Development and Benefits of Using PVT Compared to PV

Pavel Sevela[#1], Bjarne W. Olesen[#2]

Department of Civil Engineering, Technical University of Denmark
Brovej, Building 118
2800 Kgs. Lyngby, Denmark
[1]pavelsevela@gmail.com
[2]bwo@byg.dtu.dk

Abstract

The goal of this paper was to inform about the development of the building integrated photo voltaic thermal (PV-T) system and evaluate its performance in compared to PV installation built of same photovoltaic cells. The study was collaboration among the Technical University of Denmark (DTU and Danish company RAcell (end-reference to website). This project was applied and optimized with the coupled house system on FOLD house, built in purpose of international student competition Solar Decathlon Europe 2012 held in Madrid in September 2012. The proposed PVT system was awarded with first price in Solar system integration sub-contest, during the competition SDE 2012.“Highly effective and innovative integration of PV and thermal systems that is not only a machine added to a house, but added value without creating too much attention to that machinery,” said one of the jury members about the PVT system, announcing the winner.

The PV-T is a hybrid system where the significant growth of efficiency of electricity generation is caused by cooling the cells to optimal temperature by system of embedded pipes on the backside of photovoltaic panels. The thermal part removes the heat, cools down the cells and increases its el. production up to 14,8% according to PV system using the same cells in the same weather conditions. New solution was carried out for piping connection between panels. The house integrated PV-T system was compared with separate Photovoltaic and Thermal systems from energy and economy point of view. For annual usage of the FOLD house in Spain and Denmark was the PV-T system found as a more beneficial in compare to two separate systems.

Keywords – PV-T, Solar Decathlon Europe 2012, Domestic hot water tank, bore hole, Tichelmann, Drain back system

1. Introduction

As the Solar Thermal Vision 2030 document notes about the solar energy: „Buildings have the potential to be active buildings with a 100% energy needs covered by solar power. The solar technologies may become the most important energy source for the building of the future.” [3] “Architects and engineers must be able to design buildings in the complex approach, combining intelligent architecture, energy efficiency and savings, advanced control of solar gains and innovative solutions for solar systems to ensure maximization the supply of energy.” [2]

“Rational use of the building envelope for collecting solar energy and conversion to the desired form of energy resulted in the development of active solar elements integrating the equipment into the building.” [4] Great innovative potential lies in the usage of the multifunctional elements that combines the aforementioned functions in a single element.

The photovoltaic cell is the basic element that converts the energy of light to the direct current electricity during process called photovoltaic effect. Standard solar collectors turns up to 14% of solar radiation into electricity, the rest is waste heat, which partially goes into the surroundings and partially heats the PV module. High cell temperature causes a high electrical resistance that limits efficiency of the conventional photovoltaic systems. The combination of the photovoltaic and thermal system in one is the way to break these limits. PVT is a hybrid system where the thermal part removes heat from the panel, cools down the photovoltaic cells and increases its electrical production in compare to similar PV system under the same conditions. The removed heat from PVT is further contributed in relation to what kind of system is coupled with the PVT panels. To take advantage of all the benefits that PVT technology offer, it is essential for the engineer to choose a right system scheme which always provides a low supply temperature.

In the following sections is described development of PVT panel, design of the PVT system, integration in FOLD house and its effect to the energy balance.

2. Development and Testing of PVT Panel

2.1 Standards

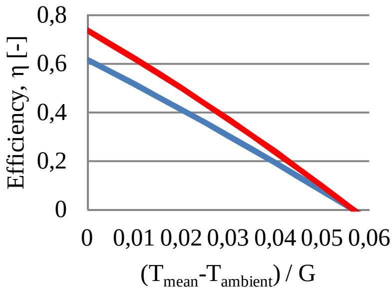
The development of this new PVT system was carried out complying the requirements of the following standards: IEC 60364-7-712 about special PV installations, IEC 60364 about installation of PV, IEC 61215 obligatory standard for custom made PV panels, IEC 61727 characteristics of grid connected PV system up to 10kW power, Royal Decree 1699/2011 Spanish standard regulating network connection, ISO 9806-1:1994 test methods for solar collectors, DS/ENV 13005 uncertainty in measurement guide.

2.2 Design strategy

The strategy was to produce extra electricity by using fluid to cool down the PVT panels. During the design phase special attention was taken in relation to hydraulic division of PVT panel, to practical solution for dismountable joints between panels and to common design of thermal and PV part. It was desired to develop solution that allows a low level of maintenance and which ensures a reliability and durability.

