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The Use of Renewable Energy Sources in a Road Lane on the Example of the Network of National Roads and Highways in Poland

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Abstract: The deteriorating condition of the environment and the increasing emission of pollutants into the atmosphere intensify the greenhouse effect. Energy production in power plants results in emissions that affect the increase of global temperatures. According to the Research Institute for Global Climate Change in Berlin there are just over 7 years to cross the critical point, which will start chain reactions associated with irreversible changes in the climate. In order to reduce the climate changes, exhaust emissions must be reduced. One of the steps is to reduce electricity consumption. In the case of roads, electricity is most related to the technical infrastructure. First steps has been taken to reduce the demand for electricity by using lighting systems equipped in the energy saving solutions. The next step should be to use renewable energy sources. There are many solutions to generate electricity that can be used directly on roads or nearby. There are many sides in the area of the road junction that can be used for producing energy. The authors, based on a review of the literature and the first usage of energy generating devices, describe the possibilities of obtaining energy and indicate the devices with their classification.

Keywords: renewable energy source; renewable energy; road; highway; wind energy; water energy; biomass; photovoltaic cells

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1. Introduction

The development of new technologies, automation and digitization requires more and more energy. The objectives set in the European Union are related to increasing the share of energy obtained from renewable sources. In Poland, investments in Renewable Energy Source (RES) are increased every year. These investments amounted to Polish Zloty (PLN) 15 billion. It was a record high sum allocated to low-emission technologies of obtaining energy. Between 2013 and 2019, the total amount of investments amounted to Polish Zloty (PLN) 48 billion. Within this, most investments related to wind farms with 62% and 28% of investments related to photovoltaics were realized [1]. Compared to other European Union countries, this is still a small amount of investment in renewable energy sources. This problem has also been pointed out by the European Union authorities obliging Poland to increase its emphasis on green energy. The construction of biogas plants, wind farms or photovoltaic farms requires a suitable location and area. Hydroelectric power plants most often require an appropriate watercourse and terrain. The problems of locating an investment so as to obtain energy efficiently may be greater than just obtaining funds. At the present time in Poland, very large funds are still allocated to infrastructural investments. The national road network is being expanded and renovated, as well as roads of lower technical classes within the framework of local government funds. Large investments are also being made in the expansion and redevelopment of the railway network. In this publication, general analyses have been carried out indicating the feasibility of renewable energy-related equipment in the case of construction, reconstruction or renovation of road sections. In 2019, 142 billion PLN was spent on road investments [2]. Planning and financing RES as part of infrastructure investments at 10% would increase investment in RES by 100%. This would improve the environment in Poland and Europe. Additionally, some areas in the road lane would be effectively developed and other areas of the country attractive for investments and nature would be saved. Therefore, an analysis of the possibility to apply RES measures in the immediate vicinity of roads was undertaken. On the basis of a literature review, an analysis was made of the possibilities of obtaining energy in the road environment and a catalogue of solutions was prepared with a procedure for selecting and implementing these investments. The topic of renewable energy sources has already been addressed in many publications. These studies have dealt with the application of RES to power vehicles on water, land and in the air. Garcia-Olvares and his team published a literature review on the state of the art of RES use in transport [3]. For the comparison of RES sources to propulsion, many studies can be identified in the comparison of hydrogen and electric propulsion [4]. According to the studies in [5], the European Union countries have a great potential to use renewable energy sources. However, in many cases, their economic situation does not allow for large investments. Analyses made for the energy market in Europe indicate the necessity of increasing investments in RES [6]. When selecting final solutions, detailed efficiency and cost-effectiveness analyses should be performed. One of the most efficient solutions can be a combination of solar and wind energy [7]. Additionally, a biogas plant can be an efficient solution [8]. Most of the publications so far are concerned with larger areas that cover different energy sources. In this article, the analysis is directly concerned with road lane areas, which are often not used. These areas are significant and using them for energy generation can be very efficient and cost-effective.

2. Literature Review

Over 400 articles were analyzed as part of the literature review. The keywords in Table 1 and their combination were used when searching for information. Publications related to the research topic of the use of renewable energy sources in the road surroundings were selected from each group.

