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Economic Aspect and Secondary Use of Electric Vehicle Batteries: EU Trends and Household Energy Balance Optimization Using Linear Programming

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Abstract

The rapid development and spread of electric vehicles is fundamentally revolutionizing transportation in the European Union and around the world. With the diffusion of electric vehicles, issues related to the batteries that power them have also become more prominent. Given that the production of these components is one of the most environmentally burdensome processes, the need for their secondary use has quickly become evident. Based on the Eurostat database, this article analyzes the indicators that may influence the prospects for the secondary use of batteries. It examines the relationship between the GDP (Gross Domestic Product) of European Union member states and the number of electric vehicles, the share of renewable energy, and household electricity consumption. The results show that electric vehicle penetration and the use of renewable energy vary greatly among EU member states. The second part of the article examines battery data from an electric vehicle, the solar panel production of a family home, and electricity consumption using a linear programming model on a monthly basis. The objective function of the model makes it possible to minimize the amount of energy purchased from the grid. The resulting savings can be quantified. The article focuses on providing a foundation for the opportunities offered by the secondary-use battery market.

Keywords: batteries; secondary market; electric vehicles; recycling; renewable energy; vehicle to grid; European Union

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1. Introduction

The article presents the possibilities and necessity of the secondary use of batteries used in electric cars. It then examines the economic performance of European Union countries and analyzes the spread of electric vehicles in relation to this. This analysis may reveal development potential in terms of where the secondary battery market could be stronger within the European Union while also contrasting the situations in Western and Eastern European countries. In addition to examining a complex set of issues, the article also explores the potential integration of a vehicle battery into a household energy system in a European Union member state (Hungary), which serves as a practical example of the possibility of a secondary life cycle, and then concludes with a summary of the main findings.

Electric vehicles have experienced rapid growth in the European Union and many other parts of the world, thanks to various government subsidies and incentives. This growth has had a particularly intense impact on the development and manufacture of lithium-ion batteries, as they have become key energy storage devices for electric vehicles.

However, the batteries used in these vehicles need to be replaced once they reach the end of their primary life cycle, which is when they retain only 70–80% of their original capacity [1]. At this point, the batteries still have considerable remaining capacity that can be used in other ways. This stage is referred to as secondary use of the battery, which takes two basic forms. Reuse involves using the battery again in its original form, with minimal intervention, for example, when a battery removed from an electric car is installed in another vehicle or application with lower energy requirements. The other form is repurposing, which requires technological intervention to enable the battery to perform a new task, such as when a used electric vehicle battery is converted into a household energy storage device.

The significance of secondary use is multifaceted and crucial from a technological, economic, and environmental perspective.

It is important to clarify that the secondary use of batteries does not only mean their use as grid-connected energy storage devices, although this is one of their most prominent applications in so-called vehicle-to-grid (V2G) systems.

Integrating used batteries from electric vehicles into the power grid can increase grid stability and provide a number of other benefits, such as reducing exposure to the main grid, providing greater energy security and independence, and promoting a cleaner energy mix.

Secondary use also means that batteries with reduced capacity are not treated as waste, but as a valuable resource. European regulations set strict requirements for manufacturers in terms of traceability, collection obligations, and circular management, thereby indirectly encouraging repurposing.

However, the biggest driver of demand may be the fact that, as the share of renewable energy increases, so does the need for storage. Secondary use can significantly reduce the cost of the systems required for this.

The market for second-life applications of electric vehicle batteries is growing steadily year by year. According to [2,3], the market could reach $9.93 billion in 2031 and $4.2 billion in 2035. Alongside market growth, there is an urgent need for standardized protocols and a regulatory environment that facilitates the spread of V2G technology and secondary markets.

The article examines a comprehensive topic from a macroeconomic and technical perspective, addressing the following questions:

1. How can vehicle-to-grid (V2G) technology contribute to balancing the energy supply and demand at the household level in a European environment?
2. What correlations can be observed between macroeconomic indicators (GDP, share of renewable energy, electricity consumption) and the penetration of electric vehicles in individual countries?

To examine this complex issue, the article is structured into several main sections and subsections. Section 2 describes the methodology and database used, while Section 3 presents and evaluates the results of a comparative analysis at the national level. Section 4 focuses on a household-level case study, examining the theoretical aspects of secondary use. The article concludes with Section Discussion and Section Conclusions, which present future development directions and research limitations.

2. Macroeconomic and Energy System Background of European Union

In order to understand the applicability of batteries in electric vehicles, it is essential to examine both macroeconomic and energy trends, as well as the number of electric vehicles registered in European Union member states. The following subsections show the spread of electric vehicles, the share of renewable energy sources, and the patterns of electricity consumption in relation to the annual GDP of each member state. The analysis is based on the publicly available EuroStat database.

The macroeconomic analysis presented in the subchapters aims to reveal the correlation between the spread of electric vehicles and the main economic and energy indicators. Two hypotheses were defined during the analysis:

1. The penetration of electric vehicles is higher in countries with a higher GDP.
2. An increase in the share of renewable energy and the level of electricity consumption promotes the integration of electric vehicle batteries into vehicle-to-grid systems and the secondary use of batteries for energy storage purposes.

Table 1 presents the GDP values of the European Union member states and other associated European countries [4].

Table 1. Gross Domestic Product at Market Prices (current prices, million Euro) [4].