2.2 Thermal Part Test

Simulation was conducted to find out the panel´s effectiveness in relation to different configurations of lateral pipes, seen on Fig. 2, namely 6 and 10 per meter. From the Fig.1 is evident that spacing of 100mm can utilize more solar energy than spacing 166mm. The most significant difference appears when the temperature difference between surrounding and PVT surface is minor. Such a situation is the goal.



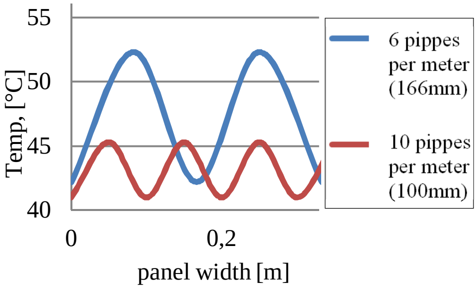


Fig. 1A Thermal efficiency for two different spacing of lateral pipes [1]

Fig. 1B Temperature fluctuation for two different spacing of lateral pipes [1]

On the Fig. 1B is seen temperature fluctuation across absorber plate for the two spacing of lateral piping in PVT panel. The simulation was carried out for solar irradiation of 1000 W/m^2, 25°C and no wind. The peaks indicate intermediate space between two pipes where the temperature raises the most. It was desired to have as even temperature over the absorber as possible, thus spacing of 100mm was chose.

The PVT panel was tested on outside testing facility consisted from boards with angle of 67,5°, oriented to the true South.

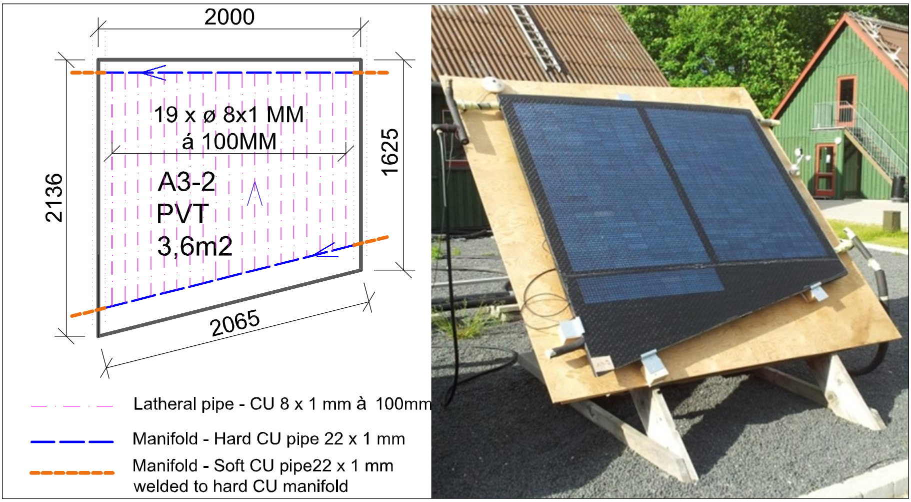


Fig. 2 The tested PVT panel [6]

$$\eta_{Thermal\ with\ \boldsymbol{passive}\ cells} = 0{,}483 - 5{,}485 \cdot \Delta T/G \quad (1)$$

$$\eta_{Thermal\ with\ \boldsymbol{active}\ cells} = 0{,}422 - 5{,}628 \cdot \Delta T/G \quad (2)$$

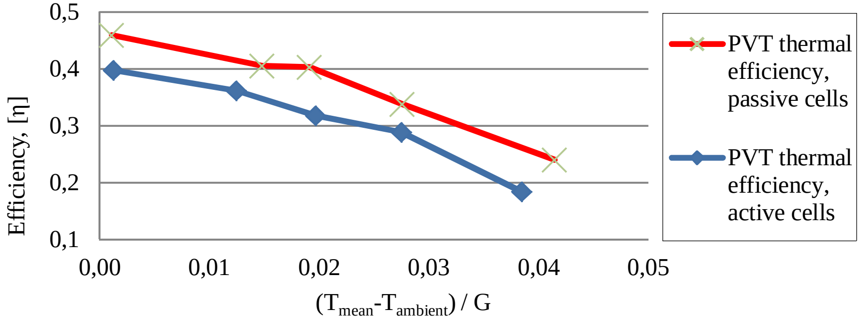


Fig. 3 Thermal efficiency of PVT panel

Thermal efficiency was measured under two circumstances: with **active** PV cells and **passive** PV cells. In the case with active cells (1) was about 42% of solar irradiation transformed to heat. During measurement with passive cells (2) was reached efficiency about 48%. Since the PV cells were placed in layer above the thermal part, the active cells "stole" share of energy that was transported from panel as a direct current. Thus thermal part, placed below the cells, obtained less energy to produce heat. This explained the anomaly with two different thermal efficiencies. The overall energy balance stayed equal.

