Building integrated PV water heating and air conditioning in the special hospital of the SPA Rusanda

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ABSTRACT

Different types of thermal activation of building structures are increasingly utilized in buildings including BIPV, multifunctional PV facades with controllable daylight/solar gain features and integrating thermal and electrical output. Much of the existing R&D is focused on these facades and structures with the rest of the building, but detailed information is scarce on relevant properties and the performance.

This paper presents dynamic analysis and optimization results of PV air-conditioning and PV based sanitary water heating system, which by heat recovery assisted, demonstrates cost effectiveness which significantly surpasses the corresponding values of direct solar thermal conversion systems. The study objective was to propose technical solution for replacing fossil fuel and electricity with solar energy for heating of water for different purposes (for pools, sanitary water, washing) in the Special hospital of the Spa Rusanda – Melenci. Crucial for the study success was prediction of air-conditioning loads and synergetic relations between energy efficiency, solar radiation intensity stochastic changes, PV system’s electricity production and sanitary water consumption dynamics.

1. REGION RELEVANT ENERGY BACKGROUND AND METHODOLOGY

The solar energy potential in Serbia is characterized by the average annual radiation of about 1.4MWh/m² on horizontal surface (see Figure 1.). Presented graph confirms that comparing with radiation in other parts of Serbia the SPA Rusanda in Vojvodina has excellent potential, better for example, than southwest mountain region of Serbia. The specific objective is to propose technical solution for replacing fossil fuel and electricity with solar energy for heating of water for different purposes (for pools, sanitary water, washing) in the Special hospital of the Spa Rusanda – Melenci. Crucial aspects for the project success is understanding of solar water heating systems dynamic behavior dependent on the TMY – Typical Meteorological Year’s data, and synergetic relations between energy efficiency, solar radiation intensity and sanitary water consumption dynamics.

Prediction and analysis of relevant subsystems dynamics, was basis for the optimization of the TES - Thermal Energy Storage role within the system energy efficiency optimization. TES is intrinsic to the solar thermal systems. Although, the solar water heating has 4 to 5 times the power density of solar electric (PV), a PV subsystem has been analyzed, concerning the possibility to recover nearly 80 - 90% of waste water heat and couple that process with the heat pump operation and TES, but in this paper will be presented only results of the solar thermal water heating system.
The Spa “Rusanda” is located near the village Melenci, about 20km far from Zrenjanin. Accommodation capacity of the Spa Rusanda is for about 400 patients. Consumption of sanitary hot water is about 70 000 litres per day, while the consumption of natural gas out of winter season is about 35 000m³ per month.

Different systems are studied through the dynamic simulations applying TRNSYS program as well as the own originally developed software. Encompassed are separately subsystems with different components and implemented different energy efficiency improvement measures on the existing thermal and technical systems and energy supply, i.e. sub-systems with which the new components and the new sub-systems have to be connected. The project approach did anticipate the preliminary design which is to be foundation of further reconstruction and additional construction of new installations, together with further renewal and significant improvements of the existing equipment energy efficiency. Performance of the economic analysis has been determined implementing domestic and European procedures as well as the powerful BLCC software.

2. BUILDINGS SITE’S LOCATION AND ENVIRONMENTAL DESIGN DATA

Spa Rusanda Site Location Data are:
Latitude: {45.85 °N ± S-}
Longitude {20.80 °W ± E+}
Time Zone Relative to GMT 1.00 {GMT+/−}
Elevation 132m

For the SPA Rusanda climatic zone the thermo-technical systems - HVAC systems relevant outdoor design conditions are: for heating and HVAC system operation mode in winter: design air dry bulb temperature \( t_{w} = -18°C \); for cooling and HVAC system operation mode in summer: design air dry bulb temperature \( t_{w} = 33°C \), and relative Humidity \( \phi = 33% \).

