GREECOPE: Green Computing with Piezoelectric Effect

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Abstract: The growing interest in the search and use of alternative resources for renewable energy can lead the future towards substantially decreasing carbon footprint and reduce the effects of global warming. The proposed research explores the possibility of harnessing piezoelectric energy from the environment of moving vehicles on road. Although the technology is still immature, it has the advantage of having zero carbon footprints thus making it ideal to investigate the potential for green energy generation. The main objective is to develop regression models that can estimate energy generated from vehicular traffic. Energy is generated when force is applied to piezoelectric transducers which depend on significant factors such as the number of piezoelectric transducers and their arrangement, load applied and frequency. We design Support Vector Machine (SVM) and Generalised Linear Model (GLM) for predicting energy. The best features for training the model were selected by incorporating feature selection techniques such as Pearson's correlation coefficient and Mutual Information Statistics. The experimental setup makes use of simulated data which takes into account vehicle count of different vehicles with and without load. The accuracy achieved from SVM and GLM are 99.6% and 99.7% respectively. The energy savings achieved by making use of generated piezoelectric energy is discussed with a sample scenario of Motorway50 of Dublin, the Irish Capital city. Through this work, we propose to investigate deeper into the feasibility towards cost-effectiveness by utilizing energy which is wasted by human and vehicular locomotion.

1 INTRODUCTION

Basic human needs largely rely upon non-renewable sources (Reeker, 2014) of energy which will become exhausted in the future**.** Thus, there's a major imperative to seek out some way through which we are able to generate energy from the available resources. This can cut back the use of non-renewable energy sources to a good extent and may help to create a better future. Solar power, windmills and geothermal energy are some examples of renewable energy (Davies, 2017). Petrol and diesel are non-renewable resources and contribute significantly to the effects of heat and climate impact over time as travel has become one of the most important requirements of our lifestyle, which is made possible by the use of a variety of vehicles. Vehicles use fossil fuels, which release large amounts of carbon and greenhouse gas. Electric vehicles are becoming increasingly more popular and their current limited use presently is expected to scale up in the coming decade. Hence with the anticipated growing trend for electric vehicles the use of electricity as its fuel would substantially increase. Fortunately, the piezoelectric effect can utilize waste locomotion energy and vehicle kinetic energy and convert it into electricity. This can be achieved through the use of piezoelectric sensors that can generate electrical energy when pressure is applied to it. Therefore, energy can be built up through the movement of road vehicles and people (Borikar, 2017).

In this work a comprehensive model to predict the piezoelectric energy output based on historical data is discussed. We explore the use of Artificial intelligence-based methods like Support Vector Machine (SVM) (Kaur, 2017) and Generalized Linear Model (GLM) (McCullagh and Nelder, 1989) for the estimation of electricity generation through piezoelectric effect from moving road vehicles is discussed. Artificial intelligence-based methods have the twofold advantage of being flexible and capable of dealing with non-linearity.

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2 BACKGROUND

This section will discuss the characteristics of piezoelectric material, their application and the formulation for calculation of generation of energy.

2.1 Piezoelectric Materials, Characteristics & Formula

Currently the most extensively used piezoelectric material is PZT (Pb- Lead, Zr- Zirconium, Ti- titanium). The working process of the piezoelectric system when placed beneath the road is explained in (Kour and Charif, 2016).

The proposed system is completely based on the sound theoretical concepts of Piezoelectric effect, which is the generation of electric charge when subjected to pressure. Materials which exhibit piezoelectric effect are known as piezoelectric material.

Certain factors affect the amount of power generated by incorporating piezoelectric plates beneath the road surfaces, such as vehicle speed, vehicle mass, traffic flow, dimension of road on which piezoelectric plates are embedded and the frequency settings depending upon locations. Speed and weight of a vehicle is directly proportional to energy generated.

Below formulas are useful while preparing the dataset mentioned in 3.2 and regression model.

