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Ministry of Industry, Trade and Supply

Ministry of Environment

The Untapped Potential of Spent EV Batteries: How Can Jordan's Economy Benefit?

Discussion Paper on Different Sustainable End-of-Life Strategies for Spent EV Battery

Discussion Paper

on

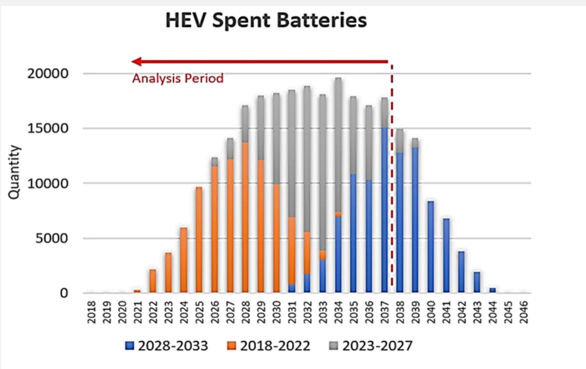
Spent EV Batteries and their Potential for Jordan

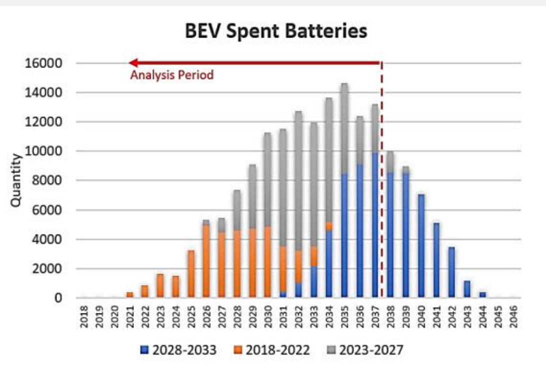
Executive Summary

In Jordan, the number of EVs continues to rise due to the promise of reduced reliance on gasoline and incentives offered by the government to allow for a green transport transition. The increasing demand for EVs has led to two major challenges in the Kingdom that should be tackled: First, EVs with batteries that have reached their end-of-life need a viable replacement battery to continue operation. Second, an increasing number of spent batteries that have reached their end-of-life (EOL) are awaiting sustainable management (practices that include disposal, recycling, repurposing, and remanufacturing)

In this discussion paper, current practices concerning spent battery accumulation are being considered to analyse the potential opportunities and challenges of adopting sustainable EOL strategies in Jordan. Data is collected and analysed to assess the current need and readiness of Jordan to support EVs and implement sustainable EOL management for EV batteries. Lastly, recommendations on the next steps for Jordan to tap into the economic potential of adopting circularity to EV battery waste are presented.

Data was collected on the number of vehicles that received customs clearance from 2018-2022. Using this data EV penetration was projected up to the year 2033. Next, these values were then used to forecast the spent EV battery accumulation, as shown below.

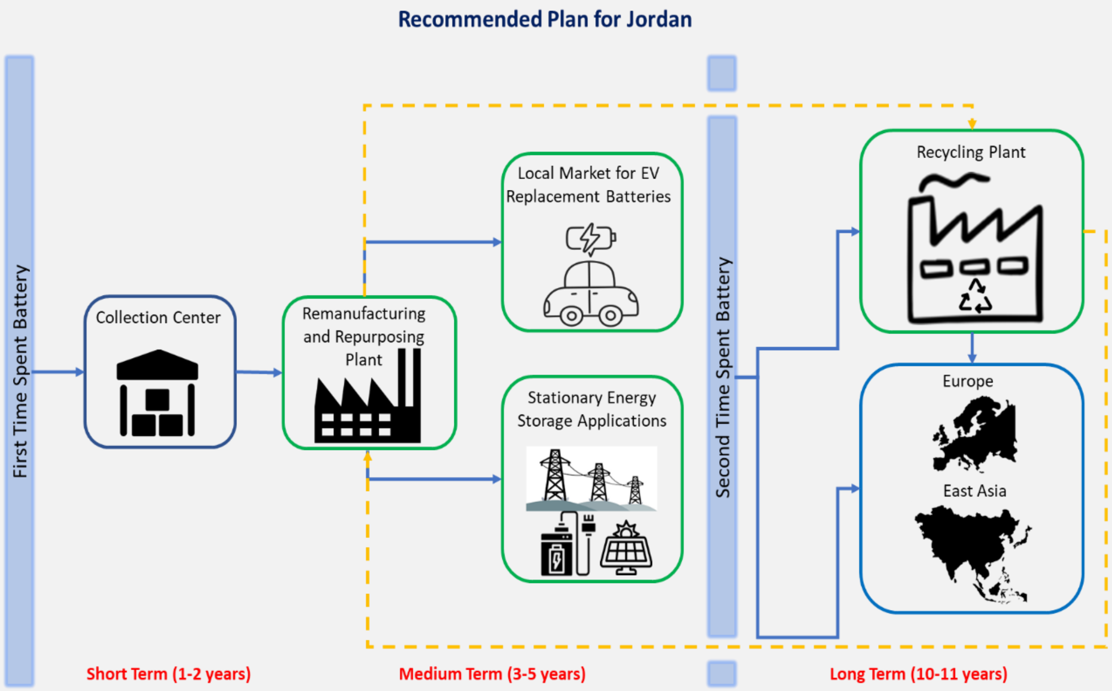




Scenario	Annual Revenue Estimates
Exporting Spent Batteries	USD 600,000
Recycling	USD 14,000,000
Repurposing	USD 22,000,000
Remanufacturing	USD 22,100,000

Afterward, the practicality of adopting end-of-life strategies in Jordan is examined. It is determined that the most environmentally friendly options are ranked, such that remanufacturing > repurposing > recycling. Also, the revenue potential for each end-of-life strategy is calculated and shown below.

Based on the results of the study, the following recommendations are proposed. In the **short-term horizon (1-2 years)**, it is necessary to open collection centres in Jordan to collect spent batteries. Moreover, policies and regulations supported via an incentive system by the government should be put into place to encourage the proper discarding of these spent EV batteries. Next, in **the medium-term horizon (3-5 years)**, the establishment of a remanufacturing and repurposing plant is recommended; the primary focus of the plant is on producing replacement batteries for EV owners. Meanwhile, batteries that are not able to be restored to a quality level acceptable for automotive applications, can be repurposed or stationary energy storage applications. Finally**, in the long-term horizon (10-11 years)**, it is advised that a recycling facility is built to process spent "remanufactured batteries" (i.e., end of "second" life).



Meanwhile, the following general recommendations are made:

- Policies and regulations around the import, repair, and disposal of EV batteries are needed.
- Training and education programs are needed to guide the sustainable use, repair, and disposal of batteries.
- Tracking and traceability should be adopted for EV batteries.

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Contents

1. Introduction

Due to their high efficiency, low operational maintenance costs, and promise in reducing greenhouse gas emissions, electrified vehicles (EVs) are gaining popularity among consumers in Jordan. This is in line with global trends: according to the International Energy Agency, in 2012 only 130,000 EVs were sold worldwide, while in 2021, more than that 130,000 are sold each week[1].

In Jordan, policies and infrastructure needed to support proper end-of-life (EOL) management of EV batteries have not been able to catch up with the quickly increasing penetration of EVs in the country. As a consequence, the current methods in Jordan for EV owners are as follows: when an EV battery reached its EOL, the EV owner will typically either go to a local mechanic and try to refurbish the battery or the EV owner will purchase an imported battery. In the case of refurbishing, the battery is repaired only to a suboptimal level (low capacity) and the EV may require yet another replacement within a short period (see Figure 1).

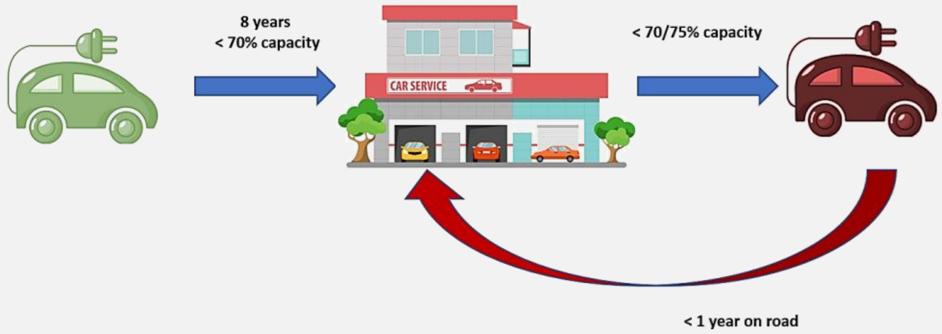


Figure 1: Spent Battery Repair in Jordan

In the case of purchasing an imported battery (new or used), it is alleged that the cost of an imported replacement battery (that is of the appropriate performance for automotive applications) can pose a financial burden to the average Jordanian EV owner. The cost of a replacement battery for a hybrid electric vehicle (HEV) may range between $1,000 to $5,000, and the of a replacement battery for a full electric vehicle (BEV) may range between $2,000 to $20,000. Accordingly, less expensive, and lower quality replacement batteries may be imported into the country due to affordability for the average consumer. Once again, if these "used" EV batteries are not at the optimal threshold level with respect to battery performance parameters, these replacement batteries may last 2-3 years and then need to be replaced again. As this cycle repeats, it creates a rapidly increasing number of spent batteries that need to be managed in Jordan, see Figure 2.