3. NOMINAL HEATING LOAD FOR SANITARY WATER HEATING

Thermal energy daily necessary for sanitary water heating is determined for the two “nominal” water consumption values as follows:
- For 70 m³ daily from 14°C. to 40°C:

\[
Q_{w} = V \cdot \rho \cdot c \cdot (T_{w} - T_{w}) = m \cdot c \cdot (T_{w} - T_{w}) = \\
= 70000 \cdot 4.186 \cdot (40 - 14) = 7618520 \text{kJ} \tag{1}
\]

- For 80 m³ daily from 14 °C. to 40 °C:

\[
Q_{w} = V \cdot \rho \cdot c \cdot (T_{w} - T_{w}) = m \cdot c \cdot (T_{w} - T_{w}) = \\
= 80000 \cdot 4.186 \cdot (40 - 14) = 8790600 \text{kJ} \tag{2}
\]

The "nominal" water consumption values have been determined using consumption data history and measurements (presented on graphs in Figures 2. and 3.)

LTP - Long Term Performance Prediction of the solar water heating systems – SWHS, or more generally of solar energy utilization system’s is of crucial importance for investors and that is most important and delicate task within the frame of designing and engineering an installation for active solar energy utilisation.

Figure 2. “Lower average” water consumption day profile - hourly data

Figure 3. Graphical presentation of all conduit pipes flowrate measurement data

The qualitative and quantitative analysis of the systems is carried out by the determination of following system parameters: the energy flux of solar radiation usefully converted to heat, the input and output heat flows of various components of the systems, the share of solar energy in the final energy use of the system, the thermal efficiency of the components and the whole system’s, the functioning of components and the system, the operating behaviour and the investment costs of the systems. One of the most important conclusions of the above given analysis of systems is that the total system efficiency can be a good deal lower than the collection efficiency of the solar collector field.

The diameters of pipe lines are to be so sized, that,
with the reference to the corresponding heat transfer fluid flow rates, pressure drops, the pump power and the electricity consumption will be kept at the smallest possible level. When appropriate piping diameters are defined the electricity consumption of solar water heating plants, including the energy demand of measuring and control instruments is minimal, and varies between 2.0 and 3.5% of the total power input.

4. SOLAR COLLECTOR FIELD SIZING AND POSITIONING

Conducted were calculations of the instantaneous thermal efficiency $\eta^*$ of the flat plate solar collector for the determined relevant design meteorological period of the year (five days in row between 9.07 and 13.07). The relevant instantaneous thermal efficiency dependence on the $\Delta T$ and $E$ was as follows:

$$
\eta = 0.84 - 3.36 \cdot \frac{\Delta T}{E} - 0.013 \cdot \frac{\Delta T^2}{E}
$$

(3)

Based, on determined collector’s instantaneous thermal efficiencies and the nominal necessary area of the collector field of certain quality - producer data on the instantaneous thermal efficiency dependence on relevant parameters and implementing calculation method, development of which was based on the described short term monitoring and long term performance prediction methodology, (/10/-/10c/), as the design daily incident solar radiation for the Rusanda Spa location has been determined the value of 6.23 kWh/m$^2$ (June 10$^\text{th}$ within the relevant meteorological period) and the nominal size of the collector field for the selected solar collectors is obtained following result:

$$
A_{\text{PST}} = \frac{Q}{q_{\text{pse}}} = \frac{7618520}{6.23 \cdot 3600} = 339.68 \text{ m}^2
$$

(4)

Collector field sizing is to be done for the maximum available incident solar radiation if there is not available thermal energy storage of the appropriate volume to store water and absorb the surplus solar heat gains. This is important designing rule, because if the solar system is not able to absorb more heat solar collector field will be without proper cooling and solar collectors will be in conditions which can accelerate aging and their thermal features degradation.