Let the total no of vehicles be T_v and individual vehicle count of car, bus, truck, motorcycle is T1, T2, T3 and T4 respectively. Consider the average mass of total no car, bus truck and motorcycle as M1, M2, M3 and M4 respectively.
Rolling resistance Fr of the wheels is calculated by

$$Fr = Nf \times Cr = Mi \times g \times C_r \tag{1}$$

Where N_f is the normal force acting on the surface
Cr - coefficient of rolling friction (0.03-0.15)
Mi = Mass of particular vehicle class, where
$i \in (1,4)$
g = Gravity
The rolling resistance of the tire can be overcome by the power given by

$$Pr = Fr \times v \tag{2}$$

Where v = speed of vehicle.
Let the time taken by a vehicle to pass over piezoelectric roads be defined as:

$$t = lp / v \tag{3}$$

L_p = length of road laid with piezoelectric generator.

The intensity of energy generated due to mechanical force of vehicles is calculated as:

$$Uin = \int_0^t Prdt \tag{4}$$

Where U_{in}= mechanical energy

$$P = \lambda \, x \, Uin \, x \, k \tag{5}$$

$\lambda = 0.078$ and P represents the Power generated by the respective vehicle class of mass M_i and k = Constant (to convert joules to kWh = 2.7778×10^{-7} kWh). Thus, P is the final output that the regression model must predict.

2.2 Applications and Estimation of Energy Savings

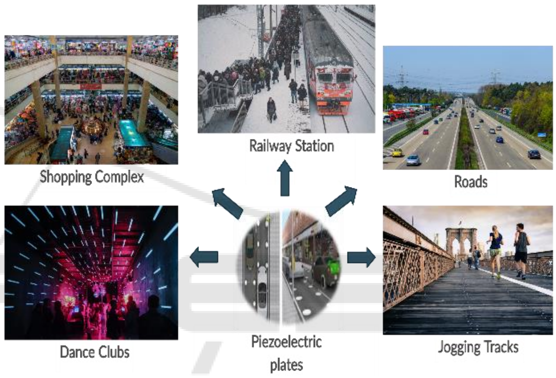

Figure 1: Different Scenarios where piezoelectric materials can be implemented.

Piezoelectricity can be generated by placing the piezoelectric tiles at various locations. The locations must have either large amounts of vehicles or human movements to harness energy in a profitable way.

Figure 1 depicts various scenarios where piezoelectric tiles/plates can be installed. For instance, a Dance club can meet 60% of its energy requirement (A., 2019), because large numbers of people are contained in small areas. The frequency of the movements is very high making them one of the ideal locations to place the piezoelectric plates. From future perspectives, airports will be an ideal location to lay piezoelectric plates.

3 EXPERIMENTAL SETUP & EMPIRICAL ANALYSIS

This section will discuss the architecture proposed by the authors, dataset used and results obtained by performing tests.

3.1 Proposed Architecture

The paper proposes an architecture which will estimate the amount of electricity that can be generated by harnessing piezoelectric effect from moving road vehicles. The process flow consists of two parts: the AI model for prediction of energy and the distribution of generated energy. The AI model takes the output of the GREECOCO (Kshirsagar et al., 2021) system as its input.

The GREECOCO system consists of the vehicle detection and classification algorithm which is the authors' previous paper. Traffic videos are fetched from the installed cameras and vehicle detection is performed using three algorithms: YOLOv3, Faster RCNN and Mask RCNN. After detecting the vehicle, it is recognized into five classes which are car, bus, truck, motorcycle and bicycle. The vehicle count is stored in a database for further analysis. We access this database to get a count which will be an input to our next module which predicts the energy generated.

Figure 2 shows the overall architecture of a system. The output of the GREECOCO system which is the individual as well as total count of four vehicle classes (**Bus, Truck, Car and Motorcycle**) is combined with features such as vehicle mass and the speed of moving vehicles. After performing feature extraction, mechanical energy is calculated. This mechanical energy is given as an input to the Artificial Intelligence (AI) module which predicts the amount of energy generated by each vehicle class during various time durations. SVM and GLM approaches are used for energy prediction. The prediction results are stored in a database for future reference and energy analysis. The generated energy will be distributed to charging stations for electric cars and streetlights.

