ENVIRONMENTAL EFFICIENCY OF ELECTRIC VEHICLES AND SUSTAINABLE DEVELOPMENT OF UZBEKISTAN: A LIFE CYCLE APPROACH

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Abstract. *The article analyzes the environmental efficiency of electric vehicles using a life cycle approach. The environmental burden at the manufacturing, operation and end-of-life stages is considered, and the decisive role of the electricity generation mix is shown. For the conditions of Uzbekistan, the paper substantiates the effect of electric transport on urban air quality, the role of regenerative braking and energy-saving control algorithms, and the contribution to the Sustainable Development Goals. The results can support practical recommendations for transition of the transport sector to a green economy.*

Keywords: *electric vehicles, sustainable development, life cycle assessment, environmental efficiency, regenerative braking, green economy.*

Annotatsiya. *Maqolada elektr transport vositalarining ekologik samaradorligi hayot sikli yondashuvi asosida tahlil qilingan. Ishlab chiqarish, ekspluatatsiya va utilizatsiya bosqichlaridagi ekologik yuklama ko‘rib chiqilib, elektr energiya ishlab chiqarish tarkibining hal qiluvchi ahamiyati ko‘rsatilgan. O‘zbekiston sharoitida elektr transportdan foydalanishning shahar havosi sifatiga ta’siri, regenerativ tormozlash va energiya tejovchi boshqaruv algoritmlarining roli hamda barqaror rivojlanish maqsadlariga erishishdagi o‘rni asoslangan. Natijalar transport sektorini «yashil» iqtisodiyotga o‘tkazish bo‘yicha amaliy tavsiyalarni shakllantirishga xizmat qiladi.*

Kalit so‘zlar: *elektr transport vositalari, barqaror rivojlanish, hayot sikli tahlili, ekologik samaradorlik, regenerativ tormozlash, «yashil» iqtisodiyot.*

Аннотация. *В статье на основе подхода жизненного цикла проанализирована экологическая эффективность электрических транспортных средств. Рассмотрена экологическая нагрузка на этапах производства, эксплуатации и утилизации, показано определяющее значение структуры генерации электроэнергии. Применительно к условиям Узбекистана обоснованы влияние электротранспорта на качество городского воздуха, роль рекуперативного торможения и энергосберегающих*

алгоритмов управления, а также вклад в достижение целей устойчивого развития. Результаты могут быть использованы при выработке практических рекомендаций по переходу транспортного сектора к «зелёной» экономике.

Ключевые слова: *электрические транспортные средства, устойчивое развитие, оценка жизненного цикла, экологическая эффективность, рекуперативное торможение, «зелёная» экономика.*

INTRODUCTION

Economic growth, urban expansion and population increase are steadily raising the energy consumption of the transport sector and its impact on the environment. Vehicles with internal combustion engines are a major source of greenhouse gases, nitrogen oxides and particulate matter, and they contribute significantly to the deterioration of urban air quality and to risks for public health. Reports of the Intergovernmental Panel on Climate Change identify emissions related to energy supply and transport as one of the main drivers of climate change [6].

The concept of sustainable development was defined in the report of the Brundtland Commission as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1]. Among the 17 goals of the United Nations 2030 Agenda, those directly related to transport are Goal 7 (affordable and clean energy), Goal 11 (sustainable cities and communities) and Goal 13 (climate action) [2].

Electric vehicles (EVs) are often described as «zero-emission». However, this description refers only to tailpipe emissions at the place of use and does not cover the entire existence of the product. A scientifically sound assessment of environmental efficiency requires Life Cycle Assessment (LCA), which accounts for all stages from raw material extraction to disposal [3, 4, 9].

In 2019 Uzbekistan adopted a strategy for the transition to a green economy for 2019–2030, which sets out tasks on improving energy efficiency, expanding the share of renewable energy and improving the environmental performance of the transport sector [7]. In recent years the use of electric vehicles in the country has been growing, and an objective assessment of their environmental impact has therefore become a relevant scientific and practical task.

The aim of this study is to analyze the environmental efficiency of electric vehicles across the stages of their life cycle, to identify the main factors affecting it, and to substantiate directions that serve the sustainable development of Uzbekistan.

MATERIALS AND METHODS

The study is based on the analysis of international scientific publications, reports of international organizations and regulatory documents of the Republic of Uzbekistan. The environmental assessment follows the principles of life cycle assessment set out in the ISO 14040 standard, using a «cradle-to-grave» system boundary [9]. One kilometre travelled by a vehicle was adopted as the functional unit, which makes it possible to compare different technologies on a common basis.

The work uses systems analysis, comparative analysis, synthesis and generalization. The efficiency of the electromechanical system was considered by assessing energy losses along the chain «traction battery – inverter – electric motor – transmission – wheel». The conclusions presented in the article are qualitative; specific numerical indicators should be supplemented by separate measurements and calculations for local conditions.