[1] **Source:** https://www.iea.org/commentaries/electric-cars-fend-off-supply-challenges-to-more-than-double-global-sales

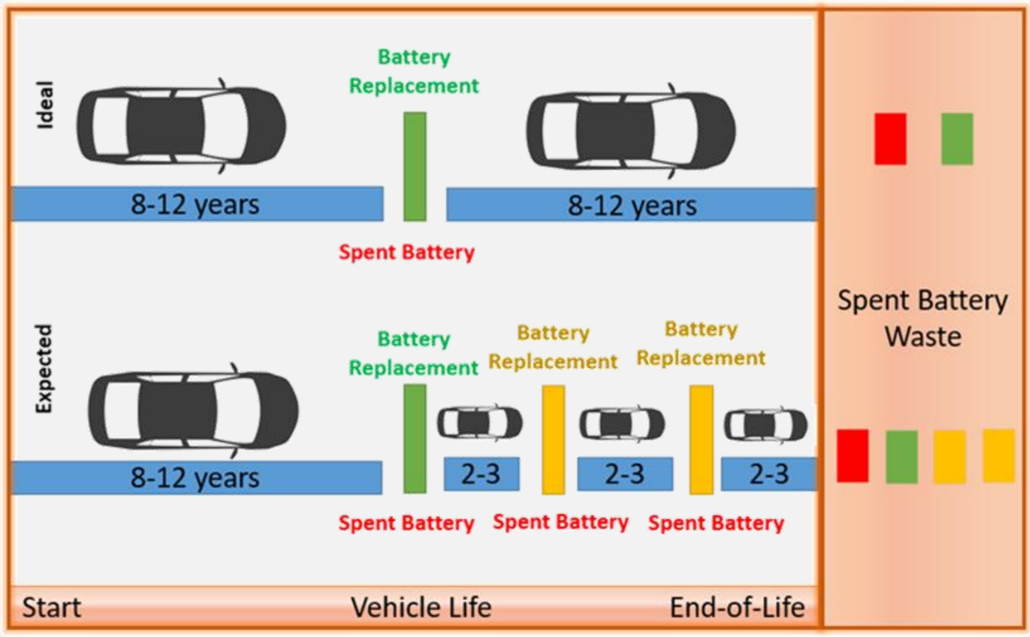


Figure 2: Impact of Suboptimal Quality Levels of Replacement Battery

In all, as EVs are becoming more and more popular in Jordan, there is an increasing number of spent batteries that need sustainable EOL processing; and an increasing number of replacement batteries required to take the place of spent batteries for already on-the-road EVs.

In this study, the potential opportunities and challenges in adopting different sustainable EOL strategies in Jordan are investigated. Data is collected and analysed to assess the current need and readiness of Jordan to support EVs and implement sustainable EOL management for EV batteries. Moreover, various EOL application scenarios are compared. Finally, recommendations are made for Jordan to implement robust EV battery EOL practices.

2. Circularity potential in EV batteries

2.1 Battery structure and value recovery potential

The batteries used in EVs have a distinctive structure with a high potential for value recovery by adopting the concept of circularity. These batteries consist of a battery management system, battery modules, battery cells, an outer casing, and other support components. Currently, the most popular type of battery in EVs is the lithium-ion battery (LIB)[2]. An outline of the EV battery assembly is shown in Figure 3. Each module is made up of LIB cells that are assembled in series and parallel to get the desired battery capacity. The cells use lithium-ions as the main component of the electrolyte. More specifically, the battery cell is made of the following components: cathode, anode,

[2] **Source:** https://afdc.energy.gov/vehicles/electric_batteries.html

electrolyte, and separator. The cathode is the positively charged electrode of the battery and defines the performance of the battery. The anode is the negatively charged electrode of the battery. Meanwhile, the electrolyte is the medium that enables the lithium ions to move from the cathode to the anode. Lastly, the separator separates the anode and cathode.

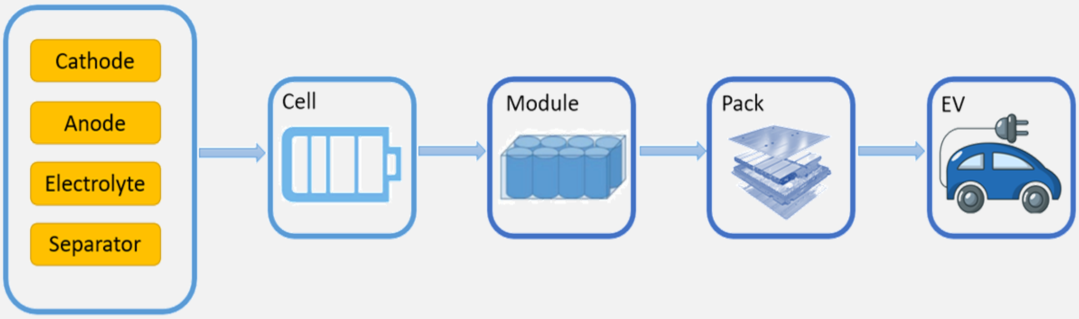


Figure 3: EV Battery assembly

Currently, great efforts in reducing EV battery costs are underway and focus on reducing the cost of the battery cells. It is estimated that 51% of the cost of a battery cell lies in the cathode material; 24% for the manufacturing operations, 12% in the anode; etc.[3]. Different EOL strategies can target value recovery at different stages in the battery's architecture which will help in reducing battery costs and mitigating the negative environmental impacts of the production and disposal of LIBs.

2.2 Overview of end-of-life management practices

Several EOL management practices exist worldwide and can be adopted in Jordan to manage spent battery waste. The current EOL strategies for EV LIBs are disposal, recycling, repurposing, and remanufacturing, as shown in Figure 4. Sustainably adopting and managing these EOL strategies will lead to both environmental and economic opportunities in Jordan. The EOL strategies are summarised as follows.

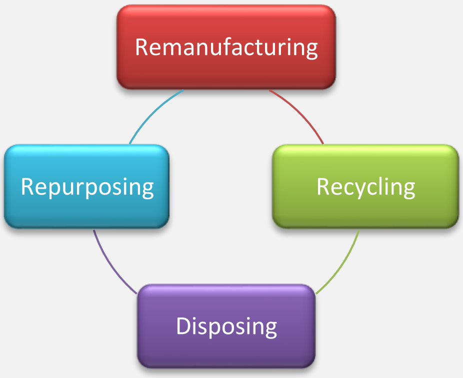


Figure 4: Waste Management Strategies

[3] **Source:** https://www.visualcapitalist.com/breaking-down-the-cost-of-an-ev-battery-cell/

Remanufacturing is defined as a process of recovering value from retired/spent products by overhauling them to like-new condition, through the replacement and reprocessing of parts. Remanufacturing can support the large adoption of LIB remanufacturing in the automotive industry. A remanufactured battery costs 60% less than a new battery and consists of replacing bad modules with good modules to improve the state of health (SoH) and capacity of the battery. Meanwhile, repurposing is the repositioning of the spent battery for a different application or in a different market. EV LIBs can be repurposed to support charging stations and stationary energy storage applications. Repurposing may require disassembling and assembling activities. Next, recycling is when the battery is stripped down to the material recovery level. The goal of this strategy is to convert spent/waste products into reusable material. With recycling, valuable materials such as lithium and cobalt are extracted from spent LIBs. Lastly, the final EOL strategy is Disposal. Disposal is when the batteries are sent directly to landfills and no value recovery methods are employed.