Country	2020	2021	2022	2023	2024
EU 27	13,579,019.2	14,787,713.6	16,136,043.0	17,199,527.6	17,956,656.6
Belgium	463,750.9	506,047.2	563,710.5	596,202.7	613,983.9
Bulgaria	61,912.5	71,378.4	86,082.4	94,709.3	103,723.0
Czech Republic	220,310.6	246,012.3	286,976.8	319,099.1	320,741.7
Denmark	312,118.3	343,318.6	380,567.4	374,173.6	392,400.7
Germany	3,449,620.0	3,676,460.0	3,953,850.0	4,185,550.0	4,305,260.0
Estonia	27,859.3	31,456.2	36,442.8	38,187.8	39,510.1
Ireland	381,728.7	448,445.1	520,718.4	524,728.8	562,794.2
Greece	167,539.5	184,574.6	207,854.2	225,196.9	237,573.4
Spain	1,129,214.0	1,235,474.0	1,373,629.0	1,498,324.0	1,591,627.0
France	2,318,276.2	2,508,102.3	2,653,997.2	2,826,541.5	2,919,899.9
Croatia	50,720.9	58,394.1	67,611.5	78,060.4	85,609.8
Italy	1,670,011.9	1,842,507.4	1,998,072.6	2,131,390.0	2,192,181.6
Cyprus	22,373.6	25,679.9	29,377.2	31,340.0	33,567.7
Latvia	29,224.3	32,283.8	36,099.7	39,372.4	40,208.4
Lithuania	50,264.6	56,679.7	67,455.5	73,792.8	78,409.8
Luxemburg	64,499.2	73,039.5	76,731.2	80,991.9	86,104.0
Hungary	138,954.5	154,971.7	169,054.8	197,902.0	206,208.5
Malta	14,370.5	16,677.3	18,273.0	20,545.9	22,462.5
Netherlands	816,463.0	891,550.0	993,820.0	1,050,133.0	1,122,459.0
Austria	380,317.9	406,232.1	448,007.4	473,226.7	484,222.8
Poland	531,827.4	583,001.4	661,712.3	751,931.7	845,651.9
Portugal	201,032.7	216,493.7	243,957.1	267,923.2	285,180.6
Romania	221,075.5	242,260.4	281,761.4	324,368.6	353,821.1
Slovenia	46,738.7	52,022.6	56,908.8	63,951.2	66,968.1
Slovakia	94,320.6	101,933.5	110,046.4	123,833.2	130,985.1
Finland	236,387.0	248,764.0	266,135.0	272,874.0	275,963.0
Sweden	478,106.9	533,953.6	547,190.4	535,176.8	559,138.7
Iceland	19,302.5	22,188.1	27,768.7	29,314.7	30,797.7

Table 1. *Cont.*

Country	2020	2021	2022	2023	2024
Liechtenstein	5618.0	6688.5	7011.9	7661.0	:
Norway	322,823.8	425,445.6	567,468.3	446,533.8	446,866.1
Switzerland	650,742.6	689,174.9	787,386.5	826,951.8	865,619.7
Bosnia and Herzegovina	17,755.9	20,014.7	23,324.1	25,523.8	26,194.8

The table shows data for the past five years, covering the period 2020–2024. Official GDP data for 2025 is not yet available in the Eurostat database. The table shows that there are significant differences in GDP data between European countries; in particular, there is a noticeable gap between Western and Eastern European Union member states. Data for the United Kingdom are not included, as the country left the European Union in 2019.

2.1. Electric Vehicle Penetration in the European Union

In July 2025, the European Union conducted a complex survey on the number of vehicles. Numerous analyses highlight the fact that the number of vehicles is steadily growing in Europe. These analyses reveal some interesting trends.

The total number of passenger cars in the European Union has grown significantly over the past five years, exceeding 259 million. There are huge differences between member states, whether we look at the number of vehicles per 1000 inhabitants or the age of the vehicles. Italy has the most cars per 1000 inhabitants, followed by Luxembourg and Finland. In 2024, Luxembourg had the youngest vehicle fleet, while the oldest vehicles were found in Romania and Finland [5]. According to surveys, in 2023 there was an average of 0.55 passenger cars per EU citizen, a slight decrease compared to 2022 [6]. In 2022, there were 560 vehicles per 1000 people, which is an increase of more than 14% compared to 2012 [7].

These figures reflect the total number of passenger cars but do not distinguish between alternative fuel vehicles. In 2024, the number of purely electric vehicles in the European Union approached 5.9 million. The share of battery electric vehicles (BEVs) in relation to all cars increased from 0.02% to 2.3% between 2013 and 2024 [5]. The highest proportions of new registrations were recorded in the following countries: Sweden, Denmark, Finland, and the Netherlands, while the lowest were in Hungary, Croatia, Slovakia, and the Czech Republic [8]. Table 2 shows the data for these countries from which conclusions can be drawn about the relationship between vehicle fleet size and GDP data.

Table 2. Number of vehicles, electric vehicle fleet, distribution, and economic indicators in 2024 [4–9].

		2024		
Country	**Total Vehicles**	**Electric Vehicles**	**%**	**GDP (Million Euro)**
Denmark	2,864,904	344,438	12.0227	392,400.7
Sweden	4,976,987	358,255	7.1982	559,138.7
Netherlands	9,247,810	569,144	6.1544	1,122,459.0
Finland	3,755,842	121,539	3.2360	275,963.0
Hungary	4,263,067	60,211	1.4124	206,208.5
Czechia	6,638,172	36,341	0.5475	320,741.7
Slovakia	2,722,491	14,612	0.5367	130,985.1
Croatia	1,987,156	10,045	0.5055	85,609.8

The table provides a summary of key data for each country in 2024, including the total number of vehicles, the number of electric vehicles, their share of the total vehicle fleet, and the GDP of each country.

Figure 1 illustrates the relationship between electric vehicle share and GDP data in graphical form. There are significant differences between countries; both the GDP and the proportion of electric vehicles in the four former socialist Eastern European states are significantly lower than those of Western European countries.