2.3 Electrical Part Test

Electricity was generated by mono cristaline silicone cells Sunpower a-300. Squered cells were divided into 3 rectangular pieces with dimensions 41x125 mm to decrease the risk of failure due to panel bending. Smaller cells can also cover more of the unrectangular areas. The bypass diodes were integrated inside the lamination (8 and 14 cells per diode entity). Thus, in a case of failure, only certain number of cells are out of order and the panel still produces power. No junction boxes were used for the PVT modules, only fixture for cable outlets.

The electrical testing was performed on the same testing setup as the Thermal test. Voltage and current were measured using the "Uganda" method", as seen on Fig. 4.

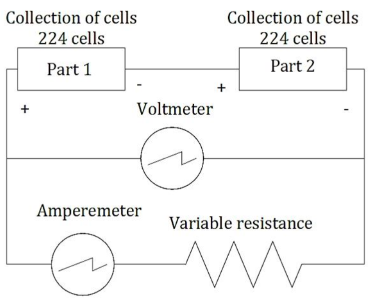


Fig. 4 Electrical scheme of testing setup [1]

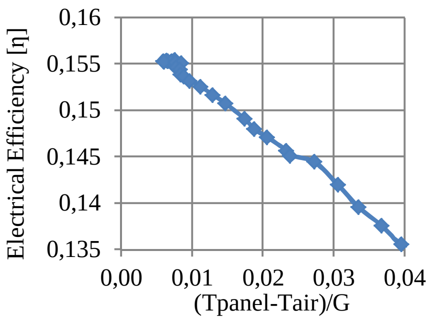


Fig. 5A Electrical efficiency measurement of PVT panel [6]

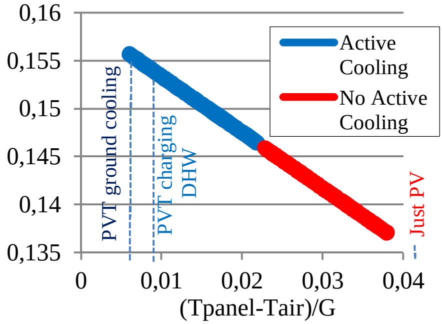


Fig. 5B Idealized electrical efficiency of PVT panel [6]

$$\eta_{PV\ cells} = 0{,}159 - 0{,}583 \cdot \Delta T / G \quad (3)$$

Table 1. Active and no active cooling effect

	Efficiency (%)	Panel temperature (°C)	Air temperature (°C)	Solar irradiation (W/ m^2)
Active cooling	~15,5	32±0,5	22,5±0,5	880÷950
No Active cooling	~13,5	66±0,5	22,5±0,5	880÷950

The results of the electrical tests, seen on Fig 5A, showed efficiency curve depending on solar irradiation and temperature difference between panel and the surrounding. The electrical test of the panel , seen on Fig 5B, was done during a normal temperature level under moderate Danish summer weather conditions, seen in Table 1. The efficiency curve was idealized and divided into two zones representing electrical efficiency when the cells are Actively Cooled by fluid circulation and to Non Active Cooled when panel is cooled only naturally. The three marked efficiency levels correspond to STC but with vary panel temperature. The three efficiency levels illustrates the following scenarios: 32°C for PVT ground cooling; 35°C for PVT charging DHW tank and 66°C for normal PV panel.

The electrical characteristics of PV cells itself stayed unchanged regardless of the variable cooling modes, but the active cooling provided higher electrical efficiency, in comparison to PV with the same boundary condition.

