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SIMULATION OF THE SOLAR DOMESTIC HOT WATER SYSTEM OPERATION

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Preliminary notes

This paper presents the optimized solution of a solar system for providing domestic hot water through the results of a system work simulation done on an hourly basis for a motel with capacity of 35 persons located in climate areas of Zagreb and Split. The analyzed system consists of two tanks for domestic hot water, capacity 1600 liters each, and appropriate collector area (43,7 m² for Zagreb and 30,4 m² for Split). The basic criterion for optimization was the shortest investment payback period with a primary goal to cover the energy demands for domestic hot water in July and August. This paper presents monthly and yearly results of performed simulation for both climate areas and description of the calculation procedure for estimating solar radiation and energy gain.

Keywords: *solar system, domestic water, simulation, investment payback period*

Simulacija rada solarnog sustava za zagrijavanje potrošne tople vode

Prethodno priopćenje

U ovom radu je prikazano optimalno rješenje solarnog sustava za zagrijavanje potrošne tople vode kroz rezultate satne simulacije za motel smještajnog kapaciteta 35 osoba smještenog u klimatskom području Splita i Zagreba. Simulirani sustav se sastoji od dva spremnika volumena 1600 litara i odgovarajuće površine solarnih kolektora (30,4 m² za Split i 43,7 m² za Zagreb). Kriterij optimizacije sustava je bio što kraći period povrata investicije uz osnovni zahtjev da sustav pokrije energetske potrebe objekta za PTV-om u ljetnim mjesecima. Dani su mjesečni i ukupni godišnji rezultati simulacije za oba klimatska područja, kao i opis proračuna Sunčevog zračenja i prikupljene energije.

Ključne riječi: *solarni sustav, potrošna topla voda (PTV), simulacija, povrat investicije*

1 Introduction
Uvod

Over the last decades, due to energy crisis and environment pollution there is growing interest in renewable energy sources - especially solar energy. Solar energy is mostly being utilized in small and medium size systems for heating of domestic water and for low temperature heating in households, apartments and hotels. Although the solar system components are continuously becoming more efficient and cheaper, still a relatively high cost of such systems and inadequate public awareness of their cost effectiveness result in a weak interest for installation of solar systems. Also, the problem is a lack of subsidies like those in neighboring countries, so that Croatia is at this moment behind those countries concerning a number of solar systems installed. That is best shown by comparison in terms of total collector area installed, which is 5 times larger in Slovenia and about 80 times in Austria. It is very important to correctly size every single system to find an optimum solution i.e. the best compromise between the cost of solar system and energy demands of an object. Concerning the nature of solar systems i.e. their dependence on climate conditions of particular location and the needs of an object, only simulation on an hourly basis can give us a real image of the system behavior. This enables a proper sizing of the system (determination of collector area and volume of water tanks) to achieve a maximum gain and shortest investment payback period. This paper provides the results of such simulation of solar domestic hot water system located in climate areas of Split and Zagreb which consists of two tanks and corresponding collector area.

2 Model description
Opis modela

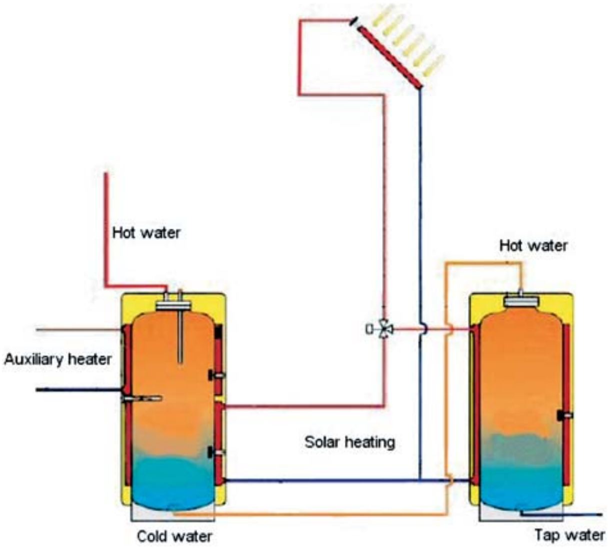
The solar system (Fig. 1) considered for preparation of domestic hot water consists of two combined tanks, capacity of 1600 liters each, connected to the array of solar collectors. First tank, from which hot water is extracted for further consumption is heated in the upper zone by auxiliary heater in the case of insufficient insolation or increased hot water consumption. Extracted amount of water is resupplied from the second tank which is fed by tap water.