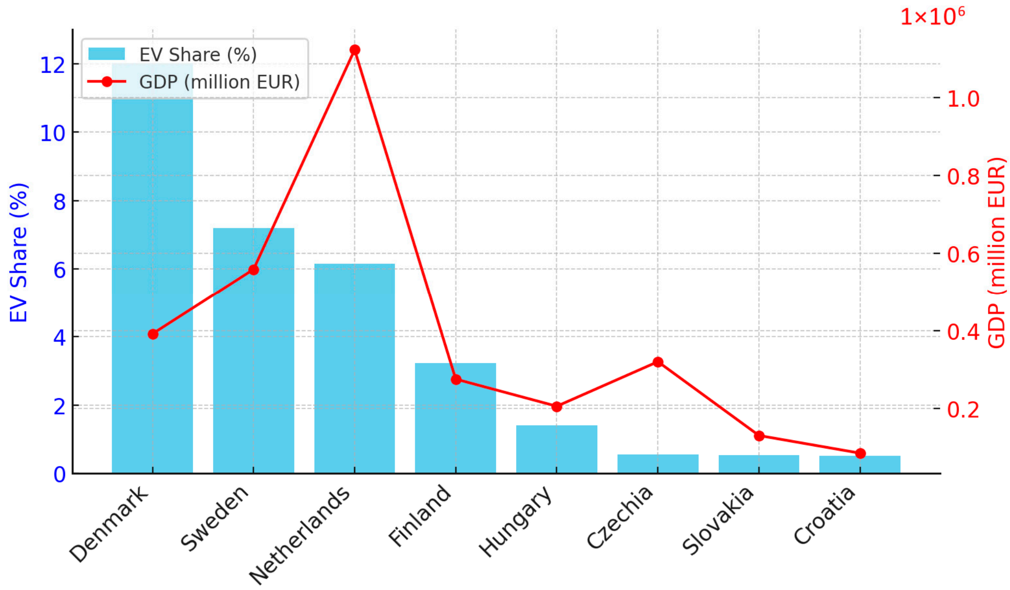

Figure 1. Electric vehicle share and GDP in 2024.

The data indicate a clear link between economic development and the spread of electric vehicles. While the EU's overall car fleet is growing steadily, there is a noticeable slowdown in the spread of electric vehicles [5]. Despite this, the trend remains positive.

The continuous growth and the wider adoption of electric vehicles are evident, yet significant differences have emerged within the European Union. These differences may influence where the secondary life of batteries will appear, whether in Western or Eastern Europe. Eastern European countries currently import large numbers of vehicles with conventional powertrains. The question is whether this pattern will also hold for electric vehicles in the future or if the import of used cars will be so strongly influenced by infrastructural disparities, such as the availability of charging networks and renewable energy sources, potentially altering these trends.

Section 2.2 examines renewable energy sources, which are not only necessary for charging vehicles but also for supporting the secondary life cycle of batteries, when they operate as large-scale power banks. Section 2.3 analyzes electricity consumption and the development of charging infrastructure.

2.2. Renewable Energy Utilization and Storage

In 2023, the share of renewable energy sources in gross energy consumption reached 24.5%, which is an increase compared to 2022 and a threefold increase compared to 2004 [10,11].

Changes can also be observed in the sectoral breakdown. In electricity generation, the share of renewables reached 45.3%, which represents a 4.1% increase compared to 2022. The main sources are wind (38.5%), water (28.2%), solar (20.5%), and other biomass and renewable sources. For heating and cooling, the share of renewables is 26.2%, and in the case of transport, it is 10.8%, with both values showing continuous growth [10].

The EU average of 24.5%—which is constantly rising—clearly shows that the use of renewable energy is becoming increasingly important among Member States. However, the EU target of 42.5% is still a long way off, so it is necessary to increase and encourage investment in renewable energy sources. There are a number of Member States, such as Sweden, Finland, etc., which are at the forefront of renewable energy use, but it should also be noted that, in many countries, such as Belgium, Luxembourg, and Malta, the use of new energy sources is extremely low [10,11].

Table 3 summarizes the share of renewable energy sources in relation to GDP for the countries examined in the previous chapter. At the time of writing, data for 2024 were not yet available.

Table 3. Renewable energy sources and GDP [4,12].

	2023	
Country	**%**	**GDP (Million Euro)**
Denmark	44.396	374,173.6
Sweden	66.393	535,176.8
Netherlands	17.42	1,050,133
Finland	50.750	272,874.0
Hungary	17.117	197,902.0
Czechia	18.586	319,099.1
Slovakia	16.990	123,833.2
Croatia	28.051	78,060.4

We see similar results to those in the previous subsection. While it might be assumed that a higher GDP leads to greater renewable energy use, this is not necessarily the case (Figure 2).

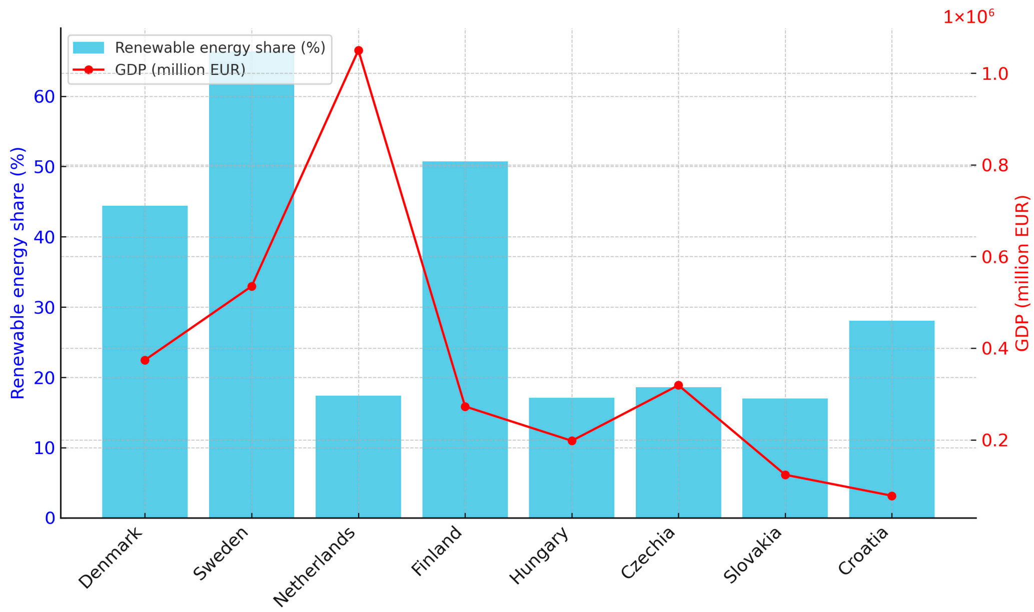

Figure 2. Renewable energy sources and GDP on graph.

