Sustainability Analysis of Innovative Transport System

Ieva Meiere[1], Gatis Bazbauers[2], [1-2]*Institute of Energy Systems and Environment, Riga Technical University*

***Abstract* – The focus of the research is to develop a new approach to transport solution based on the use of a conveyor-type system and to compare the environmental impact of the new system with the existing ones. The new transport system consists of a conveyor driven by an electric motor, with a wind power plant supplying electricity, hydrogen storage and a fuel cell for matching the wind power production with the motor load. The research tasks included the evaluation of the consumption of fossil fuels and the associated environmental impact of existing transport system and a comparison with energy consumption and associated environmental impact of the new system. The energy balance of the conveyor transport system was modelled on an hourly basis by using the EnergyPLAN computer program [1] which allows to analyze a combination of intermittent renewable energy technologies, storage and transport systems. The results show that the existing transport system has greater impact on the environment than the proposed one.**

***Keywords* – energy storage, innovative transport system, renewable energy, sustainability analysis**

I. Introduction

Nowadays, one of the biggest sources of pollution in the cities is vehicular transport. Because of the increase of traffic flow and jams, the level of carbon dioxide emissions rises. During traffic jams, the level of carbon dioxide emissions increases up to 30%; even cars that are equipped with accelerants spread a considerable amount of carbon dioxide [2]. Hence, the European Commission has developed and attested the strategy that foresees reduction in the amount of harmful emissions from cars by 60% by the year 2050. Therefore, it is necessary to find solutions for achieving the target. A combination of renewable energy technologies with fluctuating character of production with transport systems based on electric drive can be a good solution for the increased sustainability of transport systems.

The aim of the research was to develop a concept for an innovative transport systems solution which is based on the conveyor type technology and to compare the environmental impact of the new transport system with the existing system. The existing transport system consists of fossil fuel driven internal combustion engines but the new system is made up of a conveyor belt-electric motor system, a wind power generator, electrolysis and hydrogen storage system, and fuel cell equipment for electricity generation from hydrogen during low wind hours. Therefore, in the new transport system, fossil fuel is replaced by wind power and the transport system provides storage of the wind generated electricity during hours of excess production.

II. Methods

Indicators of the environmental impact chosen for comparison consist of:

- A cumulative material consumption;
- Energy consumption;
- Greenhouse gas emissions.

Environmental impact assessment includes the impact caused by the establishment, operation and maintenance of the transport system. Fossil fuel consumption and related environmental impact during the use of the existing transport system based on internal combustion engines was determined, considering a certain section of road during traffic congestion. The energy required for the production and supply of the fuel to the existing transport system and the related environmental impact is considered in the study. The energy consumption associated with the installation, operation and maintenance of the new transport system is analyzed.

The Vansu bridge in Riga with its transport flow in the direction to the centre was explored and analyzed in the research, because it is one of the places most affected by traffic jams during the periods of 8 a.m. – 10 a.m. and 4 p.m. – 5 p.m. on working days. The new automated transport system consists of an electrically-driven conveyor technology; because these technologies have relatively low electricity consumption and can transport heavy objects. A combination of the wind energy and hydrogen-based electric storage system is used in order to utilize renewable energy sources at the greatest extent and to create reliable infrastructure. The traffic intensity in the surveyed road section is analyzed to determine electricity consumption of the conveyor transport system and consumption of fossil fuel of the existing transport system. Environmental impacts of the existing transport system are estimated both for the operation phase (fuel consumption and pollution from vehicles) and the fuel extraction phase, including energy and material consumption, and emissions created. Environmental impact of the wind generator-hydrogen system is determined when the new transport system is analyzed. Environmental impact caused by the installation of the conveyor belt and electric motor system is not included in the scope of the study. In order to determine how much of the wind turbine power can be used directly to drive the electric conveyor and how much has to be stored, and subsequently recovered, by hydrogen-fuel cell system, modelling is done on an hourly basis for the whole year using the EnergyPLAN computer program which is well suited for this type of analysis. Hourly wind production profile which is used in the modelling corresponds to the actual wind power generation profile in Latvia during 2008. The modelling makes it possible to determine the optimal size of the wind generator, capacities of the hydrogen storage and fuel cell systems.

