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Analysis and feasibility of implementing solar chimney power plants in the Mediterranean region

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ABSTRACT

This paper analyzes the feasibility of solar chimney power plants as an environmentally acceptable energy source for small settlements and islands of countries in the Mediterranean region. For the purpose of these analyses, two characteristic geographic locations (Split and Dubrovnik) in Croatia were chosen and simplified model for calculation of produced electric power output is also developed. These locations possess typical characteristics of the Mediterranean climate. The solar characteristics of the chosen geographic locations are shown along with characteristic meteorological data. A solar chimney (SC) power plant with a chimney height of 550 m and a collector roof diameter of 1250 m would produce 2.8–6.2 MW of power. The average annual electric power production of this SC power plant would range between 4.9 and 8.9 GWh/year, but in reality from 5.0 to 6.0 GWh/year in average. An approximate costs analysis, which included a total investment estimate, was performed. The levelized electricity cost was also calculated. It is found that the price of produced electric energy by solar chimney power plant in Mediterranean region is considerably higher compared to the other power sources.

1. Introduction

Solar energy is an inexhaustible and environmentally renewable source of energy. The average annual potential of solar energy per square meter of earth is equivalent to burning 100 l of heating oil, but without any harmful emissions. The solar energy equivalent for the Mediterranean geographical locations used in this paper ranges from 120 to 160 l of heating oil. This energy is freely available and need not be imported. Most importantly, it does not pollute the environment, even during the production process, as does photovoltaic production. Currently, solar energy is still underutilized and unfortunately occupies a smaller portion of the total energy generation. Due to the ever decreasing amount of available conventional (fossil) fuels, renewable solar energy has become exceedingly important and more commercially affordable. This change has resulted in a strategic European decision to utilize clean technologies, which was confirmed by the signing of the Kyoto Protocol. In the near future, Europe plans to significantly reduce its usage of fossil fuels, but it does not plan to abandon fossil fuel technologies. Currently, the EU plans to provide 20% of electric energy and 30% of thermal energy from renewable energy sources by the year 2020. In addition, ASHRAE[1] plans to form a sustainable technology and product market for building a zero energy house by the year 2030.

Mediterranean countries, such as Croatia, should prepare to have the greatest possible portion of renewable energy sources serve as the basis for their energetic future, which is in accordance with the EU energy policy. The organized and efficient use of solar energy can only achieve significant growth through the implementation of new clean technologies. One such relatively new technology is the solar chimney power plant (SC), which is discussed in this paper as a possible electric power source for countries in the Mediterranean region.

The basic SC plant concept was designed by Schlaich [1], together with his partners. In simple terms, the SC plant turns solar energy into work, i.e., electric power. The main parts of the plant are the collector roof, solar chimney and machinery space, which includes turbines and generators for electric power production. The power source is the working potential of heated air, which has been defined and analyzed in detail [2]. The working potential is concentrated at the bottom of the solar chimney as a pressure differential. The difference in pressures

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Nomenclature

A_c	cross sectional area of solar chimney (m^2)
A_{coll}	solar collector area (m^2)
c_p	specific heat capacity of air (kJ/kg °C)
D_{cr}	diameter of collector roof (m)
d_c	diameter of chimney (m)
d_e	equivalent diameter (m)
dz	differential element of chimney height (m)
$E_{el\cdot an}$	annual electric energy produced (MWh/y)
$E_{el\cdot max}$	maximum annual electric energy produced (MWh/y)
f	friction factor
g	acceleration of gravity (m/s^2)
G	solar irradiance (W/m^2)
H_c	solar chimney height (m)
h	enthalpy of air (J/kg)
h_r	distance from the ground to the cover (m)
i	years
K_s	absolute roughness (m)
k_w	levelized electricity cost (€/kWh)
K_0	total invested capital (Mio. €)
$\dot{m}$	mass flow rate of air (kg/s)
n	amortization period (years)
p	calculated interest rate (% p.a.)
$P_{av\cdot an}$	average (mean) annual electric power output from the solar chimney (kW)
P_{opt}	optimal average electric output from the solar chimney (kW)
P_{el}	electric output from the solar chimney (kW)
$P_{el\cdot max}$	maximum electric output (kW)
P_j	average monthly electric output (kW)
P_{cl}	power loss due to exit kinetic energy (kW)
P_{tc}	power of theoretical air cycle (kW)
R	ideal gas constant (J/kg K)
Re	Reynolds number
R	radius (m)
r_c	radius of chimney (m)
r_{cr}	radius of collector roof (m)
r_{in}	rate of inflation (% p.a.)
r_b	maintenance and repair cost (% p.a.)
$\dot{V}$	volume flow of air (m^3/s)
v	specific volume of air (m^3/kg)
$\dot{Q}$	heat gain of the air in the collector (W)
q_{coll}	specific heat gain of the air in the collector (J/kg)
T_0	ambient temperature (K)
T_1	temperature of air at the collector outlet (K)
w_t	technical work (J/kg)
w_0	inlet air velocity of the solar collector (m/s)
w_1	inlet air velocity of the chimney (m/s)
w_2	air velocity after the turbine section (m/s)
x_i	impact parameter
z	level from the ground (m)

Greek symbols

α	effective absorption coefficient
β	factor proportional to convective energy loss ($W/m^2 K$)
η_{coll}	solar collector efficiency
η_{sc}	solar chimney efficiency
η_{sp}	overall efficiency
η_t	turbine efficiency
η_{wt}	blade, transmission and generator efficiency
ρ_0	density of ambient air (kg/m^3)
ρ_1	density of air at the inlet in the solar chimney (kg/m^3)
τ_j	monthly working hours of a solar chimney power plant (h/month)
$\sum_i \tau_i$	total working hours of a solar chimney plant for optimal electric output (h/year)
Δp_{ac}	pressure difference produced between the chimney base and the surroundings (Pa)
Δp_c	pressure drop due to friction losses in the collector (Pa)
Δp_{cf}	pressure drop due to friction losses in the chimney (Pa)
Δp_k	pressure drop due to kinetic energy losses at the chimney exit (Pa)
Δp_t	pressure difference used by the turbine (Pa)
ΔT	temperature increase between the collector inflow and outflow (°C)
ΔT_{opt}	optimum temperature increase between the collector inflow and outflow (°C)

relates to the surrounding atmospheric and internal heated air at the chimney inlet. The plant chimney intensifies the buoyancy effect, which causes the difference in pressure and energizes the turbines that, in turn, generate electric power. SC plants are analogous to hydroelectric power plants with Δp_{ac} (see Eq. (1)) being equivalent to $g \times H_d$, where H_d is the water fall and Δp_{ac} pressure difference between the air in the chimney and ambient air.

A case study of SC power plants in Northwestern regions of China [3] concluded that a SC power plant is able to produce 110–190 kW of electric power with a chimney height of 200 m and diameter of 10 m, and with a collector cover of 196,270 m^2. Through use of a mathematical model and code for sloped collector fields in MATLAB [4], another group of authors determined that a nominal power of 5 MW would be produced in three locations in Canada by a SC power plant with a collector area of 950,000 m^2 and chimney height and diameter of 123 and 54 m, respectively. They concluded that the overall thermal performance of SC power plants at high latitudes is slightly better than those with horizontal collector fields in southern locations. The potential of SC power plant applications in rural areas was studied in Ref. [5]; these authors determined the minimum dimensions of a practical SC electric power station that would serve approximately 50 households. A mini-solar chimney system for a region in Botswana was studied in detail in Ref. [6].

The objective of this paper is to analyze the potential for electric energy production in Mediterranean countries and to estimate the quantity and price of the produced electric energy. For this purpose, a more general and simplified model of a SC power plant will be established and analyzed for the selected Mediterranean locations.

