber plate to absorb sun radiation at low incidence angles and achieve superior heat transfer to the airstream, and it has a typical efficiency of 58%.[14] The collector efficiency is the ratio of useful heat gain over any time period to the incident solar radiation over the same period. Hence, the efficiency is simply given by Equation (1) in which I_G is the global irradiance incident on solar air heater collector in $\mathrm{W\,m^{-2}}$ and A_C is the collector surface area in $\mathrm{m^2}$:

$$\eta = \frac{Q_U}{I_G A_C} \tag{1}$$

The useful energy gain Q_U is given by Equation (2), in which $\dot{m}$ is the mass flow rate in $\mathrm{kg\,s^{-1}}$, c_P is the specific heat of air ($\mathrm{kJ\,kg^{-1}K}$) and T_{out} and T_{in} are, respectively, the outlet fluid temperature and the inlet air temperature of the collector:[15]

$$Q_U = \dot{m} c_P (T_{out} - T_{in}) \tag{2}$$

The Hottel–Whillier–Bliss equation, $Q_U = F_R A_C[(\tau\alpha)I_G - U_L(T_{in} - T_a)]$, models the heat gain (and thus the efficiency) of an individual panel under steady-state conditions at ambient air temperature T_a as the outcome of three compounded factors: the collector heat removal factor, F_R; the effective transmittance-absorptance product, $\tau\alpha$; and the overall heat loss coefficient, U_L.[16]

Improvements in the last decade have concerned the absorber material geometry to enhance absorption, optical transparency of the glazing cover material, thermal insulation on the back of the panel to minimize heat losses, and the intake of fresh air to the panel. In general, the absorber solar absorptivity, glazing transmissivity, and wind speed have the strongest effects on the final performance. The air intake can also be through many hundreds of small holes on the backside of the panel using multi-walled polymer sheeting as a lid, and thus creating an insulating layer provided by a static air gap between the plastic layers to minimize the heat losses to the outside ambient air and improve the overall efficiency (SolarVenti technology).[17]

A major achievement has been the recent introduction of nanochemistry-based thickness-insensitive spectrally selective (TISS) coatings for the solar absorbers, which enable achieving air temperatures in the collector of up to 90 °C. The absorber can be painted in any color (Figure 2) and still achieve high performance; simple adjustments such as the introduction of an automatic shut-off valve to prevent the penetration of cold air at night also contribute to practically useful performance enhancements.[18]

Figure 2. A glazed solar collector colored in brown for architectural integration. The panel uses a TISS nanocoating to reach high temperatures, regardless of the color. [Reproduced from solar-air.eu, with kind permission].

Developed by Borel and co-workers in Slovenia, TISS coatings for colored, glazed or unglazed solar absorbers are composed of a silicone resin binder in which low-emittance aluminium nanoflake pigments are incorporated with the help of dispersant molecules to form a low-emittance coating retaining the high-temperature tolerance, excellent adhesion, and UV and weather resistance of paints.[19]

Finally, a recent conceptual breakthrough was the solar-concentrating transpired air heating collector capable of working at 60 % efficiency for a temperature rise of 70 °C; this development is thanks to a light, inexpensive absorber made of carbon fibers combined with the parabolic design of a low-cost aluminim reflector to concentrate the solar radiation and afford 73 % maximum efficiency.[20] As the solar collector efficiency increases, the actual temperature rise of the heated air decreases, due to higher heat losses as the temperature differential increases.

2.2 Unglazed collectors

There are two types of unglazed panels: perforated (transpired collector) and non perforated (back pass). Invented by Hollick in Canada in the late 1980s, the transpired solar collector is made of a perforated steel or aluminum metal cladding with an air cavity (usually 20 cm thick) between it and the building wall. The outside air is drawn straight from ambient, uniformly through the whole surface of a perforated blackened plate (the absorber), which is exposed to the sun. Integrated onto the south, southeast, or southwest façade, the metal cladding is heated by the sun while ventilation fans create negative pressure in the air cavity, drawing in the heated air through the panel perforations. The heated air rises and is ducted into the building through existing fan inlets, so that no additional penetrations are necessary.

