OPPORTUNITIES FOR USING PHOTOVOLTAIC POWER STATIONS TO ROAD TUNNELS

Angel Pachamanov, Borislav Pregyov, Stoyan Petrov and Peter Stoev

Abstract: Summary: The main advantage when using photovoltaic stations in road tunnels is the consistency between production and consumption of electricity. The high values of day natural luminance require high values of adaptation lighting, corresponding to higher production of photovoltaic stations (PVS). Thus determination of the power of PVS should be calculated not only by annual average expenses of electric power for lighting, but also by the maximum value of the luminous flux, that is used to calculate the day adaptation lighting. If the lighting class of the tunnel varies with the intensity of traffic intensity, the duty lighting can also be achieved by lower investments for rechargeable batteries.

Keywords: Lighting of road tunnels, local photovoltaic stations (PVS)

I. INTRODUCTION

When designing lighting of road tunnels, conditions for smooth transitions through five specific areas is provided (Figure 1). The level of lighting in the threshold and the transition zones of road tunnels is realized by the adaptation luminance L_{20} for the driver in the area of approaching the tunnel (Figure 2) - 20 degree viewing area from one braking distance towards the entrance of the tunnel.

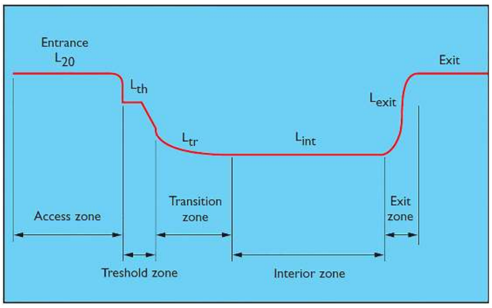


Fig. 1. The five tunnel zones defined for the purposes of lighting design [1].

The required luminance of the road surface at the entrance area L_{TH} (Figure 3) immediately after entering the tunnel tube, is determined by the formula [1, 7]:

(1) $L_{TH} = R.L_{20}$.

The R parameter can be chosen directly from Table 1 or according to the traffic conditions in the tunnel, the type of lighting system and traffic intensity I_{CAR} (Table 2 and Table 3) [8]

The luminance in the first half of the entry zone is calculated by Formula (1), then according to the formula:

$L_{TR\_1} = L_{TH\_MAX}*(1.9 + t)^{-1.4}$ (Figure 3).

Here, the time $t = l/v$ is expressed by the distance l [m] from the beginning of the entry zone to the point, at which the luminance L_{TR} is determined as well as the authorized traffic speed v [m/s] in the tunnel.

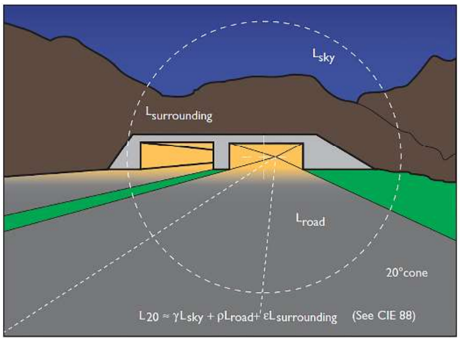


Fig. 2. Sketch showing the 20° conical field of view [1].

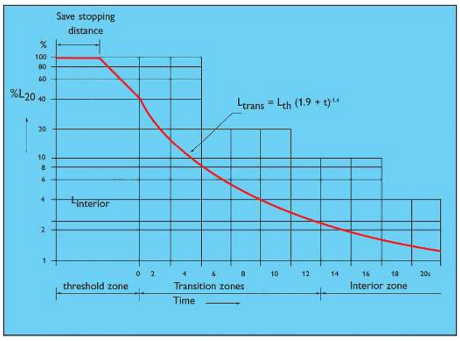


Fig. 3. Representation of lighting level in various zones [1].

