THE SWISS PV WALL SYSTEM TO MAXIMISE SELF-CONSUMPTION IN A SINGLE BUILDING ELEMENT

F.P. Baumgartner[1], R. Knecht[1], D. Lantschner[1], T. Baumann[1], H. Nussbaumer[1], J. Böhler[2], U. Brühl[2]
[1] ZHAW, Zurich University of Applied Sciences, SoE, Institute of Energy Systems and Fluid Engineering,
Technikumstrasse 9, CH-8401 Winterthur, Switzerland, www.zhaw.ch/~bauf
*phone: +41 (0) 58 934 7292; e-mail: bauf@zhaw.ch
[2] Sto SE & Co. KGaA, Ehrenbachstrasse 1, D-79780 Stühlingen, Germany; www.sto.com

ABSTRACT: With decreasing subsidies for PV energy fed into the grid other economic incentives are needed to sustain the growth of PV power. An effective solution is to increase self-consumption for grid-connected, residential PV systems by means of generating hot water by the use of a heat pump. This widely used concept of thermal energy storage has been adapted for a facade element with integrated PV modules for the first time. The so called Swiss PV Wall System (SPWS) contains all elements needed in the façade, behind the PV modules with a power of 1 kWp, like a PV inverter, a heat pump and a hot water tank. Simulation showed that virtually 100% of the PV energy can be used either by the heat pump to produce hot-water or the household's electricity needs. A functional model of the SPWS was realized and first measurements showed that the heat demand of a one family household may be covered for the majority of the months during the year. Economic analyses showed that the cost per kWh heat is at about 0.215 CHF and thus lower than standard solar thermal and some fossil solutions.

Keywords: Grid Integration, PV to heat, Self-Consumption, PV Facade

1 INTRODUCTION

In several countries the transition from the feed-in PV market regime to a non-subsidised market is going on. Today PV electricity is mostly competitive in the latter regime if the energy produced by PV is self-consumed. For a typical single household in central Europe about one third of the total annual PV energy production can immediately be used without storage if a PV generator is assumed to produce annually the same amount of electricity compare to the consumption [1]. Thus the electricity bill of the household will be directly reduced by the same amount of about one third assuming an energy related tariff structure provided by the electricity supplier. The remaining two third of the PV production will get typically much lower revenues from being sold to the distribution grid. This cost issue is the main driver to develop several approaches to increase the self-consumption of PV in the household itself.

One option to increase the self-consumption is obviously the use of electrical battery storage. The challenge to increase the self-consumption of PV electricity in a building, by the use of battery storage device is the goal of effective reduce of the todays costs of 0.7€ and 0.4€ per kWh supplied by the battery by a factor of 5 to be competitive with the cost of the grid itself [1, 2].

Today the most economically promising way is to convert PV energy into heat for the demand of a building. The cheapest solution is the electrical resistance heating by direct use of PV electricity but it is also the most electricity consuming method [3].

Innovative approaches using the hot air flow behind a PV façade to generate electricity from thermal electrical generators integrated in the façade, to finally convert this additional electricity into heat again, with up to know unclear cost structures.[4]

In another widely used solution, the electricity is used to run a heat pump. Today new products of small heat pumps (air/water) with integrated 220 to 300 litre hot water tank and of about 1.7 kW thermal powers are sold successfully e.g. on the German markets. They often producing hot water by the use of the local roof top PV installations and selected PV inverters are able to control the heat pump by standard wiring [5]. The typical hardware costs of such a combined heat pump and hot water tank solution are today in the range of 2000€ without installation and offered by several producers most of them from Germany. These systems typically feed about 3.2 kWh thermal heat into the hot water tank using only one 1 kWh PV electricity on an annual average Combined Heat and Power (CHP) factor of 3.2. Thus the electricity costs to power the heat pump are the PV generation costs divided by the CHP factor. So these final costs of electricity are well below 7 cents to generate one kWh thermal energy and thus competitive with most of the fossil solutions. These combined heat pump hot water tank systems are mounted mostly in the cellar room or near the heating facilities of the building at typical hardware costs of about 2000 € in German without labour cost. Together with the different system components like, PV roof top and this heat pump including the hat water tank lead to competitive prices of about 30 Rp of each thermal kWh heat [6].

