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Renewable Energy-Powered Traffic Signalization as a Step to Carbon-Neutral Cities (The Case of Western Balkans)

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Abstract: Global warming and its negative effect on the environment pose a great threat to the future of mankind. In order to overcome these challenges, EU countries have set the target of becoming climate neutral by 2050, a path defined through the policies of the European Green Deal. The Republic of Serbia and Bosnia and Herzegovina also agreed upon the same goal through the endorsement of the Green Agenda for the Western Balkans. One of the means to achieve this goal is by increasing the share of renewable energy sources. In this paper, we analyze the feasibility, challenges, and potential issues of substituting conventional traffic light signalization with signalization based on renewable energy sources on a national scale. An ad hoc questionnaire was used to collect data from representatives of most of the municipalities in the Republic of Srpska entity in Bosnia and Herzegovina and representatives of the city of Novi Sad in Serbia. In the city of Novi Sad, personal interviews were also carried out to collect additional information. The results of this research show that the implementation of solar-powered traffic lights is economically and environmentally viable. These results will provide the basis for understanding the benefits and challenges in the case of the application of traffic light signalization based on renewable energy sources.

Keywords: carbon-neutral; renewable energy sources; solar energy; traffic signalization; green city; energy crisis

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1. Introduction

In order to slow down global warming and mitigate its effects on the climate and environment, EU leaders committed to reducing greenhouse gas emissions by at least 55% by 2030 and becoming climate neutral by 2050 [1]. China, the country that produces the most carbon dioxide in the world, has created a strategy to become carbon-neutral before 2060. By deep decarbonization of its economy, mainly in the energy sector, China could achieve carbon neutrality and avoid a life expectancy loss of 0.88–2.80 years per person in 2060 [2]. The Western Balkan region has committed to achieving carbon neutrality by 2050 and aligned with the European Green Deal's key elements by endorsing the Green Agenda for the Western Balkans in 2020 [3]. The Republic of Serbia is following the agenda by setting strategies for the transformation of its energy sector. One of the main targets of this strategy is to increase the share of renewable energy sources to at least 49.6% by 2040, compared to 26.3% at the end of 2020 [4].

Renewable energy is energy derived from natural processes that are constantly replenished and emit drastically lower levels of greenhouse gases or other pollutants when compared to burning fossil fuels [5]. Additionally, renewable energy sources have become cheaper in most countries and enable three times more jobs than fossil fuels. Solar energy is one the cleanest and most abundant of all renewable energy sources. As a result of the decreasing costs and prices, the amount of electric energy generated from solar power has increased by 20% to 25% each year over the past 20 years [6]. This price decline has been

induced by the increased efficiency and lifespan of solar cells, advancements in manufacturing techniques [7–9], and economies of scale. In the most recent decade, the global weighted average levelized cost of energy (LCOE) of utility-scale solar PVs decreased by 85%, while installed costs decreased by 81% [10]. This sharp decline in the price of electricity generated from solar panels, which is expected to decrease even further with better policy, has driven its widespread application.

Challenges arise when switching to renewable energy sources due to differences in availability compared to conventional power sources. Often, solar and wind power are in plentiful supply during particular weather conditions or times of day, or they are preferred and available only in certain regions. Determining appropriate diversification of renewables, along with an option to enable a continuous energy supply while staying in line with the planned budgets and development plans, and complying with local and national regulations present an enormous challenge for all governments [11,12]. Drechsler et al., in [13], demonstrate that when choosing the placement of wind turbines and PV power plants that minimize human disturbance and biodiversity loss, the most advantageous harvesting circumstances should be followed. Liu et al., in [14], describe how assessments of wind–solar energy stability across the country can be used to install either simple hybrid energy systems locally or large-scale wind or solar systems in areas with reliable hybrid energy production. In many regions, hydropower is used to balance out the temporal unpredictability of intermittent renewable sources such as solar and wind. Gonzalez et al., in [15], propose a multisectoral design framework for a diversified investment approach in Ghana that lessens adverse effects on the ecosystem and improves agricultural performance.