III. THE EXISTING TRANSPORT SYSTEM

One of the biggest air pollution sources in Riga is vehicular transport. It increases during traffic congestions. The number of vehicles which cross the Vansu bridge during congestions is 1500. The highest concentration, when the speed is the smallest, is in the mornings, during the period of 8 a.m. – 10 a.m. and in the afternoons from 4 p.m. till 5 p.m. During these periods, the speed of cars is small – 0-30 km/h [3]. Most of the vehicles are powered by gasoline, i.e. 75% of the total number of vehicles which are crossing the bridge, and 25% of them are powered by diesel fuel [4]. During traffic congestion, the emissions of pollutants from exhaust gases – carbon monoxide, carbon dioxide, volatile organic compounds, hydrocarbons, nitrogen oxides, particulate matter and other pollutants increase. CO_2 emissions will increase in the idle mode, as well as during acceleration and braking [5,6,7]. Calculation of CO_2 emissions, depending on the car speed is done by using the following formula [8]:

$$EF = \left(a + bv + cv^2 \times \ln(v) + gv^3 + \frac{h}{v} + \frac{i}{v^3} \right) \times x \qquad (1)$$

where,
a – constant – 36.25 for gasoline vehicles and 43.74.for diesel vehicles;
b – constant – 0 for gasoline vehicles and -0.246 for diesel vehicles;
c – constant – 0 for gasoline vehicles and 1.65×10^{-5} for diesel vehicles;
g – constant – 1.32081×10^{-5} for gasoline vehicles and 2.7262×10^{-5} for diesel vehicles;
h – constant – 655 for gasoline vehicles and 428 for diesel vehicles;
i – constant – 12.2 for gasoline vehicles and 0 for diesel vehicles;
j – constant – 0 for both types of vehicles;
x – constant – 3.14 for both types of vehicles;
v – speed (km/h);
EF – emission factor (gCO_2/km) [8]

As a result, it was found that 562 g of CO_2 are emitted from one gasoline-driven engine vehicle, and 408 g of CO_2 are emitted from the diesel engine vehicle when driving a 700 m long distance, which is the length of the considered bridge. During the year, the total amount of the emitted CO_2 emissions is 563 tons. The fuel consumption (g/km) can be calculated using the formula (1), by changing the constant *x* to value 1 for both types of engines [9]. As a result, the specific fuel consumption of a gasoline vehicle is 179 g or 30 l/100 km and 130 g or 22 l/100 km of the diesel engine when driving the considered 700 m long distance. During the year, the total consumption of fuel is 144 tons of gasoline and 35 tons of diesel. The lower calorific value of gasoline is 43.7 MJ/kg and for diesel that is 41.8 MJ/kg. Therefore, 7.8 TJ of fossil energy is consumed per year.

The impact on the environment is also in the fuel extraction stage. The above amounts of materials, energy and emissions are determined using life cycle inventory data [10, 11]. The total material consumption is 216 tons and the total primary energy consumption is 289 MWh. 27 % of the total primary energy is delivered from renewable energy sources (wind and solar energy are used). 112 tons of CO_2 equivalent are emitted in the fuel extraction stage which is 17 % of the total emissions caused by the existing transport system.

IV. INNOVATIVE TRANSPORT SYSTEM

The innovative transport system is based on an electrically driven conveyor belt-type system which is operated only during rush hours. Accordingly, during rush hours the vehicles drive up to the conveyer, turn off their engines and are moved by conveyer across the river. Originally, conveyor belts were used to transport a variety of industrial products, minerals, as well as products of different factories. In recent years, these systems have gained popularity in the transportation of people from one place to another. In this paper, it is offered to use this type of technology for road transport during traffic congestion. As a result, there are no emissions from the vehicles and the traffic flow can be improved. It is assumed in the study that the conveyor system is installed on the Vansu bridge in Riga, across the river, and the conveyor is mounted only on one side of the bridge – in the direction towards the city centre, since this is the direction of traffic congestion in the morning and evening hours. The length of the conveyor is 0.7 km, and it would work during peak hours when traffic is at the lowest flow rate. The system could be equipped with an automated software and sensor system regulating the belt speed and halting the operation if necessary. Since the flow of traffic in each band is different, each band can be equipped with its own sensor. Similarly, the establishment of a separate bar for public transport can be created. Each lane (except for the public transport) would be incorporated into the two conveyor belts, which are a bit wider than the width of the vehicle, so that any type of a vehicle can easily drive onto the belt. When the vehicle is on the belt, the engine is turned off and it is moved by the conveyor as shown in Figure 1.