In Switzerland the standard costs of hot water generation by the use of conventional solar-thermal collectors together with a hot water tank are today between 29 up to 37 Rp per kWh thermal energy for a typical 6m^2 collector on a single house [6]. Recently, a survey of the solar thermal costs between Switzerland, Germany and Austria presented about 50% lower total costs in Austria compared to Switzerland. The main reason was attributed to the 45% share of labour costs in Switzerland, which may by higher than a factor of two compared to Austria's hourly wages [7]. It is concluded that new competitive systems to generate hot water, especially in Switzerland have to accomplish very low labour cost shares.

In this paper a prototype of a single building element is presented, containing the PV module and the inverter as well as the components to increase self-consumption like, a small hot water tank, a heat pump and optionally an electrical battery [8]. All this components are mounted within the SWISS PV WALL SYSTEM (SPWS). The SPWS may also be attached in front of an existing façade as a retrofit solution. Significant cost reductions are assumed to be achieved when the produced building element can be pre-assembled prior to be delivered to the construction site. Only the AC mains and the cold and hot water have to be connected on site. The design of the whole system, the power flow, the degree of self-consumption of a 1 kWp PV facade element is presented. In addition first results of power generation and heat generation profile in real outdoor operation will be shown and discussed.

The goal of this SPWS development project is to design an element consisting of PV modules, a PV inverter, a heat pump and the hot water components in a single facade element or facade modules in order to create additional application possibilities and enabling further cost reductions by means of mass production and pre-assembling of the system.

2 APPROACH

A prototype of the SPWS was built and installed at the ZHAW IEFE in Winterthur in April of 2015 [8]. The commercial product StoVentec ARTline served as a chassis of the facade system and was kindly provided by Sto Co [9] It consists of 12 thin film CIGS modules each 85 W produced by Manz Co. Further components according to Table I and Table II were selected and implemented after a thorough evaluation process. Whilst construction endured, performance simulations using the Software PVSyst and Polysun were conducted in order to provide a proof of concept by studying the desired energy flow characteristics of simulated production and consumption.

The measurement setup include a pyranometer (Fig. 1) to measure the solar irradiation in the modules plane, current sensors for the inverter and the heat pump mains to calculate their corresponding power and PT1000 temperature sensors to determine the water temperature in the tank and the modules backside temperature. These measurement inputs are collected and evaluated using the software LabView (see Fig. 9) and determine the status of the heat pump. Furthermore, two meters provided the data of heat-flow of thermal energy transferred from the heat pump to the tank and from the tank to the consumer.

In order to maximise self-consumption of the produced photovoltaic energy, the available commercial 500 W_{el} heat pump is turned on if the inverter provides at least 300 W and the upper layer in the hot water tank does not exceed the final 60 °C temperature. The heat pump is also turned on in case the water drops under 50 °C in order to ensure hot water supply for the household at all times. Excess photovoltaic electricity is fed into the grid.

Table I: Components integrated in the new building element SPWS to primarily heating water and feed in extra PV electricity into the grid or store it in a battery.

Components	Purpose	Optional
PV Modules	Electricity generation	
PV inverter	AC grid integration	
Heat pump	Electricity to heat	
Hot water tank	Storing the heat	
Elec. battery.	Store electricity	optional
Air-conditioner	Cooling	optional

