Abstract-The use of solar energy in buildings is a vastly developing field all over the world. Besides PV (Photovoltaic) and solar thermal technologies, a new emerging area - the use of PVT (Photovoltaic-Thermal) collectors in buildings is rapidly increasing. Since the roof top area in urban areas is limited, the most efficient concepts for cooling and heating the low energy buildings in northern latitudes must be found. PVT collectors have very good properties. E.g. production of electricity and heat takes place in the same square meter, which gives the advantage to save the roof top area. Additionally, cooling the PV cells and consequently using solar energy more efficiently, gives an advantage to PVT technology. In the current article an overview of possible solar cooling technologies is presented and a comparison of roof top area needed is given.

I INTRODUCTION
A large amount of research on the photovoltaic-thermal (PVT) collector has already been conducted over the last 30 years with a continuous increase in the number of papers and other activities [1]. Internationally, the development of the PVT technologies has been escalating from the start of the last century and continues to increase. In the current article an overview about the groundwork of PVT heating and cooling systems is given, with more emphasis on PVT cooling systems.

A PVT system is an integrated approach, where the generation of electricity and heat is combined in one device. It also can be called micro CHP (Combined Heat and Power) station where both electrical and thermal energy are generated from solar energy. Most usually there is a PV (photovoltaic) cell where solar rays are absorbed and electricity is generated. The efficiency of the monocrystalline PV collector is typically 11-17% and the rest of the solar energy is released as heat energy, which could be used to heat up the coolant integrated to flow on the backside of the PV panel (Fig. 1).

II PERFORMANCE ASSESSMENT OF A PVT COLLECTOR
The overall performance of a PVT system is not straightforward to assess. The PVT system has several components like the PV component for the generation of electricity, the thermal component for the generation of heat energy and also several auxiliary parts like inverters, accumulators for electricity and heat, controllers, thermal storage, flow conduits, etc. To reach the highest efficiencies of PVT collectors, the designer of the collector has to create the most appropriate solar fractions and all the other collector parameters must carefully be chosen as well. The total efficiency \( \eta_0 \) of the PVT collector can be found from the sum of two efficiencies: the thermal efficiency \( \eta_t \) and the electrical efficiency \( \eta_e \). According to some researchers the sum of electrical and thermal efficiency of a PVT collector (such as [2]; [3]) is given by:

\[
\eta_0 = \eta_e + \eta_t.
\] (1)

where

\[
\eta_e = \frac{V_{mpp} I_{mpp}}{G A}
\] (2)

and

\[
\eta_t = \frac{m C (T_{out} - T_{in})}{G A}.
\] (3)

\( V_{mpp} \) and \( I_{mpp} \) describe the voltage and electric current at maximum power point operation, \( m \) and \( C \) are, respectively, the mass flow rate and specific heat capacity of the coolant. \( A \) is the collector aperture area, \( T_{in} \) and \( T_{out} \) are the coolant temperatures at the inlet and outlet, and \( G \) the incident solar irradiance normal to surface.

The cell efficiency \( \eta_{cell} \) and the electrical efficiency are directly related to each other. The cell efficiency is related to the ratio of the cell surface area \( A_{cell} \) to the covered area by PV cells, named aperture area, which is also known as packaging factor \( \beta \) (usually >90%), in that

\[
\eta_e = \frac{A_{cell} \eta_{cell}}{A} = \beta \eta_{cell}.
\] (4)

The thermal efficiency can also be shown as a function of reduced temperature, which is defined as

\[
T^* = \frac{T_{out} - T_{in}}{G}.
\] (5)
where $T_0$ is the ambient temperature. From the equation we can see that if the temperature of the coolant is lowered compared to the ambient temperature, then the thermal efficiency of a PVT collector increases [4].

Alternatively, thermal efficiency connected to efficiency at gain to the maximum possible useful heat gain.

The relations of the exergy efficiency of the solar cells. The relations of the exergy input. In a defined time period $t$ is defined as the ratio of total exergy output to the total exergy input. In a defined time period $t_1$ to $t_2$ the $e$ can be expressed as

$$
\eta_t = F \left[ \left( \tau \alpha \right)_e (1 - \eta_e) - U_L \left( \frac{T_m - T_a}{G} \right) \right],
$$

where $F$ and $U_L$ are the modified heat removal factor and overall heat loss coefficient, $(\tau \alpha)_e$ is the effective transmittance, and $\eta_e$ is the electrical efficiency evaluated at ambient temperature. $F'$ is the ratio of the actual useful heat gain to the maximum possible useful heat gain.