3.2 Dataset Details

The training dataset (Table 1) of the energy prediction model was created using the NumPy library for 6 years from 2014 to 2020. The dataset consists of a count of individual vehicle classes, as well as the total

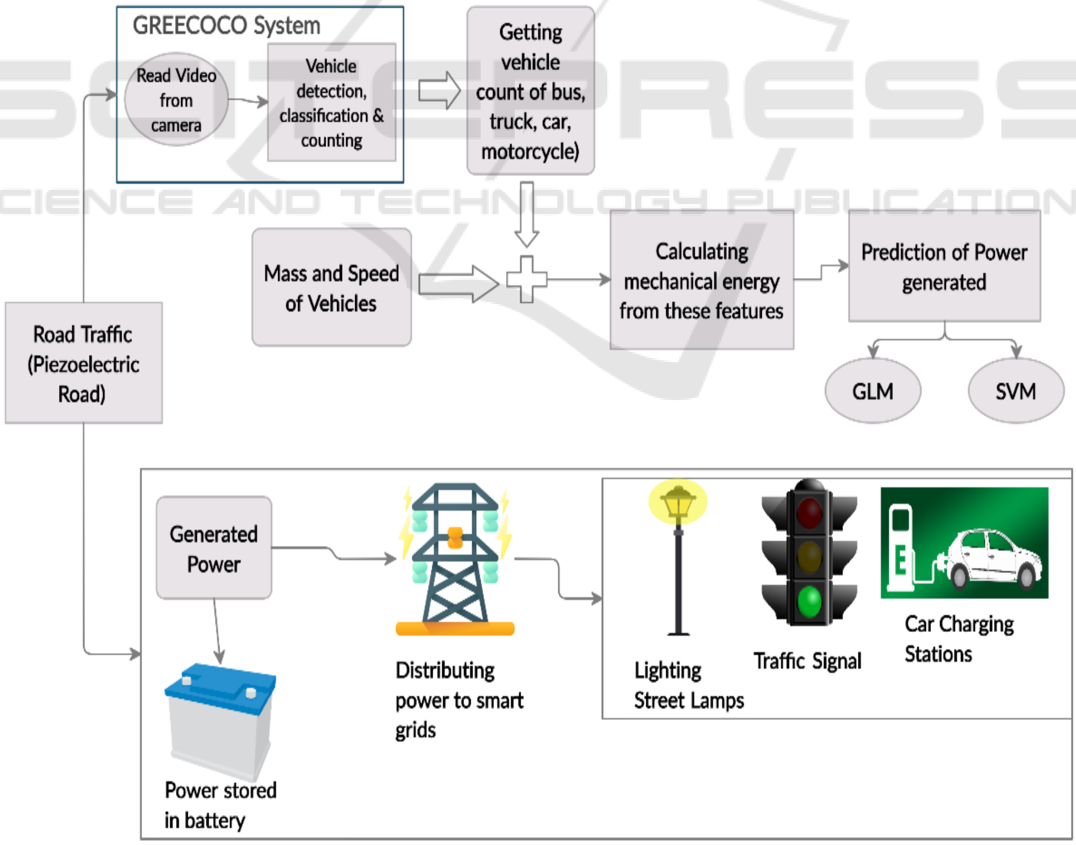

Figure 2: Proposed Architecture for GREE-COCO.

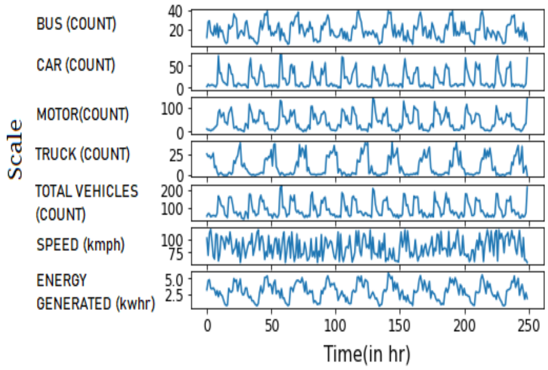

Figure 3: Dataset details for the training of SVM and GLM model.

count of vehicles from the GREECOCO system.