When power systems are considered, especially solar power systems, they can be classified as off-grid or on-grid. Off-grid power systems are completely independent of any national network and are solely responsible for supplying consumers in the region. This is mostly suitable for rural and remote locations that the grid may not be able to reach. An off-grid power system should consist of PV generation and an energy storage system. On-grid power systems are preferable since they are efficient and provide a constant supply of electricity. Pal et al., in [16], evaluate an off-grid solar photovoltaic–hydrogen fuel cell system for the generation of renewable energy in North-East India. They propose the utilization of a hydrogen FC (HFC) to overcome a common problem of batteries failing to supply energy during extended cloudy days. A comparative study of lead-acid and lithium-ion configurations of photovoltaic-battery storage systems for off-grid sensor loads for measuring the quality and depth of water in India is presented in [17]. In a proposed on-grid energy system [18], solar power works together with the backup grid and energy storage system to supply a residential electric vehicle station. The system was tested under different conditions and seasons. Nguyen et al., in [11], propose the electrification of a large highway system that is based primarily on renewable energy sources, where conventional power is only used for peak shaving. Each charging location uses local renewables, such as nearby solar or wind farms, which stimulate local businesses. No renewable energy is injected into the power grid to avoid issues with the regulation of voltage and frequency.

Systems that are universally and widely utilized as signaling devices for traffic regulation around the world are traffic light systems. Traffic light systems have undergone many changes since they were first introduced in the nineteenth century. However, they have not followed the rapid progress of communication and information technologies. There are a number of proposals for different ways to introduce intelligent design to optimize traffic flow and prevent traffic congestion [19–23]. Lin et al., in [24], introduce a novel traffic control system framework that combines micro-mechanical and electrical technologies with an embedded system, wireless transmission, image processing, and a solar power module to create an optimal traffic control system in Taiwan. Kazemee et al., in [25], suggest implementing an IoT-based smart traffic system that employs renewable energy sources. The idea is intended to prevent undesirable traffic bottlenecks, inefficient time management, covert traffic lines, and human maintenance.

Apart from work that is centered on making traffic light systems intelligent, there is significant research centered solely on increasing their energy efficiency by switching to renewable energy sources and light-emitting diodes (LEDs). A traffic signal system today consists of the lights that guide cars and pedestrians, the control electronics and power supply, and often a traffic-detecting inductive loop. Incandescent bulbs have been widely replaced with LED lamps due to their lower cost and the improved performance of LED technology, although they are still primarily supplied by a high-voltage power source [26]. Recent development has been directed toward reducing costs and improving the efficiency and safety of traffic light systems by focusing on providing a low-voltage power supply, usually relying on renewable sources of energy, such as solar power, as a primary source and batteries as a secondary power source. References [6,27,28] propose a traffic or street lighting system that uses solar energy as a primary source, batteries as a backup supply, and LEDs as the illumination source. Their research validates the efficiency of such systems and different ways to improve LED usability and battery charging and discharging control. Despite the verification of these methods in simulated scenarios and developed prototypes, practical feasibility and cost are important aspects of enabling their widespread use and standardization. Diong [26] conducted a study to help the Georgia Department of Transportation (GDOT) identify the most cutting-edge options for running road traffic operations on renewable energy sources and to assess if deploying solar and/or wind power generators would be cost-effective. According to their engineering analysis, the installed solar system could pay for itself in about 7 years and save more than $1 million in electricity costs for 1800 intersections in the area over the remaining 18 years of the usual solar panel life, or around $650 per solar panel. The economic feasibility of using a solar-powered road sign system based on LED lamps in Thailand has been verified in [29]. This research also proposes adaptive lighting control that can increase energy efficiency further and reduce initial investment costs. Due to the need to replace batteries, the LED solar stand-alone road lighting system, which includes solar and energy storage systems, has significant initial installation and maintenance expenses. As a result, it has a payback period of 8.4 years or 5.1 years when lighting control is used. The LED solar grid-connected road lighting system, on the other hand, eliminates the need for an energy storage system and offers the benefit of power cost savings and energy generated at grid cost, resulting in a shortened payback period of 1.5 years.

Recent research studies that have been summarized in this chapter provide a base on top of which our work has been conducted. There is significant research directed toward finding an optimal renewable energy source for a specific region, considering the potential of that region [12–15]. Some efforts have also been directed toward analyzing the renewable energy potential of the Western Balkans [30–35]. However, these research studies provide either a very general overview of the topic or analyze an alternative renewable energy source, such as biomass. Many research studies do provide an actual solution for a system powered by solar energy, but their results are valid for countries that are located in the most suitable regions with the highest solar potential [6,11,16–18,24–29]. They also take a very theoretical approach and base their calculations on statistically or experimentally acquired data rather than exact official information. From the analyzed studies, the only paper with a similar background that targets specifically solar-powered traffic lights and follows the economic and practical aspects defined by transportation sector officials is the research by Diong [26]. Our research expands upon this approach by providing a more thorough and exact analysis of the conventional traffic light's electricity consumption and cost. We also discuss the practical challenges that are encountered when solar-powered traffic systems are introduced. The additional value of our research is delivering an up-to-date report on current research and the benefits of renewable energy sources, as these technologies have significantly improved in recent years. Lastly, we demonstrate how this approach is viable in regions with solar potential that falls in the favorable middle range of the daily solar potential, which applies to most European countries.