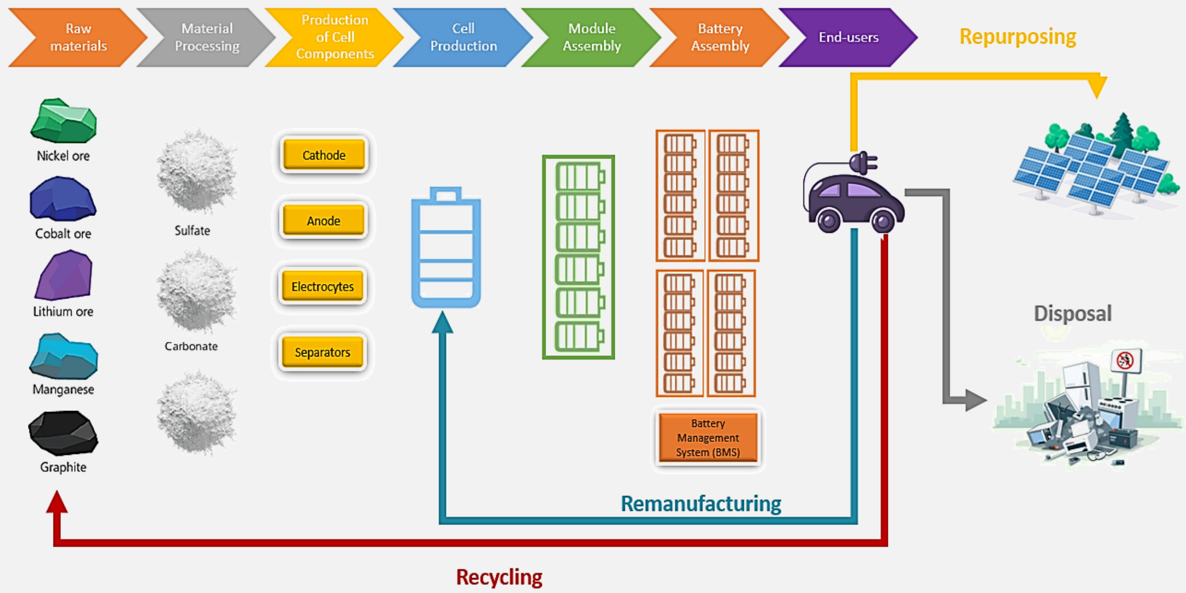


Figure 5: Value Chain for EV Lithium-Ion Battery

Figure 5 shows the value chain of EV LIBs and the impact of the EOL strategies on the value chain. As can be seen in Figure 5, value recovery can be at various stages in the battery value chain such as the material level, cell component manufacturing, cell manufacturing, module assembly, and battery pack assembly stages. To promote circularity and value recovery from EV LIBs, these EOL strategies need to be coordinated in a robust manner, so that the sustainability benefits are maximised, and the trade-offs are mitigated.

3. Methodology

In this study, the potential opportunities and challenges in adopting the different sustainable EOL strategies in Jordan are investigated. First, the EV and EV battery status quo in Jordan is investigated. Hence, qualitative and quantitative data are collected on the current state of Jordan. Next, EV penetration and the number of spent batteries were forecasted. After that, different EOL implementation scenarios were generated and analysed. Finally, the scenarios were compared, and the opportunities and trade-offs were identified. The methodological framework is shown in Figure 6.

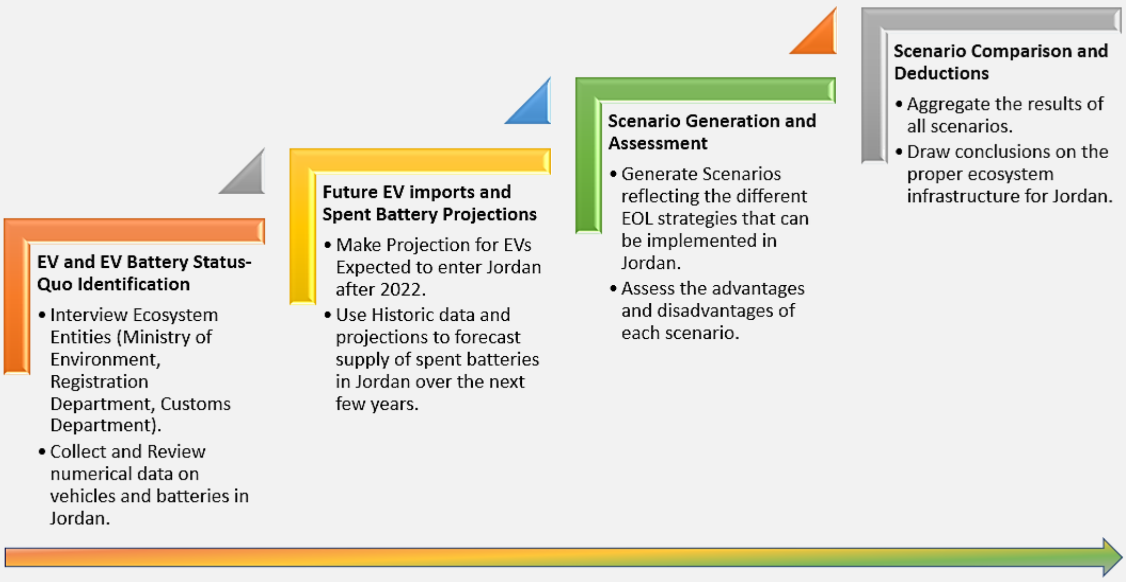


Figure 6: Outline of Methodology

3.1 Data collection

To assess the current state of spent batteries and the readiness to implement sustainable practices in Jordan, data is needed on the current infrastructure, EV market, and spent battery inventory in Jordan.

Several strategies were used to collect data and expert insights: (1) research publications (2) journal and news articles, (3) published governmental reports, (4) telephone and online video interviews, (5) semi-structured expert interviews, and (6) historical records and statistical data. Representatives from the Ministry of the Environment, the Zarqa Customs Department, and the Driver's License and Registration Department were primary sources for this data.

Data limitations: For the qualitative data that was obtained, several limitations were faced. First, only data from 2018 to 2022 was obtained. Moreover, the data did not include the model year or model type of the vehicle. Meanwhile, hybrid and plug-in hybrid vehicle (PHEV) numbers were aggregated. Consequently, in this study, BEVs will refer to the full EVs and HEVs will refer to plug-in and standalone hybrid EVs (see Figure 7). As for the battery, no record was kept on the type of battery in the vehicle, for example, nickel, lithium-ion, etc. Moreover, the battery's age, nameplate capacity, and number of modules/cells are also unknown. For this study, it is assumed that the batteries are all LIBS batteries since the technological trend for EV batteries is moving in this direction. Moreover, it is assumed that all batteries are assembled from cylindrical lithium-ion cells that have the same material composition percentages.

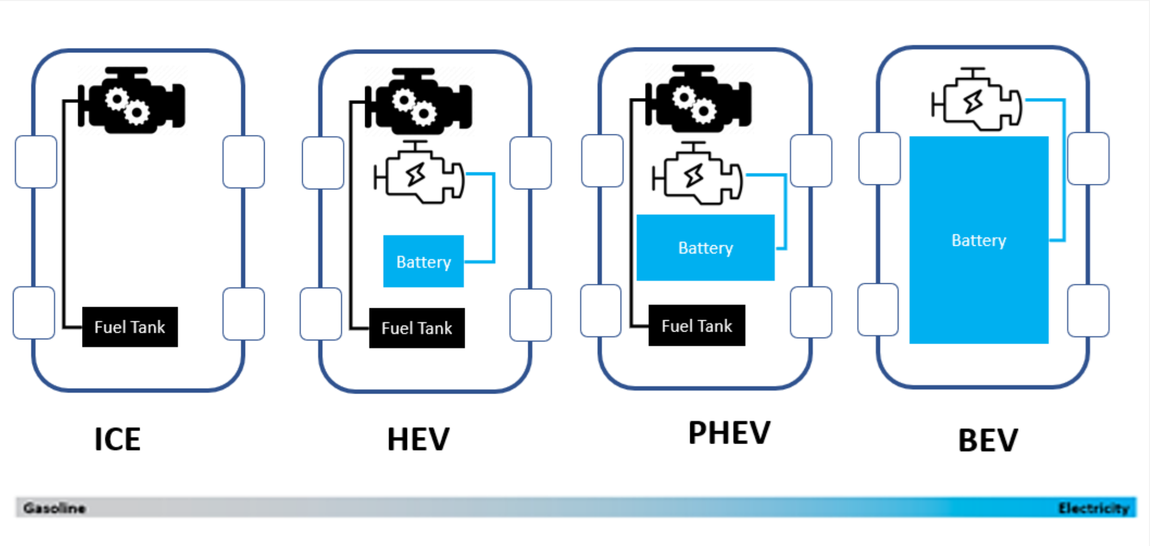


Figure 7: Vehicle Classification based on the Degree of Electrification

3.2 Projections for vehicle quantities

To forecast the number of EVs, a simple moving average method, based on the average of the previous two years, was adopted. Additionally, a 2% increase for EVs is incorporated (adopted to align with recommended goals from the Ministry of Transport related to the public EV fleet):

$$f(x) = 1.02 \times \overline{x_{m.avg}}$$

Limitations:

- The forecasting method assumes that customs and tax regulations, related to tax, customs, and fees, for imported vehicles do not change significantly and that the vehicles cleared by customs were imported in the same year.
- Since the moving average method relies heavily on historic and time series data to provide accurate results, it is recommended that the projections are updated year by year as more data comes in.

3.3 Spent battery forecasts

A naive forecasting methodology to estimate the number of spent batteries in Jordan is applied. Accordingly, using the number of BEVs and HEVs that received customs[4] clearance, the supply of spent batteries in Jordan is estimated according to the procedure in Figure 8.