The differences between the values are clearly visible in the figure. In two high-GDP countries, the share of renewable energy sources is also higher, but this is not the case in the Netherlands. In Finland, we see the opposite pattern: despite a lower GDP, the share of renewables is comparatively high, while, among the four Eastern European countries, only Croatia has a higher share.

The growing share of renewable energy sources plays a key role in enabling the secondary use of electric vehicle batteries. Higher GDP (Section 2.1) generally correlates with a larger electric fleet, which in turn increases the potential supply of used batteries. However, this is not necessarily the case for renewable energy sources. Electric vehicle batteries may not necessarily continue their second life in the country where they were installed in vehicles but are more likely to be used in regions where the expansion of renewable energy sources requires additional energy storage capacity.

2.3. Electricity Consumption Trends and Demand

In the European Union household consumption averages 1.6 MWh per capita annually. However, consumption varies greatly between member states. For example, consumption in Romania and Poland is around 1 MWh/capita, while Finland consumes 4.1 MWh/capita and Sweden 3.9 MWh/capita [13]. Table 4 shows the data of the analyzed countries from which conclusions can be drawn about the relationship between household electricity consumption and GDP data.

Table 4. Household electricity consumption and GDP [4,14].

	2023	
Country	**GWh**	**GDP (Million Euro)**
Denmark	9752.186	374,173.6
Sweden	39,550.0	535,176.8
Netherlands	21,323.539	1,050,133
Finland	22,089.000	272,874.0
Hungary	12,532.000	197,902.0
Czechia	15,476.669	319,099.1
Slovakia	5848.000	123,833.2
Croatia	6421.000	78,060.4

It is evident that higher GDP values are accompanied by higher household electricity consumption. Figure 3 presents the data in graphical form. At the time of writing, data for the year 2024 were not yet available.

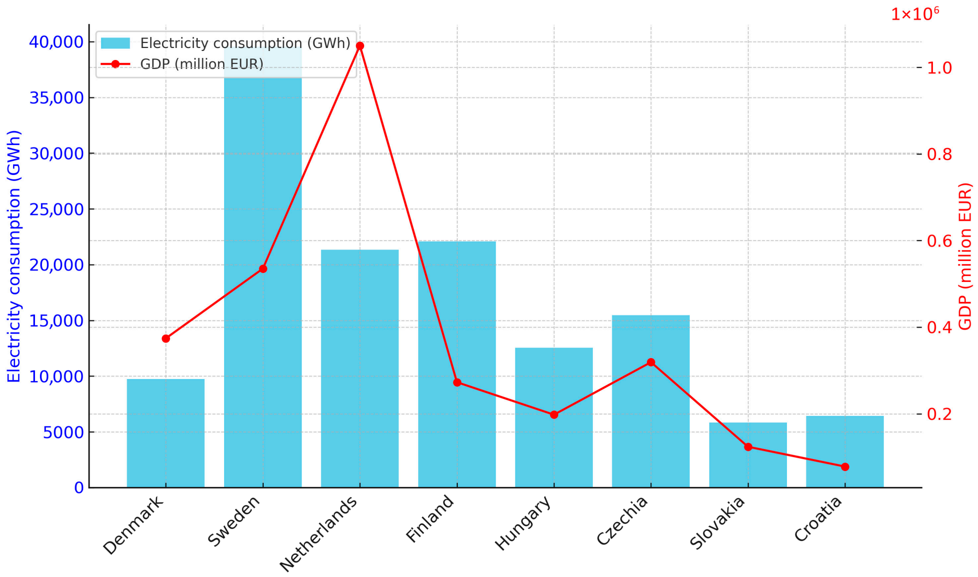

Figure 3. Household electricity consumption and GDP on graph.

Within the European Union, electricity consumption differs between member states in relation to GDP, yet, in general, electricity consumption in the EU is either stagnating or growing moderately. It is important to note that seasonal fluctuations play an important role, especially when it comes to electric vehicle charging, where demand can peak during colder months or periods of increased mobility. Therefore, the number of public charging points available in the EU becomes an important factor when we analyze future energy needs.

In 2023, there were 632,423 public charging points in operation in the EU, and this number is constantly growing. Such a network will enable the servicing of approximately 3 million purely electric vehicles. The goal is to have 3.5 million charging points by 2030, which will require the installation of 410,000 new chargers per year. Three countries account for 61% of charging points in the EU: The Netherlands, France, and Germany. Approximately 71,000 of the existing charging networks are fast chargers, i.e., with a power output greater than 22 kW [15–17].

The examination of economic factors in the second chapter shows clear links between the level of economic development and the spread of electric vehicles within the European Union. Countries with higher GDP tend to have larger electric vehicle fleets, but the relationship between renewable energy use and GDP is more complex and varies across the member states. These findings suggest that economic development is a key driver of electric vehicle spread, but additional factors, like energy policy, integration of renewable energy sources and infrastructure, also influence the extent and speed of transition.

It is also important to examine the results in the context of the hypotheses set out at the beginning of the chapter. Hypothesis 1 was fully confirmed: the penetration of electric vehicles is significantly higher in countries with high GDP, which confirms the role of economic development and purchasing power in the spread of electromobility. Hypothesis 2 was only partially confirmed. In some countries, a high share of renewable energy was accompanied by the rapid spread of electric vehicles (e.g., Sweden), but, in other cases, this relationship proved to be weaker. At the same time, it can be said that countries with higher electricity consumption show greater potential for vehicle-to-grid integration and the secondary use of batteries for energy storage purposes. This suggests that the level and structure of energy demand are key factors in the integration of electric vehicle technology. Overall, the analysis shows that economic development and energy market conditions together determine the adoption, speed, and pace of electric vehicles and their batteries.