Table 1. Example results of keyword search in Google Scholar (https://scholar.google.com, accessed on 26 February 2021).

Key Word	-	Road	Highway	Street	Pavement	Sidewalk	Noise Barrier
Renewable energy source	2,250,000	579,000	69,400	205,000	32,800	14,600	66,600
Renewable energy	2,600,000	127,000	84,500	262,000	27,300	15,500	61,500
Renewable energy resources	2,470,000	567,000	70,700	227,000	33,200	14,300	46,100
Biogas	642,000	56,100	9080	25,400	3270	934	10,900
Photovoltaic	1,660,000	137,000	21,300	74,300	8010	4070	45,200
Biomass	3,170,000	889,000	71,700	275,000	24,400	5320	37,300
Wind energy	3,590,000	2,310,000	254,000	1,060,000	99,200	35,200	171,000
Water energy	5,930,000	1,130,000	949,000	552,000	320,000	55,400	589,000
Heat energy	4,450,000	3,690,000	312,000	1,310,000	134,000	55,300	268,000

When searching for articles in the databases, a very high number of results was obtained. In the case of keyword combinations, these values changed (decreased) due to refinement.

2.1. Biomass

Biomass sources in the road surroundings can be either grass cuttings or dead animals. A number of applications for cut grass have been described in the literature. In the case of this biomass source, the first element analyzed is the content of harmful substances in the raw material. In the case of grass, no exceedances of limit values have been found. Both in the case of a study performed in Denmark and in the case of a study in Spain, the specified standards were not exceeded [9,10]. The treatment of cut grass is essential for the proper functioning of the ecosystem. Scientific studies indicate better living and feeding conditions for insects when mowing with grass removal. According to foreign experience, the most optimal scenario was found to be mowing grass twice a year with hay extraction [11]. According to analyses performed in Denmark, the economic viability of using roadside grass for bioenergy production was confirmed. The ratio of energy obtained from biomass to the energy needed to produce it is 2 [9]. The energy content of grasses is satisfactory. According to Polish experience, the energy content is 810 kWh/t from untreated grass and 2400 kWh/t from silage [12]. Biomass from roadside grass can be a valuable source of energy for use in biogas plants [13–15]. Roadside land can also be used to grow energy crops which further increases the efficiency of the biomass extracted from them or, as in the case of the United States, to grow crops from which fuel can be produced [16]. The second type of biomass can be dead animals in the road lane. The problem of disposal of dead animals is one of the most important elements of road maintenance. The use of carcasses for the production of bioenergy is controversial, but according to research results, it is energy efficient and has no negative impact on the environment. Research results showed the possibility of obtaining energy from 90 kWh/t to 1622 kWh/t depending on the substrate [12,17]. For biomass, the biggest problem under Polish conditions is the lack of a well-developed network of biogas plants. In case of long distances of substrate delivery, bioenergy production is not profitable.

2.2. Solar Energy

Solar electromagnetic radiation is high-energy radiation. Passing from the nucleus of the sun, it reaches the outer boundary of the atmosphere. The energy flux is estimated at about 173 PW [18]. It constitutes 30,000 times the power of all man-made devices [19]. About 23% of this radiation reaches the Earth's surface, causing the evaporation of oceans, the blowing of winds or the occurrence of photosynthesis. The energy of solar radiation both in its unchanged form and in the form of wind, water and biomass energy can be used directly or indirectly to produce heat and electricity.

Acoustic screens placed next to roads are vertical walls positioned in every direction. They can be used as a kind of frame to which photovoltaic panels can be mounted. This solution makes it possible to utilize unused space and eliminates the need to search for free land for photovoltaic farms.

In Switzerland, photovoltaic panels were first installed on roads as early as 1989 [20]. These were panels positioned on top of a mountain, set at the right angle to the sun. There are at least several ways of installing them. The most common is to place a row of screens along the top edge of the screens. Another solution is to place the panels on the vertical plane of the screen or completely replace the acoustic screen with a photovoltaic panel. Another option is to place the panels at an angle to the screen and spread them horizontally along the screen's height.