This paper presents the results of our research with the goal of analyzing the feasibility and challenges of using solar-powered traffic lights in the Republic of Srpska, an entity in Bosnia and Herzegovina, and the city of Novi Sad in Serbia. The research covered a large territory: all 55 municipalities of the Republic of Srpska and Novi Sad, the second-largest city in Serbia and the capital of the Autonomous Province of Vojvodina. Solar panels were chosen as a renewable power source due to the trend of decreasing prices of solar panels, their increased efficiency and lifespan, as well as the existing utilization of solar panels for flashing road signs and traffic counters, and the photovoltaic potential of the regions. This research expands the analysis of switching to renewable power sources for traffic lights by determining the economic feasibility and environmental benefits for the explored region. It also explores current setbacks and challenges defined by the interviewed government officials and explores the practical viability for each of the regions, depending on their location, how many traffic lights they contain, and the scale of benefits they would gain with the switch. The results of this research can be used as a stepping stone for expanding the utilization of solar-powered transportation systems in the analyzed countries and other countries on the Balkan Peninsula. Due to the systematization of the official data for the regions, it can be used as a reference for similar analyses in other developing countries.

2. Materials and Methods

The research was conducted in Serbia and Bosnia and Herzegovina between 2022 and 2023. In this research, we used an ad hoc questionnaire and personal interviews. The ad hoc questionnaire (Table 1) was used to collect data from representatives of all municipalities in the Republic of Srpska's entity in Bosnia and Herzegovina, as well as from representatives of the second-largest city in Serbia, the city of Novi Sad. In the territory of the Autonomous Province of Vojvodina in Serbia and the city of Novi Sad, personal interviews were also carried out to collect additional information.

Table 1. Ad hoc questionnaire format.

Survey Questionnaire for Municipalities
1. How many intersections with traffic lights are there in your municipality? Are any of them powered by a solar panel?
2. How much electricity do these intersections consume on a yearly basis and what is their annual electricity consumption in kWh?
3. Does your municipality have flashing danger warning road signs, traffic lights or other road signalizations that are powered by a solar panel? If these installations exist, how many are there?
4. Do you have allocated resources, and in what amount, for solar powering of existing traffic and road installations or construction of new road and traffic installations?

A filled-out questionnaire was received from 50 municipalities in the Republic of Srpska out of the total of 55 municipalities invited. Personal interviews were carried out with the supervisors, engineers, and the Head of the Department for the Development and Traffic Management for the city of Novi Sad, the largest municipality and the capital of the Autonomous Province of Vojvodina. The interview included a detailed discussion about the viability of solar panel integration into traffic light systems and the challenges that could emerge if solar panels replaced conventional power sources.

The goal of the research was to understand the current situation in the region related to the usage of renewable energy-powered traffic signalization based on the responses to the questionnaire and the responses during the personal interviews. Furthermore, the feasibility of implementing additional renewable energy-powered traffic signalization as a replacement for the current solutions was discussed.

3. Results

The results of the analysis of the complete data collected from the questionnaires for all of the invited municipalities are presented in Table 2. The demographic data for each municipality have been filled in according to the 2013 census [36].

Table 2. Data from municipalities in the Republic of Srpska that have traffic lights.

Municipality	Population of the Municipality	The Number of Intersections with Traffic Lights	Annual Electric Energy Usage in kWh	Annual Electric Energy Usage in kWh per Intersection	Annual Electric Energy Cost in Euros	Annual Electric Energy Cost in Euros per Intersection
Banja Luka	180,053	46	173,690	3776	17,877	389
Prijedor	80,916	8	100,000	12,500	10,292	1286
Doboj	68,514	7	71,544	10,221	7364	1052
Istočno Sarajevo	61,516	14	117,600	8400	12,104	865
Zvornik	54,407	2	4078	2039	419	210
Gradiška	49,196	6	71,907	11,984	7401	1234
Prnjavor	34,357	2	378	189	39	20
Laktaši	34,210	1	1026	1026	105	105
Trebinje	28,239	4	37,495	9374	3859	965
Novi Grad	25,240	3	20,828	6943	2144	715
Kozarska Dubica	20,681	2	2352	1176	242	121
Foča	17,580	2	1176	588	121	60
Srbac	16,993	2	8150	4075	839	420
Šamac	16,308	1	2040	2040	210	210
Mrkonjić Grad	15,926	2	16,219	8110	1669	834
Ugljevik	15,118	3	4375	1458	450	150
Čelinac	15,117	1	1400	1400	144	144
Nevesinje	12,542	1	1500	1500	154	154
Vlasenica	10,657	1	8976	8976	924	924
Bileća	10,607	2	2400	1200	247	124
Rogatica	10,302	3	12,564	4188	1293	431
Višegrad	10,118	3	15,968	5323	1643	548
Donji Žabar	3669	1	2165	2165	223	223
Total	**792,266**	**117**	**677,831**	**5793**	**69,763**	**596**