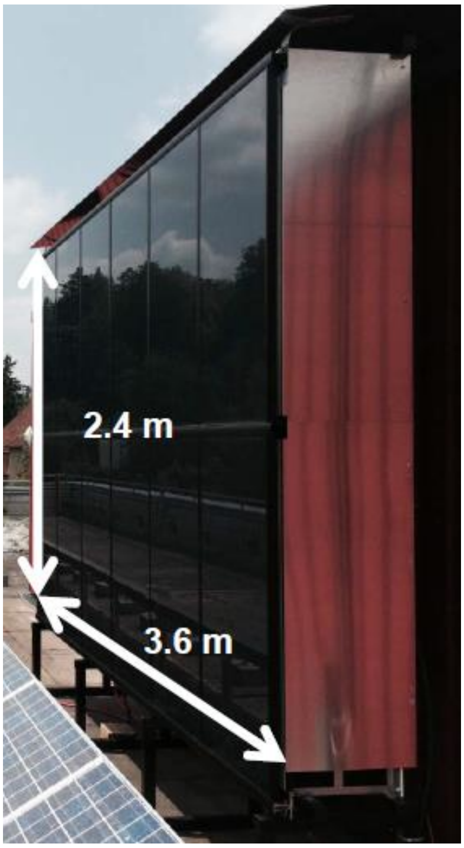

Figure 1: Front view and size of the functional prototype of the Swiss PV Wall System in operation since May 2015 on the rooftop of ZHAW IEFE building in Winterthur, Switzerland.

Figure 2: Schematics of the SPWS.

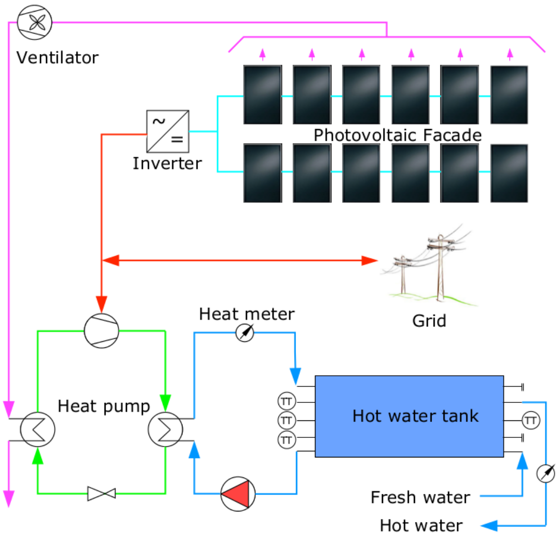

Figure 4: Energy and electricity flow in the SPWS.

2.1 Innovation

Below some of the innovation aspects related to the SPWP are listed.

- Integration of all needed technical equipment in the SPWP to increase self-consumption like, hot water tank, heat pump, electrical battery within one building element in the facade.
- Significant labour cost reductions are expected due to the above integrated solution. Thus time-consuming coordination of different craftsperson's on the construction site, like electrical installer, plumber, mason or facade specialist is significantly reduced
- No additional technical planning and design costs are needed to combine and optimize the sub-components
- Significant hardware cost reduction is expected because of the modular design and thus of higher number of the same units are produced.
- The SPWP system may be installed in larger buildings including several households. Every household can decide separately on the integration of a SPWP system. However the number of units is higher and thus lower total costs are expected.
- The SPWS has a modular design making it flexible for various applications and optionally my serve as an electrical emergency power supply.
- To reduce production costs a sub-system of the cuboid sized hot water tank on top equipped with a small heat pump could be mass produced and also placed inside into the regular central heating room of the building if requested
- Excess electricity production during sunny periods will be feed into the household electricity grid. Compared to standard solar thermal systems SPWP solves the problem of produced but unused solar energy during summer time.
- The vertical PV installation offers a nearly uniform PV generation characteristic over the whole year compared to a 30° inclined south oriented PV roof top installation.
- SPWS only require one single heating system also in winter time, by the use of conventional grid electricity powering the heat pump if for a longer meteorological period solar power is reduced. This is a major benefit of SPWP contrary to standard solar thermal solutions.
- The cold air stream coming from the heat pump may be used to cool down the back of the PV modules or used as assistance to air condition.
- To reduce taxes for PV self-consumption as it is mandatory in some countries, the heat pump could be directly powered from the DC-level of the PV Generator or the battery coupled with the PV generator, thus operation completely off-grid. An AC-heater could work as an emergency heating source for winter times.

2.2 Set up of the realized functional prototype

The PV facade is separated in different sectors, one containing the hot water tank the other one the heat pump and the inverter with this technical data of the components given in Tab. II.