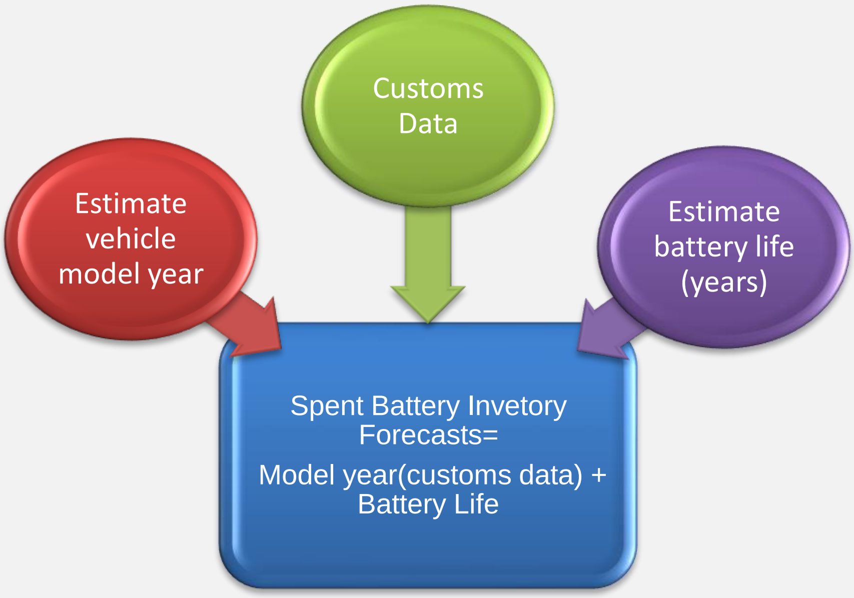


Figure 8: Procedure for forecasting spent battery inventory levels

The first step was to estimate the age of the vehicle. Based on the regulations issued by customs (i.e., vehicles older than 5 years are prohibited from entering), an age correction factor was applied. Accordingly, the total number of vehicles was divided into 10 equal bins and a random number generator was used to determine how old the car is with respect to the year it was cleared by customs. For example, if the vehicle entered in 2018 a random integer between 0 and 5 is subtracted from the vehicle clearance year[5]. This means that the age of vehicles in 2018 can have a model year anywhere from 2013 to 2018. Next, it is necessary to add a random variable to model the life of the battery. Based on literature and industrial standards, the life of an EV battery is anywhere between 8 and 12 years. Hence a random number generator for integers from 8 to 12 is used to represent the life of the battery. Finally, to determine the year that the EV battery would be considered a "spent" battery, the estimated life of the battery is added to the estimated model year of the battery. Monte Carlo simulation was used to replicate the above procedure to provide a more robust forecast for the spent battery inventory.

[4] A vehicle that has received custom's clearance is a vehicle that has left the Jordan dusty free zone and can be legally owned and operated in Jordan.

[5] **Assumption/limitation:** import year was assumed to be the same as the vehicle clearance year.

3.4 Scenario layout and criteria

Qualitative data was also collected. The factors shown in Figure 9 were identified as the major influencers of sustainable life cycles of EV batteries in Jordan. The successful implementation of these EOL strategies is determined by economies of scale. Hence, there is a need to quantify the number of EVs entering Jordan and the number of spent batteries that need EOL management.

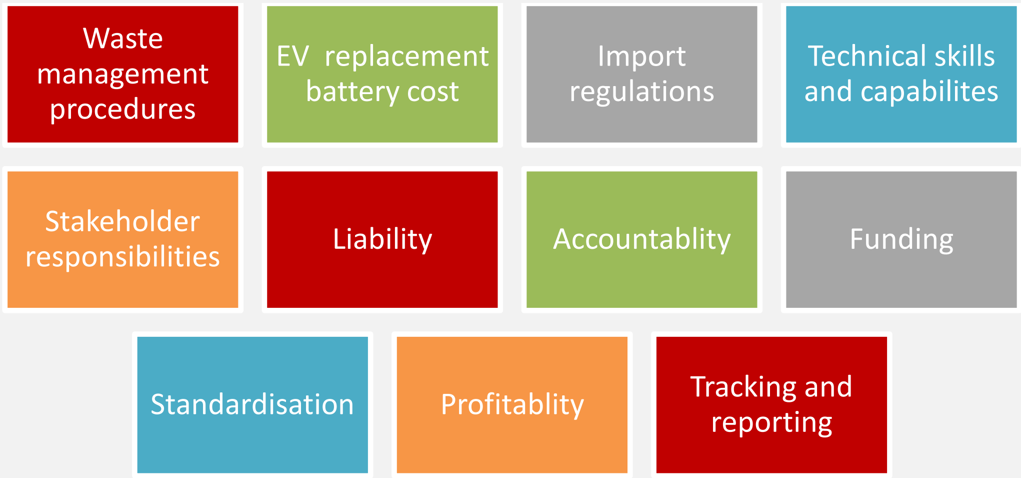


Figure 9: Factors Influencing Sustainable EOL Management of EV Batteries

The different EOL strategies' impacts, benefits, and challenges in Jordan must be investigated and compared. Accordingly, several scenarios for Jordan's EOL ecosystem are presented as follows:

- **Scenario 0**: Accumulating spent battery waste in Jordan (current state)
- **Scenario 1**: Centralised exporting of spent batteries to be processed outside of Jordan
- **Scenario 2**: Opening a recycling plant in Jordan
- **Scenario 3**: Open a repurposing plant in Jordan
- **Scenario 4**: Open a remanufacturing plant in Jordan

The different scenarios are compared based on the following criteria: EV consumer needs, waste reduction, cost, revenue potential, environmental impact, complexity, and green jobs promotion. The following scale is used for the comparison criteria:

-3	-2	-1	0	+1	+2	+3
Extremely Unfavourable Impact	Highly Unfavourable Impact	Unfavourable Impact	Neutral Impact	Favourable Impact	Highly Favourable Impact	Extremely Favourable Impact

These rankings will be set based on a combination of subjective and quantitative support. Semi-structured interviews, expert insights, and calculations applicable to each scenario will be considered. For the quantitative calculations, related to a specific scenario, a brief overview of assumptions and calculation procedure will be discussed within each scenario.

4. Projections and scenario analyses

4.1 Projection and forecasts for Jordan

Data on the number of vehicles that received customs clearance was obtained from the Jordan customs department in Zarqa for the years 2018 to 2022. The vehicles were classified as hybrid (HEVs and PHEVs), full electric (BEVs), and conventional gasoline (ICE) vehicles. The values are shown in Figure 10. The data shows a nonuniform trend for both the total number of vehicles and the quantity for each type of vehicle that are receiving customs clearance. This is most likely due to changes in import/clearance tariffs on vehicles since consumer patterns are greatly influenced by tax and tariff percentages on imported cars[6], which can be as high as 10,000 JD for a standard hybrid sedan. Moreover, the drop in 2019 and 2020 may be attributed to the COVID-19 outbreak.

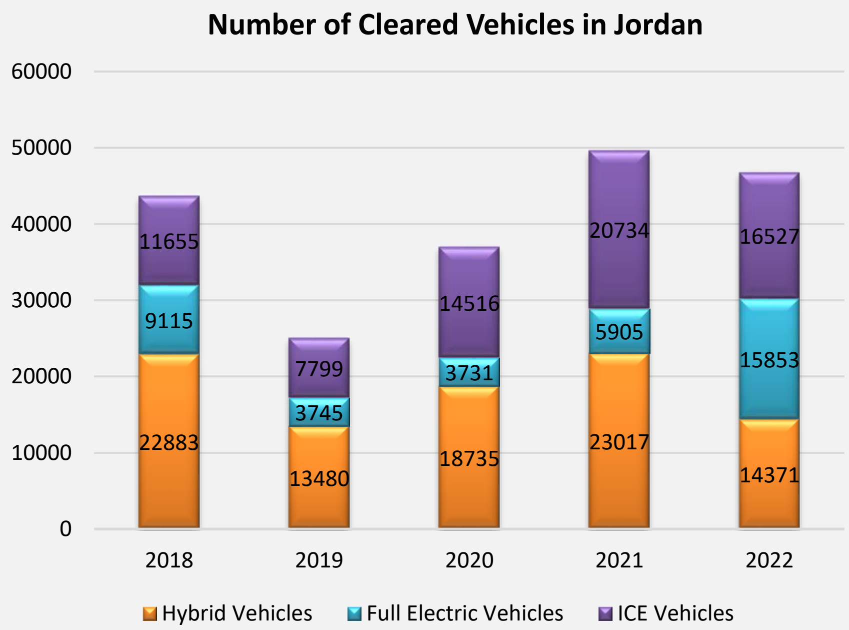


Figure 10: Vehicles Receiving Clearance from Customs between 2018 and 2022

Meanwhile, when looking closer at the percentage of each type of vehicle, the percentage of hybrid batteries had always exceeded that of ICE and full electric vehicles between 2018 to 2021; however, in 2022 the number of hybrid vehicles fell below that of full electric (i.e., BEV) and ICE vehicles. Moreover, the percentage of BEVs dramatically increased in 2022 compared to previous years with a 168.467% increase compared to 2021.

Meanwhile, data on the number of standalone EV batteries imported into Jordan were

[6] **Source:** https://www.jordannews.jo/Section-109/News/Electric-cars-market-share-increases-to-34-6-in-Jordan-over-5-years-27319

also obtained from the Zarqa customs department in Jordan from 2018 to 2022[7]. These batteries are imported into Jordan to serve as replacement batteries for already on-the-road vehicles. The numbers show that the HEV battery demand is much higher than that of the BEV battery.

The reason for this is twofold: First, BEV batteries penetrated the Jordan market several years after hybrids. Likewise, HEVs have shown to be the most popular choice among Jordanian consumers in the last few years. It is expected that the imports of batteries for both HEV and BEV will continue to increase in the upcoming years. The year-by-year number of imported HEV and BEV batteries is shown in Figure 11.