It is possible to heat the first or the second tank depending on given parameters. That is accomplished by three-way valve which is regulated by the control-unit. Depending on the temperature of water in the first tank, this valve changes the direction of the fluid which circulates through the system toward the first or the second tank. The temperature of the water in the first tank is set to 50 °C. When water temperature is higher, the collectors loop fluid will be directed by three-way valve to provide heat to the water in the second tank. Daily consumption of hot water is assumed as 80 liters of water, temperature 50 °C, which in total amounts to 2800 liters of hot water per day.

Simulation of the system work through a year can be divided in two parts: calculation of the insolation on inclined surface with the aim of finding the optimum collector angle and calculation of collectors energy gain. In the subsequent text these calculations are separately explained.

2.1 Calculation of solar radiation on inclined surface
Opis proračuna Sunčevog zračenja na nagnutu plohu

It is possible to calculate yearly distribution of solar radiation on inclined surface for any location if the meteorological information about insolation for a characteristic day in every month in a year is available for this location.



Slika 1 *Shema sustava*
Figure 1 *Scheme of the analyzed solar system*

Basic expressions for calculation of solar radiation on inclined surface

- Total solar radiation on inclined surface I_β

$$I_\beta = I_{b\beta} + I_{d\beta} + I_{r\beta} \tag{1}$$

- Direct solar radiation on inclined surface $I_{b\beta}$

$$I_{b\beta} = I_b \frac{\cos\theta}{\cos\theta_z} \tag{2}$$

- Diffuse solar radiation on inclined surface $I_{d\beta}$

$$I_{d\beta} = I_d \frac{1+\cos\beta}{2} \tag{3}$$

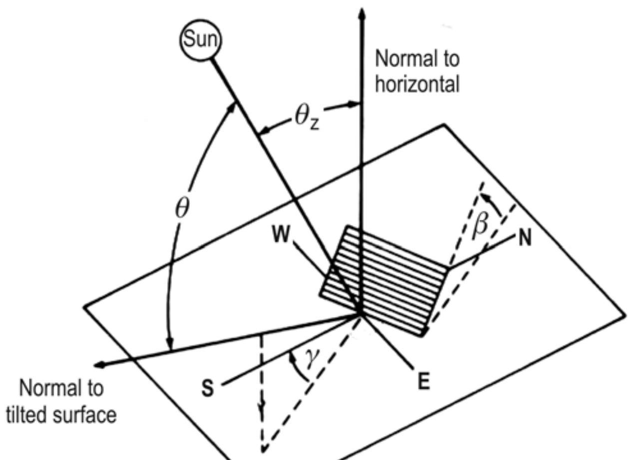


Figure 2 *Definition of the angles for a tilted surface exposed to direct beam radiation*
Slika 2 *Definicije kutova za nagnutu površinu izloženu direktnom sunčevom zračenju*

Portion of diffuse radiation in total solar radiation on the horizontal surface can be calculated from the following expressions

$$\frac{I_d}{I} = 1{,}557 - 1{,}84 \cdot k_t \tag{4}$$

$$\frac{I_d}{I} = 1{,}05 - 1{,}125 \cdot k_t \tag{5}$$

$$\frac{I_d}{I} = 1{,}6 - 4{,}17 \cdot k_t + 5{,}29 \cdot k_t^2 - 2{,}86 \cdot k_t^3 \tag{6}$$

or more accurate measured data on diffuse and total radiation can be used instead if available, like it was done in this paper for the areas of Zagreb and Split [1]

- Reflected solar radiation on inclined surface $I_{r\beta}$ can be obtained from

$$I_{r\beta} = \rho \cdot I \cdot \frac{1-\cos\beta}{2} \tag{7}$$

2.2 Calculation of energy collected by solar collector and energy balance of the system
Opis proračuna energije prikupljene kolektorom i energetske bilance sustava

Heat (in Wh) necessary for heating of the amount of tap water delivered to the tank in one hour $\dot{m}$ (15 °C for Split and 12 °C for Zagreb) to 50 °C is calculated by the following expression

$$Q_{demand} = \dot{m} \cdot c_p \cdot (\vartheta_{hot} - \vartheta_{fresh}) \cdot t \tag{8}$$

Amount of useful heat collected by collector (transferred to the fluid)

$$Q_{coll} = \eta_c \cdot I_\beta \cdot A_{coll} \cdot t, \tag{9}$$

η_c represents the collector efficiency used in simulation, calculated by the following expression

$$\eta_c = 0{,}7242 - 5{,}0967 \cdot \frac{(\vartheta_T - \vartheta_{Air})}{I_\beta} . \tag{10}$$

Change of the internal energy in the first tank in one hour due to the consumption of hot water

$$Q_{E1} = \dot{m} \cdot c_p \cdot (\vartheta_{T1} - \vartheta_{T2}) \cdot t \tag{11}$$

where ϑ_{T1} and ϑ_{T2} are temperatures of the first and second tank, respectively.