Table 1: Recommended threshold/access zone luminance ratios R [7]

Stopping distance, m	Symmetrical lighting system, L_{TH}/L_{20}	Counter-beam lighting system, L_{TH}/L_{20}
60	0.06	0.04
100	0.06	0.05
160	0.10	0,07

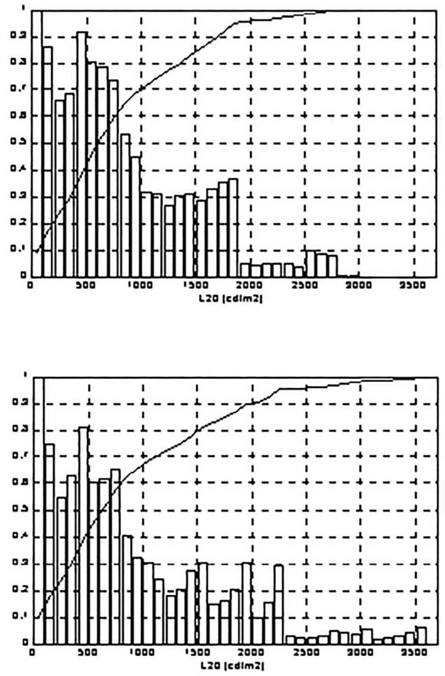
Table 2: Tunnel class according to the requirements [8]

Type of tunnel traffic	One-way						Two way					
Intensity ICAR [veh/h]	>1500		500÷1500		<500		>400		100÷400		<100	
Traffic type	C	M	C	M	C	M	C	M	C	M	C	M
Tunnel class	4	3	3	2	2	1	4	3	3	2	2	1
C – mixed traffic; M - motorized traffic												

Table 3: Recommended threshold/access zone luminance ratios R [8]

Stopping distance Tunnel class	60m (60 km/h)	100m (80 km/h)	120m (100 km/h)
4	0.05	0.06	0.10
3	0.04	0.05	0.07
2	0.03	0.04	0,05
1	Only a duty lighting (< 6 cd/m^2)		

Determining the maximum adaptation luminance L_{20_MAX}, for which the adaptation lighting is sized, is done by the annual frequency and total frequency distributions of L_{20} (Figure 4), which are derived from annual time schedules of the adaptation luminance L_{20} [cd/m2] at the two entries of the tunnel [5]. The sum of the two heights of rectangles of the frequency distribution corresponds to the annual duration of daylight hours - about 4600 hours for the geographic latitude of Bulgaria. Having in mind the chosen maximum value of cumulative frequency distribution as L_{20} (e.g. 0.99 from Figure 4), the maximum required luminance is estimated as L_{20}, which satisfies the requirement for $R = L_{TH} / L_{20}$ from Tables 2 and 3 (L_{20_MAX} = 2500 cd / m2 from Figure 4a; L_{20_MAX} = 3500 cd / m2 from Figure 4b). For the hours of the year, in which L_{20}> L_{20_MAX}, the speed through the tunnel is limited to a value, corresponding to the tunnel class with $R = L_{TH\_MAX} / L_{20}$.



a)

b)

Figure.4. Generated with the help of software [5] frequency distributions of adaptation luminance L_{20} and total frequency distributions of L_{20} (rising curves) for tunnel entries with display to the north (a) and south (b) with parameters: North location: 42 °40'56 " and East location 23 °38'33 "; braking distance 100 m; Weighting factor for the road in the visual field - below 36%; Weighting factor for the environment in the visual field - above 36%; Weighting factor for the sky in the visual field - below 18%; reflectance coefficient for the surroundings of the tunnel: when the sun is in the traffic direction - 0.3, when the sun is against the traffic direction - 0.5.

II. ANALYSIS

1. DETERMINING THE ANNUAL TIME SCHEDULE OF THE REQUIRED LUMINOUS FLUX FOR THE ZONES)

Under certain parameters of the tunnel, annual hourly schedules of adaptation luminance L_{20} [cd/m2] (Figure 5a) and traffic intensity I_{CAR} [veh/h] (Fig.5b), setting of annual time schedule required luminous flux (Figure 5c) for the entry and the transition zones is performed in the following sequence [3,4,9]:

For every hour during the year (1-8760) when calculating the parameters of the tunnel traffic (Table 2), the time schedules of the adaptation luminance L_{20} [cd/m2] and of the traffic intensity I_{CAR} [veh/h] the class tunnel (Table 2) and the coefficient R [I] are determined (Table 3), where I is the current time of the year (all values L_{20} [I] > L_{20_MAX} are accepted as equal to the maximum value L_{20_MAX});

The annual hourly schedule of the luminance of the road surface at the beginning of the entry area of the tunnel L_{TH} [I] = R[I] . L_{20}[I] is calculated on the basis of the values of R [I], preliminary set;