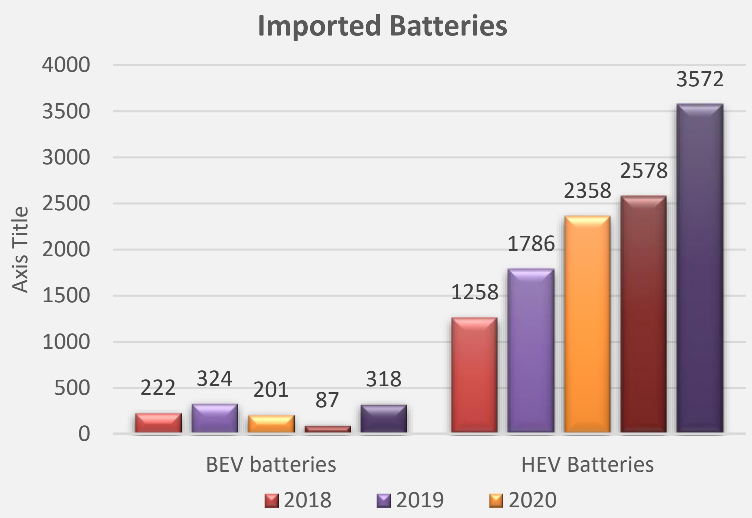


Figure 11: Imported EV batteries between 2018 and 2022

Next, using the number of BEVs and HEVs entering Jordan, the forecasts for spent battery inventory, considering that vehicles are imported (and cleared by customs) from 2018 to 2022 (historic data), is shown in Figure 12.

However, in Figure 12 the forecast fails to consider vehicles that have been imported and customs cleared after 2022. Thus, if vehicles imported and customs cleared in 2023 are at the oldest a 2018 model with a minimum life of 8 years, the number of spent batteries in the year 2026 and beyond (2027, 2028, etc.) is expected to be larger. Since the spent batteries will be a cumulative value driven by EVs entering Jordan from previous years, this cycle will repeat.

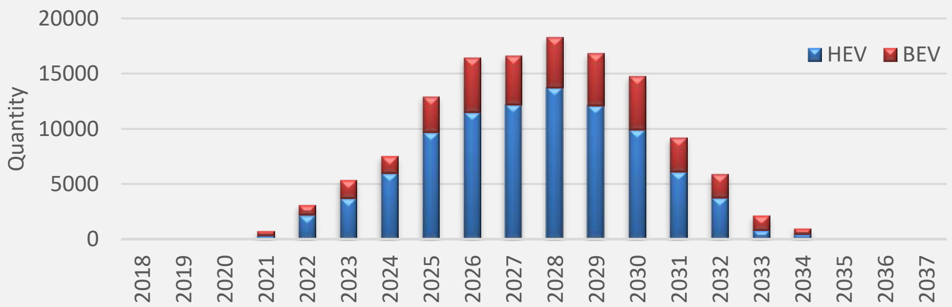


Figure 12: Spent EV Battery Forecasts

[7] These numbers represent imported batteries that may or may not have left Jordan Duty Free Zone

Hence, the projections for custom cleared vehicles are computed and shown in Figure 13. The projections follow a more uniform and steadier trend. This is due to the moving average projection method. Moreover, the projections do not consider any changes in incentive, tax, or import tariffs, which are envisioned as major contributors to the volatility in the number of imported/cleared vehicles. While this may not represent the real case, such a steady and involatile trend is needed for robust and cost-effective EOL management of spent EV batteries. This is due to the capacity sizing and expected processing rate needed for each EOL strategy.

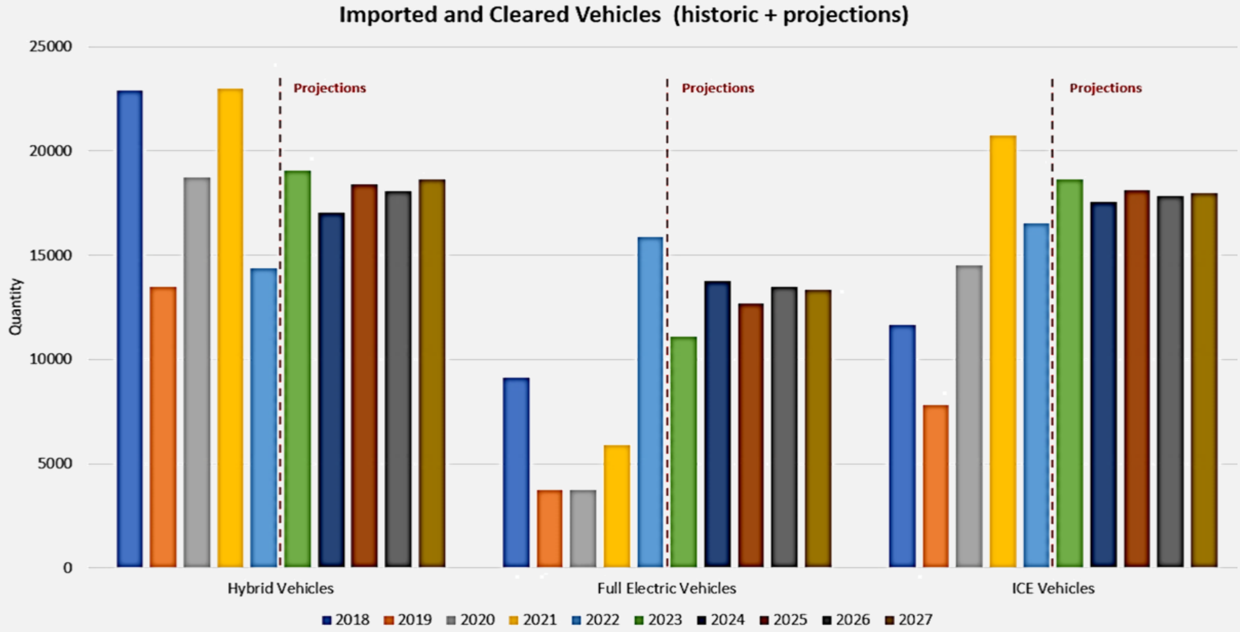
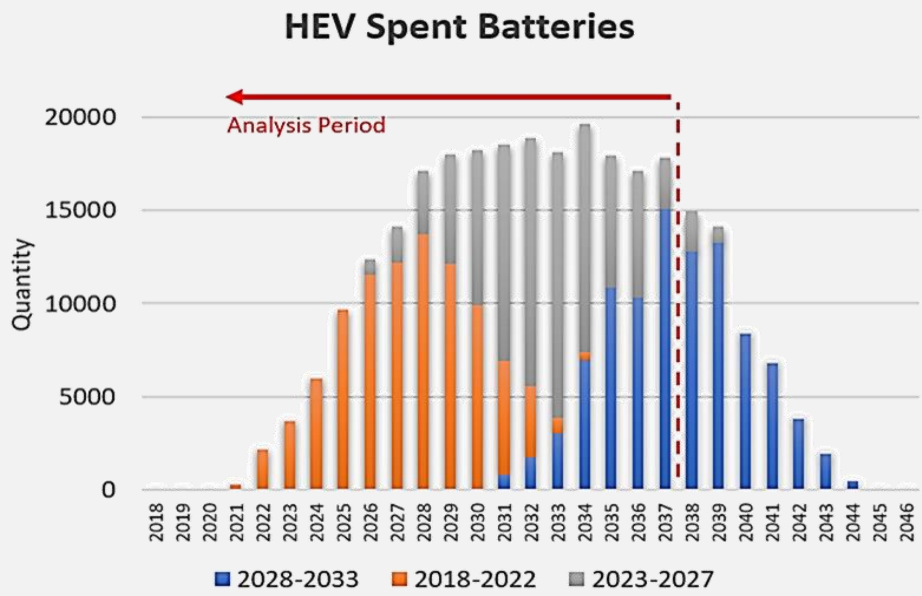


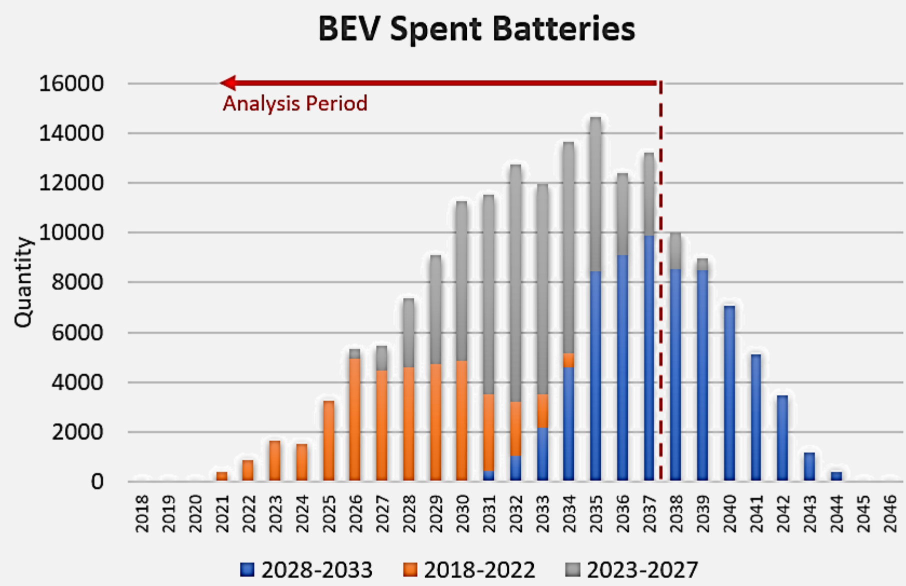
Figure 13: Projections for Vehicles Entering from 2023 to 2027

Accordingly, the projection for the number of vehicles cleared by customs from 2023 to 2033 is added to the forecast for spent battery inventory in Jordan. The forecasts are shown in Figure 14. In the figure, the orange bars represent the number of spent batteries based on actual values for EVs in Jordan; meanwhile, the grey and blue bars reflect two 5-year cycles of projection of EV batteries entering the Jordanian transportation fleet. Once again, like Figure 12, a decrease is observed after 2037 since the EV projections were only considered up to 2033. Accordingly, the cut-off period used in the analysis for the rest of the study will be only up to 2037[8].