If condition $\vartheta_{T1} \le 50$ °C the first tank is heated. The internal energy stored in the first tank Q_{T1} can be calculated from the equation

$$Q_{T1} = Q_{coll} - Q_{E1} . \tag{12}$$

If $\vartheta_{T1} > 50$ °C then the second tank is heated. This means that change of the current temperature in the first tank is affected only by the water mass flow rate and temperature difference between the water extracted from the first tank and water supplied from the second tank. In such case the internal energy stored in the first tank can be calculated by

$$Q_{T1} = -Q_{E1} \tag{13}$$

Q_{t1} stored in the first tank results in a change of temperature of water in the tank

$$\Delta\vartheta_{T1} = \frac{Q_{T1}}{m_s \cdot c_s}. \tag{14}$$

At the end of that hour the final temperature in the first tank can be calculated by the following expression

$$\vartheta_{T1_{final}} = \vartheta_{T1_{start}} + \Delta\vartheta_{T1}. \tag{15}$$

Amount of water extracted from the second tank is equal to the amount that was used from the first tank and that amount is supplied from the water-supply, so the energy extracted from the second tank can be expressed as follows

$$Q_{E2} = \dot{m} \cdot c_p \cdot (\vartheta_{T2} - \vartheta_{fresh}) \cdot t. \tag{16}$$

In the periods when the first tank is heated $(\vartheta_{T1} \leq 50\ °C)$, the temperature variation of the second tank is affected only by water mass flow rate and temperature difference between the water extracted from it and the tap water supplied. This means that the temperature of the second tank will be lower at the end of a particular hour. In that case the internal energy stored in the second tank can be calculated by

$$Q_{T2} = -Q_{E2}. \tag{17}$$

When the second tank is heated, Q_{T2} will be calculated as follows

$$Q_{T2} = Q_{coll} - Q_{E2}. \tag{18}$$

And then the temperature variation can be calculated in the same way it was done for the first tank

$$\Delta\vartheta_{T2} = \frac{Q_{T2}}{m_s \cdot c_s}, \tag{19}$$

so the final temperature of the second tank at the end of a particular hour is calculated by the following expression

$$\vartheta_{T2_{final}} = \vartheta_{T2_{start}} + \Delta\vartheta_{T2}. \tag{20}$$

Calculations for every next hour until the end of the day is done in the same way resulting in the simulation of solar system work for characteristic day in a month. When the same procedure is applied for every month the total energy gain from the solar system in a period of one year can be calculated. Now it is possible to adjust the amount of collected energy to satisfy demands/meet the conditions. This can be done by correction of the collector angle, collector area and size and number of water tanks. After the minimum collector area that satisfy energy needs of the object for domestic water in July and August is found at the optimal tilt angle of collector for those months, it is noticed that the collected energy exceeds the needs of the object (for July 5 % in Zagreb and 8 % in Split). Then, the correction of collector tilt angle was done towards the optimal angle for the whole year. Instead of having a surplus of energy in summer months it was decided to find the fixed angle that will give more energy in the rest of the year and still satisfy primary goal - 100 % coverage of the motel needs for domestic hot water in July and August.

2.3
Calculation of the investment payback period
Opis proračuna povrata investicije

After the total amount of energy collected by solar collector is calculated it is possible to calculate savings of conventional fuel which would otherwise be spent if there were no solar contribution.

In the investment cost are included solar collectors, installation work, solar circuit pipelines with insulation, control-unit for system with two tanks, solar system pump as well as the difference in cost of solar water tanks and tank for domestic hot water in the conventional fossil fuel driven system. Other expenses involved in the installation of the motel's heating system (valves, pipes etc.) are attributed to the conventional system which has to be installed regardless of the solar system.

$$C_{invest} = (C_{coll} \cdot A_{coll}) + C_{added}, \tag{21}$$

where C_{coll} is the cost of collector per m² (including installation work expenses), A_{coll} is the total collector area and C_{added} comprises costs for pipes, pump, control unit, diff. in tank size.