Technological development leads to continuous improvement of the panels. In this way, they become more and more efficient. As a result, it is possible to use glass-glass panels with increased resistance to mechanical damage, thin-layer, translucent or luminescent panels. This also entails a gradual decrease in their price. Table 2 gives examples of the use of noise barrier panels in selected countries.

Table 2. Power of photovoltaic installations on noise barriers Adapted from [20].

Country	Location	Power (kW)	Year of Installation	Angle of Inclination Relative to Horizontal	Azimuth
Austria	Motorway A1, surroundings Seewalchen	40	1992		160°
Netherlands	Motorway A27, surroundings Utrecht	48.5	1995	50°	145°
Netherlands	Motorway A9, surroundings Ouderkerk	176	1996	50°	200°
Switzerland	Motorway A13, surroundings Chur	100	1989	45°	
Switzerland	Road E41, Zurych	10	1997	90°	80°
Switzerland	Motorway A1, Zurych	10	1999	90°	140°
Switzerland	Motorway A1, surroundings Safenwil	80	2001	45°	170°
Switzerland	Motorway A2, surroundings Melide	123	2007	45°	220°
France	Motorway A21, surroundings Fouquières-lès-Lens	63	1999	45°	170°
Italy	National road SS434, surroundings Oppeano (Verona)	833	2010	45°	210°
Germany	Motorway A23, surroundings Rellingen	30	1992		200°
Germany	Motorway A31, surroundings Emden	53	2003	90°	180°
Germany	Motorway A92, surroundings Freising	600	2003	45°	180°
Germany	Motorway A94, surroundings Töging am Inn	1000	2007	45°	210°
Germany	Motorway A3, surroundings Aschaffenburg	2065	2009	45°	150°
Germany	National road B47, surroundings Bürstadt	283	2010	60°	150°
Germany	Motorway A92, surroundings Wallersdorf	1000	2010	45°	150°

As can be noted in Table 2, the power of solar farms has increased since their introduction in road construction. Among the leading countries in Europe are Germany, Switzerland and the Netherlands. The high population density in the Netherlands means that motorways, expressways or railway lines are often built in close proximity to residential areas. This determines the need for noise barriers. The estimated number of noise barriers in the Netherlands is approximately 1250 km. In Poland, it is about 1700 km [21]. This puts Poland in a good entry position. It already has a significant number of screens that can be used. However, a detailed analysis of individual sections of expressways will be necessary to select the most convenient locations. Factors to be taken into account include the number of sunny days, orientation in relation to directions of the world and the technical condition of the screens. Table 2 shows that there is no single universal setting for the panels. Each analyzed road section should be examined in terms of optimum orientation.

At present, it is difficult to clearly determine the potential of Polish roads in terms of the application of photovoltaic panels. A country with similar annual insolation characteristics is the Netherlands. It is assumed that the Netherlands and Poland are in the range of about 900–1160 kWh/m^2, and more than half of the area has an insolation greater than 1060 kWh/m^2 [22]. For Poland as a whole, the average insolation per square meter of area can be assumed to be 1000 kWh. This value was taken as a general assumption for further considerations.

2.3. Other Types of Renewable Energy Sources

Electricity from water is mainly associated with large dams and barrages on rivers. However, smaller turbines have long been used to generate energy for the production of flour in water mills, for example. Today, thanks to the development of technology, various types of turbines can be used in different configurations. One example is turbines installed in stormwater drainage pipes. A properly designed turbine can be a source of energy for road infrastructure [23,24]. In the case of traditional turbines, it is important to have the right blade shape so as to ensure adequate water flow with efficient energy extraction [25]. An analogy can be designed with a geometric water drop and a vertical water turbine. Studies indicate the high efficiency of such a solution when the slope is properly selected and the optimum fluid flow is achieved [26]. Another solution can be a vertical turbine mounted on a slope wastewater with steep gradients together with a water storage chamber [20]. Water is a very good source of energy. Using different types of turbines, a suitable solution can be adapted to the source of flowing water [27].

Wind power was the earliest source of renewable energy used by man, after wood. Wind was used both on land in the form of windmills and at sea in the form of sails.