The most important parameter dictating the collector's efficiency is the heat exchange effectiveness ($\in$),[21] which is governed by the diameter and spacings of the perforation, thickness of the absorber, and to a lesser extent by the absorber composition. Remarkably, the unglazed transpired absorber (colored in black) can also be composed of a low-thermal-conductivity polymer such as polyethylene with little performance difference in comparison to costly metals.[22]

One of the aims that guided Hollick to develop the transpired collector was the need to increase the ease of installation and the architectural versatility of the solar air heating panels. Transpired collectors, being made of metal, can be designed and shaped into a variety of forms, easily building integrated, and colored to perfectly mimick into the outer surface of the building.

The system delivers considerable cost savings requiring no maintenance over more than a 30-year lifespan. In 2006 the first installation of one such collector in the UK on a single-story industrial building provided approximately 20 % of the building's heating demand during its first year of operation, leading researchers to forecast that "the success of transpired solar collectors in the USA and Canada could be replicated in the UK".[23] Seven years later, the installation at a large distribution center in the UK became the world's largest, covering an area of 4334 m^2 and expected to reduce CO_2 emissions by 250 tons per year, with a payback time of only three years.[24]

Another example showing how transpired solar collectors can easily be integrated into existing buildings by retrofitting (required by the high energy demand of the older building environment typical of Europe or North America) is a school's gymnasium in Bedford, New York.[25] Originally built in 1968, the school's 500 m^2 gymnasium is now heated and ventilated using two sets of wall-integrated solar air collectors that collect the sun's energy on a typical sunny winter day during peak school hours, namely from approximately 9:00 am to 3:00 pm One set of panels on the southeast façade collects the morning sun, and the other on the southwest side collects the afternoon solar radiation (Figure 3). As usual, the perforated metal panels are ducted into the gymnasium ventilation system, and existing mechanical fans (wall mounted inside the gymnasium) tie the new ductwork into the existing mechanical system.

Figure 3. New York's Bedford school gymnasium after renovation to incorporate solar air collectors [Photo courtesy of Ksq Design].

It is instructive to review the outcomes of a 3-month energy metering of the heat actually generated by a 13.1 × 2.2 m^2 (width × height) transpired solar air collector installed in 2013 on the south façade of a test building in Lucerne, corresponding to Switzerland's average-sized industrial building with thermally insulated roof and walls (useful floor area: 300 m^2; height: 8.2 m).[26] The measurements lasted from November 27th, 2013 to February 28th, 2014, and the results were unequivocal. The temperature of the air delivered by the unglazed collector typically was 30 °C, with typical values of thermal efficiency primarily depending on irradiance, outside temperature, air volume flow, and wind speed and direction, reaching 60 %, which is in good agreement with previous results.[27]

The researchers concluded that solar collectors "not only serve to preheat outside air, but they also provide a substantial heat amount to cover the heating load of the building". Furthermore, the measurements performed on a sunny winter day with no wind and a high daily irradiation (5.1 $\mathrm{kWh\,m^{-2}}$), outside temperature between 5 and 10 °C, and with the air volume flow set to 50 $\mathrm{m^3\,m^{-2}\,h^{-1}}$ clearly show the sluggish thermal behavior of the collector and the limits of the steady-state approximation for evaluating the real performance of solar collectors in the open environment. In brief, due to the thermal inertia of the sheet metal panels when the sun rises, the collector is always colder than the temperature the collector would have under steady-state conditions at the considered solar radiation level. On the contrary, when the sun sets, the collector is warmer than what should be under the steady-state conditions assumption.