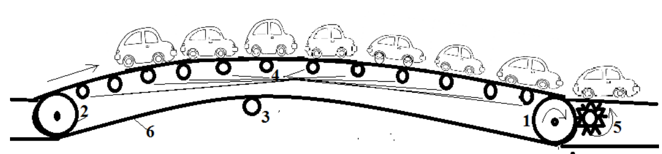

Fig. 1 The conveyor technology for transportation of vehicles.

The conveyor consists of a closed ribbon (6), which covers the engine coil (1) and change of direction coil (2), motor – operated, belt retractor (3), roller supports (4) (steelstrips of a lenght of about 5-10 cm less than the width of the ribbon) and the conveyor support structure. Retraction garantees a continous ribbon sprain. The most common conveyor belts are made of rubber, but in this case high strength steel would be used, as it would reduce wear and would be able to move heavy objects. Steel would be workable on non-slip material to prevent the vehicle from sliding. In addition, wire brush (5) would be used with the task to clean the belt. Its direction of movement is opposite to the direction of the belt. The belt is stopped using a ratchet – it consists of a ratchet and triggers the coil to apply to only one direction. If the motor stops, the coil movement in the opposite direction is stopped by the catch [12,13,14]

In order to determine the conveyor capacity, it is necessary to know such values as: the conveyor's productivity, the ribbon speed, the mass and length of the conveyor. To calculate the power, first, the driving coils circumference power has to be determined, which is calculated by the formula:

$$P = C\omega' L_1\left(q_0 + \frac{Q}{3{,}6v}\right) \pm \frac{QH}{3{,}6v} \quad (2)$$

where:

ω' – the factor which characterizes the resistance to motion caused by roller supports;

C – coefficient characterizing element of drawing the resistance to motion caused by conveyor coils;

L_1 – the horizontal conveyor length (m);

v – belt speed (m/s)

q_0 – drawing element current meter weight (N/m)

H – lifting height (m)

Q – conveyor capacity (kN/h) [14]

The coefficient of the motion resistance caused by roller supports is in the range of 0.02 to 0.06. The higher value corresponds to the conveyor's operation in unheated, damp and dusty spaces [14]. Since the conveyor is located outdoors and is exposed to road dust, the adoption of a resistance coefficient of the highest value – 0.06 is appropriate. The conveyor belt speed is 0.84 m/s. This is determined by knowing the number of cars, i.e. 1500, crossing the bridge within an hour. It is assumed that one car has a mass of 1.5 t. Since the belt carries 175 vehicles at the same time, the total moving mass on one belt is 263 000 kg.

Coefficient C can be calculated by the following formula:

$$C = 0{,}55 + \frac{35{,}1}{L_1} \quad (3)$$

Knowing the driving coils circumference force, the required engine power can be calculated by the formula:

$$N = \frac{Pv}{1000\eta}\ [\text{kW}] \quad (4)$$

where:

v – speed (m/s);

η – engine efficiency (0.93) [14]

Since the conveyor operates only during traffic congestions, i.e., 3 hours per day during a year, or 717 hours per year (it is taken into account that during vacation time and school holidays there are practically no congestions, and maintenance of the conveyor can be conducted during these periods). Therefore, the calculated conveyor power is 96 kW. As each traffic lane has a separate conveyor, the total power required for vehicle handling is 192 kW. Since the conveyor operates for 717 hours, the annual power consumption is 137 MWh per year.

V. Results and Discussion

The electricity for the innovative transport system will be provided from a renewable energy source, in order to minimise the harm to the environment. Figure 2 shows the electricity consumption of the conveyor and onshore wind power generation on an hourly basis during one working day in January, corresponding to the used hourly distribution of an annual wind generation profile in Latvia. It was estimated that the installed capacity of the wind turbine for the studied innovative transport system should be 0.2 MW.

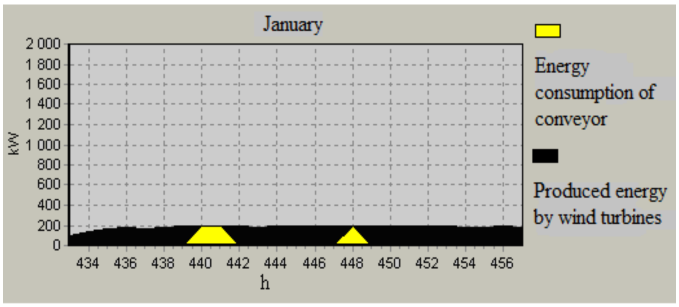

Fig. 2. Consumption of electricity by the conveyor and electricity produced by wind on a working day in January, when the onshore 0.2 MW wind turbine operates at maximum capacity.