The curve of the luminance of the transition zone $L_{TR\_1} = L_{TH\_MAX}*(1.9 + t)^{-1.4}$ is constructed on the basis of the general requirements for reduction luminance from the middle of the entry zone till the end of the transition zone (Figure 3);

The line L_{TH_MAX} (until the middle of the entry area) and the curve $L_{TR\_1} = L_{TH\_MAX} *(1.9 + t)^{-1.4}$ (from the middle of the entry zone to the end of the transition zone) are numerically integrated and from the resulting conditional zone S [(cd/m2)*m] the suspended length of the entry and transition zones $l_{\_COND.} = S / L_{TH\_MAX}$ [m] is calculated;

The luminous flux, necessary to achieve the luminance L_{TH_MAX} is calculated at a certain track width W_K [m] and a specific indicator of the lighting system L_E [(lm/m2) / (cd/m2)], taking into account effectiveness of the specific type of tunnel luminaires and the way of its installation [6]:

$F_{NEED\_MAX} = L_{TH\_MAX} * l_{\_COND.} * W_K * L_E$ [lm];

A transition from annual time schedule of luminance L_{TH} [I] to the annual time schedule pf the luminous flux required F_{NEED} [I] is realized for establishing luminance L_{TH} [I]:

F_{NEED} [I] = $F_{NEED\_MAX} * L_{TH}$ [I] / L_{TH_MAX}.

From the time schedule of the required luminous flux F_{NEED} [I] the maximum value F_{NEED_MAX} is taken into account, by which, when the flux yield æ [lm/W] of the lighting sources used is known, the maximum power $P_{NEED\_MAX} = F_{NEED\_MAX}$ / æ of adaptation lighting sources used is determined. This power can be adjusted in steps or smoothly when L_{20} is changing.

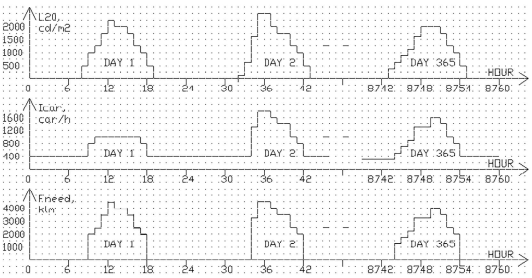


Figure 5. Annual hour schedules for adaptation luminance (L_{20}, cd/m2 from of software [5]), traffic intensity (I_{CAR}, veh/h, given by the road agency) and calculated values of the luminous flux for the entry and transition zones of the tunnel F_{NEED} [klm]

For the concrete tunnel with length of 380 meters, the luminaires are with HPSL – the adaptation lighting with 400, 250 and 150 W with asymmetric radiation and the duty lighting is with up to 250W symmetrical radiation. The maximum values of the required luminous flux are $F_{NEED\_MAX\_A}$=4841,2klm and $F_{NEED\_MAX\_B}$ = 6424,6 klm, thus at flux yield æ = 130 lm/W of HPSLs the maximum power capacity of adaptation lighting is obtained:

Side A:

$P_{NEED\_MAX}=F_{NEED\_MAX}$/æ=4841,2/130=37,24 kW;

Side B:

$P_{NEED\_MAX}=F_{NEED\_MAX}$/æ=6424,6/130=49,42 kW.

The total installed capacities for lighting are 44.1 and 56,5 kW, respectively at the north and south entry, as the duty lighting of two tunnel tubes is 5,6 and 5,72 kW respectively.

The annual energy consumption depends on how the adaptation lighting is regulated - in Table 4 it is shown as the annual duration of turning on the adaptation lighting Ta = 4600 hours and three ways of dimming. The values are obtained according to the frequency distributions of adaptation luminance L_{20} in Figure 4 by the methods, defined in [2]. When using adaptation lighting for Ta = 4600 hours, Table 5 gives the resulting average annual capacities. It can be seen that in three-level regulation of the adaptation lighting, the energy consumption is 1.8 times, while when dimming - 2.34 times less than in the case without regulation [2]. Table 6 shows Annual usability Ta = 4600 hours of adaptation lighting in gives the resulting average annual capacity. It is seen that in three-stage regulating adaptation lighting energy consumption is 1.8 times, while dimming - 2.34 times smaller than the case without regulation [2].