Yearly saving (S) can be calculated by the following expression

$$S = \frac{\sum Q_{coll}}{\eta_{heater}} \cdot \frac{C_{fuel}}{q_{fuel}}. \tag{22}$$

ΣQ_{coll} represents the amount of energy collected by solar collector in a period of one year; C_{fuel} represents the cost of conventional fuel, q_{fuel} fuel lower heating value and η_{heater} efficiency of a conventional heater.

Investment payback period is calculated as the ratio of investment cost to yearly savings in conventional fuel

$$P = \frac{C_{invest}}{S}. \tag{23}$$

2.4
Collector selection
Odabir kolektora

Comparison is made between two plate solar collectors, one with highly efficient TINOX coating of absorber and other with less efficient Cr coating, with the purpose of finding the most cost-effective solution for this solar system. Collector efficiency for each collector is calculated by the following expressions.

$$\eta_c = 0,8436 - 4,1989 \cdot \frac{(\vartheta_T - \vartheta_{Air})}{I_\beta} - 1,2491 \cdot \left[\frac{(\vartheta_T - \vartheta_{Air})}{I_\beta}\right]^2, \tag{24}$$

$$\eta_c = 0{,}7242 - 5{,}0967 \cdot \frac{(T_T - T_{Air})}{I_\beta}. \tag{25}$$

Results of comparison are shown in the next chapter in Figs 14 and 15.

In Table 1 are shown some characteristics of both collectors

***Table 1** Comparison of the selected collectors' characteristics*
***Tablica 1** Usporedba izabranih karakteristika kolektora*

	TINOX coating collector	Cr coating collector
Absorber area (m²)	1,9	1,9
Absorption coefficient	0,95±0,02	0,9
Emission coefficient	0,05	0,2
Glass transmission coefficient	0,9	0,9
Contact absorber plate/tubes	laser-welded	brazed
Insulation	mineral wool	mineral wool

3 Results and discussion
Rezultati i komentari

Figs 3 and 4 show at what rate solar system covers the object's energy demand for domestic hot water in Zagreb and Split. All calculations performed are based on the meteorological data (solar radiation and air temperature) averaged over the period of 20 years. As expected, in the period from October till March solar system contribution is much higher in Split than in Zagreb.