The team led by Sicre compared the measured average efficiency of the air collector over 5 days, reaching 56 %, using thin-film amorphous silicon photovoltaic plant modules integrated onto the same façade, whose efficiency was only 4.6 %. They further conclude that unglazed, building-integrated solar collectors are a highly efficient and cost-effective way to preheat and ventilate utility buildings.

3. Limits and barriers to overcome

The main shortcoming of the solar air heating technology is analogous to that of the solar–thermal technology to produce domestic hot water, namely that it does not operate in synchrony with the seasonal energy demand.[28] When, in winter, the need of hot air increases, the availability of solar radiation decreases, even though the vertical position of the solar collector augments winter production and partly compensates for the seasonal offset.[29] On the cloudiest days, however, the solar air collector will not even begin functioning, as reported for example in the 3 months testing study of Sicre and co-workers describing the performance of the unglazed solar collector in Switzerland.[26]

This means that solar air heating cannot be adapted as the only space heating technology, and that it will be especially useful in buildings with good insulation with low energy requirements (heating requirement $<50\,\mathrm{kWh\,m^{-2}}$ of living area per year), such as those originally built in Canada. In Europe, tens of thousand of buildings already exist with $<10\,\mathrm{kWh\,m^{-2}}$ heating requirement, whereas new legislation[30] requiring all new buildings (and all those undergoing major renovation) to be nearly zero-energy by the end of 2020 (and all new public buildings nearly zero-energy by 2018), opens the route to wide adoption of solar air heating as a space heating technology, especially useful in the transitional months during spring and autumn. Furthermore, at lower latitudes such as in southern European countries, where the availability of sun radiation is much higher, also during winter, solar air heating may well emerge as a key technology in the forthcoming fully renewable energy mix.

Two main barriers remain to be overcome for the large scale deployment of renewable solar air heating and solar ventilation of buildings: i) lack of access to the technology, and ii) policy and knowledge gaps.

3.1 Access to the technology

Access to readily available solar air collectors has been limited by the small size of the industry, regardless of the widely reported customer satisfaction. For example, commenting on the performance of his 25-year-old solar dryer company in India (Planters Energy Network), the head of the company recently emphasized that "industries have more faith in solar–thermal systems" due to a payback of less than 3 years with "many successful performances of earlier installed units creating more demand".[31] Similar excellent feedback was recorded by the authors for the occupants of the home in Sicily's countryside shown in Figure 1.[32]

The technology is perfectly suited to elegantly retrofit buildings in cities with the integration of the solar collectors in balconies (Figure 4) and façades. The deployment of solar panels in cities, indeed, is an excellent option both for producing energy (and hence contributing to a decrease of greenhouse gas emissions) and for decreasing the health threat of urban heat islands.[33]

Figure 4. Installation of a glazed solar–thermal air collector on the balcony of a city building in Palermo, Italy.

Beyond the industry's practitioners, however, knowledge of this and related best practices remains scarce, leading to low demand. In brief, the described benefits alone, no matter how significant and proven, will not cause the desirable surge in demand if managers and professionals in the solar–thermal industry, along with policy makers and educational institutions, are not proactive.

3.2 Policy and knowledge gaps

Today, thousands of transpired collectors are installed in 30 countries around the world in more than 2000 industrial, agricultural, commercial, and institutional buildings. However, nearly two decades after debuting, a Canadian newspaper reported in 2011 that the leading company was still struggling "with the commercialization of a technology that hasn't gone mainstream".[34] Asked why, the company's vice president answered that "one of our biggest challenges is that we…still have to educate people in terms of what solar air heating is."

In a situation that is common to the job market of many countries, most higher-education institutions do not offer capacity building programs in the renewable energy field, thereby creating a skill gap between demand and supply.[35] Educational institutions, thus, will continue to reshape the curricula to include solar energy science, technology, and architecture into the curricula of energy managers and professionals of the construction industry, also improving the teaching methodology by reconnecting it to individual experiences and real applications (Figure 5).[36]

Figure 5. A *Solar Master* lecture held in Sicily's Parliament in 2009.