A new type of efficiency, **hybrid efficiency**, was introduced. Up to 58% of solar energy, that incidence with surface of the PVT panel, is utilized, seen on (4). The hybrid efficiency, seen on Fig. 6, represents sum of electrical efficiency and the thermal efficiency if both systems work simultaneously.

$$\eta_{PVT\ hybrid} = 0{,}583 - 6{,}281 \cdot \Delta T / G \quad (4)$$

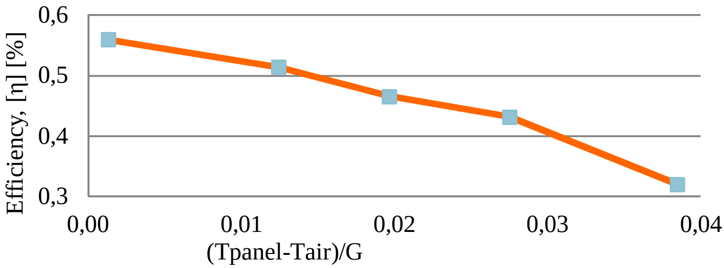


Fig. 6 Hybrid efficiency of PVT panel [1]

The top cover made of Saint Gobain - Albarino G textured glass reduced glare, supported the self-cleaning property and gave 3 % extra efficiency under IEC 61215.

The PV cells were embedded and conducted to textured glass with EVA film. The thermal part was electrically separated with Tedlar foil. The piping was coupled to the PV part by EVA material and the backside finishing was made of another Tedlar sheet. The thermal insulation Armaflex AF was glued to the back of the PVT panel.

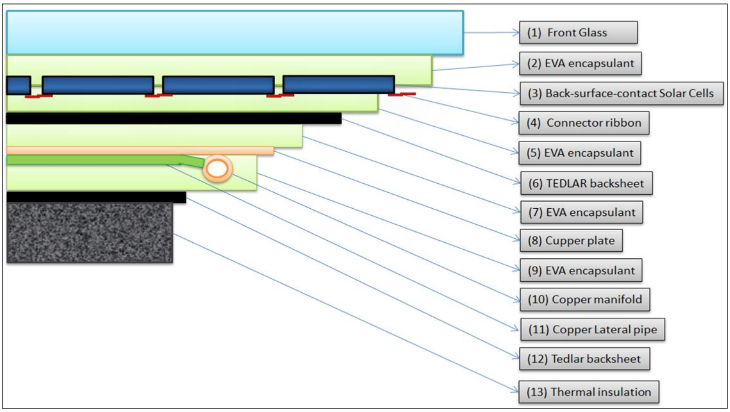


Fig. 7 PVT panel cross section [6]

3. Implementation in the FOLD House

The PVT system was the main renewable energy source for the FOLD house. The integration concept of PVT system was to firstly utilize “free” heat removed from PVT´s by water circulation and contribute in the DHW tank (heating mode). The PV cells were cooled and efficiency of the photovoltaic effect was improved, as described in section 2.2.

When no more heat to DHW tank was needed, the cooling took place via a 120m deep borehole. For purpose of SDE was the borehole simulated by chilled buffer tank. The PVT´s there ought to be able to obtain very low temperatures and hence improve the electrical performance even more (cooling mode). The borehole served as a heat sink. Since the heating mode was introduced, it was desired to control PVT panels temperature and adjust it according to the working mode. Thus the backside of PVT panels was insulated to decrease heat losses and reach better control of the input/output temperature of the circulation fluid.

3.1 Thermal Part

The roof was hydraulically divided into two arrays, A (3x3 PVT panels) and B (2x2 PVT panels), seen on Fig. 8. Intention was lowering the pressure drop on supply/return piping and independent operation of both arrays.

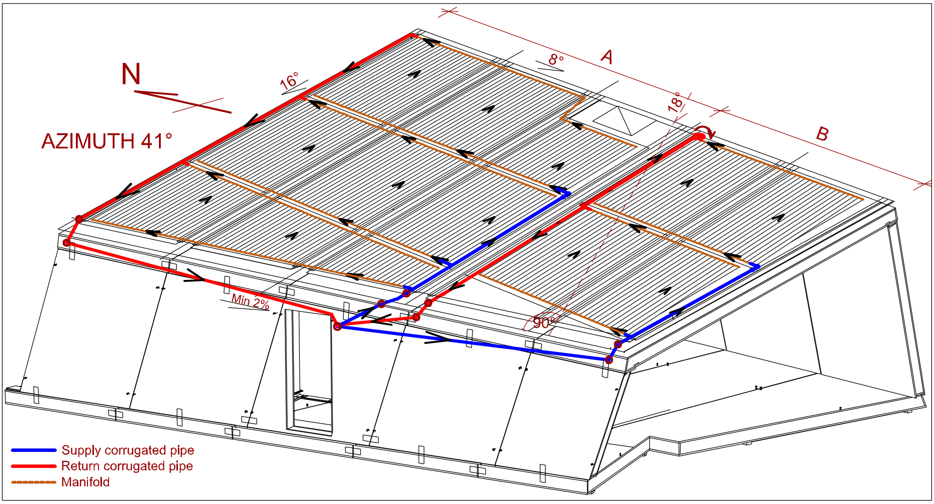


Fig. 8 Axonometry of thermal part of PVT roof system [6]