The spread of electric vehicles is growing at a significantly faster rate than the charging infrastructure. As a result, more and more vehicles are relying on existing charging points, which can cause periodic network overload and, as a result, fluctuations in the power grid. The second life of electric vehicle batteries, which is detailed in Section 3, may be a solution to reducing these network fluctuations, storing renewable energy, and then feeding it back into buildings.

2.4. Short Statistical Check

The examination of macroeconomic trends is important not only from a descriptive but also from a statistical point of view. Section 2.4 examines this and the hypothesized correlations. Pearson's correlation coefficient was used, and the data series was provided by the 2023 Eurostat database. Unfortunately, at the time of writing, the database did not contain uniform data for 2024, and using incomplete or inconsistent data would have distorted the results. Therefore, only countries listed in Tables 2–4 were included in the analysis. The full data set is illustrated in Table 5.

Table 5. Data set [4–15].

Country	EV Percent, %	GDP, Million EUR	Electric Consumption, GWh	Renewable Energy Source, %
Denmark	7.0764	374,173.16	9752.186	44.396
Sweden	5.8612	535,176.18	39,550	66.393
Netherlands	4.904	1,050,133	21,323.539	17.42
Finland	2.3132	272,874	22,089	50.75
Hungary	0.9886	197,902	12,532	17.117
Czechia	0.3446	319,099.1	15,476.669	18.586
Slovakia	0.2986	123,833.2	5848	16.99
Croatia	0.3695	78,060.4	6421	28.051

Pearson's correlation coefficient (r) was used to calculate the correlations between the data using the following formula [18]:

$$r = \frac{cov(X,Y)}{\sigma_x \times \sigma_y}, \quad (1)$$

X represents the penetration of electric vehicles, while Y represents the macroeconomic indicator under examination. The resulting values are shown in Table 6.

Table 6. Results.

Variables	r (Pearson)	N
GDP—Electric Vehicles	0.62	8
Electricity Consumption—Electric Vehicles (%)	0.51	8
Share of Renewable Energy Sources (%)—Electric Vehicles (%)	0.61	8

Interpretation of correlation values:

- 0.1–0.3: weak,
- 0.3–0.7: moderate,
- Above 0.7: strong correlation.

The results are clear. The correlation between the spread of electric vehicles and GDP is r = 0.62, while the correlation between the spread of electric vehicles and electricity consumption is only r = 0.51. The relationship between the share of renewable energy and electric vehicle penetration is r = 0.61. These results suggest a moderate positive correlation, confirming that economic development and energy infrastructure are closely linked and have an impact on the spread of electric vehicles.

- Hypothesis 1: Electric vehicles are more widespread in countries with higher GDP. The positive correlation of r = 0.62 confirms that economic development is related to the spread of electric vehicles.
- Hypothesis 2: An increase in the share of renewable energy and higher electricity consumption promotes the integration of electric vehicles into the vehicle-to-grid systems, as well as the integration of vehicle batteries into secondary life cycles. The correlations of 0.61 and 0.51 partially support this, although the relationship is not entirely deterministic.

It is important to note that the correlation analysis was based on a relatively small sample size, consisting of only eight countries. This is because the main focus of the article was not statistical analysis—this section was only included as a supporting investigation.

For this reason, *p*-values or other statistical tests were not applied. However, the results may serve as indicative findings and offer valuable insights, even if they cannot be interpreted as general rules. At the same time, the results provide a consistent picture of the relationship between macroeconomic and energy-related indicators and the spread of electric vehicles.

The Pearson correlation coefficient was selected as a representative measure of association, providing a transparent and comparable indicator across the analyzed countries. Other statistical methods could be applied in future studies, but they fall outside the scope and purpose of this work.

3. Second-Life of Electric Vehicle Batteries

The continuous growth of the used battery market and their subsequent use are influenced by two factors [19]:

- The emergence of energy communities, resulting in decentralized energy storage and local energy balancing,
- Vehicle-to-grid technology, which enables bidirectional power flow between vehicles and the grid.

Theoretically, combining these two points could create more than 200 GWh of storage capacity after 2030. Storage system and installation costs could be reduced by a further 50–70% [20]. However, the lack of technical standardization and the slow development and establishment of regulatory frameworks are key challenges that require coordinated solutions and collaborative efforts between industry, policymakers, and researchers.

3.1. Market Dynamics and Growth Projections

The key driver for the spread of secondary use is definitely cost reduction. The use of renewable energy sources is constantly growing (Section 2.2), and the integration of used batteries allows us to mitigate the fluctuations in power generation inherent to renewable energy sources. McKinsey estimates that, by 2030, retired batteries will have a storage capacity of around 200 GWh, which is sufficient to meet 180 GWh of grid demand, this way covering a large share of the flexibility needs of the electricity system [19,21,22].

From an economic perspective, it is important to note the concept of Levelized Cost of Storage (LCOS). LCOS is a metric that shows whether an energy storage system is profitable over its life cycle and facilitates the comparison between different energy storage technologies easier [23]. This indicator shows that the cost of second-life batteries ranges from USD 90 to USD 150/MWh, which is significantly lower than the cost of new systems, which ranges from USD 140 to USD 220/MWh. The main reason for this difference is that with second-life batteries we do not have to take into account the costs of extracting raw materials and other processing-related costs. These technological steps account for 40–50% of the cost of a new battery. In addition to reduced costs, second-life batteries also meet one of the most pressing challenges of today (2025) by contributing to the reduction in the so-called carbon footprint. For example, reusing a 60 kWh battery can reduce carbon dioxide emissions by up to 8–12 tons compared to recycling [21,24].

Despite their favorable characteristics, the battery market is highly segmented geographically. In 2024, local energy storage will account for 55.1% of the total market. Such systems are typically used to bridge peak loads, regulate frequency, and serve as backup power sources. Certain telecommunications companies use these batteries to reduce their exposure to diesel generators.