2. Thermodynamic cycle of air in SC power plant

The theoretical and real processes of air in a SC power plant are illustrated in the h–s thermodynamic chart (Fig. 1). The state of air at the collector inlet is 0, and the theoretical state of air at the collector outlet with negligible velocity is 1. The state of air at the exit from the turbines, without exit losses, is 2^t, while 2^t–3^t represents the process of air rising to the top of the chimney (height H_c).

The theoretical cycle is closed by the heat rejection process 3^t–4 and by isentropic downdraft movement of air to the collector inlet 4–0. The process 0–1–2^t–3^t–4–0 represents the ideal Brayton cycle in a gravitational field. Due to hydrodynamic losses in the collector in the real process, there is a small pressure drop. Hence, the real state of air at the front of the turbine is point 1^p. The real process of expansion in the turbine is 1^p–2^p, with exit kinetic energy $e_{k_2^p} = h_{2^{po}} - h_{2^p} = \Delta h_t$. The state of air at the chimney outlet is point 3^p, with exit kinetic energy $e_{k_3^p} \cong e_{k_2^p} \cong h_{3^{po}} - h_{3^p} = \Delta h_c$. As a result, the exit loss at the chimney outlet is Δh_c in Fig. 1. In Ref. [7], the ideal air standard cycle analysis was performed, with implementation of gas turbine theory using similar thermodynamic principles.

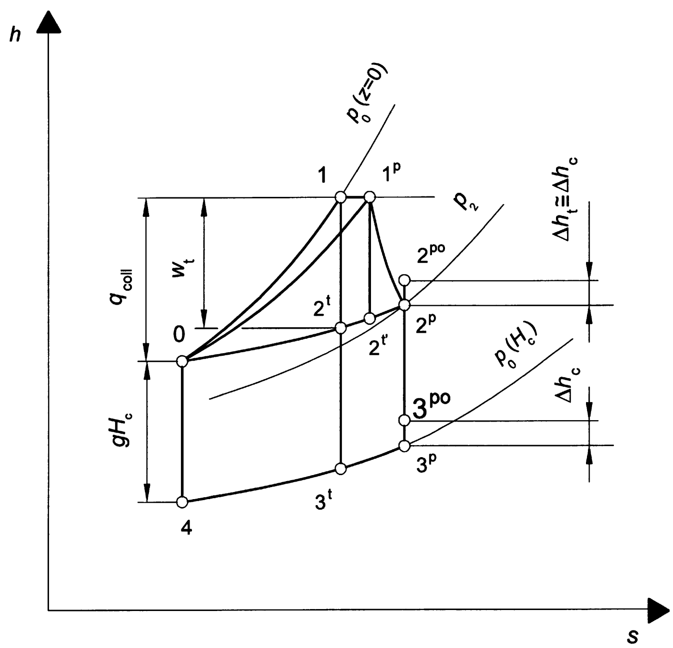

Fig. 1. Theoretical and real process of air in SC power plant.

3. Theoretical review of solar chimney power plants

In Fig. 2, the three basic parts of a SC plant (collector roof, solar chimney and turbines with electric power generators and machinery space) are shown. The physical principle on which the plant operation is based is simple and fundamental. The relatively colder surrounding air enters along the circumference in the space below the collector roof. Solar radiation passes through the collector roof (glass or special foil) and heats the ground under it.

The air is heated in the collector, from the ambient temperature T_0 to the air temperature at the collector outlet T_1. The temperature increase in the collector $\Delta T = T_1 - T_0$ is usually between 10 and 30 K. The pressure difference Δp_{ac} develops due to the different air densities at the chimney bottom. The greatest working potential is also concentrated at the chimney bottom and it is defined according to the following [8]:

$$\Delta p_{ac} = g \times \int_0^{H_c} (\rho_0 - \rho_1)\,dz = \rho_1 g H_c \frac{\Delta T}{T_0}, \tag{1}$$

where g is acceleration of gravity (m^2/s); ρ_0 the density of ambient air (kg/m^3); ρ_0 the density of air at the inlet in the solar chimney (kg/m^3); dz (m) the differential element of chimney height; H_c (m) the chimney height and T_0 (K) is the ambient temperature.

Essentially, the total working potential is the work of the buoyancy force gained by raising the air from the bottom ($z = 0$) to the top of the chimney ($z = H_c$). Most of this potential is consumed by the turbine and electric power production. The remainder of the work is lost due to internal friction and the kinetic energy at the chimney outlet.

The role of the plant chimney is to convert the thermal flow brought into the collector $\dot{Q}$ by the sun into the turbine specific work w_t and kinetic energy at the exit. As indicated by Fig. 1, chimney efficiency equals:

$$\eta_{sc} = \frac{w_i}{q_{coll}} = \frac{h_i - h_{2'}}{h_1 - h_0} = \frac{v_1\,\Delta p_{ac}}{c_p(T_1 - T_0)} = \frac{v_1\,\Delta p_{ac}}{c_p\,\Delta T}, \tag{2}$$

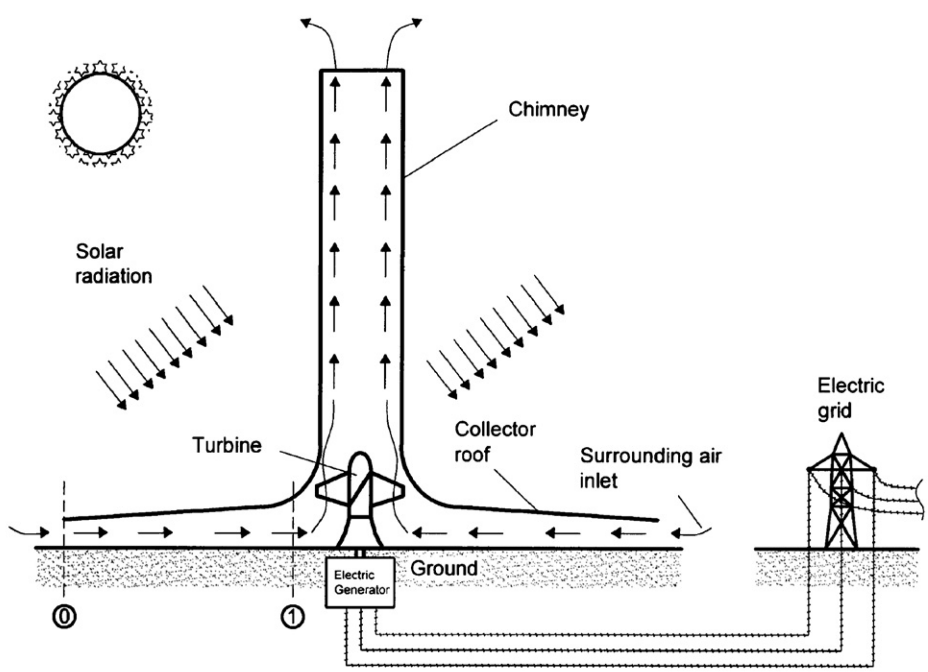

Fig. 2. Schematic overview of the solar tower principle.

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where q_{coll} (J/kg) is the specific heat gain of the air in the collector; h_1 (J/kg) the enthalpy of air at chimney inlet; h_0 (J/kg) the enthalpy of ambient air; h_{2t} (J/kg) the enthalpy of air after turbines; v_1 (m^3/kg) the specific volume of air at chimney inlet and c_p (kJ/kg/°C) the specific heat capacity of air.

If the ideal gas law is applied, a simplified relation for solar chimney efficiency is obtained, as follows:

$$\eta_{sc} = \frac{gH_c}{c_p T_0}. \quad (3)$$

The solar tower plant efficiency is low; however, solar energy is "free". As a result, this investment makes sense.

The pressure drop due to flow friction loss in the chimney Δp_{cf} is negligible. More specifically, for selected SC power plant parameters ($T_0 = 288$ K, $H_c = 550$ m and $d_c = 82$ m, in accordance with Fig. 3a), the calculated pressure drop Δp_{cf} is a function of the velocity of air flow at the chimney inlet. The friction factor f (Fig. 3b) is calculated from Colebrook relation (4), [9], for three different values of absolute roughness K_s:

$$\sqrt{\frac{1}{f}} = -2\log\left(\frac{2.51}{Re\sqrt{f}} + \frac{K_s}{3.7d_c}\right), \quad (4)$$

where Re is the Reynolds number and d_c the diameter of chimney.