The difference in density of air masses heated by solar radiation causes the air to move upwards. The resulting negative pressure sucks in cold air masses causing the movement, which we call wind. It is estimated that about 1–2% of the solar energy reaching our planet is converted into kinetic wind energy, which corresponds to an estimated power of 2700 TW [19]. This energy can be used by locating wind power plants, e.g., in the form of windmills. These power plants do not pollute the environment and can be built on wasteland and unattractive areas.

Green lanes near roads remain largely unused land. They generate maintenance costs and are not a source of revenue. This state of affairs can be changed with appropriate legal regulations related to road administration activities. The use of air mass movement energy can generate a significant amount of electricity.

There are many renewable energy sources and more are being explored. In addition to those described in the previous chapters, there are also those that directly affect the road such as piezoelectric installations and those that affect service buildings. One example is geothermal energy for heating buildings at passenger service areas or maintenance premises [28]. For this solution, the energy source is the occurrence of geothermal sources. They only occur in specific regions. Another source of power for devices related to Motorways of the Future and smart signage for autonomous vehicles is piezoelectric installations. When driving over such a device, an electrical charge is generated. This is a very promising technology. However, it requires careful preparation as such devices under the influence of heavy traffic may be destroyed [16,29] All countries are currently placing great emphasis on the development of fields related to renewable energy sources. Many researchers are working on new solutions. Each of them is an opportunity to reduce the negative impact on the environment and improve the quality of life.

3. Effectiveness Evaluation of Exemplary Solutions for Use in Poland

In the area of roads (road lanes), there are many locations where panels can be used. As described in the literature review, solutions in road lanes with solar energy are increasingly used. Based on a study [30], the effectiveness of panels in the vicinity of roads was found depending on the location. The results are presented in Table 3.

Table 3. Photovoltaic installations in the vicinity of roads Adapted from [30].

Country	Type	Length	Power
India	Panels in the form of roofing	1 km	1.23 MWh
Netherlands	Photovoltaic farm	1.6 km	176 MWh
Netherlands	Photovoltaic farm	0.55 km	30 MWh
Switzerland	Photovoltaic farm	0.8 km	108 MWh
Austria	Photovoltaic farm	0.264 km	31.5 MWh

In Poland, as it was stated earlier, the length of noise barriers is estimated at 1700 km, mainly located along national roads [19]. Assuming that the average height of screens is 4 m, this results in approximately 6.8 million m^2. Part of this very large area may be effectively used in the future for energy generation. A simplified analysis has been carried out below, which has been divided into three parts due to the possible use of the screens. The analyses assume that 25%, 50% and 75% of the noise barriers will be used for photovoltaic installations. The efficiency of photovoltaic panels was considered at 14%, 15% and 16% [31]. The results of the electricity generation analysis are presented in Table 4.

Table 4. Results of the analysis of the feasibility of applying photovoltaic installations on noise barriers (on national roads) in Poland.

Use of Existing Noise Barriers	Length of Photovoltaic Installation (km)	Installation Area (m^2)	Energy Generated at 14% Panel Efficiency (MWh)	Energy Generated at 15% Panel Efficiency (MWh)	Energy Generated at 16% Panel Efficiency (MWh)
25%	425	1,700,000	238,000	255,000	272,000
50%	850	3,400,000	476,000	510,000	544,000
75%	1275	5,100,000	714,000	765,000	816,000

On the basis of the above assumptions and the obtained results, it may be stated that the application of photovoltaic installations along roads may be justified, assuming that acoustic barriers are changed or reconstructed. Depending on the solutions adopted and the use of noise barriers, different energy values may be obtained. Such a solution could successfully compete with commonly used solid fuel power plants. Thanks to research in the Netherlands, Switzerland and Austria, it can be concluded that this is an effective solution. These results confirm their durability, which confirms their justification for use. Another theoretical analysis concerns the extraction of thermal energy from road surfaces. The road as a black flat surface can serve as a kind of solar collector converting solar energy into heat energy. Assuming a minimum width of the national road of 7 m, it is possible to estimate the solar energy that the pavement will absorb. Three variants were considered, with 25%, 50% and 75% utilization of the surface of national roads in Poland. The length of roads was obtained from the report of the Central Statistical Office. The results are presented in Table 5.