The Asia-Pacific region has a 47% market share, with China in second place. China's goals include building 30 GWh of secondary life energy storage facilities by 2025. Europe ranks third, where in 2023 the EU adopted a directive, known as the EU Battery Regulation, which mandates recycled content and supports remanufacturing. In North America, there are state-level regulations, with California standing out for its plan to build 10 GW of storage capacity by 2045, of which 30% they want to cover with second-life cycle batteries [21,24–28].

It is clear that battery reuse is a key component in the energy transition. However, it should be noted that the development, establishment, and improvement of regulatory frameworks is an essential task. In the European Union the Circular Economy Action Plan requires manufacturers to consciously plan to achieve a 70% collection target for end-of-life batteries by 2030. The United States has also introduced measures, and, as part of the Inflation Reduction Act, projects that use second-life batteries receive tax credits, which can lower initial investment costs by as much as 20–30%. In other markets, such as India, projects and companies that do not reuse batteries are penalized [24,26,28].

Standardization still faces serious challenges. Tests related to the state of charge (SoC) of batteries and overall battery health vary significantly across regions. The United Kingdom's Office for Product Safety and Standards (OPSS) uses a method known as "gateway testing" to check whether batteries are suitable for a secondary life cycle. This method further reduces the cost of remanufacturing and also strengthens investor confidence by providing official government certification [19–31].

3.2. Costs—Short Overview

In Germany, secondary life cycle batteries typically operate with a payback period of 4 to 5 years, and the strongest demand comes from residential use. Countries such as Australia, where solar PV systems are extremely widespread, have generated significant demand for affordable devices capable of storing electricity. A system with a capacity of approximately 10 kWh costs USD 3000, while a system equipped with a new battery can cost twice or even three times as much [24,32,33].

It is important to note that battery technology is constantly and rapidly evolving. Systems with increasingly better energy density are coming onto the market and, importantly, at increasingly lower prices. The cost of new-generation lithium iron phosphate (LFP) batteries is competitive, and, by 2030, they could cost as little as USD 80/kWh, which will reduce the gap with batteries used in electric vehicles, which are expected to cost around USD 50–70/kWh [24,32,33].

Automotive manufacturers play a key role in the spread of this technology. Several companies have projects in this area: Nissan is working with Eaton [34], while BMW is collaborating with Off Grid Energy in South Africa [35]. In many cases, these solutions result in special ownership rights. Original Equipment Manufacturers (OEMs) retain ownership of the batteries but lease them to service providers. This ensures a continuous and profitable revenue stream even after the vehicles are no longer in use [36]. Several companies are involved in battery reuse and are working to establish standards for reuse [37]. This is important because, according to IDTechEx estimates, 65% of used batteries will come from OEM-certified suppliers, for whom tracking and quality control are key [28].

3.3. Risks, Safety and Recycling

In addition to the various business solutions, it is important to mention the risks associated with batteries. One of the most important problems is the heterogeneity in the chemical composition of batteries, which complicates reuse and standardization. Design requirements for power electronics are also critical, as over time, batteries lose their performance and reliability due to degradation within their internal structure.

Battery degradation can vary greatly between different manufacturers, especially during the first cycle of use. This makes it difficult and risky to integrate them into specific secondary applications. Power electronic devices must therefore be adapted to the specific characteristics of each battery. It is clear that the chemical composition of batteries from different manufacturers is not the same, even batteries produced by the same company can reach very different end-of-life (EoL) conditions. Degradation during the second life cycle further complicates the situation and can even lead to completely new operating processes. These problems make integration processes difficult. Batteries must be equipped with dedicated energy management systems that can handle issues arising from degradation and chemical differences [22,38,39].

In addition to integration problems, safety aspects must also be taken into account. One of the most important of these is thermal runaway, which can easily lead to fire. Based on research conducted at the University of Newcastle, it is essential to use appropriate standards and certify batteries. This ensures that batteries can be used for secondary applications in a safe and verifiable manner [40,41].

The risks and safety factors listed above are extremely important. At first sight, their reuse may seem like the obvious choice, yet a significant obstacle has to be taken into account as recycling and dismantling technologies advance rapidly. Modern hydrometallurgical processes can recover up to 95% of the lithium, cobalt, and nickel from batteries. In countries where the prices of these materials are high, recycling may become more attractive than reuse; therefore, the secondary market use of batteries is at risk. Disassembly and metal reuse can cost as much as $10–15/kWh, which in some cases can be significantly more profitable than secondary use. Policymakers need to find a balance between recycling and reuse, in order to prevent market distortion [21,24].

3.4. Conclusion and Adaptation in Eastern Europe

The second chapter summarizes the potential future growth opportunities for the secondary use of batteries. It is clear from the above that this is an intensively and continuously growing market. Despite this growth, there are a number of risks and problems associated with secondary use. Three major factors influence this development:

The lack of standardized testing and certification, global harmonization of safety factors and indicators.

Technological developments, like battery diagnostics, and the design of Battery Management System (BMS).

Policy decisions, a coordinated regulatory framework that harmonizes reuse and recycling in a way that strikes the right balance between environmental and economic interests.

By 2035, the secondary life cycle of batteries could cover 25% of storage needs and reduce annual CO_2 emissions by up to 150 million tons. Close cooperation between OEMs and policymakers is needed to implement and harmonize developments. It is essential to coordinate strategies from a technical, manufacturing, and political perspective [6,9].

The spread of electric vehicles has become a key element of the European mobility transition, which is supported by various government incentives in the European Union. At the same time, there are clear differences within the continent, such as those between Eastern and Western Europe. Although the spread of electric vehicles in the Eastern European market is growing steadily, it is not nearly as much as in Western Europe. As a result, the secondary market for batteries is also not growing as fast as in the West. It can be said that the Eastern European market faces specific challenges due to infrastructure deficiencies, policy adoption, and market immaturity.