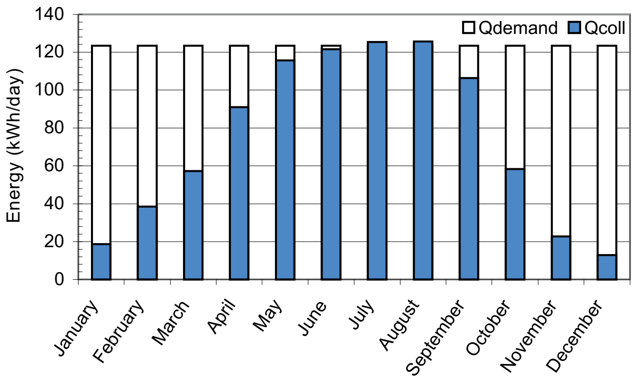


***Figure 3** Solar contribution for Zagreb*
***Slika 3** Solarni doprinos Zagreb*

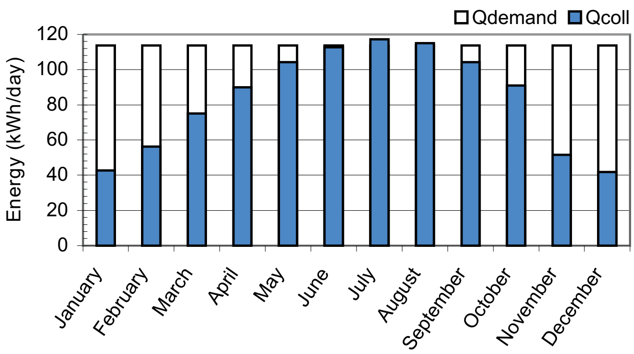


***Figure 4** Solar contribution for Split*
***Slika 4** Solarni doprinos Split*

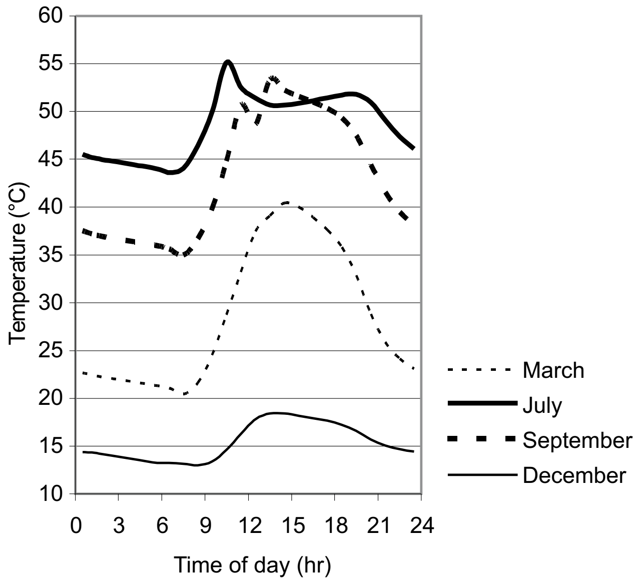


***Figure 5** Daily temperature variation of water in the first tank for Zagreb*
***Slika 5** Dnevni hod temperature vode u spremniku br. 1 za Zagreb*

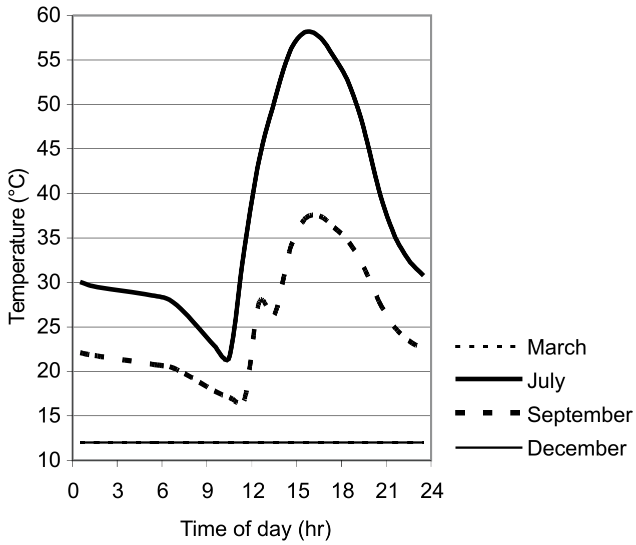


***Figure 6** Daily temperature variation of water in the second tank for Zagreb*
***Slika 6** Dnevni hod temperature vode u spremniku br. 2 za Zagreb*

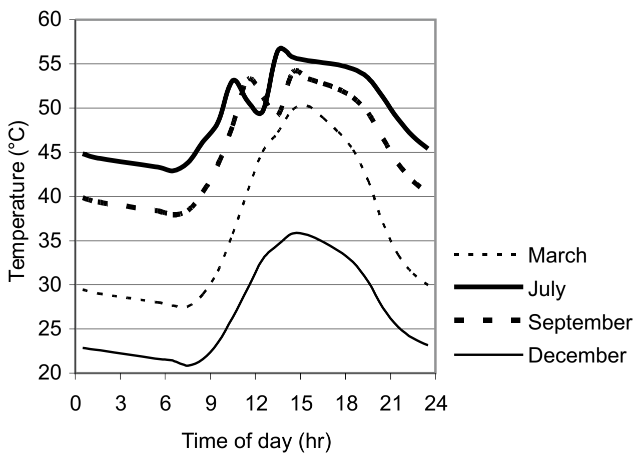


***Figure 7** Daily temperature variation of water in the first tank for Split*
***Slika 7** Dnevni hod temperature vode u spremniku br. 1 za Split*

Figs 5 and 6 show daily temperature variation in the tanks in March, July, September and December for Zagreb while Figs 7 and 8 for Split. Those diagrams show that in summer months second tank is being heated up in the part of the day when solar radiation is very strong. Because of low water temperature in the tank, high outdoor air temperature and high value of solar radiation relatively high values of collector efficiency η are achieved (η=0,36 in winter and η=0,49 in summer for Zagreb and η=0,47 in winter and η=0,54 in summer for Split).