Policy makers in turn will design and implement new policies encouraging the adoption of building-integrated solar–thermal technology by the solar retrofitting of building walls, façades, and balconies. It should also not be forbidden a priori as for example in most of Italy's cities or islands due to outdated legislations that were originally conceived to protect the landscape from the ugly installations of the first solar–thermal and solar photovoltaic systems of the 1970s.

4. Industry in transition

The solar air heating industry is a niche sector of the solar–thermal industry which has followed a path similar to that of the solar energy industry for about 40 years since the invention of the silicon solar cell (1954), namely a small community of experts and manufacturers acting within a stagnant, small market in which players acted not only as manufacturers and contractors but also as customer educators. We had to wait until the great solar boom induced by the feed-in tariffs in Germany, Spain, and eventually in Italy to observe mainstream growth in photovoltaic technology.[3] It is instructive, in this respect, to review how Germany's press recounted in 2009 the foundation of the Solar Air Heating World Industry Association:[37]

> "Air collectors are confronted with a lack of information on the part of planners and consumers, and only rarely are they explicitly included in support programmes. For this reason, most manufacturers of solar air collectors wouldn't object to the basic argument put forward by…the Canadian air collector company Conserval Engineering who stated that the sector lacked a body to represent its own interests. However, some were not so pleased that his company organised the founding of its own association Solar Air Heating World Industry Association (SAHWIA) without consulting other manufacturers. Conserval Engineering—better known under their brand name Solarwall—organized the first association meeting in a Munich beer hall during the Intersolar 2009 trade fair at the end of May.
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> 'I find it a little bit odd when an association is founded and structures are put in place unilaterally before people have even sat down at a table together for the first time…' criticised the sales manager of Grammer Solar. Apart from the aforementioned German company, Enerconcept Technologies from Canada, and Solar Breeze from Australia, there were in fact no other manufacturers present at the meeting…
>
> Conserval counters by saying: 'The inaugural meeting of SAHWIA was attended by private and public sector organizations from eleven countries on three continents. The feedback was overwhelming in support of this organization.' He added that the start of any new organization would always have its 'growing pains', but that these would be resolved over time'."

In late 2015, SAHWIA launched the “Solar AiR” logos. For example, to qualify for use of the AiR Solar Heated mark, a company or user must ensure that its building or process maximizes the solar energy usage from solar air heating technology.

4.1 Industrial development

A recent thorough survey of the solar–thermal industry, for which industry analysts contacted 550 flat plate, vacuum tube, and air collector manufacturers from 68 different countries in September 2015, found that 32 companies based in 18 different countries were manufacturing solar air collectors.[31]

The largest players of the industry (based in Austria, Brazil, China, Turkey, Greece, Israel, Germany, Australia, Mexico, and Italy) generally refused to widen their product portfolio to include air collectors even though the latter, being preferentially installed on façades and walls, basically do not compete for roof space with solar water heaters.

The entire solar–thermal collector industry was found to be under significant pressure, with quick price drops due to increasing competition and overcapacity, resulting in mergers, acquisitions, and market exit of uncompetitive players. Remarkably, the biggest fluctuations were reported in the field of air collectors. In total, 13 of the companies present on the air collector map in 2014 have since stopped production. On the other hand, three new companies (one in Jordan, one in Moldavia, and one in China) started manufacturing air collectors in 2014 or 2015.