Table 4: Electricity for adaptive lighting at Ta = 4600 hours by the frequency distributions of luminance L_{20} in Figure 4 (A - without adjustment, B - with three-stage adjustment, C – with smooth regulation)

.	We_max = Pc *Ta, kWh **(A)**	We=Σ{P[I]*ΔT[I]}, kWh **(B)**	We=Σ{P[I]*ΔT[I]}, kWh **(C)**
Tube A	171304	95169	73207
Tube B	227332	126296	97150
Total of Tunnel	398636	221464	170357
Energy in %	100%	56%	43%

Table 5: Computing power Pc (A) for adaptive lighting and average annual values of the power if Ta = 4600 hours in three-stage adjustment (B) and with smooth regulation (C)

2.	Pc. kW **(A)**	P_{AV_YEAR}, kW **(B)**	P_{AV_YEAR}, kW **(C)**
Tube A	37.24	20.69	15.91
Tube B	49.42	27.46	21.12
Total of Tunnel	86.660	48.14	37.03
Energy in %	100%	56%	43%

In this case, the total computed power Pc = 86.66 kW is higher than the real one, since at different geographical disposal of the two entries of tunnel, their adaptation lighting does not work simultaneously on the two computing powers. It is more correct the schedules F_{NEED} [I] for the two entries to be united and the resulting schedule F_{NEED} to take into account the maximum luminous flux F_{NEED_MAX}, from which to calculate $P_{NEED\_MAX} = F_{NEED\_MAX} / æ$ [kW].

2. *POWER SUPPLY OF ROAD TUNNEL LIGHTING*

As near the tunnel no power supply system exists, a feasibility study will be done for the construction of local photovoltaic station (PVS). It can be situated at the southern entrance, close to the electric distribution board for the two tunnel tubes.

3. *DEFINING THE PARAMETERS OF THE PV STATION*

The parameters of the solar panels from polycrystalline silicon, which are used for the PVS are shown in Table 6. The necessary parameters (Table 7) for the design of the PV station are derived from the database for the sunshine in the area of the tunnel [11]. The results of the calculations are exported in Table 8 and Table 9 for clarity.

Table 6: Parameters of the solar panels from polycrystalline silicon use

Peak power, Wp	505
Panel length, mm	2309
Panel width, mm	1645
Thickness, mm	14
Weight, kg	103

Table 7: Average daily Ed: and monthly Em electricity production [kWh / kWp] by the modules of the given system

Month	E_d	E_m
Jan	1.7	52.7
Feb	2.54	71.2
Mar	3.7	115
Apr	3.99	120
May	4.19	130
Jun	4.49	135
Jul	4.75	147
Aug	4.65	144
Sep	4	120
Oct	3.35	104
Nov	2.32	69.7
Dec	1.61	50
Yearly average	3.45	105
PVGIS estimates of solar electricity generation; Location: 42°40'56" North, 23°38'33" East, Elevation: 558 m a.s.l.; Solar radiation database used: PVGIS-CMSAF; Nominal power of the PV system: 1.0 kW (crystalline silicon); Estimated losses due to temperature and low irradiance: 9.1% (using local ambient temperature); Estimated loss due to angular reflectance effects: 2.8%; Other losses (cables, inverter etc.): 14.0%; Combined PV system losses: 24.0% (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#)		

Table 8: Dimensioning of the photovoltaic station (PVS)

Electrical energy of adaptation and duty lighting (the latter by charging the batteries), kWh/year	217578
Average daily electricity production from 1kWp inst. power, kWh/ден	3.44
Days of the year in which the PV station operates	365
Annual production of 1kWp (365 * 3.44), kWh/year	1256
Required peak power of PV station (217578/1256), kWp	173.24
Number of panels needed for peak power (173.24/0.505)	345
Number of panels in a row	15
Number of rows of PVS	23
Number of panels PVS	345

Peak power P_{PP} of PVS, kWp	174.23
Energy produced per year (1256*174.23), kWh/year	218810
Purchase price of energy on a daily rate, BGN/kWh	0.25
Price of energy produced by PVS (218810*0.25), BGN/year	54702