Alternatively, thermal efficiency connected to efficiency at inlet temperatures reduced to zero, $\eta_{0\infty}$ can be found

$$
\eta_{0\infty} = \eta_{\infty} - \alpha T^*\eta,\qquad (7)
$$

where the slope $\alpha$ relates to the heat loss factor of the collector. Alternatively, if $T_a$ is the mean fluid temperature in the collector and $F'$ the collector efficiency factor, then

$$
\eta_t = F \left[ \left( \tau \alpha \right)_e (1 - \eta_e) - U_L \left( \frac{T_m - T_a}{G} \right) \right].
$$

When using formula (9), one has to be careful, since there are some authors, who consider that electricity converted from solar energy is of higher value compared to thermal energy. The energy saving efficiency is then introduced (as in [6] [7]), in that

$$
\eta_{saving} = \frac{\eta_e}{\eta_{power}} + \eta_t,\qquad (9)
$$

where $\eta_{power}$ is the electric power generation efficiency of a conventional power plant. In addition to efficiency analysis, sometimes an exergy analysis is needed to be performed. Exergy measures the maximum quantity of work that can be produced in some given environment. Exergetic efficiency ($\epsilon$) is defined as the ratio of total exergy output to the total exergy input. In a defined time period $t_1$ to $t_2$ the $\epsilon$ can be expressed as

$$
\epsilon_{pv} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} (A E_{pv} + A_{cool} E_{pv}) \, dt = \epsilon_j + \beta \epsilon_{pv},\qquad (10)
$$

where $E_{pv}$ is the thermal exergy output per unit collector area, $E_{pv}$ the photovoltaic exergy output per unit cell area, $E_{sun}$ the exergy input of solar radiation, $\epsilon_j$ the exergetic efficiency of the thermal collector and $\epsilon_{pv}$ is the exergetic efficiency of the solar cells. The relations of the exergy outputs are as follows [8]:

$$
\dot{E}_{X_{pv}} = \dot{E}_{pv},
$$

and

$$
\dot{E}_{X_j} = \dot{E}_j \left(1 - \frac{293}{293 + (T_2 - T_1)}\right),
$$

where $\dot{E}_j$ is the thermal power output per unit collector area, $\dot{E}_{pv}$ the photovoltaic power output per unit cell area, and $T_2$ is the final temperature of the coolant.

To evaluate the economics of a PVT installation, the life cycle of the PVT collector must be evaluated. This will give the total cost of the PVT collector [9], including investment and operation costs over its entire service life. Most of the PVT collector costs occur beyond the acquisition date, because of that reason PVT collector costs must be evaluated using the time value of money. Calculations have to include inflation, tax and/or company discount rates. There is also a simplified approach where the time element is neglected and therefore the cost payback time (CPBT) can be used. CPBT means that cash inflows from successive years are added together until the cumulative cash inflow reaches the same level as the required investment.

To evaluate the environmental cost-benefit parameters, the greenhouse gas payback time (GPBT) and the energy payback time can be used (EPBT). EPBT is defined as the ratio of embodied energy to annual energy output. The embodied energy refers to the amount of energy used to produce the PVT collector, from material to packaging process. E.g. for Building Integrated PVT (BIPVT) collector

$$
EPBT = \frac{\Sigma_{PVT} + \Sigma_{bos} - \Sigma_{mlt}}{E_{pv} + E_j + E_{ac}},
$$

where $\Sigma_{PVT}, \Sigma_{bos}$ and $\Sigma_{mlt}$ are, respectively, the embodied energy of the PVT collector, of the balance of the collector, and of the replaced building materials. $E_{pv}$ is the annual useful electricity output, $E_j$ is the annual equivalent useful heat gain, and $E_{ac}$ is the annual electricity saving of the Heating, Ventilation and Air Conditioning (HVAC) system due to the thermal load reduction.