A drain-back tank was implemented in the thermal circuit. In addition to the heat transfer medium also about 75 l of air was added. All piping in level above the drain back tank was made with minimal slope of 2% to the reservoir. In idle pump mode the heat transfer medium drains from the collectors into the 100 l reservoir tank, from where the liquid fill the collectors when the pump starts to circulate again.

Low-pressure drop of the solar thermal part with Tichelmann connection is using drain back tank system. This combination allows use the system without any chemicals, just with ordinary water and even free of thermosyphoning effect and without boiling or freezing risk in any climate around the world.

To keep as much equal flow rate per square meter across the array as possible the flow was optimized by various diameter of piping and by balancing valves. The balancing was done in situ when the FOLD house was assembled in Madrid.

The mutual connection of the PVT panels should be dismountable due to house transportation. The manifold of PVT panel was made of hard copper pipe ø22x1 mm. Both ends were soldered to the soft copper pipe of the same diameter. The two neighbors soft copper pipes were connected by the flexible stainless corrugated pipe and two fitting Armaflex SO-SDN25-CU22, as seen on Fig. 9.

Keeping the FOLD envelope look slim was one of the biggest challenges for the team DTU and for the PVT system design. The cavity for all piping was only 60 mm.

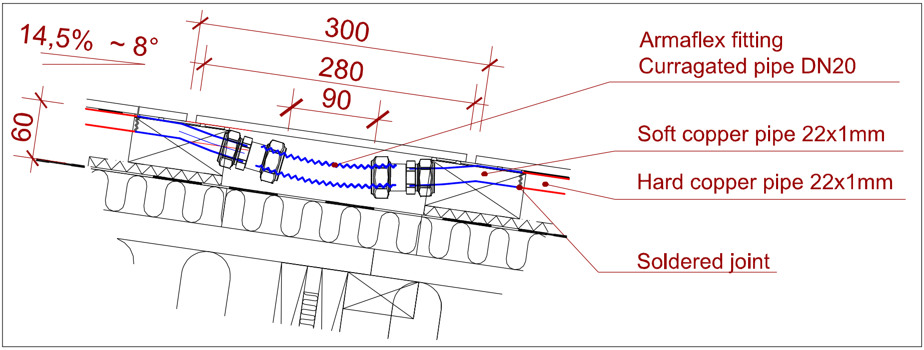


Fig. 9 Detail of PVT panels conection

3.2 PV Part

The PVT panels were interconnected in 6 separate electrical strings according direct to dependence thermal conditions, seen of Fig. 10. The most of the strings were made up of 448 full cells (3 cut cells) with maximal power voltage of 298V (0,66V per cell) and short circuit current 8A. Total installed nominal power was 10,8 kWp that was electronically cut down by two inverters to 9,2kWp. In total was used 9914 cells with total cell area of 50,81 m^2.

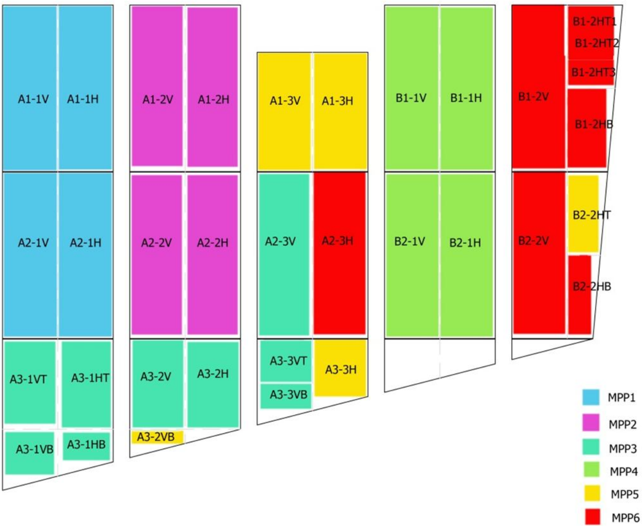


Fig. 10 Photovoltaic circuits of the PVT arrays [7]

Fig. 11 Bird's-eye view of PVT system

FOLD was connected to the electrical grid according to the net metering concept, when the energy is firstly used on site and only surplus or deficiency is traded with the grid. Energy surpluses were sold to the electrical grid.