After reviewing the processed economic data and literature, it is clear that secondary use appears to be promising from an economic and technical perspective. Section 4 presents a concrete simulation based on data from a household in Hungary. Data from a Tesla battery was used for the simulation. The model attempts to show how a second-life battery can be integrated at the household level and what role it plays in supporting domestic energy needs.

3.5. Manufacturer Solutions

In recent years, electric vehicle manufacturers have invested increasing amounts of time, money, and energy in the industrial implementation of vehicle-to-grid technologies and the secondary life cycle of batteries. These developments serve multiple purposes. Not only do they enable manufacturers to increase the flexibility of the power grid, but they also extend the life of batteries, create a new regulatory environment and business models, and transform the user experience.

The E-Stor system is a joint development between Renault and Connected Energy, which uses batteries from electric vehicles. In these setups, the batteries are in their second life cycle, functioning as energy storage devices at fast charging stations. This solution makes it possible to implement fast charging even in places where network development would be costly [42].

The BMW Group is developing its own secondary life cycle solutions in the United Kingdom with the involvement of several partners [35]. In Hamburg, Germany, a group of three companies is developing a 2 MW secondary life cycle battery storage facility, which provides network services. The three companies are Vattenfall, BMW and Bosch [43].

The Mobility House launched its vehicle-to-grid business solutions in 2024, which simultaneously address bidirectional charging solutions for vehicles and the integration of batteries as static storage. Renault and Mercedes are participating in this development [44]. In the United States, EVgo has utilized used BMW i3 batteries in energy storage units. These units are used to reduce peak network load at fast charging stations [45].

The above examples clearly show that many manufacturers are not only interested in the primary vehicle market but also in the implementation of secondary market solutions. Industrial developments and prototypes prove that vehicle-to-grid and secondary life cycle use can be a viable alternative in practice for batteries that can no longer be used in electric vehicles. These solutions can contribute to the flexibility and sustainability of energy supply in the long term.

4. Simulation of a Second Life of an Electric Vehicle

4.1. Basic Data and Explanation

The previous chapters provided an overview of the current situation in Europe and the status of secondary battery life cycles. The fourth chapter examines how the battery of a Tesla Model 3 Long Range vehicle can be integrated into the electrical network of a family home. The data used below include the amount of electricity generated from a rooftop solar panel system installed on a family home in Hungary, along with the monthly consumption data. For the purpose of the calculation, the usable capacity of the vehicle's battery is set at 80%. Linear programming was used for the analysis, which has appeared in several studies on similar topics [46–48].

Table 7 presents the key technical specifications of the vehicle.

The table shows that the vehicle's battery capacity is 82 kWh, but this cannot be fully utilized in practice, as during everyday use, the usable capacity is limited to 77 kWh. As can be seen from the literature reviewed previously, most vehicles can start their second life cycle with 80% of their original battery capacity, which is 80% of the net usable capacity listed in the table, or 61.6 kWh in this case. The energy storage device of the case study is not installed in a vehicle used for transportation; the battery pack under investigation plays a secondary life cycle role, meaning that it has been removed from the vehicle and functions as a stationary energy storage device.

Table 7. Tesla Model 3 Long Range (2025) [49].

Model	Tesla Model 3
Modification (Engine)	Long Range 82 kWh (498 Hp) Dual Motor AWD
Gross battery capacity	82 kWh
Net battery capacity	77 kWh
Battery technology	Lithium nickel cobalt manganese aluminum (Li-NCMA)
80% of Net battery capacity	61.6 kWh

The annual solar panel production data and monthly consumption of the building under review are shown in Table 8. The building is a family house located in Debrecen, Hungary.

Table 8. Solar panel production and consumption data for a family home.

Month	Solar Energy Production (kWh)	Electricity Consumption (kWh)
January	128.15	270
February	219.021	238
March	452.164	240
April	408.435	210
May	618.864	210
June	681.759	240
July	626.496	300
August	588.187	300
September	336.329	240
October	279.741	240
November	120.415	240
December	72.636	270

4.2. Setting up the Problem

The initial data required for the calculation can be easily read from Tables 7 and 8. It is very important to note that the energy use and production do not simply reset each month but continue in a constant flow over time. In winter, when solar panels do not generate extra electricity, the battery cannot cover the shortage. In this way seasonal limitations are taken into account, and the results reflect real-life conditions.

The efficiency of the battery was calculated as follows: in the case of charging, the efficiency was considered to be 100% (with minimal, practically negligible losses), while in the case of discharging, an efficiency of 90% was introduced. This 10% loss realistically covers the various losses that occur in the system. This solution attempts to realistically reflect practical conditions, even though it is not possible to simulate completely real conditions.

The decision variables are designed to reduce the amount of electricity purchased from the grid and allow the household to rely more on its renewable energy:

- pv_{dir}: direct PV consumption (kWh);
- pv_{bat}: energy charged from PV to battery (kWh);
- bat_{dis}: energy discharged from the battery to the house (kWh);
- grid: energy purchased from the grid (kWh);
- SOC_m: battery state of charge at the end of the month (kWh);

- PV_m: monthly solar panel production (kWh);
- D_m: monthly household demand (kWh);
- C_{bat}: battery capacity (kWh);
- m: number of months;
- η_c: charging efficiency, 1;
- η_d: discharge efficiency, 0.9.

In addition to the decision variables, the following constraints had to be set:

Solar energy distribution:

$$pv_{dir} + pv_{bat} \leq PV_m, \tag{2}$$

Household demand:

$$pv_{dir} + bat_{dis} + grid = D_m, \tag{3}$$

Battery SOC change:

$$SOC_m = SOC_{m-1} + \eta_c \; * \; pv_{bat} - \frac{bat_{dis}}{\eta_d}, \tag{4}$$

Battery capacity:

$$0 \; \leq \; SOC_, \; \leq \; C_{bat}, \tag{5}$$

Discharge of previously stored energy:

$$bat_{dis} \; \leq \; \eta_d \; * \; SOC_{m-1}, \tag{6}$$

Objective:

$$min \sum_{m=1}^{12} grid_m \tag{7}$$

4.3. Objective Function and Model

Based on the specified conditions, as well as the production and consumption data, it is possible to calculate the amount of energy that can be stored in the battery. The results of the calculations are shown in Table 9.