During the period shown in Figure 2, the wind turbine with the given installed capacity can completely cover the electricity consumption of the conveyor, and there is no need to use a hydrogen-driven fuel cell system for electricity generation. However, during the days when the wind turbine produces power which cannot be fully utilized by the conveyor, this electricity has to be stored for the periods of low-wind production when the electricity consumption of the conveyor exceeds the wind power production (Fig. 3).

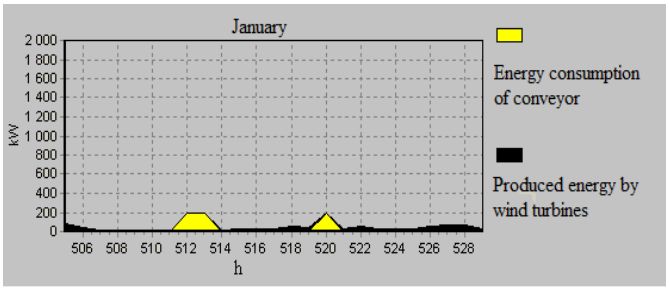

Fig. 3 Consumption of electricity by the conveyor and electricity produced by wind during a day in January, when the onshore 0.2 MW wind turbine is not operating at maximum capacity.

As Figure 3 shows, depending on the weather conditions, there are days when the electricity generated from wind can provide only a small amount of electricity required by the conveyor. Therefore, it is necessary to use the previously stored energy. It is typical during autumn and winter (e.g. October and February) that the total wind generated electricity is larger than the one required by the conveyor. During other periods of the year, there is a need to make use of the stored energy because of the insufficient wind generation. Therefore, it is necessary to establish a system for storing wind energy, in order to ensure a smooth supply of electricity when needed by the conveyor system (Fig. 4).

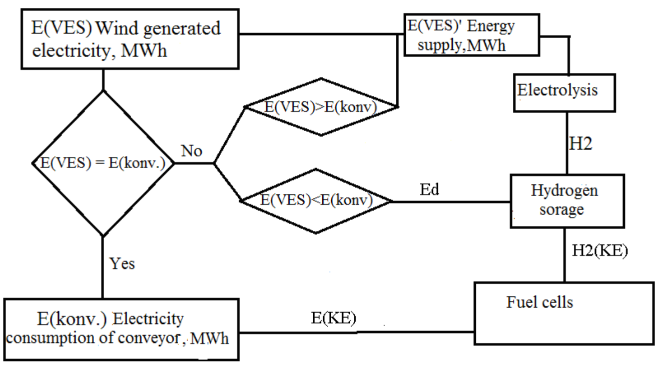

Fig. 4. Algorithm of the operation of the wind – hydrogen – fuel cell system.

Wind turbine electricity production (E_{VES}) covers the electricity consumption of the conveyor (Ekonv) (Fig. 4). If the amount of the generated electricity by wind turbines is larger than the power consumption of the conveyor, the part equivalent to the electricity consumption of the conveyor is directly covered by the wind turbine, but the excess amount of the electricity (E_{VES}') is used in electrolysis to obtain hydrogen. Electricity surplus is calculated as follows:

$$E_{VES}' = E_{VES} - E_{konv} \qquad (5)$$

where,
E_{VES}' – wind turbine electricity production surplus (MWh)
E_{VES} –electricity generated by the wind turbine (MWh)
E_{konv} –electricity consumption of the conveyor (MWh)

Wind generated electricity is converted into hydrogen and stored even when the conveyor is turned off. If the amount of the electricity generated by the wind turbine is less than the electricity consumption of the conveyor, the deficit amount E(KE) is provided by using the previously stored energy from the fuel cell equipment. Electricity consumption of the conveyor, which can not be directly covered by the wind turbines, is calculated as follows:

$$E_d = E_{konv} - E_{VES} \qquad (6)$$

where,
E_d – the electricity deficit, which needs to be covered from the stored energy in the hydrogen-electrolysis-fuel cell system (MWh)

In order for the fuel cell produced electricity to be able to cover the electricity deficit, the following conditions must be satisfied:

$$E_d = E(KE) \qquad (7)$$

where,
E(KE) – the fuel cell generated electricity (MWh)

As a result, by using the above scheme, the wind-hydrogen system is able to fully cover the electricity consumption of the conveyor.