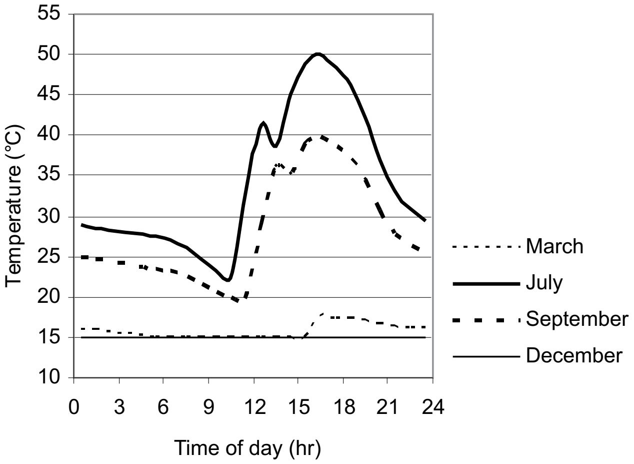


Figure 8 *Daily temperature variation of water in the second tank for Split*
Slika 8 *Dnevni hod temperature vode u spremniku br. 2 za Split*

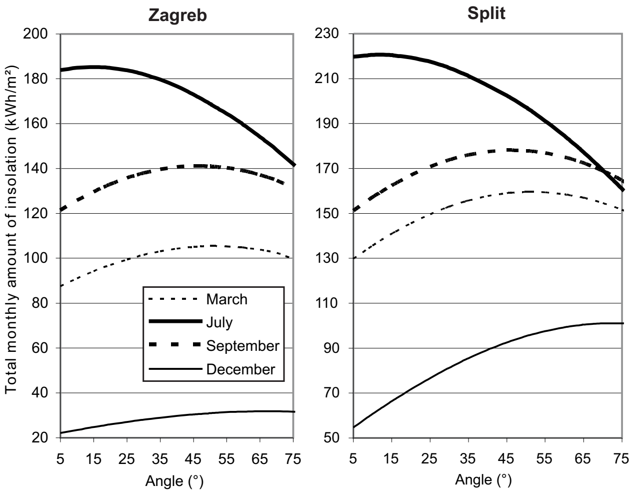


Figure 9 *Effect of collector tilt angle on monthly insolation for Zagreb and Split*
Slika 9 *Utjecaj nagiba kolektora prema horizontali na mjesečno primljeno zračenje za Zagreb i Split*

During the period from October till March only the first tank is used in Zagreb while that period in Split is a little shorter and lasts only 4 months i.e. from November till February. Greater contribution of the solar system in winter months is a result of almost twice as high values of solar radiation in climate area of Split in that part of the year as shown in Figure 9.

Figs 10 and 11 show collector tilt angles that provided the most energy for each month. In summer months the best effect is attained with the lower angles and higher angles in winter months. It also shows that the optimal monthly angles for Zagreb and Split are similar.

Considering the fact that solar collectors are mostly installed at a fixed angle, the optimal collector angles for a whole year were calculated. They are shown in Figs 12 and 13 showing the difference between the optimal angles for Zagreb and Split.

Monthly optimal angles are relatively high in winter months (for Split: January 70º, February 64º, November

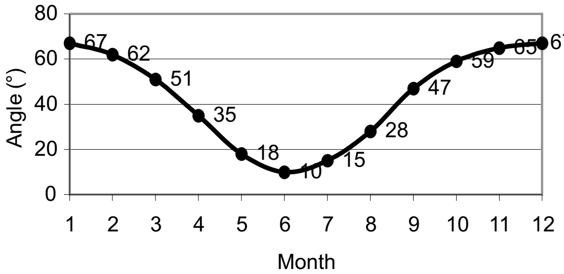


Figure 10 *Monthly optimal angles for Zagreb*
Slika 10 *Prikaz mjesečnih optimalnih kutova za Zagreb*

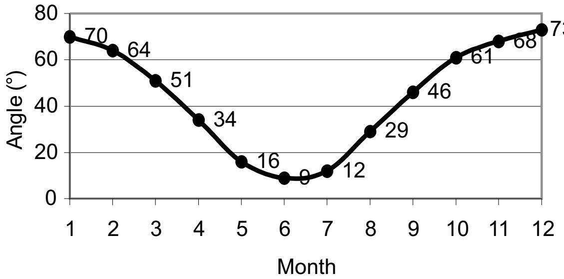


Figure 11 *Monthly optimal angles for Split*
Slika 11 *Prikaz mjesečnih optimalnih kutova za Split*