According to Eq. (1) and for the adopted SC power plant parameters (see Section 6), the calculated pressure drop Δp_{ac} is from 200 to 600 Pa, depending upon the temperature at the collector outlet. If we compare pressure drop Δp_{ac} with the pressure drop due to friction losses in the chimney, it is apparent that Δp_{cf} is almost negligible (Fig. 3a). Furthermore, the pressure drop due to kinetic energy losses at the chimney exit Δp_k is negligible due to the simplified geometry (constant distance from the ground to the cover) and relatively large chimney diameter. According to our calculations, the pressure drop Δp_k is not greater than 3% if we compare it to the total pressure drop Δp_{ac}. The pressure drop due to friction losses in the solar collector Δp_c is also negligible. If we apply the Bernoulli equation to the simplified cases shown in Fig. 4, Eqs. (5), (6), and (7) are obtained, where w is the radial velocity on an arbitrary radius. This relationship is derived from the continuity equation $w = w_0 r_{cr}/r$:

$$\frac{\Delta p}{\rho} = \frac{w_1^2 - w_0^2}{2} + \int_{r_c}^{r_{cr}} f\frac{dr}{d_e}\frac{w^2}{2} = \frac{w_1^2 - w_0^2}{2} + \int_{r_c}^{r_{cr}} f\frac{1}{d_e}\frac{w_0^2 r_{cr}^2}{2}\frac{dr}{r^2} = \frac{w_1^2 - w_0^2}{2} + f\frac{1}{d_e}\frac{w_0^2 r_{cr}^2}{2}\frac{1}{r}\Big|_{r_c}^{r_{cr}}, \quad (5)$$

where Δp (Pa) is the pressure difference; ρ (kg/m^3) the density of air; w_1 (m/s) the inlet air velocity of the chimney; w_0 (m/s) the inlet air velocity of the solar collector; r_c (m) the radius of chimney; r_{cr} (m) the radius of collector roof and d_e (m) the equivalent diameter.

By further integration, we obtain Eq. (6):

$$\frac{\Delta p}{\rho} = \frac{w_1^2 - w_0^2}{2} + f\frac{(w_0 r_{cr})^2}{2d_e}\left(\frac{1}{r_c} - \frac{1}{r_{cr}}\right). \quad (6)$$

According to Fig. 4, for an element of specified width $\Delta\varphi$ on radius r, the equivalent diameter is $d_e = (4 \times r\Delta\varphi h_r)/(2 \times r\Delta\varphi)$. Hence, the equivalent diameter for the arbitrary radius is $d_e = (4 \times 2r\pi h_r)/(2 \times 2r\pi) = 2h_r$, where h_r is distance from the ground to the cover assumed to be constant.

The potion of the pressure drop that is related to friction loss in the solar collector equals:

$$\Delta p_c = \rho f\frac{(w_0 r_{cr})^2}{4h_r}\left(\frac{1}{r_c} - \frac{1}{r_{cr}}\right), \quad (7)$$

where the friction factor f is calculated from the Moody expression [10].

For specified solar chimney power plant parameters, the pressure drop due to friction loss in the solar collector Δp_c is not greater than 4% (depending upon the velocity of air at the collector outlet), compared with Δp_{ac} which has an average value of 2%. Following further analysis, this pressure drop is found to be negligible. Based on previous observations, we conclude that the overall pressure difference is $\Delta p_{ac} = \Delta p_t + \Delta p_{cf} + \Delta p_c + \Delta p_k$, and the useful pressure drop for the turbine drive is Δp_t. On a

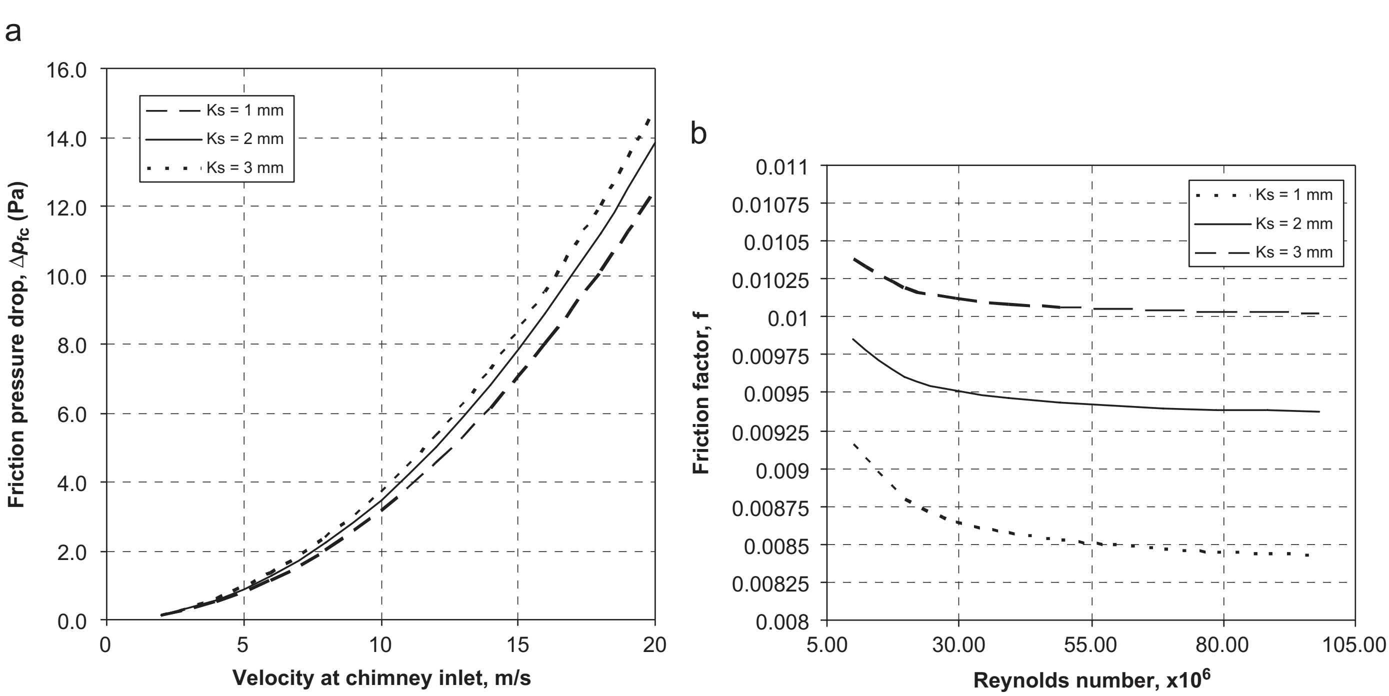

Fig. 3. (a) Pressure drop in the chimney as a function air flow velocity and (b) friction factor as a function of Reynolds number.