[8] The reference period is not based on steady state, but rather on the inflection point before a drop in spent battery quantity. This drop is not representative of the practical pattern spent EVs are subject to and is merely because the cycle for the projection of cleared EVs ended. This results in a 17-year analysis period that will be used in the rest of the study.



(a) Hybrid vehicles



(b) Full electric vehicles

Figure 14: Spent EV Battery Forecasts
from Custom's Cleared Vehicles between 2018 to 2033

4.2 Scenario Analysis

If EOL strategies are implemented in a robust and sustainable manner, value recovery and life extension of batteries can be achieved. This in turn will provide Jordanian EV owners with affordable battery replacement alternatives, increase the life-cycle sustainability of EVs in Jordan, and open a revenue stream that will result in the creation of eco-friendly jobs.

4.2.1 Scenario 0: Current Status

In **Scenario 0**, the current state of Jordan is represented (see Figure 15). In this scenario batteries can be returned to the automotive dealership (after which they will be exported out of Jordan) or sent to either landfills or collection enters.

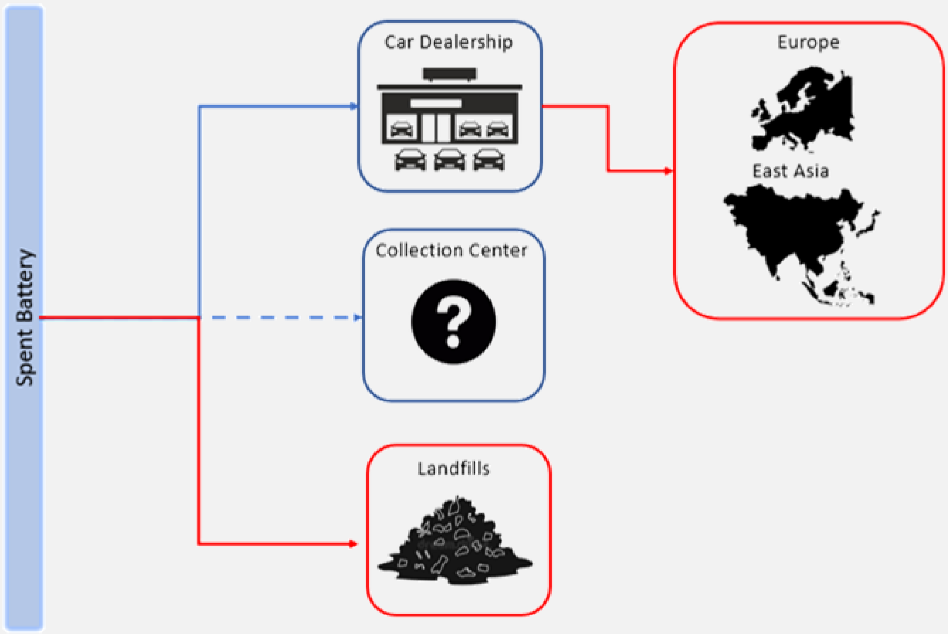


Figure 15: Accumulating Spent Battery Waste in Jordan – Scenario 0

Such a scenario can provide benefits in consolidating the pathways of spent batteries and create opportunities to determine more sustainable EOL management. Nonetheless, these methods face challenges. First, the dealership taking responsibility for the management of their customers' spent batteries can be a very important strategy in reducing the accumulating battery waste in Jordan. However, not all vehicle owners rely on their dealership; hence, spent battery returns to the dealership are not guaranteed. Moreover, based on interviews with private and public sector representatives, there is not currently any tracking or follow-up method by the public sector to ensure that dealerships are taking accountability for their spent batteries.

Meanwhile, for disposal in landfills, there lacks EV designated disposal sites for EV spent batteries. Currently, EV batteries are being sent to a hazardous waste disposal site, Swaga Landfill. This makes the return and tracking of spent batteries difficult and unreliable. Moreover, regulations on the obligation for proper disposal of batteries to this landfill are not mature. Finally, in the case of batteries being sent to designated EV battery collection centres, the spent batteries can either be sent by the EV owner directly or by the car mechanic. For this pathway to be sustainable, a strategy for managing batteries, after they reach the collection centres, needs to be developed.

Factor	EV consumer needs	Waste Reduction Potential	Cost	Revenue Potential	Environmental Impact	Complexity	Green Jobs Potential
Score	-3	-3	-1	0	0	+1	0

4.2.2 Scenario 1

In the next scenario, spent EV batteries are collected and sent to a collection centre, after that the public sector takes responsibility for exporting spent batteries to other countries for EOL management (see Figure 16). This scenario was proposed by several public sector stakeholders as a potential solution for Jordan to deal with spent battery waste.

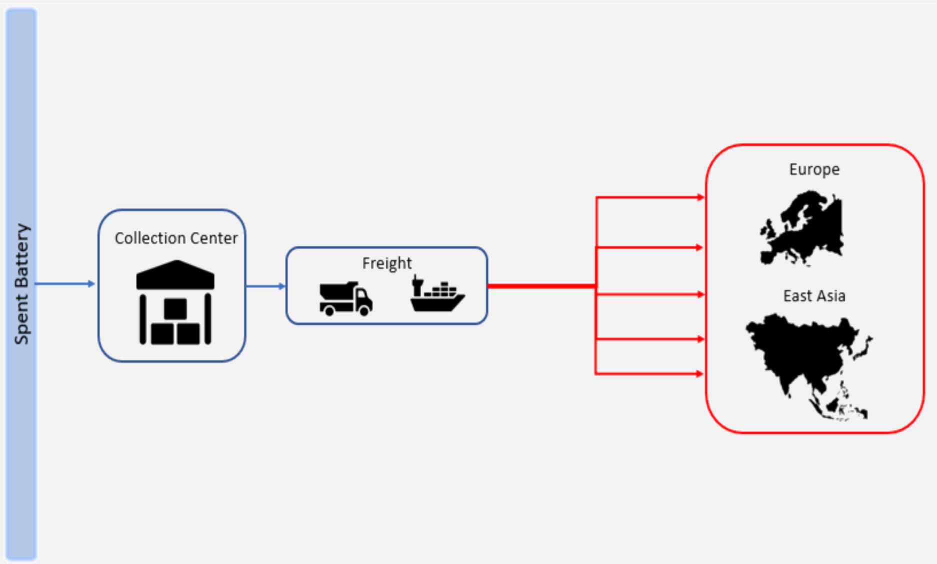


Figure 16: Public Sector Exporting Spent Batteries – Scenario 1

The advantage that this scenario provides is that the storage cost at collection centres is reduced. Moreover, a revenue stream can be generated from selling these spent batteries. Meanwhile, the disbenefits of this scenario are as follows. First, transporting such hazardous material over long distances can pose a safety concern. Also, EV owners are not offered a sustainable solution when seeking to replace their spent batteries.

The cost and environmental impact (emission) of having to export spent batteries and import a replacement battery are quite high. Using the spent battery forecasts, the cost and environmental impact of shipping spent batteries outside of Jordan are calculated. It is assumed that spent batteries are either shipped to Germany or China (50/50 split) where the development of new markets for spent EV batteries is proactively being advanced. Moreover, assuming the average weight of an HEV battery is 125 kg and the average weight of a BEV battery is 475 kg. Assuming 140g of CO_2 emissions are generated per tonne-km[9], the results for the total emissions for the assumed case from 2021 to 2077 are shown in Figure 17. Multiplying the total emissions by 2, to account for importing replacement batteries for Jordanian EV owners, the emissions value is 8,013 tonnes of CO_2 per year on average.