Also factors such as weight and speed of vehicle are attributes of the dataset, along with force, mechanical energy, and the expected energy generated by each vehicle class. In the dataset, the average mass of individual **car, bus, truck and motorcycle** is 1000 kg, 7500 kg, 9500 kg and 170 kg respectively. The data was used for the training of SVM and GLM regression models, which predicts the power generated for each vehicle class depending upon the number of vehicles.

The testing dataset consisted of 10000 (416 days) hours of data. Figure 3 demonstrates the cyclic nature of each vehicle class's count during an entire day. This portrays the daily life situation of traffic distribution throughout the day.

3.3 Data Pre-processing

Feature selection is a method of defining and selecting a subset of input variables that the output variable is most dependent. Our dataset consists of 40,000 sample, each with 15 input features, and we employed Correlation Statistics (Sedgwick, 2012) and Mutual Information Statistics (Beraha et al., 2019) to perform selection.

The Correlation coefficient (r) is used to measure the linear associativity between variables.

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \tag{6}$$

Here x_i and y_i are the values of sample dataset and $\bar{x}$ and $\bar{y}$ are the mean values respectively. Here the value $r = 1$ means a perfect positive correlation and $r = -1$ means negative correlation.

Mutual information is a measure of dependence or mutual dependence between two random variables. The mutual information between two random variables X and Y can be stated formally as follows:

$$I(X;Y) = H(X) - H(X|Y) \tag{7}$$

Where *I(X ; Y)* is the mutual information for X and Y, H(X) is the entropy for X and H(X | Y) is the conditional entropy for X given Y.

Mutual information is always larger than or equal to zero, where the larger the value, the greater the relationship between the two variables. If the calculated result is zero, then the variables are independent.

Table 1: Dataset used for training SVM and GLM models.

Bus	Car	Motor	Truck	Total vehicles	Speed	Time	C mass	M mass	T mass	B mass	C force	M force	T force	B force	Total Energy Generated (kWh)
12	3	11	25	51	102	35	3000	1870	187500	114000	1470	916	91875	55860	3.225542
28	8	7	22	65	69	52	8000	1190	165000	266000	3920	583	80850	130340	4.657807
29	5	7	23	64	112	32	5000	1190	172500	275500	2450	583	84525	134995	4.800588
18	6	3	20	47	119	30	6000	510	150000	171000	2940	249	73500	83790	3.448096
16	7	7	22	52	95	37	7000	1190	165000	152000	3430	583	80850	74480	3.370941

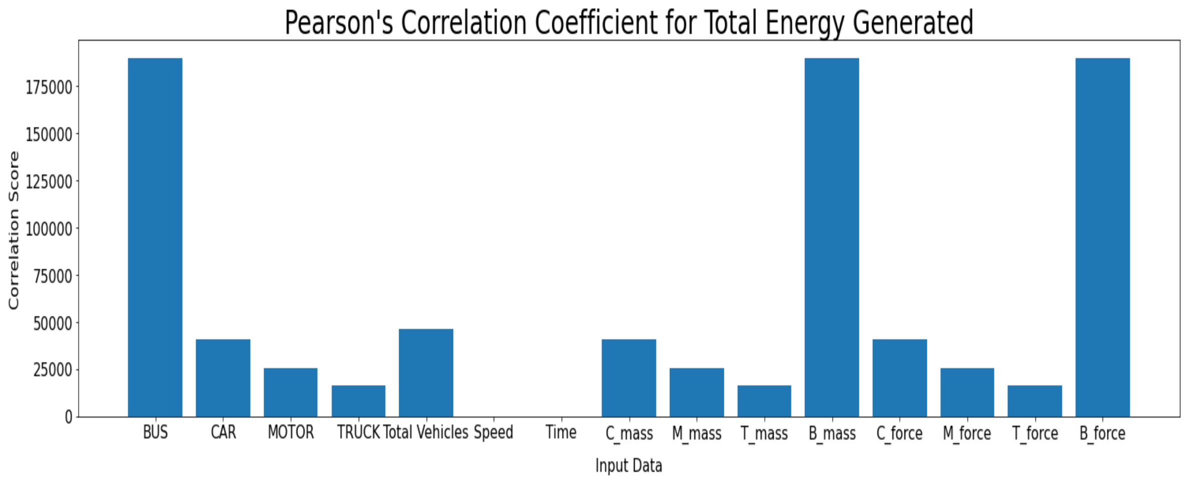

Figure 4: Feature Selection Results by Correlation Statistics.