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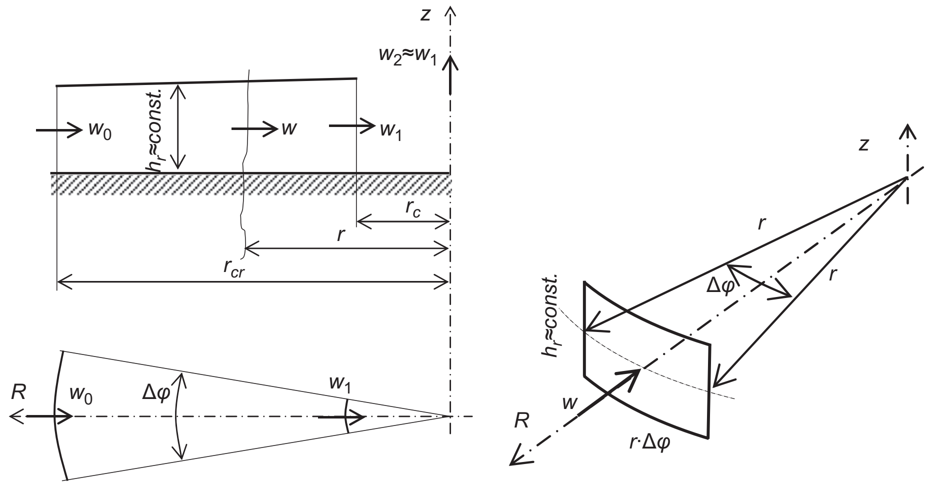

Fig. 4. Simplified overview of a flow stream in the solar collector.

prototype SC power plant in Manzanres [11], measured losses due to friction in the chimney and at the inlet section were somewhat higher than the theoretical values obtained from calculations. The author in Ref. [11] pointed out that, with better construction solutions, the previously mentioned losses could be significantly reduced.

The collector, an important part of the plant, transforms the overall available sun irradiance G (in W/m^2) on the collector area A_{coll} (m^2) into useful thermal flow $\dot{Q}$ (in W). By definition, the collector efficiency is:

$$\eta_{coll} = \frac{\dot{Q}}{A_{coll}G} = \frac{\dot{m}c_p\,\Delta T}{A_{coll}G} = \frac{\rho_1 \times w_1 \times A_c \times c_p \times \Delta T}{A_{coll}G}, \tag{8}$$

where $\dot{m}$ (kg/s) is the mass flow rate of air and A_c cross sectional area of chimney.

According to Ref. [12] and data from Ref. [1], the collector efficiency for a single glass roof can be expressed as a function of two parameters, ΔT and G:

$$\eta_{coll} = \eta_{coll}(G, \Delta T) = -13.116\left(\frac{\Delta T}{2G}\right)^2 - 6.3364\left(\frac{\Delta T}{2G}\right) + 0.72. \tag{9}$$

The authors in Ref. [1] have defined the SC collector efficiency in another manner, by considering radiation absorption, expressed with the effective absorption coefficient (α) and convective energy losses to the surrounding environment. This alternative expression for collector efficiency is [1]:

$$\eta_{coll} = \alpha - \beta\frac{\Delta T}{G}, \tag{10}$$

where β (W/m^{2}K) is a factor that is proportional to convective energy losses, and α and β are coefficients that depend on the temperature difference.

The SC power plant uses axial turbines, which can be categorized as wind or gas turbines. The main task of the turbine assembly is efficient power transformation of a portion of the available working potential. The most important turbine loss in the SC power plant (besides the internal fluid friction power loss) is the exit kinetic energy. In the case under consideration, the appropriate turbine efficiency η_t is defined as follows:

$$\eta_t = \frac{P_{tc} - P_{cl}}{P_{cl}} = \frac{\dot{Q}\eta_{sc} - \dot{m}\,\Delta h_t}{\dot{Q}\eta_{sc}} = \frac{\dot{m}c_p\,\Delta T\eta_{sc} - \dot{m}(w_1^2/2)}{\dot{m}c_p\,\Delta T\eta_{sc}} = 1 - \frac{w_1^2}{2c_p\,\Delta T\eta_{sc}}, \tag{11}$$

where P_{tc} (W) is the power of theoretical air cycle; P_{cl} (W) is the power loss due to exit kinetic energy and Δh_t (J/kg) is the specific turbine loss due to the exit velocity of air:

$$\Delta h_t \approx \frac{w_{2^p}^2}{2} = h_{2^{po}} - h_{2^p} \approx \frac{w_1^2}{2}, \tag{12}$$

where according to Fig. 2, w_{2^p} is the velocity of air after real turbine expansion; $h_{2^{po}}$ (J/kg) the enthalpy of air after real turbine expansion with exit kinetic energy and h_{2^p} (J/kg) the enthalpy of air after real turbine expansion without exit kinetic energy.

The air velocity at the turbine exit w_1 (chimney outlet) is defined by:

$$w_1 = \frac{v_1\dot{m}}{A_c} = \frac{\dot{m}RT_1}{p_cA_c}, \tag{13}$$

where R (J/kg K) is ideal gas constant and p_c (Pa) the pressure of air at the collector outlet.

Overall turbine assembly efficiency varies. According to Refs. [1,11,13], the turbine efficiency varies from 40% to 90%. Extremely high velocities of air flow are not suitable, as they unfavorably influence turbine efficiency. The lowest flow velocity needed for the production of electric energy is approximately 3.0 m/s for pitch-regulated turbines. This restriction will be used in further calculations of the quantity of produced electric energy.

The overall plant efficiency η_{sp} is equal to the product of the partial efficiency of each plant component:

$$\eta_{sp} = \eta_{coll}\eta_{sc}\eta_t, \tag{14}$$

respectively,

$$\eta_{sp} = \left[\frac{\dot{m}c_p\,\Delta T}{A_{coll}G}\right] \times \left[\frac{gH_c}{c_pT_0}\right] \times \left[1 - \frac{w_1^2/2}{c_p\,\Delta T\eta_{sc}}\right]. \tag{15}$$

According to Eq. (3), we conclude that the chimney height H_c has the greatest influence on its efficiency (which is almost exactly proportional to the H_c). The efficiency increases with chimney height. Unfortunately, due to techno-economic constraints, the chimney height is limited to approximately 1000 m. The importance of this height on overall SC power plant efficiency is shown in Fig. 5 (which is based on data from Ref. [1], with chimney height $H_c = 550$ m). It should be pointed out that the actual thermodynamic efficiency of the chimney is considerably greater. Namely, the relatively low quantity of work produced by the chimney, as a thermal engine (which is proportional to the numerator in Eq. (2)) is a better quality form of energy, as compared to the relatively large amount of heat taken in the collector (proportional to the denominator in Eq. (2)).

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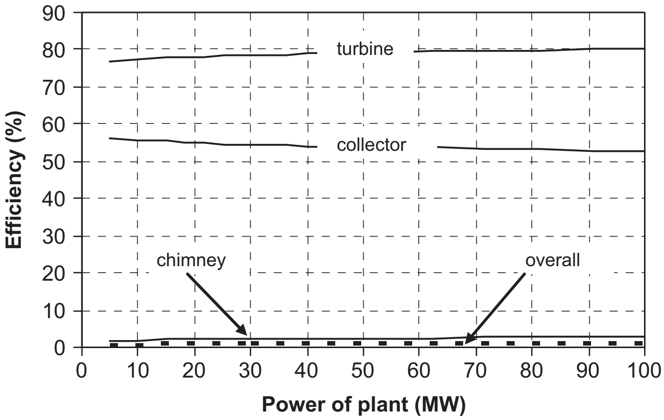

Fig. 5. Influence of SC components on overall efficiency (η_{sp}).

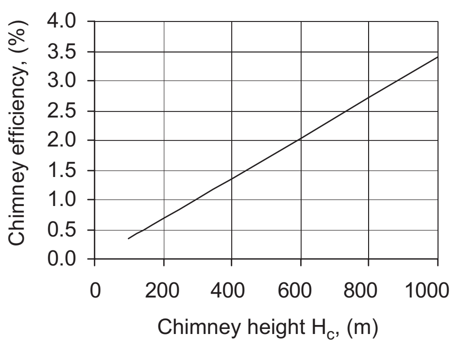

Fig. 6. Influence of SC height on chimney efficiency ($T_0 = 288$ K).

The importance of chimney height to chimney efficiency is shown in Fig. 6. The ambient temperature influence T_0 on the produced electric power is negligible; this relationship was studied in detail in Ref. [3].

Interestingly, we observed that the efficiency of the chimney itself as a thermal engine, according to Eq. (3), does not depend on the air temperature increase ΔT. According to the efficiency definition, its numerator contains the buoyancy force work up to the chimney top, while the denominator contains the received heat. This value is independent of the temperature difference because of the proportionality between work and heat with temperature increase in the collector ΔT.