4. Results and Discussion

The results were carried out using hand calculations or the simulation software TRNSYS for typical annual weather conditions of Madrid and Copenhagen.

- PVT annual electrical production in Madrid (Copenhagen) was **11 391 kWh (7434 kWh)** [5].
- **107 771 MJ** (29 919 kWh or 1558,28 MJ/m^2) of primary energy used to construct 1266 kg of PVT panels. About 50% of inbuilt energy was accumulated in the PV cells.
- **6985 kg of CO_2** equivalent (101 kg CO_2/m^2) to Global Warming Potential was inbuilt to PVT [8].

Table 2. PVT annual simulation [6]

Unit	Variable	PVT (heating mode)	PV	Solar thermal	PVT - (PV+T)
m^2	System active area	67,76	67,76	67,76	-
%	Annual efficiency	15,34+36,6	13,59	42,8	
kWh/ year	Net annual el. en.balance; CPH	7434 + 242*	7214	259	+ 203 (2,6%)*
kWh/ year	Net annual el. en. balance; Madrid	11393 + 495*	10970	530	+ 388 (3,3%)
Years	Simple payback time (Denmark)	14,9	9,8	188	-72
Years	Simple payback time (Spain)	14,6	9,8	140	-52

*Heat transferred to electricity in a way, how much el. would be used to charge the 180 l DHW to 60°C by a heat pump (COP 3,28 for heating)

The maximum thermal efficiency of the PVT panel, with passive solar cells was measured as 48%, when the PVT panel was cooled by fluid at temperature about 20 °C. With active solar cells the maximum efficiency was decreased by 6% to 42%.

The junction of electrical and thermal system in one positively influences the annual energy balance even using half the space in compare to the two separate systems. Benefits of PVT panels in compare ordinary technologies were examined from energetic and economical point of view. The annual energy balance raised by 2,6% (12,9% relatively) for Copenhagen or respectively by 3,3% for Madrid.

The obtained payback time was found below 15 years, calculated very conservative way. To reach 10 years payback time, the price should be decreased by 33% or the heat from PVT cooling should be utilized smarter way that create overall energy savings of 33%. The current PVT system should be investigated in different scenarios where is paid attention to low temperature utilization, such as coupled absorption chiller or pre-heated cold water tank connected in series with DHW tank.

5. Conclusions

Nowadays, the market conditions of PVT are very confusing. Many producers promote number of varied technologies combination, but they offer only the end-product which is not the only key to sustain the proclaimed “hybrid efficiency**”**. The way seems to be the right choice of PVT technology that is suitable to the coupled system. Good combination can bring the proclaimed rise of effectiveness and let the PVT to excel the advantages in compare to the "conventional solutions".

Acknowledgment

I would like to express my gratitude to professor, director, PhD Bjarne W. Olesen, Associate Professor Simon Furbo, Elsa Andersen and Toke Rammer Nielsen for consultation beyond the framework of their duties. I would like to thank to fellow students for their hard work during design process and competition period on SDE2012.

References

[1] Børgesen J., Nielsen K., Afgangsprojekt ”Test af PVT panel”, februar – juli, år 2012, *Technical university of Denmark*, (15th April 2012)

[2] Charalambous, P. G. a kol.: Photovoltaic thermal (PV/T) collectors: A review. Applied Thermal Engineering 27, pp. 275-286. (2007)

[3] European Solar Thermal Technology Platform: "Solar Thermal Vision 2030 document" http://www.esttp.org. (2006)

[4] Hestnes, A. G.: Building integration of solar energy systems. Solar Energy 67, No. 4-6, pp. 181-187, 1999

[5] Kazanci, O.B., Skrupskelis, M., Solar Sustainable heating, cooling and ventilation of a net zero energy house, *Technical university of Denmark*, (2012)

[6] Sevela, P., Energy management in DTU Solar Decathlon house”, *Technical university of Denmark*, (2012)

[7] Team DTU, Project manual, Delivery #6, *DTU, Denmark*, (2012)

[8] Wiedemann M., Energy Performance of zero-energy Houses: LCA on the FOLD Project Building, DTU, 2012