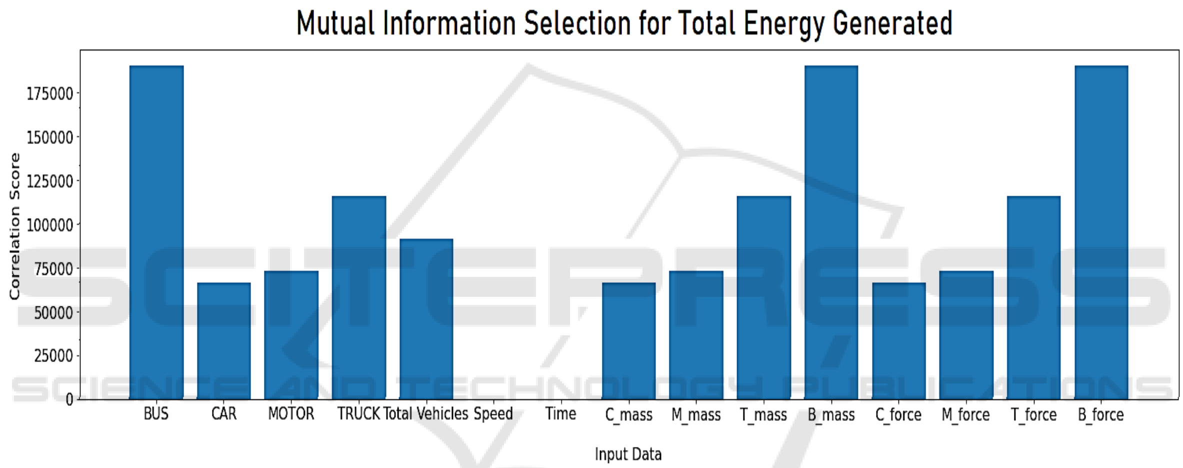

Figure 5: Feature Selection Results by Mutual Information Statistics.

3.4 Regression Models for Estimating Energy

To predict the generated energy by the vehicle, AI models using SVM and GLM have been designed. Support Vector Machine (SVM) algorithm, is a decision boundary where the distance between the closest member of different classes is maximum. Many nonlinear decision boundaries, and kernels are modelled by the SVM algorithm. The major benefit of using SVM is the robustness, especially in high-dimensional space, against data overfitting. Another common training technique for a diverse set of regression models is Generalized Linear Models (GLM). GLM enables to express the relation between covariates X and response y in a linear, additive manner. As a result, GLMs is a perfect option for real world datasets which are not linear and heteroscedastic and where we cannot predict the model's error distribution.

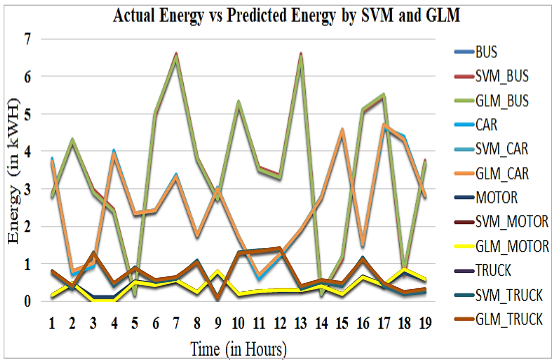

Figure 6: The expected energy by different class vehicles.

Figure 6 illustrates the prediction of **Car, Motorcycle, Bus and Truck** for 50 hours respectively. The figures highlight the SVM and GLM predicted energy vs. actual energy generated for a particular set of vehicles during a specific hour. Throughout the table, Car generated more energy than the other vehicle classes. The energy generated by a vehicle depends upon the amount of load it carries. If a vehicle is not carrying any load, then the amount of energy generated differs in a measurable amount than the vehicle carrying enormous load. Figure 7 the comparison of vehicle's generated energy in 2 scenarios with and without load is illustrated. We can see there is a significant amount of difference in two scenarios output.