Based on the data received through the questionnaires answered by each municipality representative from the Ministry of Transport and Communications of the Republic of Srpska, 23 out of 50 municipalities that responded to the questionnaire have traffic lights. Municipalities that have traffic light systems listed the number of intersections with traffic lights. They also provided the total annual electric usage in kWh and the annual cost of electricity for all traffic lights in their municipality based on the electricity price at the end of 2022. The annual electric energy usage and cost per intersection were also calculated.

The largest municipality investigated in this part of the research, Banja Luka, with 46 intersections with traffic lights, accounts for more than a third of the total number of intersections in the entity. Out of 23 municipalities with traffic lights, 13 have two or fewer intersections with traffic light systems. Although their annual electric energy usage varies, their total annual cost is low and does not cause a burden on the budget, even with the increase in the price of electricity. Municipalities with three or more intersections reported annual electricity consumption and cost for traffic light systems that are significant, especially during the span of several years. The only exception is Ugljevik, of which three intersections consume a low amount of electric energy.

The total number of intersections in the 23 municipalities that responded and have traffic lights is 117. The total annual electric usage in kWh for all the traffic lights is 677,831 kWh, which leads to an annual cost of 69,763 euros. The annual cost represents only the cost of consumed electric energy, according to prices at the end of 2022, without additional costs of maintenance, repair, and the replacement of equipment.

According to the data received from the questionnaires, in the Republic of Srpska, there are no traffic light systems powered by solar panels. However, there are 55 solar-powered road traffic counters and 10 solar-powered flashing traffic signs. As they consume less electric energy compared to traffic lights, the continuous, stable functionality of these devices can be achieved while relying solely on solar panels and is, therefore, simpler to implement, even in remote locations.

Apart from lowering annual costs, another important aspect to recognize when considering the transition to solar-powered traffic lights is the environmental benefits. According to [37], Bosnia and Herzegovina emit 482 g of carbon dioxide equivalents (CO_2-eq) per kWh of electricity, the measurement that captures all greenhouse gas emissions, not only CO_2. When the emission of electricity consumed annually for traffic light systems in the entity of the Republic of Srpska is calculated, it amounts to a total of over 327 tons of CO_2-eq.

The officials responsible for the development and traffic management in the city of Novi Sad in Serbia provided a map of all the traffic light systems in the city of Novi Sad (Figure 1). The map presents the complete number, layout, and location of all the intersections with traffic light systems. The map also provides information about the type of communication that is established with the traffic light systems, whether it is optics, GPRS, or RS-485 communication.