4. Electric power output

In this paper, the achieved power outputs are calculated depending on chosen turbine working regimes, where the type of turbine and $\dot{V} - \Delta p_{ac}$ characteristics are determined in advance. The optimum regimes, volume flow, and the electric power output of the plant calculated in this way are uniformly determined with six parameters: $G, A_{coll}, H_c, D_{cr}, d_c$, and ΔT, according to the physical relationships in Eqs. (9), (11), (13), (15) and (17) (equation defined in proceeding of paper). The parameters related to the geometry of the SC power plant are chosen according to the recommendations given in Ref. [1]. These parameters are as close to the economic optimum as possible. In addition, the air temperature increase in the collector ΔT is varied in order to find the parameters that permit maximal electric energy production. Hence, electric power output calculated in this way gives the energetic potential that can be used in SC power plants in the analyzed regions.

A working regime for a SC power plant that permits the greatest production of electric power $P_{el \cdot max}$ for the given weather conditions is preferable. If the temperature increase in the collector ΔT is defined, then the maximum electric power output by the regime is achieved with only 2/3 of Δp_{ac} used in the turbine and 1/3 used as exit kinetic energy. In such a working regime, the mass flow and specific work per kg of air are optimized. Then, according to Ref. [1], the blade, transmission, and generator losses included in η_{wt} dictate that the maximum electric power output $P_{el \cdot max}$ can be calculated as follows:

$$P_{el.max} = \frac{2}{3}\eta_{coll}\frac{g}{c_p T_0}H_c A_{coll} G \eta_{wt}, \tag{16}$$

where η_{wt} are blade, transmission and generator efficiency.

In Eq. (16), Schlaich [1] began with the assumption that volume flow is not defined by only Δp_{ac}, or respectively, with ΔT, using Eq. (1). In this case, the optimal volume of air flow $\dot{V}$ must be chosen with respect to a set Δp_{ac}. Here, volume flow is (2/3) Δp_{ac}, as the pressure drop in the turbines. Backström and Fluri [14] analyzed the influence of the volume flow of air on power output in different conditions of hydrodynamic losses and working characteristics of turbines. Further, the authors concluded that the factor 2/3 gives maximum electric power output only with a constant value of ΔT, or according to Eq. (1), Δp_{ac}. In this paper, we use another approach, as previously mentioned, in which the power outputs P_{el} are calculated with a more general and simplified relation:

$$P_{el} = \dot{Q}\eta_{sp}\eta_{wt} = A_{coll} G \eta_{coll}\eta_{sc}\eta_t\eta_{wt}, \tag{17}$$

in which variable temperature increases ΔT is a parameter.

Comparisons of results simulated by the proposed simplified model and experimental readings from the prototype in Manzanares [11] are shown in Fig. 7. The comparisons were performed to verify the proposed simplified model.

It can be seen that the results of the simulations and the results of the experimental readings from Manzanares are in relatively good agreement. Divergence between the simulated and experimental readings is not more than 5% (for example in Fig. 7). The only modification in the model was modification of Eq. (9) (which was derived for a single glass roof) to an approximation for a plastic cover (as in Manzanares), which was performed using data from Ref. [11]. According to Fig. 7, somewhat greater divergence in the results for produced electric power output was observed in the early morning (8–9 a.m.), later afternoon (4 p.m.–7 p.m.) and

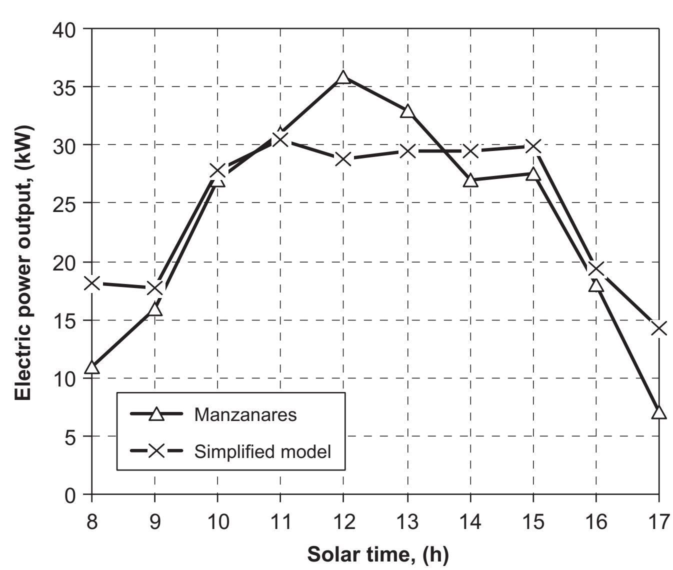

Fig. 7. Comparison of simulated and experimental results from a prototype SC power plant in Manzanares, Spain.

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midday hours (11 a.m.–1 p.m.). This divergence is mostly due to the assumption that the air temperature increase in collector ΔT is constant. In the early morning and later afternoon hours, the air temperature increase ΔT is higher than the real temperature increase, and in midday hours it is lower.

Although this model is simplified, it is useful for the purpose of this analysis. This simplified model yields credible values for the energetic potential of a SC power plant in the analyzed regions.

5. Solar characteristics of specified locations

Two characteristic geographical locations on the Croatian coast were chosen for the purpose of this analysis. These locations were chosen because they are representative of the Mediterranean climate. The Croatian coastal area is divided into northern, central (central Dalmatia), and southern Adriatic regions (southern Dalmatia).

Forty-three weather stations have recorded solar irradiation averages over the years, with complete land coverage of the areas of interest. The total sun irradiation on a horizontal surface in central and southern Dalmatia was registered by 13 weather stations. Table 1 compares the irradiated sun power in various regions.

The total daily-irradiated solar energy on a horizontal surface for the Adriatic coast ranges between 1.2 and 1.8 kWh/m^2 per day in January, and between 6.0 and 7.0 kWh/m^2 per day in July. The greatest climatic advantage occurs in the winter months. In January, the continental part of Croatia receives twice the amount of solar energy received by northern Europe. The southern part of Dalmatia receives three to five times more solar energy than northern Europe, and twice as much as central Europe. In the continental part of Croatia, the annual average is approximately 1200 kWh/m^2 per year, while in the coastal area it exceeds 1600 kWh/m^2 per year. For an optimal surface inclination, the average irradiated solar energy increases about 20% relative to the data depicted in Table 1. We conclude that the difference in the amount of irradiated sun energy received by central and southern Dalmatia is almost negligible. The continental parts of Croatia—e.g., the area of Zagreb—receive up to 40% less solar energy (annual average) than Dalmatia. Fig. 8 depicts the monthly mean air temperatures for central Dalmatia. In January, the daily mean air temperature is 8.8 °C, while in July it is 24.5 °C.

In Fig. 9, the distribution of the irradiated solar energy (kWh/m^2 per day) is presented. The data record a typical day in the hottest (July) and coldest (January) months for central Dalmatia.