Table 9: Financial parameters for the construction of PVS

Unit price for PVS (PV modules, Inverters, Construction), BGN/W	2.0
Assembly and tuning work (20%), BGN/W	0.4
Total unit cost PVS (PV modules, Inverters, Construction), BGN/W	2.4
The necessary investment K for PVS (174.23*2400), BGN	417864
T period of the Bank's loans, years	10
Interest rate r on the Bank's loans, %	5.00%
Income funds from electricity production (218 810 * 0.25), BGN / year	54702
Annual dues Ca = K / (1 / r-1 / (r * (1 + r) ^ T)) for loan servicing K = 417864 BGN, BGN/year	54115
Real price of PVS (returned to the bank Ca * T), BGN	541153
Net incomes for the period of the loan T, BGN (NPV = -K + Cb * (1 / r -1 / (r * (1 + r) ^ T)))	4534
Net income after payment of the loan (from T+1 to '25), BGN	820537
Costs (+) and income (-) 25 years in the lighting through PVS	
Price PVS (Ca * T), BGN	541153
Operating costs for the PVS for 25 years: operating costs = 100% PVS installation cost, BGN	417864
Revenues for the period of credit from additionally produced, BGN	-4534
Revenues after the period of credit from energy produced, BGN	-820537
Recapitulation of 25 annual expenses on PVS, BGN	**133946**

4. DETERMINING THE NUMBER OF BATTERIES FOR DUTY LIGHTING AND ADDITIONAL PV PANELS TO RECHARGE THEM

When the maximum traffic intensity of the tunnel is known (4550 veh/h, 45500 veh / day), the necessary duty lighting at night is determined by computing capacities for both tubes 5.6+5.72=11.32 kW. Battery capacity is calculated for the average traffic during the longest nights in December - 15 hours. During the first 5 hours after dusk it is assumed that the traffic is above 1000 veh/h, during the next 3 hours as well as 2 hours before dawn – it is from 100 veh/h to 1000 veh/h and 5 hours after midnight - below 100 veh/h. The average power for duty lighting, according to Table 10 will be: 11.32*(5+(4/6)*5+(2/6)*5)/15 = 7,55 kW. Further calculations are shown in Table 11 for clarity.

Table 10: Recommended interior zone illuminance, lx [1, 7]

Stopping distance, m	Traffic density < 100 veh/h	Traffic density 100 < veh/h < 1000	Traffic density > 1000 veh/h
60	1	2	3
100	2	4	6
160	5	10	15

Table 11: Expenses (+) for power for the on-duty lighting with batteries

Duty lighting power for both tubes, kW	11.32
Duration of traffic> 1000 veh / h per night 15 pm., hour	5
Duration of traffic 100 <veh / h <1000 night 15 pm., hour	5
Duration of traffic <100 veh / h per night 15 pm., hour	5
Average power of duty lighting according to Table 10 (11.32 (5+ (4/6) * 5 + (2/6) * 5) / 15), kW	7.55
Energy derived storage in batteries (15h * 7550W), Wh	113200

Defining additional panels for battery charging g

E_d: Average daily electricity production from the given system (kWh/kWp) Dec	1.61
Wp, Peak power of a panel	505
Efficiency in battery charging	0.7
Number of additional panels to charge the batteries in winter	199

Defining the number and expenses for batteries

Reduced battery voltage, V	230
Necessary batteries' capacity with reduced voltage (113200Wh / 230V), Ah	492
Number of traction batteries 12V/100Ah (492/100)*(230/12)	94
Unit cost of traction battery 12V / 100Ah / 1000 charge-discharge cycles, BGN	300
Total cost of the batteries for the 1000 charge-discharge cycles (94*300), BGN	28300
Number of battery kits for the whole life of the regulation system (25 years) (25/(1000/365))	8
Price of all battery sets (25 years), BGN	226400
Operating costs for the batteries for 25 years: operating costs = 100% batteries installation cost, BGN	226400
25 annual cost of batteries, BGN	**452800**

Table 12: Total costs for 25 years in power supply with PVS

25 annual expenses on PVS (from Table 9), BGN	**133946**
25 annual expenses on batteries (from Table 11), BGN	**452800**
Total expenses for 25 years power supply from PVS (473403+452800), BGN	**586746**
Annual expenses for supply from PVS (586746/25), BGN	23470

5. DETERMINING THE EXPENSES FOR ENERGY SUPPLY FROM THE ENERGY SYSTEM IN THE TUNNEL

For a period of 25 years one option for purchasing of energy from the energy system is valuated. The results of the calculations are shown in Table 13 for clarity.