Greenhouse gas (GHG) emission is similarly found

$$
GPBT = \frac{\Omega_{PVT} + \Omega_{bos} - \Omega_{mlt}}{Z_{pv} + Z_j - Z_{ac}},
$$

where $\Omega$ stands for the embodied GHG (or carbon dioxide equivalent) and $Z$ the reduction of annual GHG emission from the local power plant thanks to the BIPVT operation. In addition to the efficiency, economical and environmental payback time evaluations, there are other possibilities to estimate the PVT collectors’ performance by determining the money savings according to the current heating and electrical energy tariffs. The tariffs are always influenced by political decisions and the situation in the market can rapidly change. However, it is one suitable way to evaluate the performance if
it is considered that the market does not change rapidly [8]. Finally, the output of the PVT collector always varies depending on the location of the collector and therefore the previous work has to be critically evaluated before using the results in an analysis. Results from different locations cannot be compared directly.

III  PVT COLLECTOR TECHNOLOGIES

A. Flat Plate PVT Collectors

Various types of flat plate PVT collector configurations exist. For example sheet-and-tube with and without cover, channel above PV, channel below PV, free flow collector, one or two absorber collector and various collectors with additional air flow for cooling the PV cells exist. The electrical efficiency of a PVT collector is dependent on the selected PV technology varying from 4-14%. The thermal efficiency is varying from 50%-75% (see Fig. 2). Zondag et al. developed a simulation of PVT collectors. Nine different configurations were analyzed and experimentally measured. It was found that the results of the PVT collectors were agreeable and the experimental results were within 5% of the simulated results. The thermal efficiency was measured at zero reduced temperature. The most promising concepts, especially in the colder climates, are the single covered sheet-and-tube collector, which has a thermal efficiency of 58% and an electrical efficiency of 8.9%, and the water-channel-above-PV collector with a thermal efficiency of 64% and an electrical efficiency of 8.4% [10].

<table>
<thead>
<tr>
<th>PVT collector type</th>
<th>Total efficiency</th>
<th>Electrical efficiency</th>
<th>Thermal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV laminate</td>
<td>0.097</td>
<td>0.097</td>
<td></td>
</tr>
<tr>
<td>Sheet and tube PVT-collector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 cover</td>
<td>0.617</td>
<td>0.097</td>
<td>0.52</td>
</tr>
<tr>
<td>1 cover</td>
<td>0.669</td>
<td>0.089</td>
<td>0.58</td>
</tr>
<tr>
<td>2 covers</td>
<td>0.661</td>
<td>0.081</td>
<td>0.58</td>
</tr>
<tr>
<td>PVT-collector with channel above PV</td>
<td>0.734</td>
<td>0.084</td>
<td>0.65</td>
</tr>
<tr>
<td>PVT-collector with channel below opaque PV</td>
<td>0.69</td>
<td>0.09</td>
<td>0.6</td>
</tr>
<tr>
<td>PVT-collector with channel below transparent PV</td>
<td>0.72</td>
<td>0.09</td>
<td>0.63</td>
</tr>
<tr>
<td>Free flow PVT-collector</td>
<td>0.726</td>
<td>0.086</td>
<td>0.64</td>
</tr>
<tr>
<td>Two-absorber PVT-collector (insulated type)</td>
<td>0.745</td>
<td>0.085</td>
<td>0.66</td>
</tr>
<tr>
<td>Two-absorber PVT-collector (non-insulated type)</td>
<td>0.734</td>
<td>0.084</td>
<td>0.65</td>
</tr>
<tr>
<td>Thermal collector</td>
<td>0.83</td>
<td>0.83</td>
<td></td>
</tr>
</tbody>
</table>

The total energy production per unit surface area from PVT collectors can be, as shown in previous studies, also higher than one PV and one solar thermal collector. [11]. These conclusions however are not fully true because authors used to evaluate electrical energy production according to the Equation (9).

PVT collectors can additionally be improved by increasing the efficiency of absorbing more solar energy and transferring as much heat as possible to the transfer liquid. A few suggestions for improving the efficiency are:

- designing a better collector absorption coefficient;
- developing new materials, which will increase the efficiency of the collector and at the same time reducing the payback period - solution is very attractive if roof space is limited;
- by improving the efficiency also the payback is improved, which shall be less than 10 years;
- new methods have to be developed to integrate collectors into one value added product.

B. Concentrated PVT Collectors

Concentrated PVT collectors are systems where the solar rays are falling either directly through a wide diameter concentrating lens and are concentrated on the PV cell or where the solar rays are reflected from the surface of a parabolic or a cylindrical disk and concentrated on the PV cell.