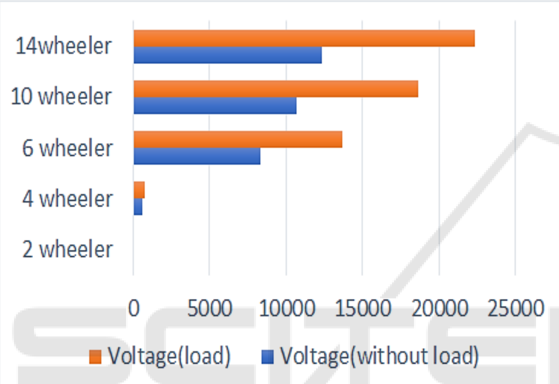

Figure 7: Comparison of Voltage Generation of different vehicles with load and without load.

3.5 Performance Analysis of Regression Models on Varying Traffic Count

The table 2 below shows five different scenarios with varying vehicle counts and estimation of energy generated from our AI models.

Scenario 1 depicts a total vehicle count of 100 where the categorical count for each vehicle class is further distributed as 45 for the vehicle class car, 10 for the vehicle class bus, 5 for trucks and 40 for motorbikes. In scenario 1, hence the total energy generated by each class would be, for car 0.477 kWh, bus 0.796kWh, truck 0.504 kWh and motorbikes 0.072 kWh. The combined energy amounts to 1.84 kWh, which can be used to light up 1 LED bulb consuming 100w for a total duration of 18.4 hrs. Similarly, scenarios 2-5 depict energy generation according to different traffic counts assumptions.

In scenario 5, same number of vehicles are considered irrespective of the vehicle class, though it is noticeable that larger difference in the generated energy.

Table 2: Analysis of Generated Energy from varying vehicle count.

Vehicle Count	Energy Generated(kWh)	Lighting Up of LED Bulbs Period (100 W)
100 (C:45, B:10, T:5, M:40)	1.84 (CE:0.477, BE:0.796, TE: 0.504, ME:0.072)	1 bulb for 18.4hrs
500 (C:250, B:100, T:50, M:100)	15.83 (CE:2.654, BE:7.962, TE: 5.042, ME:0.180)	6 bulbs for 24hrs
1000 (C:20, B:150, T:440, M:210)	58.82 (CE:2.123, BE:11.943, TE:44.378, ME:0.379)	24 bulbs for 24hrs
5000 (C:1200, B:900, T:550, M:2350)	144.11(CE:12.74, BE:71.663, TE:55.472, ME:4.241)	60 bulbs for 24hrs
10000 (C:2500, B:2500, T:2500, M:2500)	482.26 (CE:26.541, BE:199.064, TE:252.147, ME:4.512)	200 bulbs for 24hrs

4 DISCUSSION

This part will explore the returns of the investment and the challenges that the system may face in the real world.

4.1 Estimation of Return of Investment

We now illustrate the scenario of Motorway 50 (M50) of Dublin, Ireland to demonstrate the returns obtained by installing it with piezoelectric plates. The construction cost of the entire motorway was €1 billion (Paschal Donohoe, 2020). Consider the following requirements for infrastructure development for the construction roads laid with piezoelectric plates.

The estimated number of generators required for a 1 km patch of a 2-way road are 13,333. Thus, the entire 4-lane motorway will require 53,332 generators considering the cost of each individual generator to be €25 (Garland, 2013). For a 4-lane road covering a distance of 45.5 km we have the approximate cost as 45.5×53332×25 which results in €60,665,150 (approximately €60.6 million). Moreover, labour and installation costs needed for laying the piezoelectric tiles beneath the road will be around € 5 million and €7 million respectively (Chew et al., 2017), also an additional miscellaneous amount of € 10 million is considered. Hence the entire budget becomes €1 billion + €60.6 million + €5 million + €7 million + €10 million which amount to €1.082 billion.