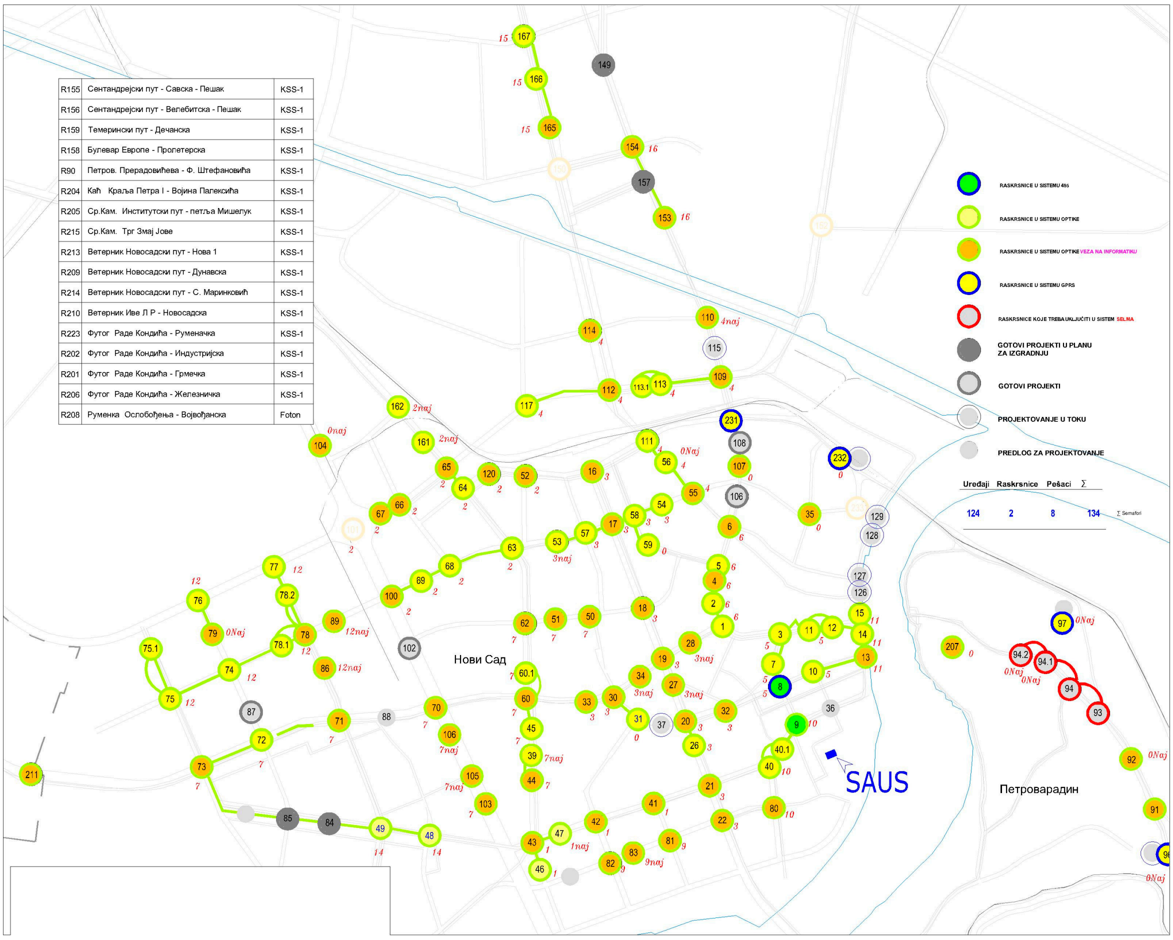

Figure 1. Map of all traffic lights in the city of Novi Sad.

The data acquired for the city of Novi Sad are presented in Table 3. There are 134 intersections with traffic lights in the city, and their total annual electric usage is 493,013 kWh. This accounts for the annual cost of 52,117 euros. As before, the annual cost represents only the cost of consumed electric energy, according to prices at the end of 2022, without the additional costs of maintenance, repair, and the replacement of equipment. Based on this data, the annual electric energy usage and cost per intersection have been calculated.

Table 3. Data from the city of Novi Sad.

Region	Number of Intersections with Traffic Lights	Annual Electric Energy Usage in kWh	Annual Electric Energy Usage in kWh per Intersection	Annual Electric Energy Cost in Euros	Annual Electric Energy Cost in Euros per Intersection
City of Novi Sad	134	493,013	3679	52,117	389

In the territory of the city of Novi Sad, there are also no traffic light systems powered by solar panels, but dozens of solar-powered road traffic counters and solar-powered flashing traffic signs are in use. All traffic light systems use LED lights.

The environmental benefits of a transition to solar-powered traffic light systems have been analyzed for the city of Novi Sad. Serbia emits 546 g of CO_2-eq per kWh of electricity, according to [37]. Therefore, the annual emission of CO_2-eq from electricity consumed annually for traffic light systems in Novi Sad is 269 tons.

The Challenges of the Transition to Solar Power

Based on the interview with the Head of the Department for the Development and Traffic Management of the city of Novi Sad and the engineers and supervisors of this department, we received information about the challenges and issues of using solar-powered traffic light systems. The main challenges emphasized during the interview have been systematized.

(a) Uninterrupted traffic light functionality

As pointed out, the most important function of the traffic light system is to enable safe and reliable traffic. Traffic lights must work properly at all times. Therefore, it is important for the power supply to be reliable and independent of the weather conditions. Moreover, the system must continue to operate in the event of damage to the solar panel or the battery. This is a challenge because solar-powered systems always have unpredictable energy input, having to rely on a backup power source. Additionally, in the case of damage, the system must immediately switch to using other energy sources until the damage is remediated.