The overall amount of irradiated energy received by an optimally inclined surface is up to 70% greater than in most parts of central and northern Europe. For example, the sunniest parts of the Croatian coast do not fall behind Greece. The sunniest parts of Europe receive only slightly more solar energy, ranging from 4% to 8%. According to Refs. [15–17], the data represent the 30-year

Table 1
Annual average solar irradiance for different regions of Croatia (averages for a decade) [12]

Location in Croatia	Annual average (kWh/m^2 day)	January-average (kWh/m^2 day)	July-average (kWh/m^2 day)
Dubrovnik (south Dalmatia)	4.4	1.8	7.0
Istra (north Adriatic)	3.4	1.2	6.0
Split (middle Dalmatia)	4.2	1.7	6.6
Slavonija (continental region)	3.4	1.0	6.0
Zagreb (continental region)	3.2	0.9–1.0	5.7

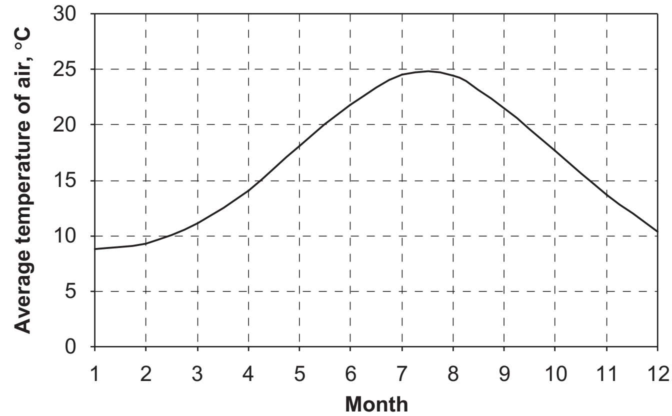

Fig. 8. Monthly average air temperature for Dalmatia region.

average measurements by the Croatian Weather Bureau, completed by the Croatian Energy Institute, "Hrvoje Pozar".

For the purpose of the analysis in this paper, we use solar irradiation values for two characteristic geographical locations, specifically Split (central Dalmatia) and Dubrovnik (southern Dalmatia). The recorded data are from the following weather stations: SPLIT–Marjan–WMO[2] (14445)—latitude 43°31′, longitude 16°26′; and DUBROVNIK–Gorica–WMO (14472)—latitude 42°39′, longitude 18°5′. As previously mentioned, these two locations possess typical characteristics of the Mediterranean climate, and thus are suitable for further analysis of the annual production of electric energy.

6. Annual production of electric energy for specified locations

For calculation of the annual amount of electric power produced by a SC power plant at the chosen Mediterranean geographical locations, the following technical features have been adopted:

Basic technical features of a SC power plant:

- collector roof diameter, $D_{cr} = 1250$ m,
- solar chimney height, $H_c = 550$ m,
- chimney diameter, $d_c = 82$ m,
- single glass collector roof,
- no additional heat storage and no nocturnal production,
- chosen temperature difference ΔT from 7.0 to 25.0 K,
- blade, transmission, and generator efficiency: $\eta_{wt} = 0.8$.

According to the adopted input parameters, and with Eq. (17), electric power outputs are calculated for each working plant hour. Calculated electric power outputs are graphically shown in Fig. 10 in the form of columns for June and the location of Split. The choice of optimal electric power output P_{opt} for the specified month is related to an additional criterion. This criterion is constant power production through the entire working day of the plant (which is technically possible with pitch turbine regulation).

The conditions that must be satisfied for optimal power are constant temperature increases in the collector, ΔT, and maximal quantity of produced electric power. In the example shown in Fig. 10, for air temperature increases of $\Delta T = 15$ K, the achieved optimal power is $P_{opt} = 5232$ kW for the period from approximately 8 a.m. to 16 p.m., or, more precisely, 7.8 h/day, with 40,811 kWh/day of produced electric energy.

[2] WMO—World Meteorological Organization.

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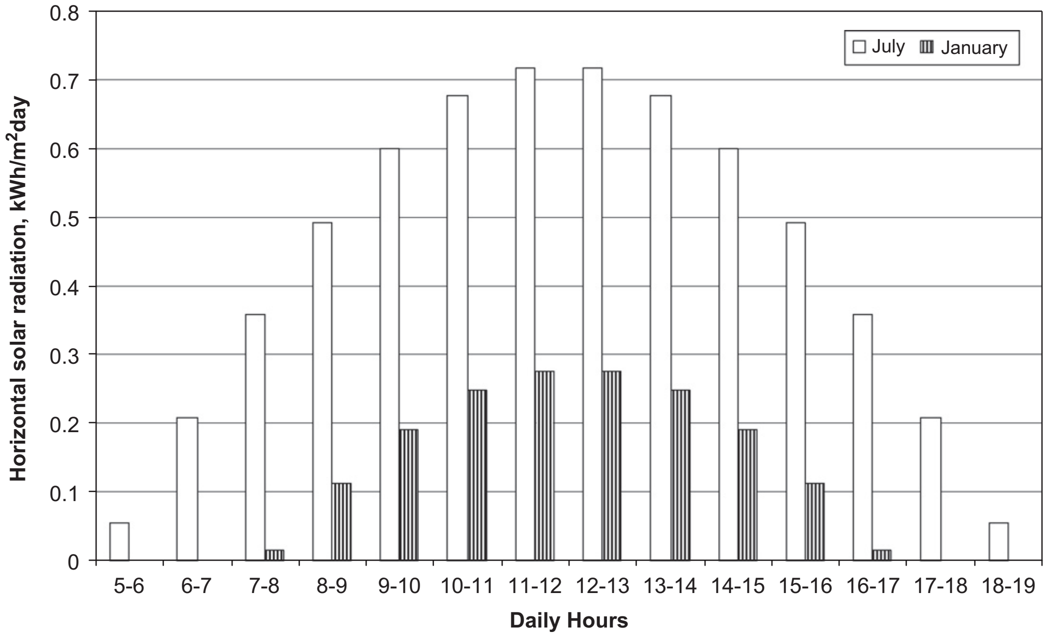

Fig. 9. Daily and hourly average radiated energy, kWh/m^2 per day, for horizontal surface and central Dalmatia region.

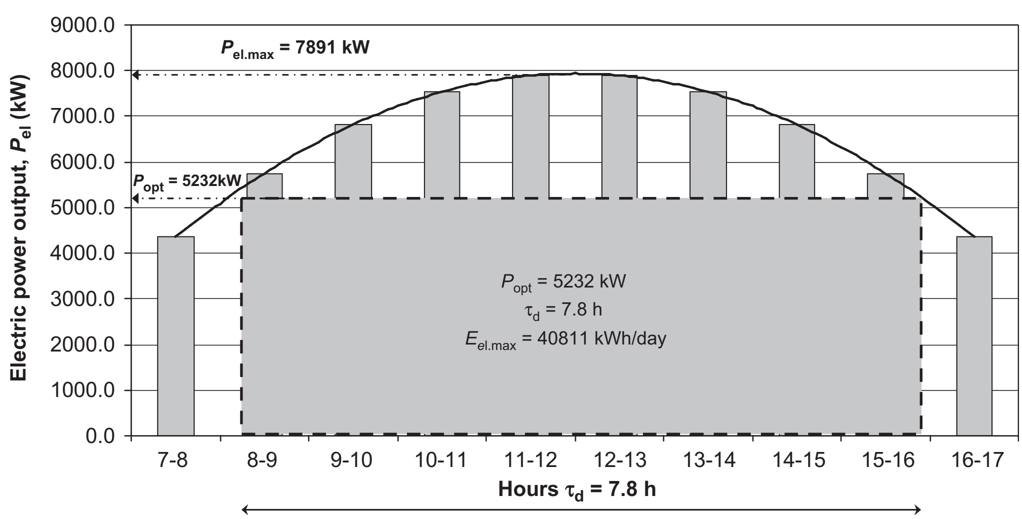

Fig. 10. Monthly optimal achieved electric power output achieved P_{opt} (Split, June, $\Delta T = 15$ K).

Each combination of power intensity and time duration would give a lower quantity of produced electric energy for a typical day in June. Specifically, for the conditions depicted in Fig. 10, the ratio between pressure drop in the turbine and the total pressure drop for maximal power equals 0.92. This is in accordance with optimal values mentioned in Refs. [14,18].

The annual average amount of power achieved by the plant $P_{av \cdot an}$ (or nominal power) for a set ΔT is calculated from the optimal monthly P_j according to the following expression:

$$P_{av.an} = \frac{\sum_j P_j \tau_j}{\sum_i \tau_i}, \tag{18}$$

where P_j (kW) is the average monthly electric output; τ_j (h/month) monthly working hours of a solar chimney power plant and τ_i (h/year) total (annual) working hours of a solar chimney power plant.