- The mounting solution of the commercial PV facade elements [9], 3 strings with each 4 modules, was modified to power the SPWS.
- A commercial standard string inverter was integrated.
- A special flat cuboidal hot tank placed within thermally isolated material was build and integrated behind the PV modules, temperature losses 1.8°C for 8 hours at a temperature difference of water to ambient of 30°C.
- A commercial small scale air/water heat pump was integrated behind the PV modules.

Table II: Technical Parameter of the functional prototype (see Fig. 3)

Component	Data	
PV Modules	Manz CIGS 85 Wp	
PV inverter	SMA SB 1300TL	
Heat pump	Ochsner Europa Mini IWP, $P_{electrical}$ = 500 W COP max = 4.4	
Hot water tank	2.5 x 0.2 x 0.6 m^3 = 300 l	Custom
Elec. battery.	N/A	optional

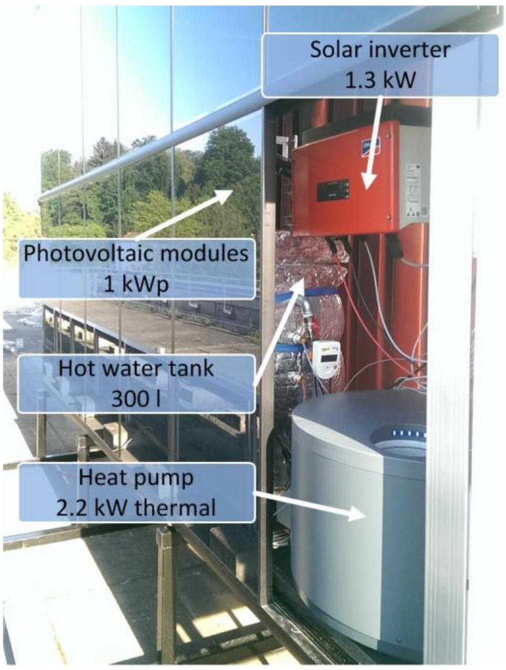

Figure 5: Sub components mounted within the functional SPWS prototype (see Table II).

3 MODELLING OF THE ENERGY FLOW

The typical application for the SPWS is calculated to fit for a one-family house in Switzerland inhabited by four people. The daily hot water demand amounts to 180 l/d at 55°C [11]. The components in the simulation were reproduced according to Table II.

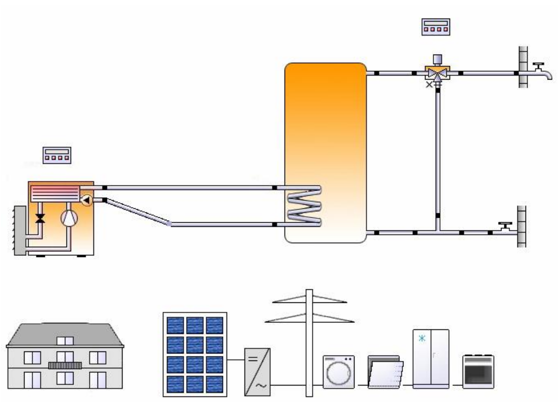

Figure 6: Setup of the PV combined thermal simulation using the commercial tool Polysun [8].

3.1 Simulation Results

The simulation of the PV output was performed in PVsyst on an hourly interval and was in good comparison with the Polysun results. It served as a basis to determine the percentage of own consumption over the year. Due to the fact that the relatively small PV nominal power of the SPWS compared to the electricity demand of the household all of the PV production of the 1kW façade not used by the heat pump is totally consumed within the household at all times. No feed-in into the AC distribution grid is found.

The turn on threshold of the heat pump at 300 W is elevated and close to their nominal electrical power of 500W. However, almost two thirds of the PV energy is used to produce hot water all year around (see Fig. 7). More than half of the energy demand of the heat pump is provided by the inverter while the rest is drawn from the grid. Approximately two thirds of the thermal energy provided by the heat pump can be obtained from the ambient air (see Fig. 8). The hot water demand of the household was covered at all times thanks to the control algorithm covered in Section 2 and implemented in LabView during the test run.