(b) Regular and emergency maintenance of the system

In order to ensure that the equipment is functioning correctly, regular maintenance is required. Most manufacturers deliver and install the equipment but do not provide regular and emergency maintenance services. Additionally, in the traffic maintenance sector currently, there is not enough trained manpower to handle the maintenance of such traffic light systems. Due to the location of the solar panels, their cleaning and repair could also interrupt traffic, which would be difficult to carry out on a regular basis.

(c) Exposure to extreme weather conditions

Considering their previous experience, the interviewees expressed concern about the effect of extreme temperatures on the system, especially on the battery power supply. As the system would be located outside and protected only by the regular metal case, extremely low or high temperatures could reduce its performance significantly. Solar-powered road traffic counters and solar-powered flashing traffic signs operate better, regardless of weather conditions, as their batteries are placed in a bigger case, and they are protected well from

extreme temperatures. Strong winds and hail could also potentially damage the solar panel and would require expensive equipment repairs.

(d) Cumbersome equipment

Another challenge with solar-powered traffic light systems is the size of the complete equipment, as it consists of the solar panel, light installation, battery, and charger. The power storage system, mainly the battery, can be especially cumbersome and requires a lot of space. A solar panel also needs to have a large surface area, depending on the amount of electricity it must generate.

(e) Vandalism

The traffic light supervisors pointed out the issue of vandalism, which could become aggravated when switching to these systems due to the equipment's frailty when compared to traditional traffic light systems. If some of the equipment is damaged or stolen, the replacement could cost much more than is currently the case.

4. Discussion with Conclusions

4.1. Current State and Solutions

In the researched regions, there are no intersections with solar-powered traffic lights, except for dozens of solar-powered road traffic counters and solar-powered flashing traffic signs. The analyzed territory has 251 intersections with traffic lights. The total annual electric energy consumption for all the traffic lights is 1,170,844 kWh, which, according to prices at the end of 2022, amounts to a total annual cost of 121,880 euros. The annual emission of CO_2-eq from electricity consumed for all the traffic lights at the 251 intersections included in this research is 596 tons. The existing traffic lights rely on conventional energy sources, which are not optimal in terms of cost and environmental impact. During the course of this research, there were no ongoing constructions or implementations of solar-powered traffic lights in the discussed region.

The transportation sector representatives emphasized several issues and challenges that would emerge if traffic light systems were to be powered by solar energy. However, with constant technological advances in the solar energy sector and in practical applications of solar panels, there are different solutions to each of these challenges. Stable operation of the solar-powered system is enabled through battery storage units [6,16–18,27–29], connection to the grid [11,18,29] or to a secondary renewable energy system [13–15], usually a wind turbine. Additionally, by switching to the latest LED luminaire technologies with a long lifespan, a significant amount of energy can be saved [26–29]. Although the analyzed region does experience temperature variations, the maximal and minimal yearly temperatures fall into the range of typical battery operating temperatures. With appropriate storage location and conditions, the weather conditions should not pose an issue for the implementation of a solar traffic light system. As solar panels do not require complicated and frequent maintenance, they would not cause additional disturbance when compared to conventional traffic lights. With the expansion of the solar industry, it is expected that the availability of regular maintenance in the region will increase.

4.2. Feasibility and Benefits of the Transition to Solar Power

The annual electric energy usage per intersection for all 23 analyzed municipalities that have traffic lights in the Republic of Srpska and for all the intersections in the city of Novi Sad is presented in Figure 2. It can be noted that Prijedor, Doboj, Istočno Sarajevo, Gradiška, Trebinje, Novi Grad, Mrkonjić Grad, and Vlasenica report above-average annual electric energy consumption per intersection. The reason for their high electricity consumption is that the intersections covered by the traffic light systems in these municipalities are large and have a higher number of traffic lights, which, therefore, require more electricity for their operation. The additional reason could be that their traffic lighting systems are inefficient due to outdated and less efficient light and power supply technologies. On the other end of the spectrum are Prnjavor, Laktaši, Kozarska Dubica, Foča, and Bileće, whose

annual electric consumption per intersection is significantly below average. Their low electricity consumption is because the intersections in these municipalities consist of very simple traffic light systems.