Table 5. Possibility of using the road surface as a solar energy collector.

GDDKiA Branch		Length of Roads (km)	Road Surface Area (km^2)	Annual Renewable Energy Possible to Obtain (GWh)	Energy Gained from Percentage of Road Surface (GWh)			
					10%	25%	50%	75%
1	Białystok	936	6552	6552	655	1638	3276	4914
2	Bydgoszcz	1014	7098	7098	710	1775	3549	5324
3	Gdańsk	805	5635	5635	564	1409	2818	4226
4	Katowice	920	6440	6440	644	1610	3220	4830
5	Kielce	750	5250	5250	525	1313	2625	3938
6	Kraków	969	6783	6783	678	1696	3392	5087
7	Lublin	1004	7028	7028	703	1757	3514	5271
8	Łódź	1377	9639	9639	964	2410	4820	7229
9	Olsztyn	1297	9079	9079	908	2270	4540	6809
10	Opole	854	5978	5978	598	1495	2989	4484
11	Poznań	1500	10,500	10,500	1050	2625	5250	7875
12	Rzeszów	891	6237	6237	624	1559	3119	4678
13	Szczecin	1042	7294	7294	729	1824	3647	5471
14	Warszawa	4546	31,822	31,822	3182	7956	15,911	23,867
15	Wrocław	1720	12,040	12,040	1204	3010	6020	9030
16	ZielonaGóra	891	6237	6237	624	1559	3119	4678
Total		20,516	143,612	143,612	14,361	35,903	71,806	107,709

The results presented in the table above show the possibilities of using the road surface in particular branches of GDDKiA on national roads. These are only theoretical considerations, as there are no technologies commonly available yet that would make it possible to collect this energy and use it. This shows, however, how great the energy potential may be in the future. However, the technical solutions needed to convert solar energy into electricity or heat will have to be developed [32].

The second most common renewable energy source available on the road is biomass. The first type of biomass that can be used is cut grass. On the basis of the analysis of the length of the network of national roads, expressways and motorways, the ability of obtaining biomass from cut grass in the area of the road lane was assessed. The roads were divided into three groups according to their geometrical characteristics. The first group analyzed was national roads. In order to simplify the analysis, a single carriageway cross-section with trapezoidal ditches on both sides was adopted. In order to determine the width of the mowing area, 3.8 m was assumed, taking into account a trapezoidal ditch with a depth of 0.5 m and a bottom width of 0.4 m. A similar approach was used to analyse the potential use of grass cuttings as biomass in Denmark. The authors in the Danish analysis adopted three scenarios assuming widths ranging from 2 m to 5.75 m mowing width [3]. Analyzing the S8 expressway section, taking into account the total width of the road lane and technical facilities such as reservoirs and other equipment. Based on calculations and data from the tender documentation of the General Directorate for National Roads and Motorways for the grass cutting service on the analyzed section, the mowing area was determined to be 80.95 ha over a distance of 84 km. The calculations resulted in 77,960.8 m^2 of grass cutting area. For expressways and motorways in Poland, 9.6 ha of grass cutting area per 1 km of road was assumed. The analysis assumed 22,676.16 ha for motorways and 16,087.68 ha for motorways. The second step in the analysis was to determine the amount of grass harvested per hectare of mown area. Based on the literature review, three values were determined for Denmark, Wales and Germany. For Denmark, the average annual value of grass yield from mowing is 2.04 t/ha [9]. For Wales, the authors define this value as 3.34 t of cut grass per hectare [33]. For Germany, the average value is 5 t/ha [34]. The average value for Germany was used for further analysis. Poland has similar climatic characteristics. On the basis of the obtained data, calculations of the amount of mown grass on the network of national roads, expressways and motorways were made. The results of the analyses are presented in Table 6.

Table 6. Possibilities of obtaining biomass substrate in the immediate vicinity of national roads.