And, for the same maximum available daily gained solar energy of 6.23kWh (Table 5.5.2. second day 10.07), daily water consumption of 80,000 m$^3$ and related nominal heating load of 8.790.600kJ, is necessary solar collector field of:

$$
A_{\text{PST}} = \frac{Q}{q_{\text{pse}}} = \frac{8790600}{6.23 \cdot 3600} = 390 \text{ m}^2
$$

(5)

As, the total thermal energy efficiency of the whole system for solar energy utilization for sanitary water heating is lower than the collector’s instantaneous thermal efficiency, because of heat and energy losses of different components and subsystems (subsystem of heat distributin, subsystem of heat transfer, subsystem of heat storage, and subsystem of sanitary water utilization), the total necessary area – size of solar collector field is to be bigger. This has to be taken in account when the final design of the system will be approached.

By the performed simulations for different areas of flat plate solar collector fields particularly those determined as the nominal in previous Section Part, and different storage volumes, has been predicted usefully received incident solar radiation by the heat transfer fluid, and by its circulation transferred to water in thermal storage reservoir to be finally delivered to sanitary water users. All simulations had been performed for 8760 hours of the TMY for Zrenjanin defined earlier. A series of simulations results are given in Figures 4. It is visible that the synergistic increase of solar collectors area and thermal energy storage volume contributes to higher percentage of covering sanitary water heating needs by the solar radiation. With the 390m$^2$ collector area and 50m$^3$ storage could be covered more than 94% of sanitary water heating loads.

Figure 4. Useful transferred heat to water in thermal storage reservoir for sanitary water heating for solar collector area of 390m$^2$

5. WASTE WATER HEAT RECOVERY

The new original concept of solar energy utilization for water heating is here defined which is based on the introduction of very effective measure to increase energy efficiency, exactly nearly maximal possible increase of energy efficiency of final energy utilization by implementation of waste water heat recovery system which can recover 90% of waste heat.

After recovering waste heat, the solar PV powered heat pump’s compression work through the release of condensation heat in heat pump condenser, heats earlier
preheated fresh water in the heat recovery unit. Thus waste water heat recovery is very effective mean to reduce thermal energy consumption and increase energy efficiency of sanitary water heating installation. There are on the market waste water heat recovery systems in reliable and efficient operation. Based on our previous experience for the waste water heat recovery in Spa Rusanda is preliminary selected as an appropriate unit Menerga AquaCond waste water heat recovery system. The Menerga AquaCond waste water heat recovery units incorporate patented automatic heat exchanger cleaning in order to ensure continuity of operation and low maintenance costs.

A wide range of material specifications are available to resist different forms of acid and alkali attack. Its layout and scheme of operation is given on Figure 5. These units are suitable for heat recovery in swimming pools, water treatment, food processing, brewing, and many areas of manufacturing and industry. The scheme of its implementation for several, different waste water sources heat recovery, as it is the case of the Special Hospital of Spa Rusanda is given on Figure 6. and its functioning description is as follows.

Inside the unit, the waste water passes through the inner tubes of the recuperator and into the heat pump evaporator, while the same volume of fresh water flows through the outer pipe of the recuperator and into the heat pump condenser. Within the recuperator, a large proportion of the heat held in the waste water is transferred directly to the fresh water with no additional energy requirement. Inside the evaporator, further heat is recovered from the waste water, cooling it down to below the temperature of the incoming fresh water – 8 deg C, the temperature which is excellent inlet temperature for Air-Conditioning, the HVAC unit chiller.

The heat gained is transferred by the compressor to the fresh water (already preheated in the recuperator) passing through the condenser. The electrical energy used to drive the compressor, is also taken up by the fresh water. In this way, the fresh water can be heated up above the poolwater temperature and almost up to shower water temperature. Automatic flow regulation provides a constant flowrate of waste water even under varying external conditions eg. reducing head of water in waste water tank. The waste water heat recovery unit can also be supplied with automatic heat exchanger cleaning (eg. for shower water recovery). In order to prevent a build up of bacteria growth and pollution by fats and soap, porous pellets are forced through the waste water pipework at regular intervals. The cleaning pellets detach sediment and material building up on the heat exchanger walls. The cleaning pellets last for a long time and can be easily replaced.