The average power output obtained from the piezoelectric generators can be estimated by considering the following traffic scenario:

- Average traffic volume is 420,000 per day (Baker., 2020)
- Average Speed of vehicles: 60kmph
- Power generated 175176.4 $\times 10^{-7}$ kWh (per vehicle) from formulas (1) - (5) discussed in section 3.2
- Total power generated from the average traffic volume = 7357.4 kWh

To calculate power generated from the entire road patch of 45.5 kms we have,

Total power generated = 45.5 × 7,357.4 × 365
= 122,188,020.5 kWh

Currently, the Government of Ireland charges 17.67 cent/kWh for the electricity, thus revenue generated from the generated electricity would be

= 122,188,020.5 kWh × 17.67
= €21,590,623.22
= €21.6 million (approx.)

Hence, the amount invested to lay piezoelectric plates on M50 road will be recouped in approximately 5-6 years with the added labour costs and other requirements. Knowing that the average life of piezoelectric tiles to be around 30 years strongly implies that the income generated by adopting this technology can have roughly 24 years of profits.

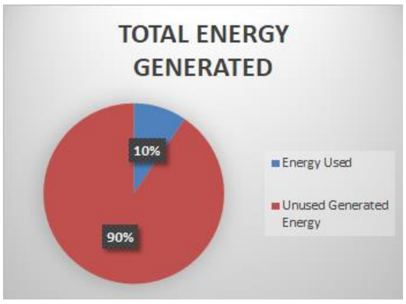

Figure 8: Total energy generated and energy consumed.

Now let's consider the scenario, for instance, on a 200m patch of a road with 100,000 vehicular traffic each day. Let this stretch have around 9 street lamps (High-Pressure Sodium (HPS) Lamp) installed. Now assuming that these 9 lamps each utilize 225 W per hour, the energy required to light up the 9 street lamps for 2 months, assuming they are used for 10hrs per day, is 1215kWh. If we lay piezoelectric tiles on this 200m patch, then the energy generated is 12,740 kWh (2 months), which further can be used to light up the lamps. The comparison of energy generated and energy consumed for lighting 9 HPS lamps is highlighted in figure 8. The unused generated energy (11525kWh) can be stored in Energy storage devices. In addition to this, it can be used for electric vehicle charging stations or can be distributed through the electrical grid.

4.2 Challenges

The energy harnessing system using piezoelectric material produces green, safe, and renewable energy which can be generated at a high scale. In-spite of all these positive sides, the system needs to resolve the issue with respect to storing the generated energy. The batteries' efficiency to convert the energy is not constant and sometimes it is low. The available technology of the storage system (for instance Batteries) highly influences the efficiency of the energy harnessing system. It must be understood that the rechargeable batteries have a fixed lifespan to consider the option of recharging the depleted batteries. In some cases, due to limited storage, batteries can seldom store only 50% of the generated energy. However, dependency upon batteries can be reduced or eliminated by choosing an independent method for the energy harvesting system on the roads. Thus, the direct use of generated electric energy is highlighted by the above approach Si.e., energy must be used as it is produced. In such a self-sustaining way, energy loss can be reduced. The other aspect to address is around maintenance costs of the piezoelectric plates or sensors which are embedded within the pavement layers. Therefore, each time the plates need to be repaired or changed, the asphalt layers of the road must be removed and reopened. Such repairs will incur additional costs. This issue can be resolved by improving robustness of transducers.

5 CONCLUSIONS

This paper discussed the possibility of harnessing piezoelectric energy from vehicular traffic in busy roads. The authors design SVM and GLM regression models to estimate the electricity that can be generated from traffic counts of different road vehicles. The authors comprehensively discuss the potential return on investment by adopting this architecture for a sample express highway case. The authors strongly validate the potential advantages that can be incurred by adoption of this technology through depiction of vast amounts of energy that can be generated and potentially redistributed in various settings. Finally, the authors through a comparative tabulation with other popular renewable energy sources bring forth the low maintenance and natural environment preservation that is possible through adoption of this technology.

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