Type of Road	Quantity of Grass Cut (t)
National roads	38.98
Express roads	113,380.8
Motorways	80,438.4

Having the value of the harvested amount of grass, the value of the harvested energy from biomass can be calculated. In the case of grass, its energy efficiency in the dry state can be determined as 810 kWh per dry tons of material harvested [12]. The energy values of the different substrates of the biogas plant are presented in Table 7.

Table 7. Energy efficiency of substrates Adapted from [12,17].

Substrate	Energy Value of the Substrate ($kWh \cdot t^{-1}$ s.m.) ($kWh \cdot t^{-1}$ d.m.)
Grasses	810
Fruit and vegetable wastes	950
Secondary fats	1300
Post-slaughter waste-pigs	1620
Sewage sludges	2000
Post-slaughter waste-poultry	2180
Grasses—silage, meadow vegetation	2400
Sugar beets	3000
Fodder beets—silage	4500
Post-slaughter waste - cattle	4680
Animal fats	8500

The analysis was performed according to road types and their location in the country. On the basis of the results obtained, it was found that most electricity from biomass can be obtained in the Łódź province. Most biomass comes from national roads. The lowest value of energy obtained from one mowing was obtained in the Białystok province. The results of the analysis are presented in Table 8.

Table 8. Possibilities of obtaining electricity from biomass in each branch of GDDKiA.

No	GDDKiA Branch	National Roads		Express Roads		Motorways		Total
		(MWh)	(%)	(MWh)	(%)	(MWh)	(%)	(MWh)
1	Białystok	1.44	0%	1286.93	100%	0.00	0%	1288.37
2	Bydgoszcz	1.56	0%	2888.78	31%	6415.20	69%	9305.54
3	Gdańsk	1.24	0%	4016.30	61%	2562.19	39%	6579.73
4	Katowice	1.42	0%	5151.60	38%	8312.54	62%	13,465.56
5	Kielce	1.15	0%	4101.84	100%	0.00	0%	4102.99
6	Kraków	1.49	0%	1205.28	17%	5870.88	83%	7077.65
7	Lublin	1.55	0%	5276.02	100%	0.00	0%	5277.56
8	Łódź	2.12	0%	8670.24	50%	8794.66	50%	17,467.02
9	Olsztyn	2.00	0%	9377.86	100%	0.00	0%	9379.85
10	Opole	1.31	0%	0.00	0%	3425.33	100%	3426.64
11	Poznań	2.31	0%	10,408.18	56%	8184.24	44%	18,594.72
12	Rzeszów	1.37	0%	1166.40	16%	5929.20	84%	7096.97
13	Szczecin	1.60	0%	10,431.50	91%	983.66	9%	11,416.77
14	Warszawa	7.00	0%	13,421.38	84%	2581.63	16%	16,010.00
15	Wrocław	2.65	0%	7877.09	48%	8627.47	52%	16,507.21
16	Zielona Góra	1.37	0%	6559.06	65%	3468.10	35%	10,028.52
	Summary (MWh)	31,57	0%	91,838.45	58%	65,155.10	41%	157,025.13
	Summary (GWh)	0,03	0%	91.84	58%	65.16	41%	157.03

In the case of analysis on national roads and expressways, the highest energy values were obtained in the Mazowieckie province. The lowest value of biomass obtained for national roads was recorded for the Świętokrzyskie province, and for expressways—for the Podkarpackie province. The highest result for motorways was obtained for the Łódzkie Province and the lowest for the Zachodniopomorskie province. The results are presented in Figure 1