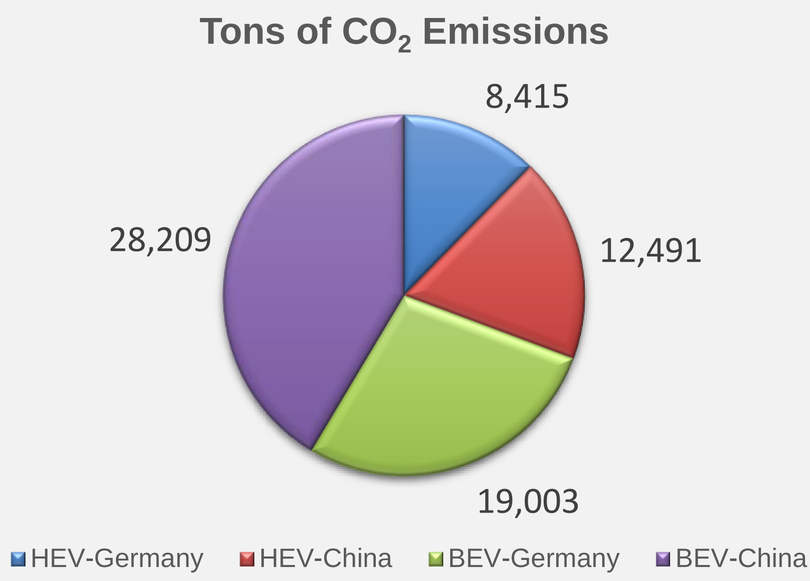


Figure 17: Emission from Exporting Spent Batteries for EOL Processing

Next, the cost of freight is calculated using the average cost per kilometre of $0.58. Moreover, the maximum load that a truck can carry is 22 tonnes[10]. For HEV batteries that will be 160 batteries per trip and for BEV that will be 42 batteries per trip. This results in an average cost of $831,445 per year ($14,134,656 for the 17-year analysis period). The cost breakdown for the assumed base is shown in Figure 18.

[9] eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2#tab-chart_1
[10]https://della.eu/cost/w1/https:/www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2/#tab-chart_1

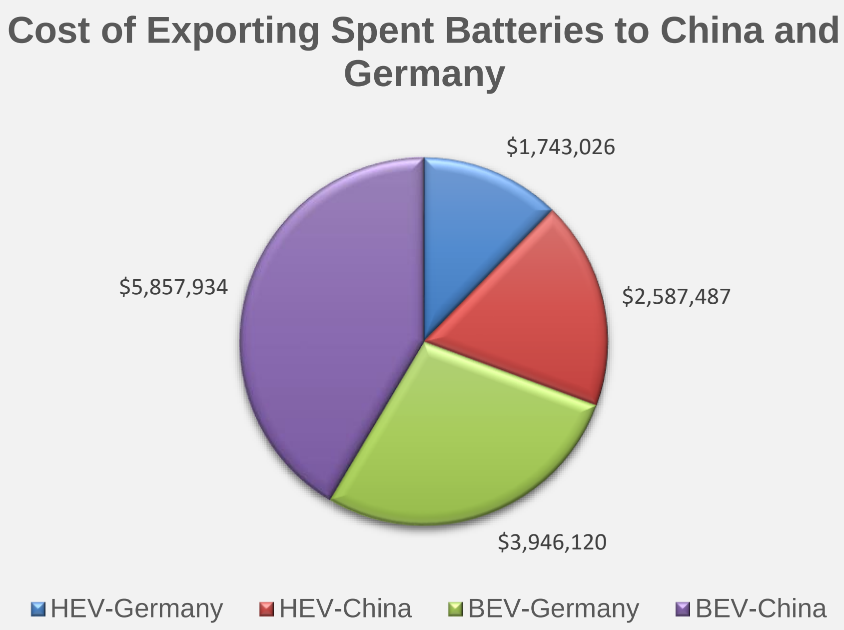


Figure 18: Cost of Exporting EOL Batteries for Processing

Assuming the scrap value of LIBs is around $110.23/tonne[11], the revenue that can be generated from selling all spent LIBs in Jordan is $10,309,047 over the 17-year analysis period, or $606,415 annually. This shows that the cost of shipping is greater than the revenue from the sold lithium scrap, hence, this is not an economical option. Moreover, Jordanian car owners are still faced with challenges related to car battery replacement needs.

Factor	EV consumer needs	Waste Reduction Potential	Cost	Revenue Potential	Environmental Impact	Complexity	Green Jobs Potential
Score	-1	0	-1	-1	-2	0	0

4.2.3 Scenario 2

Subsequent, Scenario 2 is such that a recycling plant is open in Jordan (see Figure 19). The spent batteries are recycled and materials such as nickel, lithium, cobalt, etc. are retrieved. The material that is retrieved can either be sold locally or exported.

[11] https://www.batterypoweronline.com/markets/batteries/is-it-time-for-a-lithium-ion-recycling-revolution/

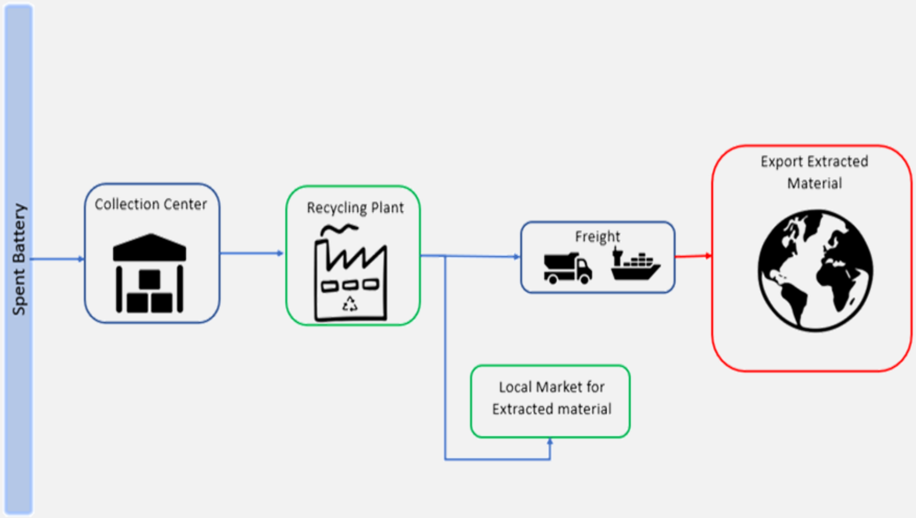


Figure 19: Opening a Recycling Plant in Jordan - Scenario 2

The benefit of this scenario comes from the reduction of waste and value recovery of the batteries. The economic value of the material extracted through recycling batteries is expected to be significant and is estimated as follows. First, assumptions were made in calculating the economic value of the recycled material. It is assumed that the spent batteries are Lithium-ion batteries that have the percent composition and cost shown in Table 1. The recycling process efficiency is 65%. Once again, the average weight for the HEV is 125 kg, and for the BEV battery 475 kg.

Table 1: LIB Material Composition and Unit Costs

Material	% of battery weight[12]	Cost per tonne[13]
Nickel	15.7%	$12,600
Cobalt	4.3%	$27,500
Lithium	3.2%	$20,000

The results show that over the 17-year analysis period, the potential economic revenue is $231,044,502. Meanwhile, the average annual economic value for each material is shown in Figure 20, with a yearly average of $13,590,853. If this recycled material is exported to battery manufacturers, it will stimulate domestic economic activity that can lead to job creation and a substantial revenue stream for Jordan.

[12] https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/
[13] Assumed based on multiple online sources

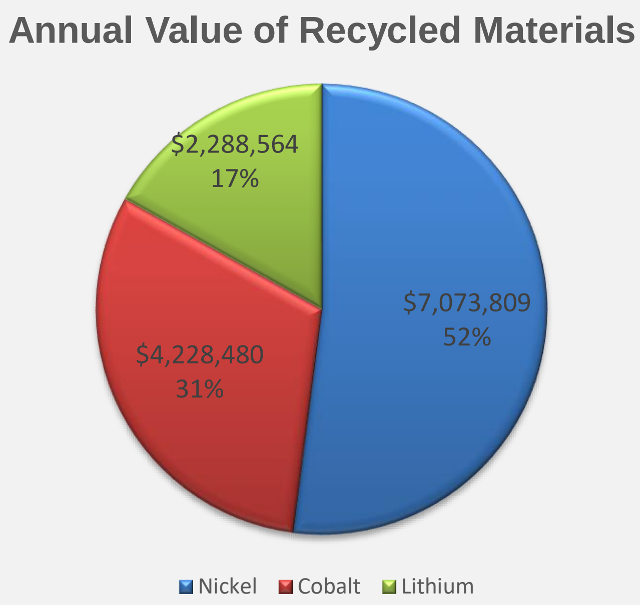


Figure 20: Recycled Material Economic Value

Despite the promising revenue stream, a major disadvantage of this scenario is that the recycling process is shown to be very costly, and the value of the material extracted may not be significant enough to justify capital costs. Hence, a low-profit margin is expected for this EOL strategy.

Moreover, considering the relatively small supply of spent batteries in Jordan compared to other countries, competing in this industry will be challenging. Lastly, the challenges faced by Jordanian EV owners in finding high-quality and affordable replacement batteries are not addressed in this strategy.