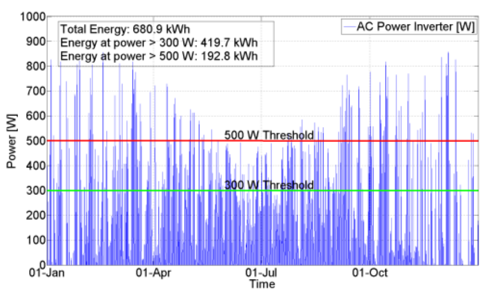

Figure 7: Results of PV production of the vertical 1kW south oriented PV facade and power levels to switch on the heat pump is shown.

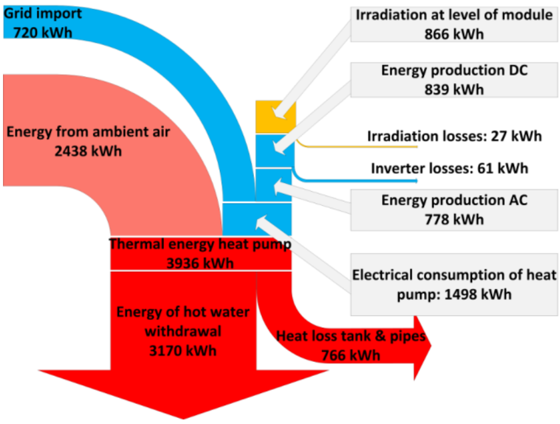

Figure 8: Results of the simulation for the annual energy flow of the thermal energy production to supply domestic hot water.

4 TEST AND MEASUREMENT RESULTS

Actual measurements during outdoor operation of the SPWS (see Fig. 5) are performed since May 2015 and are constantly monitored and analysed thereon. A graphical user interface (see Fig. 9) shows the present PV production of the vertical south oriented PV facade and power levels to switch on the heat pump as well as the recorded temperature values.

A measurement run of PV energy and heat energy on May 18th 2015 showed that 80% of the energy consumed by the heat pump was provided by the PV system while 20% were drawn from the power grid. The 2 kWh PV electricity produced during 4.5 hours of measurement were converted into 9 kWh of heat energy. Together with the energy drawn from the grid, the heat pump provided 300 litres of hot water (see Figure 10). This amount of hot water covers the demand for two days of a typical Swiss household of four persons.

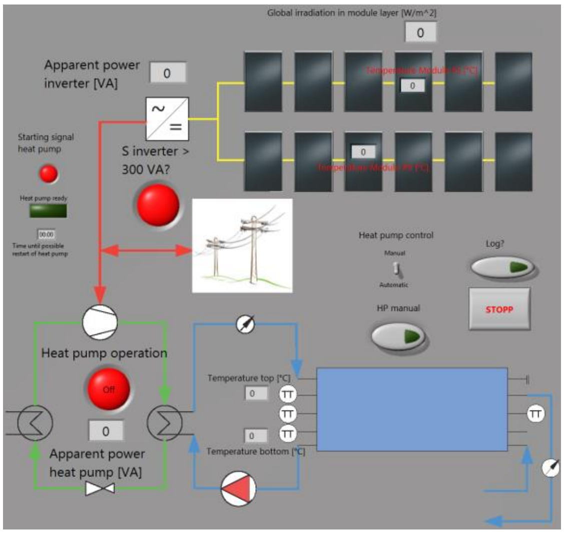

Figure 9: Graphical user interface to monitor the measurement results of the outdoor test of the SPWS.

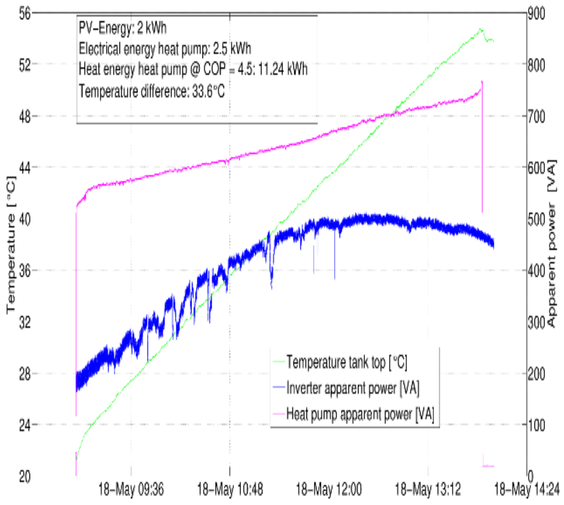

Figure 10: Measurement results of heating 300 l water from 22°C to 54°C by the use of the heat pump powered by the 1 kW PV facade between 9:00 to 14:00 on May 18 in 2015.