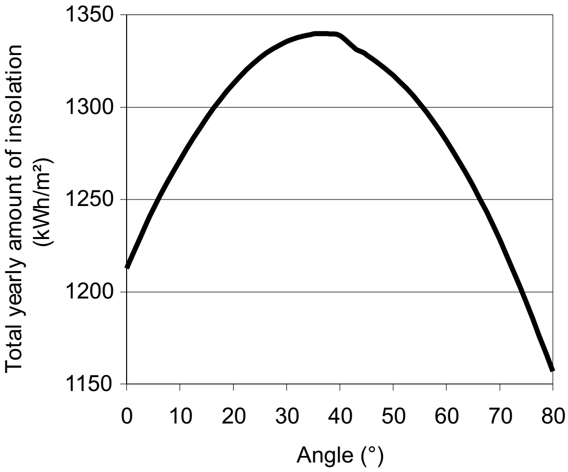


Figure 12 *Effect of the collector tilt angle on total yearly insolation for Zagreb*
Slika 12 *Utjecaj nagiba kolektora na ukupno godišnje primljeno zračenje za Zagreb*

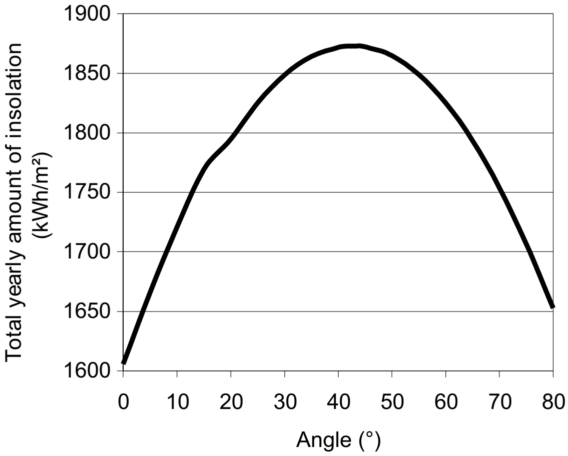


Figure 13 *Effect of collector tilt angle on total yearly insolation for Split*
Slika 13 *Utjecaj nagiba kolektora na ukupno godišnje primljeno zračenje za Split*

68º, December 73º). Considerably higher values of insolation in winter months in Split compared to those in

Zagreb result in a greater influence of these months on the yearly optimal angle which means that yearly optimal angle will be higher for the Split area than in Zagreb (Split-43°, Zagreb-37°).

Since the basic criterion in sizing of the analyzed solar system was to achieve the shortest investment payback period it has also affected the selection of collector. Figs 14 and 15 show results of comparison of two plate solar collectors. From these diagrams is noticeable that for nearly equal amount of collected energy (2,8 % more for Zagreb and 3,1 % more for Split) the cost of collector with TINOX absorber (higher collector efficiency and higher cost per m²) is significantly higher (7,6 % for Zagreb and 11,7 % for Split). This however results in a longer investment payback period for TINOX collector and selection of the collector with Cr absorber as the most cost-effective solution.

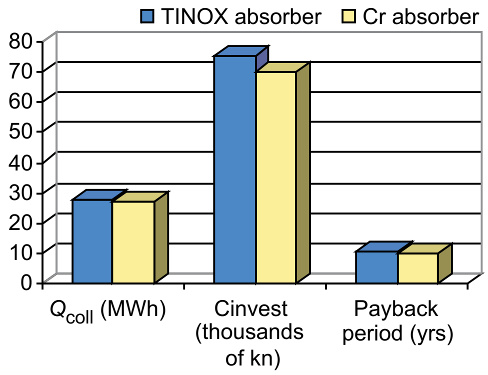


Figure 14 *Comparison of solar collectors for Zagreb*
Slika 14 *Usporedba kolektora za Zagreb*

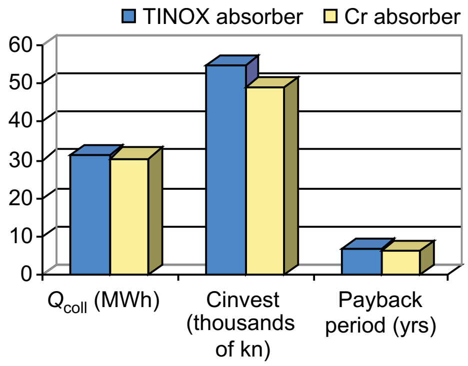


Figure 15 *Comparison of solar collectors for Split*
Slika 15 *Usporedba kolektora za Split*