The table starts with an initial State of Charge (SOC) value of 30.8 kWh, which can be modified as required. The model shows that, in January, the building consumed the amount of 30.8 kWh, and then, in the following month, the battery was not recharged, as the building's electricity demand exceeded the amount generated by the solar panels. As a result, an additional 18.979 kWh of energy had to be purchased from the grid.

In March, a surplus of energy from the solar panels was already observable, which was used both to charge the batteries and to supply the building with the necessary amount of energy. From March until November, there was no discharge from the battery, as the solar panel system continuously produced a surplus. In November, however, 55.44 kWh of energy was fed into the building, limited by the 90% discharge limit. At the same time, the table shows that an additional 64.145 kWh of grid electricity was also needed. In December, the system did not generate enough energy to cover demand, so the SOC value of the battery was reduced to 0.

Overall, the model showed that it is technically possible to integrate an electric vehicle battery into a building as an energy storage device during its secondary life cycle, but, as can be seen above, the contribution was relatively limited; only 83.16 kWh was fed back from the battery to the building in one year.

Table 9. Analyzed data.

Month	PV_m (kWh)	D_m (kWh)	SOC Start (kWh)	pv_{dir} (kWh)	pv_{bat} (kWh)	bat_{dis} (kWh)	Grid (kWh)	SOC End (kWh)
January	128.15	270	30.8	128.15	0	27.72	114.13	0
February	219.021	238	0	219.021	0	0	18.979	0
March	452.164	240	0	240	61.6	0	0	61.6
April	408.435	210	61.6	210	0	0	0	61.6
May	618.864	210	61.6	210	0	0	0	61.6
June	681.759	240	61.6	240	0	0	0	61.6
July	626.496	300	61.6	300	0	0	0	61.6
August	588.187	300	61.6	300	0	0	0	61.6
September	336.329	240	61.6	240	0	0	0	61.6
October	279.741	240	61.6	240	0	0	0	61.6
November	120.415	240	61.6	120.415	0	55.44	64.145	0
December	72.636	270	0	72.636	0	0	197.364	0
Σ	4532.197	2998	523.6	2520.222	61.6	83.16	394.618	

The monthly breakdown model in the table shows certain patterns, but the results do not seem convincing. This is because it looks at monthly production and consumption. In reality, solar panels generate energy during the day when consumption is low in a family home, while consumption increases in the evening, so batteries may be suitable for storing surplus energy generated during the day. The monthly aggregated data balances out these daily fluctuations and are therefore no longer visible. Based on the table, it may appear that batteries are completely unused during the summer months, even though numerous charging and discharging cycles may occur on a daily basis.

5. Discussion

The article presents a complex analysis. At the macroeconomic level, it shows that the spread of electric vehicles in European countries correlates strongly with economic development and GDP. In countries with higher economic development (e.g., Norway, Germany, etc.), the spread of electric vehicles is significantly greater. This fact confirms the assumption that income level and purchasing power are fundamental determinants of the spread of electromobility. However, it is important to note that this correlation is less clear with regard to the share of renewable energy sources. In some countries, such as Sweden, the share of renewable energy sources is high and, in parallel, the spread of electric vehicles is also high, while in other countries this relationship is much weaker. This situation shows that the share of renewables does not determine the spread of electric vehicles.

The results presented in this article are consistent with other studies. The IEA's analyses for 2023 and 2025 also show that the spread of electric vehicles is increasing mostly in countries where, in addition to economic development, energy policy support and infrastructure development are also adequate [50,51]. Similar conclusions are also presented in [52], where the authors examine the possibilities of support mechanisms and other incentives, as well as income levels. This correlation is also confirmed by [53], which states that an adequate infrastructure network is a key factor in the spread of electric vehicles. Ref. [54] confirms that vehicle-to-grid technology can make a significant contribution to achieving a balanced energy system.

The analysis in this study is based on monthly data. Although daily or hourly data could provide a more accurate picture of energy consumption and the dynamics of battery integration, such data are not uniformly available for most of the countries studied, due to database, technical, or bureaucratic constraints. However, the monthly breakdown is suitable for showing macroeconomic trends and correlations observed in the energy system. Future research may benefit from examining finer (daily or hourly) data sets, which would allow for a more accurate assessment of the short-term effects of V2G technology. Extracting daily or even monthly data from such a system requires significant development, planning, and regulatory approval from service providers, which is a lengthy process.

The results presented are consistent with the calculations in the case study, which confirmed that secondary life cycle batteries, as energy storage devices, can contribute to balancing the energy mix with sufficient efficiency. In addition, the experiences of manufacturers' pilot developments (e.g., BMW, Renault, Bosch, etc.) also show that vehicle-to-grid and the secondary use of batteries can be a viable alternative in practice.

The article does not cover cost–benefit analysis and quantitative analysis of battery degradation, as these are separate research topics. It is important to note that the examination of these factors can seriously influence the development and spread of vehicle-to-grid and secondary life cycle applications.

6. Conclusions

The findings of the article highlight that the spread of electric vehicles depends primarily on economic development and the associated purchasing power, while the share of renewable energy sources alone does not determine the growth of electric mobility.

One of the most important conclusions of the research is that electric vehicle batteries can play a significant role as energy storage devices during their secondary life cycles. This type of application can contribute to increasing grid flexibility, stabilizing the energy supply of households and businesses, and reducing the hazardous waste generated by worn-out batteries.

Experience from industrial projects also confirms that the secondary use of batteries that are no longer suitable for use in electric vehicles is important not only from a technical point of view, but also from an economic and environmental perspective. Overall, it can be said that secondary life cycle batteries can play a key role in the sustainable transformation of energy supply and may be an important area of future research.

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