6. COMPARISON OF LIGHTING EXPENSES WHEN SUPPLYING FROM PUBLIC POWER SYSTEM OR FROM PVS

The results of the research are summarized in Table14 – the expenses for the whole the lifetime of the system (25 years) and the average annual expenses, related to the year of establishing the system.

Table 13: Expenses for lighting when buying electricity from the energy system

Electric power for duty lighting for both tubes, kW	11.32
Average power of duty lighting according to Table 10 {11.32*[4+(4/6)*8]/12}, kW	7.55
Annual energy consumption by duty lighting (12*7.55*365), kWh	33054
Price of energy for duty lighting (7*0.25+8*0.15)/15, BGN/kWh	0.1967
Annual energy expenses for duty lighting, BGN/year	6501
Annual electricity consumption by adaptation lighting, kWh	170357
Annual energy expenses for adaptive lighting (170357*0.25), BGN/year	42589
Total annual expenses for lighting (6501+42589), BGN/year	49090
Expenses for 25 years lighting when supplying from public power system (25*49090), BGN	**1227249**

Table 14: Comparison of the expenses for lighting from public power system and PVS (case 1)

Expenses for 25 years when supply electricity from public power system, BGN	1227249
Expenses for25 years when supply electricity from local PVS (**operating costs = 100% PVS installation cost** + 100% battery park installation cost), BGN	586746
Saving money in the delivery of electricity from local PVS to delivery of the public power system during 25 years, BGN	**640503**
Annual average expenses when supply electricity from public power system, BGN / year	49090
Annual average expenses when supply electricity from local PVS, BGN	23470
Saving money in the delivery of electricity from local PVS to delivery of the public power system, BGN	**25620**

Table 15: Comparison of the expenses for lighting from public power system and PVS (case 2)

Expenses for 25 years when supply electricity from public power system, BGN	1227249
Expenses for25 years when supply electricity from local PVS (**operating costs = 200% PVS installation cost** + 100% battery park installation cost), BGN	1004610
Saving money in the delivery of electricity from local PVS to delivery of the public power system during 25 years, BGN	**222639**
Annual average expenses when supply electricity from public power system, BGN / year	49090
Annual average expenses when supply electricity from local PVS, BGN	40184
Saving money in the delivery of electricity from PVS to delivery of the public power system, BGN	**8906**

III. CONCLUSIONS

The technical and economic comparisons of expenses for lighting when supplying from local PVS or from public power supplying system show that at current prices the option with PVS is with nearly twice lower annual expenses. It is correct to note that the preliminary set for PVS annual maintenance expenses is low (4% of the investment for installation of PVS and 4% of the investment for installation of battery park). If maintenance expenses are 8% of the investment for PVS and 4% of the investment for battery park, both variants are comparable by annual costs (Table 15) - refining maintenance expenses appear to be a key element for using PVS. In case building a power supply network at 20kV is necessary, the PVS is preferable, especially when the distance to the electric power station is long.

Because of the constant decrease in the price of solar panels, the perspectives for the construction of local PVS for tunnels, situated far from settlements, become fully realistic. Now they are also more profiTable than centralized power supply especially if the problem with the power supply for duty lighting finds solution, thereby avoiding costly maintenance of expensive battery park.

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Contacts:

Angel Pachamanov, Ph.D, eng., Professor at the Department of Electrical power supply, Electrical equipment, and Electrical Transport (ESEEET), Technical University of Sofia, 8 Kl. Ohridski Blvd, Bulgaria, e-mail: pach@tu-sofia.bg;

Borislav Pregyov, Ph.D, eng.;

Stoyan Perov, Ph.D student, eng., at the Department of Electrical power supply, Electrical equipment, and Electrical Transport (ESEEET), Technical University of Sofia, 8 Kl. Ohridski Blvd, Bulgaria;

Petar Stoev, part-time assistant professor at the Department of Electrical power supply, Electrical equipment, and Electrical Transport (ESEEET), Technical University of Sofia, 8 Kl. Ohridski Blvd, Bulgaria.