Assessment of the environmental impact also considers the amount of energy and materials needed to manufacture wind turbines, electrolysis system, pipes and compressors, fuel cells and hydrogen storage tanks, as well as emissions created by these processes. The above amounts of materials, energy and emissions are determined using the life cycle inventory data [15, 16, 17]. The greatest amount of materials is needed for manufacturing of the wind turbine, i.e. 96 tons. 1.7 tons of materials are required for production of the electrolysis equipment and 1 ton for the fuel cell. Energy consumption is the largest for production of the electrolysis equipment, i.e. 22 MWh, for the fuel cell 10 MWh are required and for the wind turbine only 5.4 MWh are needed. Manufacturing of the given wind turbine causes 4 tons of CO_2 emissions, 3 tons are caused by production of the electrolysis equipment and 5 tons originate from manufacturing of the fuel cell.

In order to determine whether the proposed transport system is superior over the existing fossil-fuel driven system from the point of sustainability, it is necessary to compare the material consumption, the energy input and the emissions resulting from the installation and operation of both systems. Figure 5 shows a comparison of the material consumption of the existing and new transport systems calculated per one year of service.

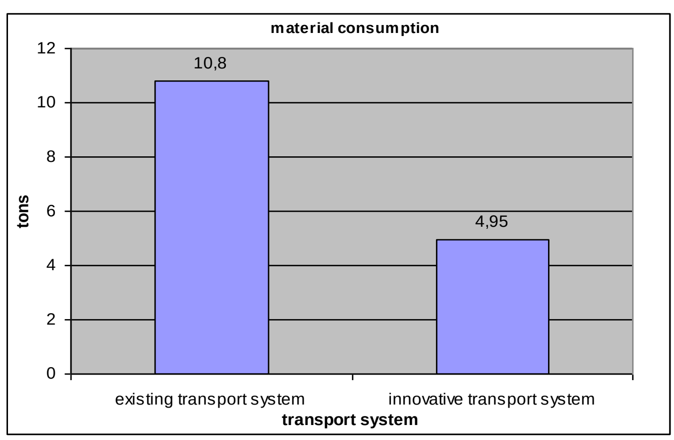

Fig. 5 Comparison of material consumption of the existing and the new transport systems calculated per one year of service.

The material consumption of the existing transport system is twice as large as that of the innovative transport system. Water accounts for 85% of the total resource consumption of the existing transport system and 13 % of the resource consumption consist of rocks. The rest is made up by materials such as barites, bentonite, calcium carbonate, clay, iron, sand and ground. The wind turbine requires 97 % of the total resource consumption needed for an innovative transport system. Hydrogen storage tanks require mainly steel as the material, because steel has a high degree of strength to be able to store the hydrogen under 200 atmospheres of pressure.

Also, the energy consumption calculated per one year of service of the existing transport system is significantly greater, i.e. six times, than for the innovative transport system (Fig. 6).

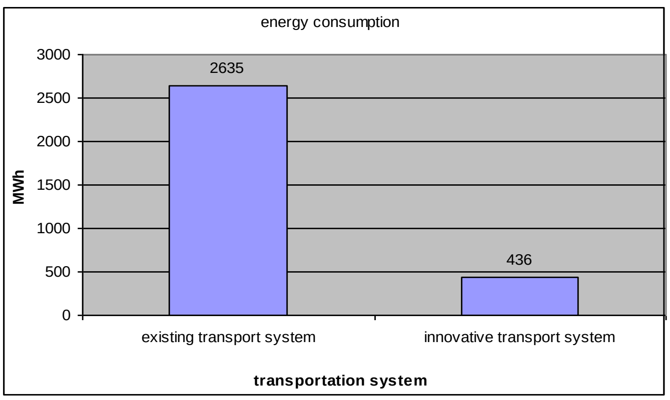

Fig. 6 Comparison of energy consumption of the existing and the innovative transport systems calculated per one year of service.

89% of the total energy consumption of the existing transport system comes from the fuel consumption of internal combustion engines during the operational stage. The remaining 11 % are input in the fuel extraction stage. Of the total energy input to the existing transport system, 3% are delivered from renewable sources. The wind turbine produces 91% of the total energy consumption needed for the innovative transport system and 9%, which are needed for creating the system itself, are supplied from fossil energy sources.

The results of the study have revealed that the CO_2 emissions calculated per one year of service are only 0.6 tons for the new transport system, as opposed to 669 tons of CO_2 for the existing system. This great difference is explained by the emissions created during the fuel combustion of the existing transport system. Since a renewable energy source is used during the operation of the innovative transport system, CO_2 is emitted from the system only during the manufacturing and construction phase.