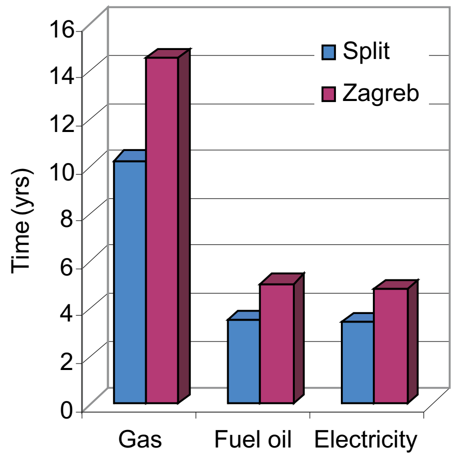


Figure 16 *Comparison of investment payback period for Zagreb and Split*
Slika 16 *Usporedba perioda povrata investicije za Split i Zagreb*

Figure 16 shows investment payback period with selected collector (Cr absorber). It can be noticed that investment payback period is relatively short for Split (for gas-10,26 yrs, for fuel oil-3,57 yrs, for electricity-3,43 yrs) while the payback period is much longer for Zagreb (for gas-14,61 yrs, for fuel oil-5,08 yrs, for electricity-4,88 yrs). The system is especially cost effective in cases when electricity and fuel oil are replaced by collected solar energy. Since the lifetime of the present solar system is around 20 years, i.e. longer than any of the calculated payback periods, this system can be regarded an economically viable.

5 Conclusions
Zaključak

Cost of energy from renewable sources is at the moment higher than cost of energy obtained from fossil fuels. Yet, use of renewable sources has some advantages such as: assurance of energy supply, reduction of dependence on imported energy and fossil fuels as well as the environment preservation. Results of performed simulations show that installation of such systems for domestic hot water purposes in medium size objects like motels can be cost-effective for both climate areas in Croatia. Here presented method for daily simulation of work of solar system with two tanks can serve designers for proper sizing of similar solar systems, which is an important issue for making a solar system economically feasible. Calculated optimal monthly tilt angles of collector and corresponding received insolation can be used for quick calculation of collected solar energy and determination of needed collector area based on a given consumption and a period of the year when energy demand is highest.

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Nomenclature
Popis oznaka i mjernih jedinica

A_{coll} - collector area (m²)
c_p - specific heat capacity of water extracted from the storage tank at average temperature between ϑ_{fresh} and ϑ_{hot} (kJ/kg K)
c_s - specific heat capacity of water in particular storage tank at current temperature ϑ_{T1} or ϑ_{T2} (kJ/kg K)
C_{fuel} - conventional fuel cost (kn/m³)
C_{invest} - investment cost (kn)
I - total solar radiation on the horizontal surface (Wh/m²)
I_b - direct solar radiation on the horizontal surface (Wh/m²)
$I_{b\beta}$ - direct solar radiation on inclined surface (Wh/m²)
I_d - diffuse solar radiation on the horizontal surface (Wh/m²)
$I_{d\beta}$ - diffuse solar radiation on inclined surface (Wh/m²)
$I_{r\beta}$ - reflected solar radiation on inclined surface (Wh/m²)
I_β - total solar radiation on inclined surface (Wh/m²)
k_t - clearness index
$\dot{m}$ - mass flow rate (kg/s)
m_s - mass of water in the storage tank (kg)
P - payback period (years)
q_{fuel} - fuel lower heating value (kWh/m³ for gas and kWh/kg for fuel oil)
Q_{coll} - usefull heat collected by collector (Wh)
Q_{E1} - change of internal energy in the first tank (Wh)
Q_{E2} - change of internal energy in the second tank (Wh)
Q_{demand} - heat needed for heating of the tap water (Wh)
Q_{T1} - internal energy stored in the first tank (Wh)
Q_{T2} - internal energy stored in the second tank (Wh)
S - yearly saving (kn)
t - time period (h)
ϑ_{Tfinal} - final temperature in the first tank in a period of one hour (°C)
ϑ_{Tstart} - starting temperature in the first tank for a period of one hour (°C)
ϑ_T - temperature in the tank currently heated by the collector (°C)
ϑ_{T1} - temperature in the first tank (°C)
T_{T2} - temperature in the second tank (°C)
ϑ_{fresh} - temperature of tap water (15 °C for Split and 12 °C for Zagreb)
ϑ_{hot} - required temperature of water (50 °C)
ϑ_{Air} - air temperature, hourly values (°C)
$\Delta\vartheta_T$ - temperature change in the tank over one hour (°C)
ΣQ_{coll} - heat collected by solar collector in one year (Wh)
β - collector tilt angle,(°)
δ - solar declination
η_c - collector efficiency
η_{heater} - efficiency of a conventional heater
θ - angle of incidence (°)
θ_z - zenith angle (°)
γ - surface azimuth angle (°)
ρ - reflectance factor