A parabolic disk installation, with an aperture area of 0.95m² under normal beam insulation of 900W/m² was experimentally measured (Fig. 2). The parabolic disk concentrated available radiation to one triple-junction cell with an efficiency of 32%. It was found that the efficiency of the collector was 80% and 140-180W/m² of electricity and at the same time 400-500W of heat was generated. It was also measured that the PV cell temperature was around 10°C higher than the temperature of the coolant and typical working temperatures of the coolant with the concentrator were 50-100°C. Higher temperatures reaching 200°C are promising because of the development of new high temperature PV cells [12].

The MCPV unit during solar testing [12].

Another cylindrical low concentrating PVT collector installation in the higher latitudes (Lund, Sweden, at 55.7°N) was installed and investigated (Fig. 3). The electric and thermal active glazed area equals to 3.5m² and 3.7m² respectively.
Fig. 3. PVT concentrator trough and photovoltaic cells laminated on one side of the thermal absorber [13].

The nominal efficiency of monocrystalline PV cells was 16% at 25°C and the surface area of the cell equals 0.33m². The parabolic reflector area had a reflectance factor of 90%. The total peak electrical output under insolation conditions of 997W/m² was found to be 61W/m². At the same time thermal output was 435W/m². The electrical efficiency $\eta_e$ and thermal efficiency $\eta_t$ of the installation were respectively 6.4% and 37-46% while the coolant temperature was 28°C in inlet and 39°C in outlet [13]. The coolant temperatures however were considerably low compared to the parabolic disk tracker. One possible reason is the low concentrating factor of the cylindrical system.

Another study with c-PVT collectors was conducted by Mottelman et al. The integration possibilities of a single effect absorption chiller where the outlet temperatures of the c-PVT collector were set in range 65-120°C was investigated. The nominal efficiency of the triple junction PV cells was 37% and the paper revealed that the temperature did not considerably affect the electrical efficiency [14].

Another study conducted in Australia in 2004 investigates the performance of a PVT collector with a geometric concentration ratio of 37. The measurement results show the overall efficiency of 69%, where electrical and thermal efficiency was respectively 11% and 58%. The collector temperature was varied from 30-80°C and at the same time it was noted, that the used PV cell with nominal electrical efficiency 20% considerably decreased in the efficiency (Fig. 4) [15].

Fig. 4. The effect of temperature on the electrical efficiency [15].

C. Building Integrated PVT Collectors

Population growth and urbanization takes place every day and this means, that more energy is needed in cities to cover the needs of the population. Additionally, more efficient or even zero energy housing is needed in order to create less CO$_2$ in the cities and a better living environment. Lately, because of the development of nearly zero energy buildings and passive house technologies, the need for locally produced energy is raising. Therefore, the integration of PV technologies into buildings is a rapidly expanding area. Integrating PV technologies into the buildings is not only important because of the city’s environment, but also to reduce the energy costs of the buildings [16].

The type of BIPV module integration is also very important to note. According to Guiavarch et al [17], the efficiencies of BIPV installations vary. Their research shows that PV modules fixed on the roof in the location of Paris have an average efficiency of 14% and if the PV modules would be integrated on the wall and preheating the ventilation air then efficiencies could reach 20%. The conclusion of the paper is that BIPV should be coupled with an air collector to increase the PV modules’ efficiency.

IV SOLAR COOLING TECHNOLOGICAL POSSIBILITIES

Cooling of a house can be implemented by using many various technologies. Using solar energy on buildings is confronted with several limits as for example incident solar radiation, the temporary usage of energy, available roof area, PV cell technology and others. To categorize the cooling technologies for cooling a house or an indoor area, hot air/liquid or electricity can be used.

D. Solar Cooling with Thermal Energy

For cooling with hot liquid, absorption/adsorption chiller or ejector technologies can be used. In order to reach good efficiencies (Coefficient of Performance (COP) = 0.7) of one stage absorption process, the coolant from the PVT collector has to be at least 80°C hot.

For the two stage absorption process, a coolant with higher temperatures (>100°C) has to be provided in order to reach a high efficient absorption process (COP = 1.1-1.2) [18], [19]. Ejector based technology is more simple because there are no moving parts in the system, but still the COP of the system is low as 0.7. The temperatures needed for the ejector based cooling are 80°C to 160°C [20].