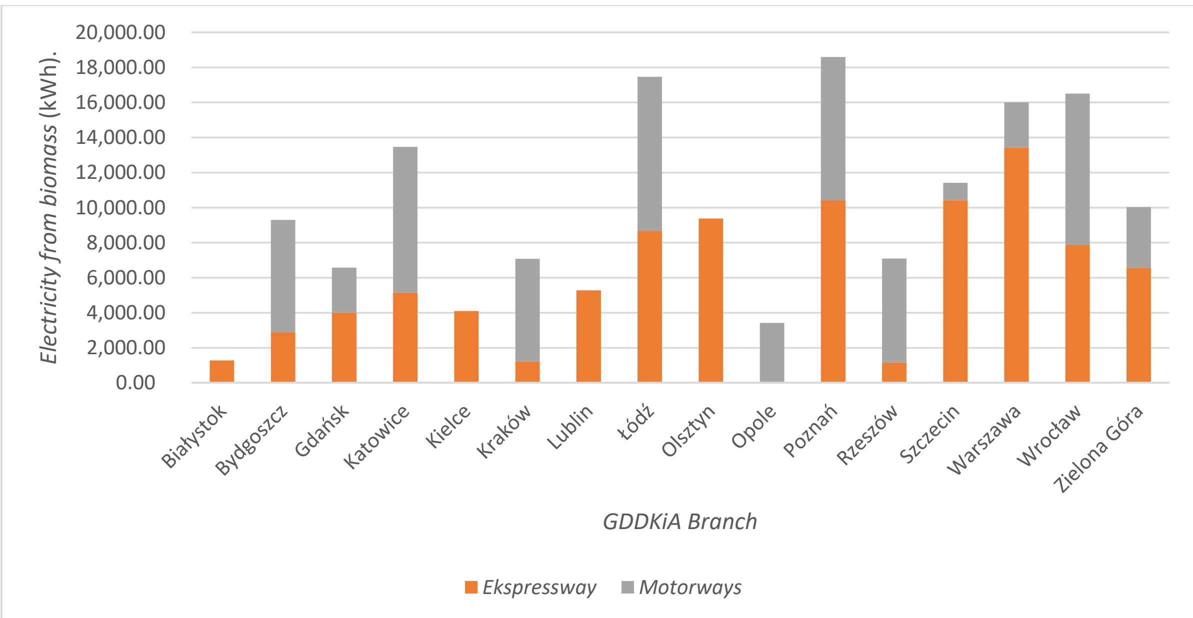

Figure 1. Biomass energy in the surroundings of expressways and motorways.

According to analyses, the greatest amount of energy can be obtained from biomass on expressways. Motorways are the second group. The least energy can be obtained from national roads. It is the biggest group of roads which were analyzed. However, they have a much narrower road lane than expressways and motorways.

4. Discussion

In Poland, the electricity sector produced around 170 TWh of electricity in 2018 [35]. Domestic demand at that time was 175.7 TWh. The shortfall in energy had to be imported from abroad. Table 9 below shows the average annual electricity consumption according to the number of household members.

Table 9. Annual electricity consumption by household size Adapted from [36].

Type of User	Annual Consumption (KWh)
Single person	1250
Two-person family	1500
Three person family	1800
Four-person family	2100

Covering 25% of the noise barrier surface with photovoltaic installations with 14% efficiency panels would allow powering approximately 113,000 4-person households all year round. Using 16% efficient panels would increase this number to about 130,000 households. Using half of the existing screens would double these numbers, to 226,000 and 260,000. Such a number would provide the energy needed to power the households of towns in the Podlaskie or Lubuskie voivodships. The production of electricity using solar radiation falling on national road surfaces could bring much higher benefits. Table 10 shows the electricity consumption in households in cities in the individual provinces.

Table 10. Electricity consumption by province Adapted from [37].

Province	Annual Consumption (MWh)	Number of Inhabitants	Energy Consumption per Inhabitant (MWh/person)
Dolnośląskie	1,533,700	1,984,000	0.773034274
Kujawsko-pomorskie	854,500	1,220,400	0.700180269
Lubelskie	644,900	979,400	0.658464366
Lubuskie	498,700	656,500	0.759634425
Łódzkie	1,210,000	1,531,000	0.790333116
Małopolskie	1,464,200	1,644,200	0.890524267
Mazowieckie	3,225,600	3,495,700	0.922733644
Opolskie	401,700	523,100	0.767922003
Podkarpackie	533,800	880,600	0.606177606
Podlaskie	461,300	716,900	0.643464918
Pomorskie	1,125,100	1,488,100	0.756064781
Śląskie	2,733,200	3,460,700	0.789782414
Świętokrzyskie	366,700	560,200	0.654587647
Warmińsko-mazurskie	541,000	842,100	0.642441515
Wielkopolskie	1,485,600	1,889,400	0.786281359
Zachodniopomorskie	854,300	1,160,700	0.736021366

An estimated 157.03 GWh of electricity from biomass is able to power over 74,774 households with 4-person families for a year. It should also be pointed out that apart from grass mowing, roadside greenery maintenance works are constantly being carried out, which can also be a substrate for energy generation.