4.2 Regulation and standardization

As also shown by the Solar Keymark, a European brand for solar–thermal products,[38] standardization and subsequent certification increase consumer confidence and accelerate the uptake of a technology. Given that a standardized procedure for testing solar air collectors did not yet exist in the early years of development, the first testing of most series-produced solar air collectors (at that time mainly from Canada and Australia) was commissioned to the Austria Centre for Research and Testing by the International Energy Agency program in solar heating and cooling (Task 19 “Solar Air Systems”) after the first six years of the effort (1993–1999). The outcomes pointed to significant performance differences among the few collectors then available on the market.[39]

However, no standard for solar–thermal air collectors was developed until 2013. Recounting in 2012 the interaction of regulation and innovation for solar air collectors, Kramer emphasized that the process of integrating the innovative products “was only possible through the financial support from German government, as the producers of these products would by far not have been able to finance the standardization work necessary”.[40] In brief, public researchers in Germany developed the test stands and measuring equipment to ensure accuracy for the characterization of solar air heating collectors,[41] which requires the computation of $\tau\alpha$ from Equation (2) and measurements of cover transmittance and collector reflectance, computation of F_R from a test in which the heat loss term equals zero, and computation of U_L from a test in which insolation equals zero.[42] A draft international standard describing testing methodology for solar–thermal technologies, including solar air heating collectors and concentrating medium-temperature collectors, was developed and published as a result. The final version of the standard for assessing the durability, reliability and safety for fluid heating collectors was approved by the international standard committees with more than 90 % of the votes in September 2013, and was published as EN ISO 9806:2013 “Solar energy—Solar–thermal collectors—Test methods”.

For the first time, there was a modern global standard for the testing procedures of solar–thermal collectors to which different countries, the solar–thermal industry, and consumers could refer. It is perhaps not surprising that solar air heating companies started to publish the outcomes of comparative performance tests around the same time. For example, one company in Europe recently compared the performance of one of its models (SolarVenti SV7) with that of a collector of similar size imported from China (GS20) in filling with air a 4 m plastic bag following exposure to the sun. The former required 17.5 s to fill the bag, whereas it took the Chinese model as long as 46 s, eventually also with lower pressure.[43]

5. Outlook and Conclusions

Similar to the use of solar–thermal technology to heat water,[44] solar air heating to preheat and ventilate buildings is a highly cost-effective way to use freely available solar energy to reduce energy costs and improve indoor health and environmental conditions. Thousands of buildings and new design solutions today complement the 33 exemplary case studies using different solar air systems that are illustrated in the *Solar Air Systems—Built Examples*[45] and *Solar Air Systems: A Design Handbook*,[46] published at the end of the 1990s as an outcome of the “Solar Air Systems” Task of the International Energy Agency.

Complementing a series of studies aimed at streamlining and enhancing the adoption of distributed solar energy and energy efficiency technologies in urban centers,[47] remote islands,[48] and street lighting,[49] this study also shows that solar air collectors are ideally suited for being building integrated, offering exquisite architectural versatility, which will become one of the key factors supporting the forthcoming growth in the well-suited building environments of islands, cities, and protected areas.

As the world’s solar energy boom continues, we also suggest, series-produced solar air collectors will be used in warmer climates, beyond North America and northern Europe, where they have been used since the late 1980s. Beyond colder-climate countries such as Canada, Germany, and the United Kingdom, the technology will be increasingly used in geographical areas where it has so far been largely ignored, such as in Mediterranean countries and their 3000 inhabited islands where dampness and mold formation are well-known issues that negatively affect the inhabitant quality of life as well as the built structures.

Difficult access to the technology and poor societal/market recognition are the two main hurdles to be addressed prior to widespread adoption of solar air collectors to preheat, heat, and ventilate indoor spaces of different size and utilization purposes. In a rapidly evolving global context in which the energy–population conundrum quickly unfolds,[50] countries will eventually evolve to a fully renewable energy mix,[51] following the 2016 ratification of the legally binding COP21 international agreement to significantly reduce carbon dioxide emissions in 114 of 191 world's countries.[52] This efficient, reliable, and aesthetically pleasant technology will emerge as a key component in the mix of renewable energy technologies that will be used to curb carbon emissions from the built environment while improving the environmental and health conditions experienced by citizens around the world.

Keywords: air ventilation • building technology • renewable energy • solar energy • solar air heating

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