5 ECONOMICS

The investment to realize the SPWS is used to produce hot water and partially substitute the purchase of electricity from the grid in a small amount of demand.

Table III: Thermal production costs of SPWS hot water

Component	Amount	Cost
PV facade and inverter water tank and heat pump installation and material	1 kWp 300 litres	CHF 3000.- CHF 2650.- CHF 3000.-
total investment cost		**CHF 8650.-**
electrical yield usable yield (60 %) excess yield (40 %) power from grid total power for heat	681 kWh/p.a. 409 kWh/p.a. 272 kWh/p.a. 105 kWh/p.a. 514 kWh/p.a.	CHF -81.- CHF 32.-
average COP heat pump system heat yield	3.7 1900 kWh/p.a.	
years of operation total system yield	20 years **38'000 kWh**	
total excess power total power from grid exchange inverter after 10 years of operation	5440 kWh 2100 kWh	**CHF -1620.-** **CHF 630.-** **CHF 500.-**
total production costs		**CHF 8160.-** **0.215 CHF/kWh**

A recent market survey of standard solar thermal installations in Switzerland, Germany and Austria found an average system price of a 16600 SFr inc. VAT for a 5 square meter thermal collector and a 500 litere tank to supply about two third of the hot water energy demand of a single house [7].

A little smaler standard solarthermics system 4m^2, 300 l is assumed in [8] for a four person household used for service water heating at costs of about CHF 14'500.- including installation. The anual yield of this system is about 1870 kWh heat and covers up to 50 % of the hot water heat requirement from the four person household. The production costs in this case are estimated at about 0.39 CHF/kWh heat [8]. The same thermal demand was set for the SPWS (see Tab. III). This cost are also in good accordance to the values discused in the introduction sector of the published values by the Swiss Federal Office of Energy for a standard solar thermal system [6]. A standard solarthermics system is an island system wherefore excess yield during summer is unused and additional heat has to be produced by a separate gas-, oil- or pellet heating during winter.

Table III shows the production costs calculation of the SPWS with a result of 0.215 CHF/kWh heat. Thus the costs of heat production of the SPWS roughly cut in half compared to the costs of a standard solarthermics system. Additinally the SPWS offers the advantage that excess power can be fed into the power grid and if more heat is needed no second system is required but powered by grid electricity.

Installation costs of the SPWS were assumed to be 3000 SFr. (see Tab. III). This value is set to be about half of the installation costs of a regular solar-thermal system at the high Swiss labor of about 6000 SFr given in [7].

6 DISCUSSION AND APPLICATION

During the outdoor test of the functional prototype of the SPSW in the roof of ZHAW in Winterthur confirmed the operation of the PV powered heat pump solution as simulated. Further development is need to design a prototype for mass production focussing on a smaller sized heat pump, below 60cm diameter, with a much lower switching on level power to increase further on the PV self-consumption rate. New promising development results of heat pump technology were reported [12] to achieve useful power levels below 100 W to increase the real self-consumption rate within the SPWS itself.

The SPWS offers various forms of applications because of its modular design. Fig. 10 shows two examples. In multi-family houses the system offers the possibility for each party to get a higher degree of autarky. In pre-existing houses or houses with garages the system could also be placed in front of the existing house façade as a retrofit solution. With just three connections (electricity, cold and warm water) to the house infrastructures the SPWS is ready to use and produce heat and power for the house.