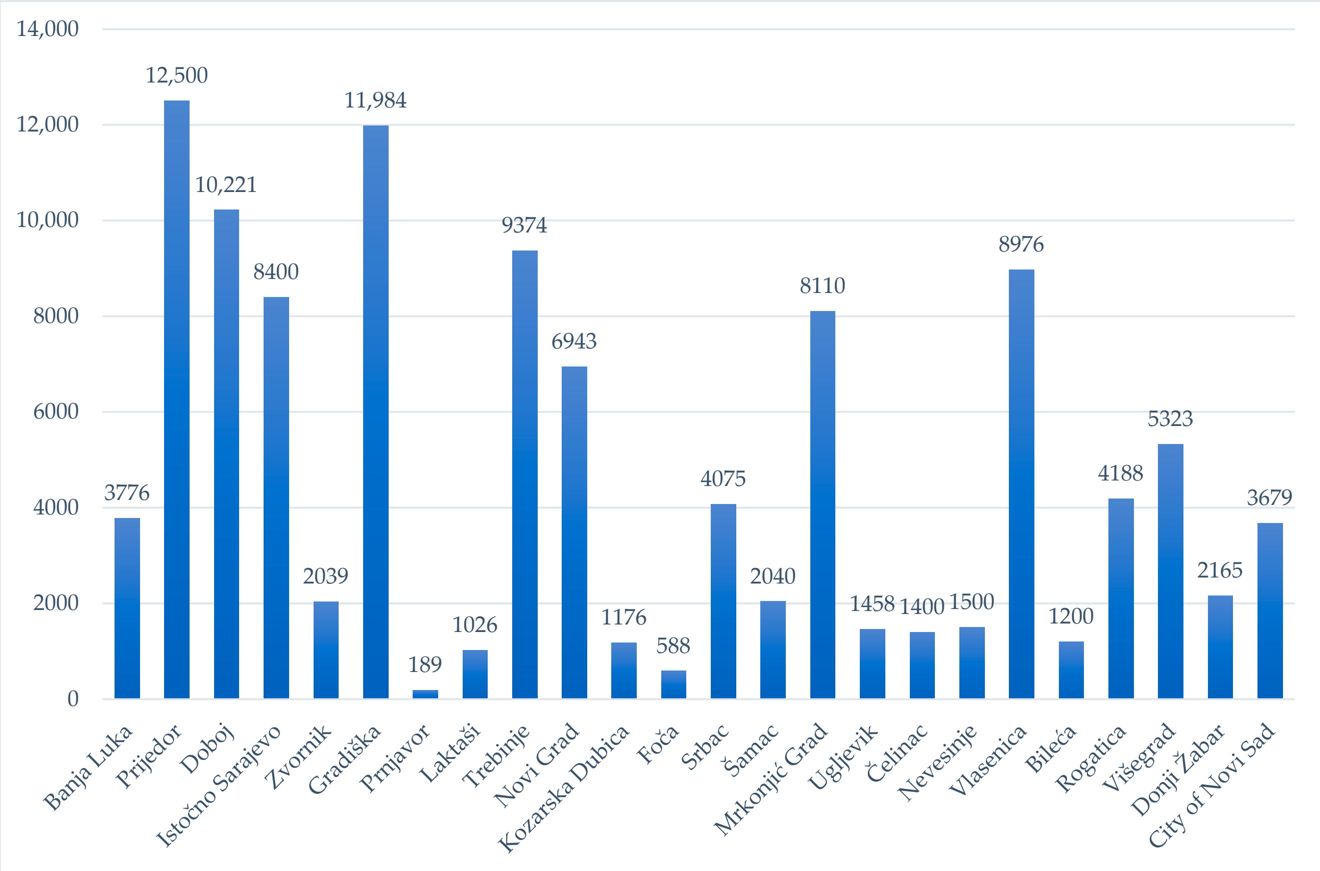

Figure 2. Annual electric energy usage in kWh per intersection for municipalities in the Republic of Srpska and the city of Novi Sad.

One of the main benefits of the transition to a solar-powered traffic light system is reducing or completely stopping the consumption of traditionally generated electric energy, which amounts to 1,170,844 kWh for the explored regions. As a result, the overall annual electricity cost of 121,880 euros would be greatly reduced. To calculate these cost benefits, the electric power that can be generated by a solar panel must be calculated. The Global Photovoltaic Power Potential by Country report published by the World Bank Group in 2020 [38] provides an evaluation of the practical solar PV potential, which is the power output that can be produced by a typical PV installation (PVOUT). This potential simulates the conversion of the available solar resource to electric power, taking into account the impact of air temperature, terrain horizon, and albedo, as well as other factors affecting the system's performance. The long-term daily solar potential of the analyzed regions falls in the favorable middle range between 3.5 and 4.5 kWh/kWp. However, it is noted that even in regions with a lower PVOUT, solar PVs may still be a profitable choice and play a significant part in the energy mix with other energy sources. The average daily practical potential for Bosnia and Herzegovina is 3.570 kWh/kWp, while the average daily practical potential in Serbia is 3.520 kWh/kWp. This means that a 1 kWp solar panel can generate around 1303 kWh of electric energy per year in Bosnia and Herzegovina and around 1285 kWh of energy per year in Serbia.