6. PHOTOVOLTAIC SYSTEM

There are several different types of PV modules: "mono-Si," "poly-Si," "a-Si," "CdTe," "CIS". The PV module type selected will depend on a number of factors, including: price from suppliers, product availability, warranties, efficiencies, etc. Without further information either "mono-Si" or "poly-Si" may be used as a first selection as each have similar prices on a $/Wp basis and are the most common PV modules used today. Module efficiency depends primarily on the type of cell used (mono-Si, poly-Si, a-Si, CdTe, CIS). However within each of these categories there are wide variations in module efficiency from manufacturer to manufactur-
PV modules performance relevant data have been determined by the dynamic simulations and have been used in sizing of PV modules area. For stand-alone PV systems, the nominal PV array power aims at providing 100% of the load for the worst month. The task was to calculate the area that will be covered by the PV array, in m². This is simply the nominal PV array power divided by the nominal module efficiency. If the PV array is mounted on a wall, the required area should not exceed the surface available on the wall. Special Hospital of the Spa Rusanda PV array is assumed to be integrated in the roof/roofs of pavilion structure. For building facade’s integration IBPV arrays inclination angle will be the same as the certain building wall inclination angle is. This seldom corresponds to an optimum in terms of energy production, but can reduce significantly installation costs by eliminating the need for costly cladding and a support structure, or may be more desirable from an esthetics standpoint.

For selected PV panels, for available roof areas for PV installation on the buildings of Hydrotherapy - swimming pool house (a =10°, P = 85m²), Pavillion 8 (a = 35°, P = 200m²), Pavillion 5 (a =17°, P = 240m²), and on the Pavillion 9 (a = 0°, P = 350m²), are performed dynamic simulations of solar PV system operation and have been determined the monthly and annually sums of received and converted solar radiation to electrical energy.

### Table 2. BIPV performance simulations results

<table>
<thead>
<tr>
<th></th>
<th>Maximal</th>
<th>Installed</th>
<th>El. en.out.</th>
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<tr>
<td></td>
<td>[W/m²]</td>
<td>[kW]</td>
<td>[kWh]</td>
</tr>
<tr>
<td>Sw. pool</td>
<td>134.47</td>
<td>10.69</td>
<td>12.06</td>
</tr>
<tr>
<td>Pav. 8</td>
<td>148.58</td>
<td>33.51</td>
<td>34.2</td>
</tr>
<tr>
<td>Pav. 5</td>
<td>148.43</td>
<td>27.84</td>
<td>28.44</td>
</tr>
<tr>
<td>Pav. 9</td>
<td>144.3</td>
<td>42.25</td>
<td>48.6</td>
</tr>
<tr>
<td>Σ</td>
<td>575.78</td>
<td>114.29</td>
<td>123.30</td>
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</table>

IBPV predicted performance results, justifying PV arrays implementation by the significant amount of produced electricity are shown in the Table 2. and graph on Figure 7. Simulations have been made using TRNSYS software.

![Figure 7. Monthly sums of four roof’s PV converted solar to electrical energy in kWh](image)

The Table 2. presents this study’s crucial output data for preliminary design of a PV system for powering the Menerga heat pump operation. So, by the produced PV electricity, using waste water heat recovery as the heat-pump heat source, PV based water heating system can be highly cost-effective. The total available installed solar PV electrical power can be 123.3kW if four roofs available area of 875m² is used for integration of PV arrays. Yearly electrical output of corresponding PV system can be 136.513,09kWh (Table 2.).