The costs for renewable energy sources are constantly decreasing. To determine the optimal energy solution, all costs must be taken into account. The Levelized Cost Of Energy

(LCOE) is often used in cost analyses. The Levelized Cost of Energy (LCOE) for different energy sources has been compared and is presented in Table 11 [38,39].

Table 11. The Levelized Cost Of Energy Adapted from [38,39].

Year	Biomass (USD/kWh)	Solar Photovoltaic (USD/kWh)	Concentrating Solar Power (USD/kWh)	Onshore Wind (USD/kWh)	Hydro (USD/kWh)	Conventional Energy Sources (USD/kWh)
2010	0.07	0.36	0.33	0.08	0.04	0.07
2017	0.07	0.1	0.22	0.06	0.05	0.07
2020	0.07	0.06	0.1	0.04	0.04	0.07

On the basis of the above table, a decrease in the costs of obtaining energy from some sources (solar, wind hydro) can be observed. Analyzing the costs for the assumed achiev-able values for the analyzed roads in Poland, a preliminary economic efficiency was esti-mated. Analyzing the cost of obtaining 1 MWh from biomass will be USD 70, approxi-mately the same as for conventional sources. Using photovoltaic cells, the cost of 1 MWh is USD 60. When analyzing the benefits, the environmental impact must also be taken into account. In this case, biomass and solar energy compare favorably with conventional energy sources. These analyses need to be refined and adapted to the costs in the individ-ual countries.

5. Conclusions

The Member States of the European Union have set themselves the courageous task of increasing the proportion of electricity generated from renewable energy sources. This will help to improve air quality, clean the environment and reduce the number of people suffering from respiratory and cardiovascular diseases. In the context of these upcoming changes, the road industry can make an important contribution to energy generation. There are a number of solutions to be applied in road construction that can improve the environmental impact of roads. On the basis of the literature review and our own analyses, we can conclude that some technical solutions (solar and biomass energy generation) are advanced enough to be used in infrastructure investments. All these solutions are still being developed and optimized. The introduction of elements of renewable energy sources in road construction requires the preparation of appropriate procedures for the analysis and selection of RES solutions and the verification of their effectiveness, as well as formal issues of energy production. From the theoretical analysis of the installation of photovoltaic panels on noise barriers, it can be concluded that there is a possibility to collect a large amount of electricity. It is estimated that in the pessimistic scenario, 238 GWh can be obtained, and in the most optimistic scenario, 816 GWh. Even in the case of the pessimistic variant, this is, for example, one third of the annual electricity demand of the cities of the Lublin province. Acquisition of electricity from solar radiation falling on the surface of national roads according to Table 5, gives even greater chances for obtaining energy. It is estimated that utilization at the level of 10% will make it possible to supply electricity to all households in towns in Poland (excluding towns in the Mazovian voivodship). Roads can be a source of biomass for methane production processes. Mowed grass from the closest surroundings of roads can provide a substrate for obtaining 55.32 MWh of electricity. This is not a large amount, but when taking into account all green areas in the road lane and road surroundings on expressways and motorways, an average of 38.89 MWh can be obtained, giving a national total of 157.03 GWh. Compared to solar energy, this is less efficient. However, it produces a large amount of energy with a small investment in substrate. A requirement, however, is having a biogas network prepared and built beforehand, which entails high costs [40]. External investors can participate in this investment. The annual cost of electricity purchase by the General Directorate for National Roads and Motorways is PLN 87.2 million [41]. The use of renewable energy sources can significantly reduce these costs and contribute to improving the environment in Poland and Europe. On the basis of the analyses performed, the thesis that the road and road lane can be an effective source of renewable energy was confirmed.

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