As the Republic of Srpska utilizes 677,831 kWh of electric energy for its traffic light systems, it would be required to install a total of 520 1 kWp solar panels. In [39], Lugo-

Laguna et al. calculate the investment and maintenance costs for solar panels in the capital cities of European countries, where the costs are mostly dependent on the location and standard of the country. Bulgaria was taken as a reference value for our estimation, as it is, by all measures, the most similar to the analyzed countries. The investment costs are calculated at 517.86 euros per fixed solar panel, while the maintenance costs are 5.18 euros/year for each panel. Therefore, the initial investment for 520 panels would be 269,287 euros, and 2694 euros would be spent yearly for the maintenance of the panels. As the current annual cost of electricity for the traffic light systems is 69,763 euros, it would take 3.86 years (3 years, 10 months, and 10 days) to return the whole investment, without calculating the maintenance costs. When maintenance costs during the initial period are included in the investment cost, we calculated that the investment is returned in 4.01 years (4 years and 6 days). After the calculated number of years, when the initial investment is returned, the financial benefits of using solar-powered traffic lights are significant.

In the city of Novi Sad, the annual consumption of electric energy is 493,013 kWh, which means 384 1 kWp solar panels would be required. If investment costs are also set at 517.86 euros per solar panel, and maintenance costs are set at 5.18 euros/year per solar panel, the initial investment cost for all the panels would be 198,858 euros, with 1989 euros of maintenance costs per year. Considering the current annual cost of electricity for all the traffic lights, which is 52,117 euros, the investment would be returned in 3.81 years (3 years, 9 months, and 25 days). With maintenance costs, the return period is 3.96 years (3 years, 11 months, and 16 days). It must be pointed out that this evaluation method does not take several factors into account. First, the solar potential is not uniform across the regions, and the amount of generated electrical energy can be greater or lower than the calculated average. Second, it is not possible to generate the same amount of electricity throughout the whole year, so in the winter months, electricity from the grid, a different renewable power source, or additional batteries would be required. Lastly, potential damage and replacement of the equipment have not been calculated. Nevertheless, with the forecasted price reduction of solar panels and an increase in the cost of electricity, the long-term savings prove the economic viability of the proposition, even in the case of significantly higher initial investment costs.

A second, more important benefit of the substation of conventional traffic light systems with solar-powered ones is the environmental benefit. When the data from the previous chapter are summed, the emission of electricity consumed annually by the 251 intersections with traffic lights is 569 tons of CO_2-eq each year. According to [40], the carbon footprint of the households for the EU's middle 40% is around 10 tons of CO_2-eq each year. Moreover, in [41], yearly CO_2-eq emissions of one gasoline-powered passenger vehicle in the US are calculated to be 4.64 tons. Emissions of CO_2-eq for a round-trip flight per passenger are presented in [42], where a return flight from London to San Francisco emits around 3.1 tons of CO_2-eq, which means that current traffic lights' emissions correspond to emissions from 57 average households in the European Union, 123 gasoline-powered passenger vehicles driven for one year in the United States, and 184 round trips per person from London to San Francisco. The installation of solar-powered traffic lights on a global level, a significant but long-term, economically viable investment, would significantly reduce the carbon footprint of the transportation sector and pave the path to a carbon-neutral, environmentally sustainable society.

This paper shows how replacing conventional traffic light systems with solar-powered traffic light systems would have significant environmental and economic benefits. This is highlighted through the calculation of the estimated electrical energy cost reduction and CO_2-eq emission reduction. The current challenges and issues regarding traffic light systems and solar-powered systems were also systematized. The presented conclusions are based on official data acquired from transportation sector representatives and provide valuable information for the research community to apply to projects related to solar-powered systems in other regions. Although this paper focuses specifically on traffic light

systems, the results can be relevant for any widespread system, such as signalization, measuring, or lighting systems.

Considering the current level of renewable energy utilization in the transportation sector of the analyzed regions, there is a lot of room for improvement. Due to the high initial investments required for implementing solar-powered traffic light systems on a national scale, it is possible to carry out this transition in phases, which would represent a smaller burden to local budgets. This would also leave more time to retrain existing and train additional manpower to work with solar-powered systems, which would have a positive impact on employment levels. The direction of future research can be to determine the exact number of solar panels required for each municipality, with possible utilization of alternative renewable energy sources, depending on the renewable energy potential of the region. The research can be expanded to include other widely used systems, with the possibility of using one renewable power source across multiple systems.

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