### 7. PRELIMINARY DESIGN BIPV MODEL SPECIFICATION MPV200/HR&HP

Based on the simulations and performance prediction results, preliminary design has been made for the system Model which encompasses following subsystem PV (200m²), Heat Recovery and Heat Pump - MPV200/HR&HP. With the reference to all calculations and determined daily quantity of sanitary water used and waste water released, and available capacity of the Menerga AquaCond’s selected has been the Menerga unit 44 36.2 with following characteristics: water flow rate 2.4m³/h (72 m³/h in 20 hours), compressor power 2x3.4kW, operating power 8.96kW, and maximal power of 20kW. Price of unit with the automatic cleaner is 64.344 EUR.
MPV200/HR&HP – related to MO1 - without cold waste water utilization for AC
Investment costs 531,844 EUR
Investment increase 231,844 EUR
Annual consumption of thermal energy 389 – 718,361 = 3,781,028 kWh
Annual saving of thermal energy use 718,361 kWh
Value of thermal energy saving 28,404 EUR
Annual consump. of electrical energy 720,072 – 33,316 = 686,756 kWh
PV produced electrical energy 33,316 kWh
Total annual energy costs 201,007 EUR
Total annual costs of thermal energy 149,502 EUR
Total annual costs of electrical energy 39,145 EUR
Annual maintenance costs 270 EUR
Annual value of saving energy 215,222 – 188,646 = 26,576 EUR
SPBP – Simple Pay Back Period of increased Investment
SPBP = 231,844 / 26,576 = 8,7 year

Table 3. Daily summs of cooling energy for HVAC/m²

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Σ</td>
<td>1.1716</td>
<td>3.6026</td>
<td>2.3871</td>
</tr>
<tr>
<td>June</td>
<td>0.3050</td>
<td>0.9761</td>
<td>0.6406</td>
</tr>
<tr>
<td>July</td>
<td>0.3548</td>
<td>0.9859</td>
<td>0.6704</td>
</tr>
<tr>
<td>August</td>
<td>0.3412</td>
<td>0.8855</td>
<td>0.6134</td>
</tr>
<tr>
<td>September</td>
<td>0.1706</td>
<td>0.7552</td>
<td>0.4629</td>
</tr>
</tbody>
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8. SYSTEMS COMPARISON & CONCLUSIONS

MO1 - Zero reference model is defined as the reconstructed thermal energy supply system with two new boilers, currently in the final phase of main engineering design with the total value of investment of 300,000 EUR for installation of two new gas boilers. Concerning the thermal and electrical total energy consumption this model corresponds to the lower value of the determined energy consumption range.

All costs values in economic analysis are obtained using following final energy sources prices: Electrical energy - 0,057 EUR/kWh; Thermal energy - gas for health institutions 0,03954 EUR/kWh.

Heat absorbed/collected by the solar collector field is transferred to thermal storage by the circulation of heat transfer fluid. In thermal storage tanks are immersed heat exchangers. Their heat exchange surface area has been sized with the reference to the maximal power which is solar collector field receiving (0,93 kW/m²). That way determined maximal power of the solar collector field of 390 m² is 362,7 kW.

Preliminary design specifications were obtained for the MPV200/HR&HP, as it is presented in previous Section, and for three solar thermal models here, as follows:

M390/50, M340/50, and M390/40 (390; 340 are flat plate solar collectors fields in sq.m. and 50 and 40 are thermal energy storage volumes in m³ – five or four warm water storage tanks of 10 m³ volume. One storage tank of 10 m³...
volume STP Product, Belgrade has price 3.500EUR. Flat plate solar collector of the assumed instantaneous thermal efficiency curves; 2,3m² area and unit price 160EUR/m². Heat exchanger specific price given by the STP Company Belgrade is 150EUR/m². The final engineering results for economic analysis are values of SPBP – Simple Pay Back Period of increased investment. Relevant SPBP values for the three best models with the reference to the model MO1 are as follows: M390/40 - 96.140/13.204 = 7,28 years, M390/50 - 5,89 years, and for M340/50 is 5,7 years.

Comparing these results with the system MPV200/HR&HP, variant b. - with cold waste water utilization for Air-Conditioning, demonstrates superb features of the BIPV system combined with the heat recovery and heat pump, a system with the shortest SPBP value of 5,4 years. When the BLCC economic analysis is made taking in account all relevant economic parameters, the same system is the with the lowest lifecycle costs, and its Payback is also the best - PP is 1, that is the investments return already for one year.

REFERENCES