RESULTS AND DISCUSSION

3.1. Manufacturing stage: Life cycle studies show that the environmental burden of an EV at the manufacturing stage is higher than that of a conventional car. The main reason is the high energy and material intensity of producing the traction lithium-ion battery [3, 4]. Battery production requires electrode materials (lithium, nickel, cobalt, manganese, graphite), copper and aluminium, whose extraction and processing are associated with water use, land disturbance and air pollution. The environmental advantage of an EV therefore appears through compensating this initial «environmental debt» during the use phase.

3.2. Use phase and the electricity mix: During operation, the environmental performance of an EV depends primarily on the sources of the electricity used for charging. Comparative LCA studies indicate that in regions where electricity is generated mainly from coal, the climate benefit of EVs is limited, whereas in grids with low-carbon generation it is considerably higher [3, 5].

In the power sector of Uzbekistan, most thermal power plants operate on natural gas. Because natural gas releases less carbon per unit of energy than coal, this creates a comparatively favourable starting condition for EVs. At the same time, the expansion of the share of renewable sources, namely solar and wind power plants [7], is the main factor that can further increase the environmental efficiency of EVs. In other words, the electrification of transport and the decarbonization of the power grid are interdependent processes and must be carried out together.

From the standpoint of urban ecology, the most important advantages of EVs are the absence of local exhaust emissions and lower noise levels. In densely populated cities such as Tashkent, Andijan and Samarkand, road transport is one of the principal sources of air pollution; electrification of public transport and service

vehicles therefore has a direct positive effect on public health. It should be remembered, however, that part of the particulate matter originates from brake and tyre wear and from road dust resuspension, and these sources remain in EVs as well.

3.3. Energy efficiency of the electromechanical system: The energy efficiency of an EV depends on the efficiency of its electromechanical system. An electric drive has a higher efficiency than an internal combustion engine, so a larger share of the energy is delivered to the wheels. Nevertheless, every link of the system, namely the battery, inverter, motor and transmission, has losses, and together they determine the final energy consumption [8].

Regenerative braking makes it possible to return part of the kinetic energy to the battery as electricity during deceleration. This is especially effective in urban stop-and-go driving cycles: it reduces energy consumption, slows the wear of friction brakes and consequently reduces particulate emissions [8]. Optimization of motor operating modes, energy-saving control algorithms that adapt to driving conditions, and battery thermal management are further important reserves for reducing energy consumption in use. Each percent of energy saved means a proportional reduction of emissions associated with electricity generation over the entire life cycle.

3.4. End of life and second use: The final stage of the life cycle, which includes collection, recycling and disposal of batteries, is an important component of EV environmental efficiency. Given the limited availability of resources, recovering valuable metals through recycling reduces the demand for primary raw materials and the associated environmental burden. Using batteries that no longer meet vehicle requirements but are still functional in stationary energy storage systems («second life») extends their service life and helps integrate renewable energy into the grid. Creating such a system in Uzbekistan requires collection infrastructure, standards and a regulatory framework that allocates responsibility among producers, importers and users.

Table 1. EV life cycle stages and environmental impact

Life cycle stage	Main environmental impact	Mitigation direction
Raw materials and manufacturing	High energy and material use, mining impacts	Use of clean energy, material efficiency, responsible sourcing
Operation	Indirect emissions depending on electricity mix; particulates	Grid decarbonization, regenerative braking, control algorithms
End of life	Battery waste, hazardous substances	Recycling, «second life» use, collection system

3.5. Practical directions for Uzbekistan: On the basis of the analysis, the following directions can be proposed to increase the contribution of EVs to sustainable development in Uzbekistan. First, transport electrification should be combined with decarbonization of the power grid, including development of solar-powered charging stations. Second, public passenger transport and urban service vehicles should be electrified as a priority, since their annual mileage is high and the environmental benefit materializes faster. Third, a regulatory framework for the collection, recycling and second use of batteries should be created. Fourth, scientific research on improving the efficiency of electromechanical systems should be supported, and an LCA database adapted to local conditions (hot climate, dusty air, road quality) should be developed. Fifth, objective information on the full environmental impact of EVs should be disseminated among the population and entrepreneurs.

CONCLUSION

The results show that the environmental efficiency of electric vehicles is not a single-stage indicator but the outcome of a complex system covering manufacturing, operation and disposal. The higher burden at the manufacturing stage is compensated during use faster the cleaner the electricity mix is. Therefore, in Uzbekistan, the electrification of transport will contribute most to the Sustainable Development Goals when it is carried out together with the development of renewable energy, the introduction of energy-saving electromechanical systems and the creation of battery recycling infrastructure. Future work is planned to perform quantitative LCA calculations for the local electricity mix and climate conditions.

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