It is assumed that the optimally achieved monthly power gives the highest electric power production for the studied month.

Using this monthly calculation, the highest annual electric power output $E_{el \cdot an}$ is gained for the chosen ΔT. The optimum air temperature increase ΔT_{opt} is the increase which corresponds to maximum annual electric power output $E_{el \cdot an}$. In the economic analysis, this power is called the nominal power. The $E_{el \cdot an}$ calculation results for Split and Dubrovnik are shown in Fig. 11.

The highest mean annual electric power output for Split is $E_{el \cdot max} = 8916$ MWh/year for $\Delta T_{opt} = 10.3$ K, while it is $E_{el \cdot max} = 8958$ MWh/year for $\Delta T_{opt} = 10.6$ K in Dubrovnik. The physical explanation for the existence of the optimum air temperature increase in the collector ΔT_{opt} is two-fold. With small ΔT values, the collector efficiency is extremely high, but the turbine efficiency is very low, and vice versa. The reason for the low turbine efficiency lies in high air flow velocities, where kinetic energy losses dominate.

Fig. 11 shows that, in the interval of temperature increase from 5.0 to 10.0 K, the annual quantity of produced electric energy is slightly higher for Split compared with Dubrovnik (although

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Dubrovnik has a higher quantity of produced electric energy on an annual scale). The reason for this difference is the somewhat better solar characteristics of Dubrovnik, and they have an unfavorable effect on turbine efficiency (i.e., the quantity of produced electric energy) for relatively small temperature increases in the collector.

Based upon the analyses and simulations performed for Split and Dubrovnik, an average of 3.0–7.0 solar tower plant-working hours per day can be expected. For the given meteorological conditions and chosen geographical locations, it was established that a SC plant can produce an annual average of between 4.8 and 8.9 GWh/year of electric energy, depending on the achieved temperature difference ΔT. In this case, the mean (nominal) power would range from 2.8 to 6.2 MW. In reality, from 5.0 to 6.0 GWh/year of produced electric energy is expected to be produced in Mediterranean region countries (because optimal values for ΔT is hard to achieve).

The cumulative annual production of electric power, simulated on a monthly scale for Split and for $\Delta T = 10\,^{\circ}\mathrm{C}$, is shown in Fig. 12.

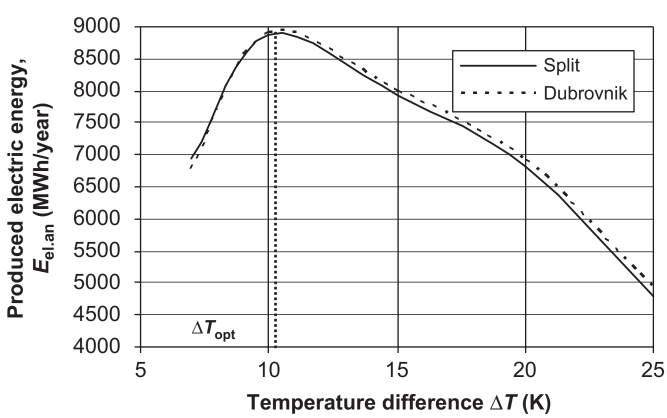

Fig. 11. Annual amount of electric energy produced for the central and south Dalmatia regions.

7. Limiting error analysis

The amount of produced electric power is directly dependent on the overall efficiency of the SC power plant for relatively small temperature increases in the collector. The limiting error in the overall efficiency calculation can be analyzed as a function of parameters ΔT, w_c, and T_0. The limiting error is defined from the differential of the dependent variable:

$$\mathrm{d}\eta_{sp} = \frac{\partial \eta_{sp}}{\partial(\Delta T)}\,\mathrm{d}(\Delta T) + \frac{\partial \eta_{sp}}{\partial w_1}\,\mathrm{d}w_1 + \frac{\partial \eta_{sp}}{\partial T_0}\,\mathrm{d}T_0 \tag{19}$$

and with,

$$\Delta\eta_{sp} = \pm\sum_{i=1}^{n}\left|\frac{\partial \eta_{sp}}{\partial x_i}\,\Delta x_i\right|, \tag{20}$$

where $\mathrm{d}\eta_{sp}$ is the differential of the overall SC power plant efficiency and x_i is the impact parameter.

After derivation of Eq. (15), the expression for the limiting error of the overall efficiency can be obtained as follows:

$$\Delta\eta_{sp} = \pm\left(\left|\frac{\dot{m}gH_c}{A_{coll}GT_0}\,\Delta(\Delta T)\right| + \left|\frac{\dot{m}w_1}{A_{coll}G}\,\Delta w_1\right| + \left|\left(\frac{\dot{m}\,\Delta TgH_c}{A_{coll}G}\times\frac{1}{T_0}\right)^2 \Delta T_0\right|\right). \tag{21}$$

For example, the calculated quantitative response to the varying input parameters of the SC power plant (D_{cr}, H_c, d_c, etc.) (with parameters $T_0 = 297$ K, $G = 491$ W/m^2, $\Delta T = 20$ K, with SC overall efficiency $\eta_{sp} = 1.044\%$), as a function of the unit impact parameter change, response equals: $\Delta\eta_{sp}(\Delta T) = \pm 0.0599\%/1$ K, $\Delta\eta_{sp}(w_1) = \pm 0.008738\%/1$ m/s, and $\Delta\eta_{sp}(T_0) = \pm 0.112\%/1$ K. For the previous example, the largest generated limiting error is from an air temperature increase, $\Delta\eta_{sp}(\Delta T)$, and equals approximately $\pm 5\%$ if we compare it to the overall efficiency η_{sp}. It can be concluded that the limiting error of each impact parameter $\Delta\eta_{sp}$ has an almost negligible influence on the amount of produced electric energy for the different working parameters of the SC power plant.

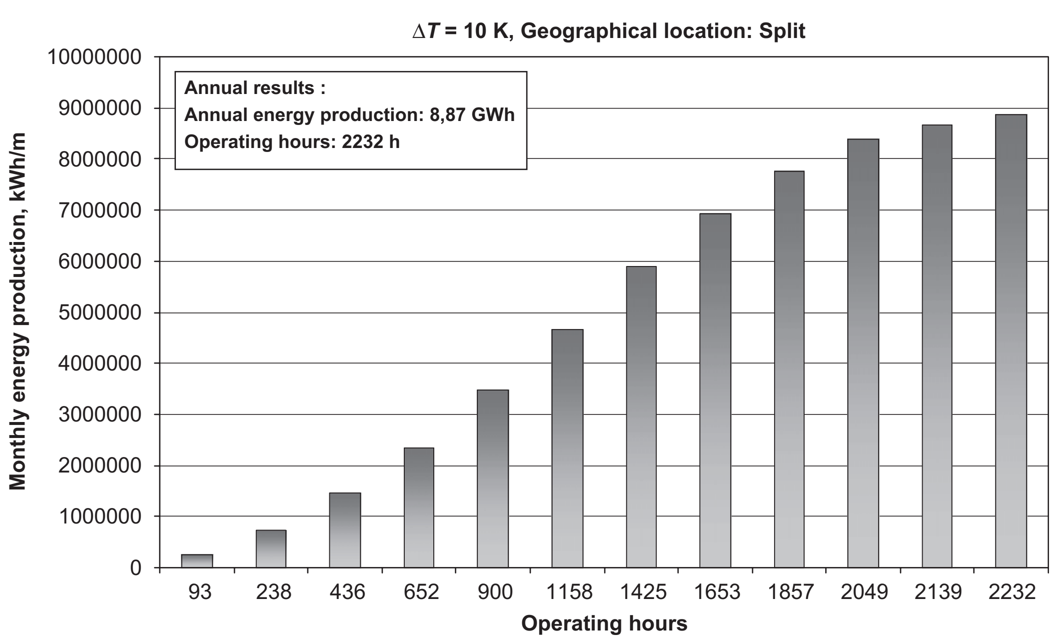

Fig. 12. Simulation example of annual electric energy production.