VI. Conclusions

As the results show, the environmental impact, according to the chosen environmental indicators, of the existing transportation system is many times greater than that of the innovative transport system. This large difference is due to the considerable fossil energy consumption and emissions associated with that of the existing transport system. The proposed new transport system is an effective solution for increasing the share of renewable energy sources in the transport sector and may improve the traffic situation during congestion periods. Therefore, this type of innovative transport system is advancement to a more sustainable transport system. Further research could consider heat generated by the hydrogen-electrolysis-fuel cell system for district heating purposes and a combination of some other renewable energy and storage solutions.

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Ieva Meiere, Mg.sc.ing., Riga Technical University, Institute of Energy Systems and Environment. Ieva Meiere has been student of Faculty of Energy and Electrotechnics, Riga Technical University Institute of Energy Systems and Environment from the 2006 to the 2011. The main research area is renewable energy resources, hydrogen, and energy storage. She has Environmental Protection Bachelor Diploma (2009) and Environmental Protection Master Diploma (2011). Master thesis "Sustainability Analysis of Innovative Transport System" was presented in the 52nd International Scientific Conference of Riga Technical University, Section "Environmental and Climate Technologies" (13. October 2011).
Address: Kronvalda bulv.1, LV-1010, Riga, Latvia
Phone: +371 22123149
E-mail: ieva.meiere@inbox.lv

Gatis Bazbauers, Dr.sc.ing., has a diploma of thermal engineering (1990), master of science degree in mechanical engineering (1995), doctor of science degree in engineering (1999) and bachelor's degree in business administration (2002). He works in the Institute of Energy Systems and Environment, Faculty of Energy and Electrical Engineering at Riga Technical University from the year 2000, and currently is a Professor. He worked as a Managing Director in the energy company "Vattenfall Latvia" (1995-2007), as a Project Manager in the energy consulting company "EEE" (1992-1993) and as an Assistant in the Riga Technical University (1990-1993). The main research interests are district heating systems and cogeneration, energy system planning and economics, renewable energy sources, ecodesign, life cycle assessment. Gatis Bazbauers is a member of the council of Latvia's District Heating Association.
Phone: +371 67089911
E-mail: gatis.bazbauers@rtu.lv

Ieva Meiere, Gatis Bažbauers. Inovatīvas transporta sistēmas ilgtspējības analīze.
Darba mērķis ir izstrādāt jaunas transporta sistēmas risinājuma koncepciju, kas balstās uz konveijertipa sistēmas izmantošanu un salīdzināt šīs sistēmas ietekmes uz vidi rādītājus ar pastāvošo sistēmu. Darba uzdevumos iekļauts fosilo energoresursu patēriņu un ar to saistīto ietekmi uz vidi izvērtējums esošai transporta sistēmai, aplūkojot noteiktu ceļa posma daļu sastrēgumstundās, kā arī aprēķini, lai noteiktu jaunās transporta sistēmas enerģijas patēriņu un ar to saistīto ietekmi uz vidi, aplūkojot iespējamos energoresursu veidus un izvērtējot jaunās transporta sistēmas iespējas vēja elektrostaciju ražotās elektroenerģijas uzkrāšanā. Lai noteiktu inovatīvās transporta sistēmas ietekmi uz vidi, vispirms ir nepieciešams noteikt konveijera elektroenerģijas patēriņu, lai pēc tam varētu noteikt visus pārējos lielumus – vēja turbīnas jaudu, vēja – ūdeņraža sistēmas ietekmi uz vidi. Vēja turbīnas jaudas noteikšanai, tiek izmantota EnergyPLAN datorprogramma. Ar šīs datorprogrammas izmantošanu, tiek noteikts arī saražotais vēja elektroenerģijas daudzums, elektrības daudzums, kādu nepieciešams uzkrāt u.c. lielumi. Rezultātā tiek iegūti dati, ka inovatīvai transporta sistēmai ir ievērojami mazāka ietekme uz vidi. Tas izskaidrojams, ar esošās transporta sistēmas ievērojamo enerģijas patēriņu un emisiju apjomu, kas ir saistīti ar degvielas patēriņu. Inovatīvā trnsporta sistēma ir efektīva, lai samazinātu šo emisiju daudzumu, kas rodas sastrēgumu laikā.