To reach 80-100°C of liquid temperature, vacuum tube thermal collectors or concentrated solar collectors have to be used. Flat solar thermal panels and PVT collectors rarely reach temperatures of 80-100°C and therefore it is not economical to use them. Concentrated solar installations, such as parabolic dish or cylindrical dish PVT collectors (as analyzed in the previous chapter) are reaching temperatures over 100°C in a clear day and therefore are suitable solutions for the absorption or ejector cooling process (see Fig. 5) [12].
For solar cooling with a hot liquid, vacuum tube collectors can also be used. In a hot summer day the temperatures in a vacuum collector can increase easily over 100° C. In the current paper, vacuum tube collectors are not considered for solar cooling, but in a future article an economical calculation must be done and results should be compared with the results from different PVT collector studies.

E. Solar Cooling with Electrical Energy

PVT collectors deliver higher electrical output than the conventional PV modules installation, since PV cells are cooled and therefore the ohmic losses are reduced. In the previous work by Hartmann [18] configurations of cooling the house directly with a compression chiller are analyzed. The results show that although using a vacuum tube solar thermal collector for delivering a hot liquid to absorption process, the price of the absorption installation is currently too high and even in the year 2015 the price perspective is still not economical. Compression chiller systems are, at the same time, more economical to use, since the price per W of a PV installation is continuously dropping. The compression chiller installation is already cheaper than an absorption pump installation and additionally COP of a compression chiller technology is rather high (COP = 3 and higher) [18].

F. Comparison of Cooling Technologies

To compare the PVT collector technologies for cooling a building area the parameters of the cooling system have to be defined. Cooling of buildings in northern latitudes (>50°) is needed only from May until August. There are exceptions when the facades of buildings are very much opened for the sun rays and cooling is needed earlier already in March. Energy needed for cooling, Ecool, can be defined therefore only for the summer period, when the average outside temperatures are 5°C and higher. For an average low energy family house the Ecool is typically varying from 142kWh in May and 563kWh in July. The COP of the cooling system has to be defined. For one stage absorption and ejector process 0.7 and for two stage absorption process a value of 1.2 can be used. Compression chiller systems have a COP of 3. The average electrical energy generation efficiency of PV cells is taken 14% for the separate PV module installation and 15% for a PVT collector because of the cooling of the PV cells by a liquid coolant. To compare different cooling technologies, the available roof space area for solar installation has to be taken as a basis for comparison. According to TABLE II, the needed roof top area for cooling a low energy house is smallest when a concentrator PVT (c-PVT) collector is used. The generated heat by the c-PVT is directly fed into an absorption cooling process and electrical energy can be used to track the sun. Although the absorption cooling and c-PVT collector show the best performance, the c-PVT combination with compression chiller should be considered because of lower installation costs.

TABLE II

<table>
<thead>
<tr>
<th>Cooling technology</th>
<th>Energy generation from the sun</th>
<th>Surface area of installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>COP</td>
<td>Type</td>
</tr>
<tr>
<td>Compression chiller</td>
<td>3.0</td>
<td>PV</td>
</tr>
<tr>
<td>Compression chiller</td>
<td>3.0</td>
<td>PVT</td>
</tr>
<tr>
<td>Compression chiller</td>
<td>3.0</td>
<td>c-PVT parabolic</td>
</tr>
<tr>
<td>One stage absorption</td>
<td>0.7</td>
<td>c-PVT parabolic</td>
</tr>
<tr>
<td>Two stage absorption</td>
<td>1.2</td>
<td>c-PVT parabolic</td>
</tr>
<tr>
<td>Ejector</td>
<td>0.7</td>
<td>c-PVT parabolic</td>
</tr>
</tbody>
</table>

V CONCLUSIONS AND FURTHER WORK

The current article gave a short overview about possible PVT collector technologies for cooling buildings in the summer. At first, an overview of flat plate PVT collectors was given. According to TABLE II, the electrical and thermal efficiencies of a sheet-tube PVT collector are 8.9% and 58% respectively. The electrical efficiency highly depends on the used PV cell technology and therefore can be easily increased. The flat plate PVT collector cannot deliver high temperatures for solar absorption or ejector cooling, but concentrated PV collectors with tracking systems can. The temperatures in concentrated systems rise up to 160-200°C and therefore the systems are extremely suitable for absorption cooling. Another possibility is to use flat plate PVT collectors in combination with compression chiller technology because of the availability of reliable technology and low installation costs of the chiller system. Still, not enough knowledge is available to evaluate which technology is more economical to use for cooling buildings as there are only a few c-PVT installations experimentally measured in higher latitudes. Additionally, high efficient cells that are available today in the market are not yet experimentally measured to make conclusions about cell efficiencies in high temperature applications.

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