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8. Economic aspects of electric energy production

The solar tower plant capital investment includes the chimney, collector roof, and turbine assembly construction costs. The cost structure, relative to the overall investment, is as follows: the chimney bears approximately 30–50% of costs, while the collector roof constitutes about 20–40% of the expenditures. Depending on the nominal plant power medium, the orientation price for a collector roof made of single glass amounts to 6.0–9.0 €/m^2, while that of the chimney, which is made of reinforced concrete, amounts to 250–500 €/m^2. It is important to say that reinforced concrete chimney is more expensive than a chimney made of steel. If the collector roof is produced with special plastic film, the investment is reduced by about 30% compared to the costs associated with the traditional glass covering. The turbine assembly cost analyses are more complex. The portion in the total cost of SC plant incurred by the turbine increases with decreasing of nominal power of turbine. For a nominal power of 200 MW, for example, the overall specific turbine expenses amount to 700 €/kW$_{el}$, while, for a power of 5 MW, they amount to 1600 €/kW$_{el}$. In addition to capital costs, testing and commissioning amount to 6–10% of the total investment, and annual operation and maintenance costs amount to 4–5% of the total investment.

The above-mentioned costs for the individual components of the solar power plant are intended for reference purposes only and depend on the nominal power of the plant and the performance of the specifically designed collector roof. The costs indicated above include labor costs.

According to Ref. [8] for a plant with the technical features specified within Section 6, an estimate of investment costs was conducted.

Overall investment:

- collector roof: approximately 10.0 Mio. €,
- chimney: approximately 35.0 Mio. €,
- turbines: approximately 8.0 Mio. €,
- engineering, tests, misc.: approximately 7.0 Mio. €.

Total invested capital: $K_0 = 60.0$ Mio. €

Average costs of produced electrical energy are calculated in accordance with [18]:

$$k_w = \frac{K_0}{E_{el.an} \times n} \sum_{i=1}^{n} \left(\frac{f_w}{(1 + r_{in})^i} + r_b \right), \quad (22)$$

where $E_{el \cdot an}$ (MWh/year) is the average annual electric energy produced; n (years) is the amortization period; r_b (% p.a.) the maintenance and repair costs and r_t (% p.a.) is the rate of inflation.

Factor f_w is defined as follows:

$$f_w = \frac{(1 + p)^n \times p}{(1 + p)^n - 1}, \quad (23)$$

where p (% p.a.) is the calculated interest rate.

Based upon the calculations carried out in Section 6, and depending upon the chosen temperature difference ΔT and the geographical location, the expected SC electric power plant energy production $E_{el \cdot an}$ in reality would range from 5.0 to 6.0 GWh/per annum.

Certain parameters must be considered in order to determine the price of produced electrical energy in the Mediterranean region. The necessary parameters are as follows:

- rate of inflation: $r_{in} = 6.0\%$ p.a.,
- maintenance and repair costs: $r_b = 5.5\%$ p.a.,

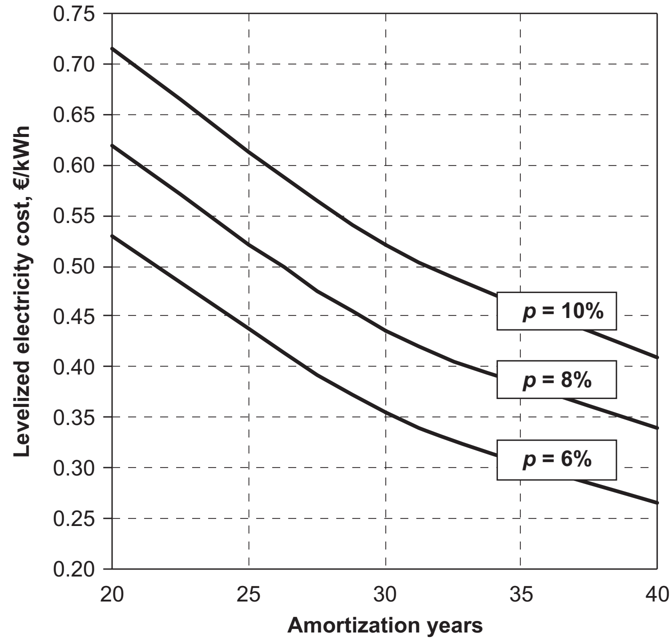

Fig. 13. Influence of amortization period on levelized electricity cost.

- calculated interest rate: $p = 6.0$–10% p.a.,
- period of amortization: $n = 20$–40 years.

The price of produced electrical energy (€/kWh) can be calculated using previously adopted data and Eqs. (22) and (23). The results of the calculations for the two locations, depending upon the calculated interest rate and period of amortization, are shown in Fig. 13.

Through this analysis conducted for two specific geographical locations, we conclude that the average price of electrical energy kWh produced by a SC power plant in the Mediterranean region would range between 0.24 and 0.78 €/kWh.

The analysis and cost estimates were based on price data obtained from Refs. [8,19].

9. Conclusions

A complete techno-economic analysis was conducted on a SC power plant with specific technical features in preparation for future applications of electrical energy production by small settlements and islands in the Mediterranean region. From the analysis performed for two selected Mediterranean locations (Split and Dubrovnik), we conclude that a SC power plant with the technical features presented in Section 4 would produce from 4.9 to 8.9 GWh per annum (last value is for optimal ΔT), depending on the achieved air temperature difference ΔT. The plant nominal power will range from 2.8 to 6.2 MW, while the "peak" would be reached in July, e.g., 8.2 MW for $\Delta T = 20$ K. Annually, an average of 4.1–7.36 kWh$_{el}$/m^2 year could be expected per m^2 of collector surface. However in reality the average annual electric energy production would be close to 5.0–6.0 GWh/per annum, because the higher values for produced electric power output are only for optimal air temperature increase in collector.

The levelized electricity mean price depends on the annual quantity of produced electric energy and on the calculated interest rate. For an amortization period of 30 years, with an

Table 2
Comparison of different electric power sources

	Coal stations	Parabolic troughs	Photovoltaics	Solar chimney in south of Europe
Cost of produced electric energy (cent/kWh)	5–7	15.5	30–40	>80
Area needed to produce 1 million kWh/year (m^2)	250	6000	6000	140,000–250,000
Working hours (h)	24	8	8	8

interest rate of 8%, the levelized mean price of the produced electricity would be variable (for previously mentioned reasons), within a range of 0.31–0.68 €/kWh. In reality (and for average annual electric energy production), the levelized mean price would range from 0.60 to 0.70 €/kWh because of economic constraints (namely, the maintenance cost for cleaning the large collector area would be significant). The lowest average price of produced electric energy would be 0.24 €/kWh, assuming an amortization period of 40 years and a calculated interest rate of 6%. On average, the present electricity price in the EU is 0.15 €/kWh. Hence, construction of a SC electric power plant is not profitable in the analyzed Mediterranean region at the moment. Thus, because of economic reasons, it is better to use, for example, energy towers or parabolic troughs, which require less collector surface. Because of previous reason in Table 2, we compared different electric power sources.

However, most European countries grant subventions for stimulation and popularization of renewable energy sources that lower the levelized electricity price. In addition, the SC electric power plant's great advantage is its long life (up to 60 years). Ref. [8] presented a comparison between the life of a SC electric power plant and a traditional fossil fuel driven power plant. From a long-term perspective, the SC electric power plants are more favorable because a traditional fossil driven plant has a shorter life of about 20 years, high maintenance costs, and variable but significant fuel costs. Importantly, the life span of a fossil driven plant may exceed 20 years, but maintenance costs greatly increase with increasing plant life.

Based upon this analysis, we conclude that building of SC electric power plants in the Mediterranean region is only profitable over the long term, but not the short term. If the previously presented facts and conclusions are considered, construction of electric power plants similar to that described in this study becomes a serious and viable option in unstable energetic future.

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