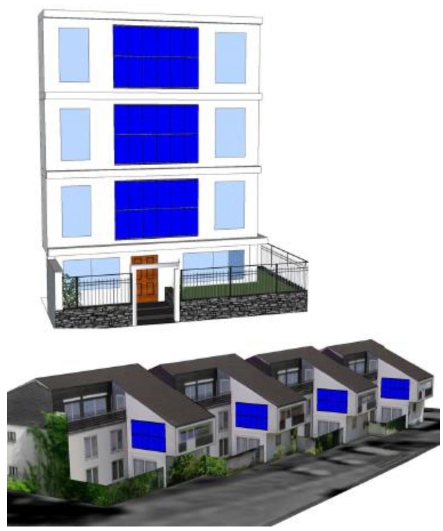

Figure 10: Sketch of a possible application of the SPWS.

7 CONCLUSION

A prototype of facade element, the so called SPWS, has been developed, which can convert photovoltaic generated electrical power into heat by means of a heating pump in combination with hot water storage. This element enables the owner to either use the generated electrical power directly via the integrated inverter or to convert the energy efficiently into heat. The prototype has demonstrated to be functional. A PV self-consumption rate of close to 99% is expected with a system consisting of a PV facade element of about 1 kWp power, a heat pump as a heater to maximum 60 °C, a hot water demand of 180 l/d and an annual total electricity consumption of 3’500 kWh for the household.

The functional prototype system went into test operation in May 2015 in Winterthur as a vertical PV facade oriented to the south and the collected several measurement results during summer time will be reported at the conference.

The components have to be further optimized with regard to single component efficiency and dimensions in order to the maximum benefit out of the system.

The SPWS could open new market applications such as the implementation in houses with several households. Due to pre-assembling and easy on site integration the thermal costs are low. The expected final costs of hot water supply of about two third of the typical need by the use of SPWS is promising compared to solar-thermal and other solutions.

Because of the modular design it is easy to supplement the SPWS with a battery. Thus the excess yield can be stored in the SPWS and has not to be feed into the power grid. This battery system may serve as an emergency power supply for electricity needs in the house and not primarily to power the heat pump.

Further on development my show larger façade or flat roof top elements to supply the house with heat an air coediting solutions powered by the PV module just beside.

REFERENCES

[1] P. Korba, F. P. Baumgartner, B. Völlmin, A. P. Manjunatha, „INTEGRATION AND MANAGEMENT OF PV BATTERY SYSTEMS INTO THE GRID”, EUPVSEC 2012, Frankfurt.

[2] C. Lorenz, Market Survey of home battery systems, University of Hamburg, Leipziger Institut für Energie GmbH; Jan 2014[2] A.C. Oliveira; Int. J. Low-Carbon Tech.-2015, “A NOVEL SOLAR FACADE CONCEPT FOR ENERGY POLYGENERATION IN BUILDINGS“.

[3] PV heater product from Advanced energy former REFU PV heater, http://www.advanced-energy.de/de/PV_Heater.html.

[4] A.C. Oliveira et al; International Journal of Low-Carbon Technologies 2015, 0, 1–5.

[5] Product Datasheet, Stiebel Eletron, “Hot Water-Heat Pump”, May 2015; www.stiebel-eltron.de.

[6] Swiss Federal Office of Energy (SFOE); Solarwärme und Photovoltaik – ein Technologievergleich , 25. Feb 2015, www.news.admin.ch/NSBSubscriber/message/attachments/38426.pdf.

[7] M. Müller et al., “Preise und Kosten thermischer Solaranlagen“, Ernst Balser + Partner, Zollikon, Schweiz, 4. Nov. 2014; www.ebp.ch/files/pdf/20141104_preisanalyse_solarwaerme.pdf.

[8] R. Knecht, D. Lantschner, ZHAW/IEFE Bachelor thesis, “Autonome Solarstromwand”, July 2015.

[9] Product data sheet of STO; StoVentec ARTline Inlay CIS Panel; www.stoag.ch/umweltarena.

[10] Polysun V8, Switzerland, www.velasolaris.com.

[11] energie.ch AG. Daily hot water demand in Switzerland; Available cited 2015 Aug 31 from: www.energie.ch/warmwasser.

[12] M. Spinnler, L. Hörth, F. Böing, S. Wolf, T. Sattelmayer, „NOVEL HEAT PUMP SYSTEM FOR HIGHLY TRANSIENT PV OPERATION“, EUPVSEC 2014, Amsterdam