Factor	EV consumer needs	Waste Reduction Potential	Cost	Revenue Potential	Environmental Impact	Complexity	Green Jobs Potential
Score	0	+2	-3	+3	+2	-3	+2

4.2.4 Scenario 3

Next, for **scenario 3** spent batteries are sent from the collection centre to a repurposing plant (see Figure 21). In this repurposing plant, batteries are prepared for other applications (such as load balancing in the grid). This scenario is advantageous because it extends the life of the battery. Moreover, it generates a revenue stream considering the high popularity of solar panels in Jordan.

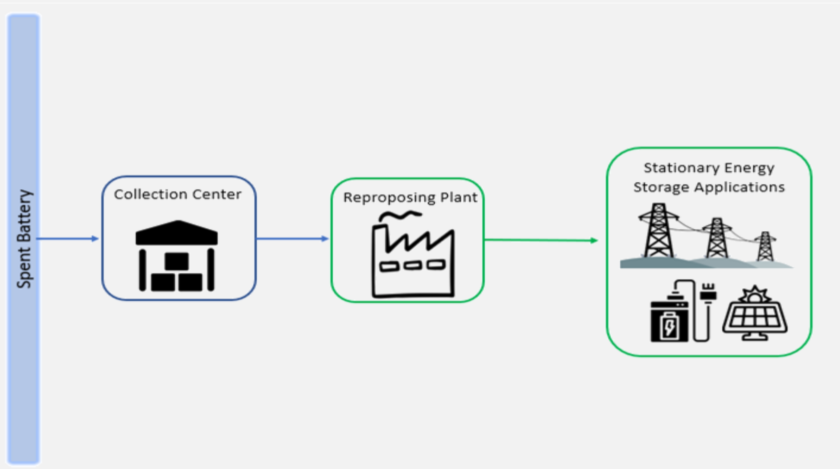


Figure 21: Opening a Repurposing Plant in Jordan - Scenario 3

In Jordan, 29% of the energy in Jordan comes from renewable energy (i.e., solar and wind power) and is expected to grow to 50% by 2030. Jordan has a lack of storage capacity, as the electrical capacity is approximately 6,500 MW, while consumption is at a rate of 3,500 MW during days of extreme cold and extreme heat. The excess renewable energy challenges can be solved using storage capacity; However, this is very expensive due to the high cost of storage batteries. Luckily, spent EV batteries can be a cost-effective solution to this challenge.

If a repurposing plant were to be opened in Jordan, the potential revenue is calculated according to the following: The average capacity per kg for a BEV is 0.155 kWh/kg and 0.08 kWh/kg for an HEV. Meanwhile, the expected profit per remanufactured battery is between 36-96 $/kWh . If 50% of batteries in Jordan can be repurposed, this will result in a potential revenue stream for Jordan of $592,826,527 over the 17-year analysis period (or $34,872,149 annually) according to the economic modelling.

Under the scenario of repurposing, high investments in research and development, as well as processing and testing operations are required and would need to be mobilised. Moreover, a strategy for electricity generation plants to access funds to purchase and process these repurposed batteries must be devised. Meanwhile, from the perspective of EV customers in need of replacing their spent EV batteries, this scenario does not offer additional local replacement options.

Factor	EV consumer needs	Waste Reduction Potential	Cost	Revenue Potential	Environmental Impact	Complexity	Green Jobs Potential
Score	-1	+1	-1	+1	+3	-1	+1

4.2.5 Scenario 4

Finally, in scenario 4 the collected spent batteries are sent to a remanufacturing facility for processing (see Figure 22). The batteries are remanufactured to a level such that they are suitable for automotive applications. Such a strategy will help EV owners gain access to locally sourced replacement batteries. Moreover, remanufacturing will help reduce the accumulating spent battery waste in Jordan, while avoiding the need to export spent batteries for EOL processing.

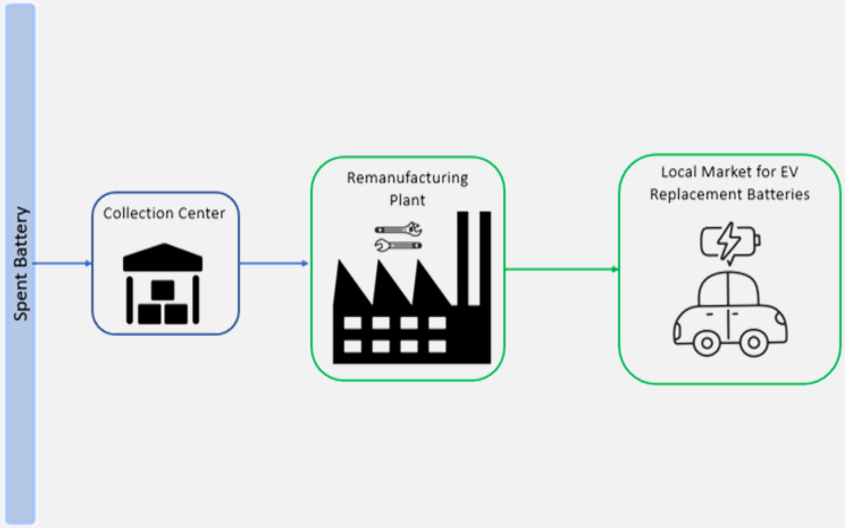


Figure 22: Opening a Remanufacturing Plant in Jordan - Scenario 4

Challenges that remanufacturing faces are the considerable financial investment for such a strategy, and the access to technical expertise and resources needed for such an endeavour. However, remanufacturing is expected to provide a substantial revenue stream for Jordan that will justify the needed investment.

Accordingly, the remanufacturing market value/revenue potential is approximated. First, the expected cost for Jordanian EV owners to replace their batteries at the EOL is estimated. Afterward, the cost of a replacement battery needs to be estimated. Considering the various types of HEVs and BEVs, the capacities and costs of the batteries can vary greatly.

For HEVs, the cost of a replacement HEV battery is assumed to be between $1,000 to $5,000, with a most likely value of $2,000. Meanwhile, the cost for a BEV replacement battery is assumed to be between $2,000 to $20,000 with a most likely value of $4,500. Finally, a 1% per year reduction in the cost of the battery is assumed. Accordingly, the EV replacement battery costs needed to support Jordan's EV fleet each year are shown in Figure 23. This results in a total economic value for the needed replacement batteries to be $885,067,712 over the 17-year analysis period (or $52,062,807 annually).

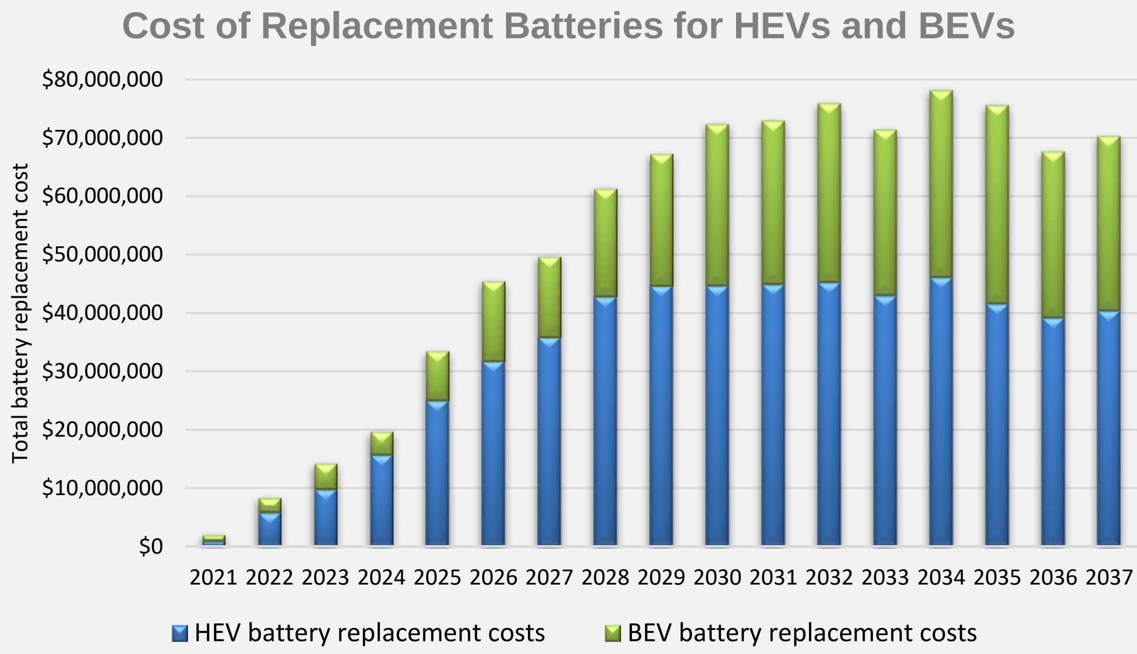


Figure 23: EV Battery Replacement Costs

Next, the market value in Jordan is calculated according to the following. First, 85% of spent batteries are assumed to be suitable for reuse in automotive applications while the remaining 15% of spent batteries are assumed to be damaged beyond repair.[14] Moreover, to support Jordanian EV owners by providing an affordable battery replacement alternative, the selling price of the batteries is set to be 50 percent of the cost of an imported battery. Accordingly, the market value for remanufactured batteries in Jordan from 2021 to 2022, is shown in Figure 24.

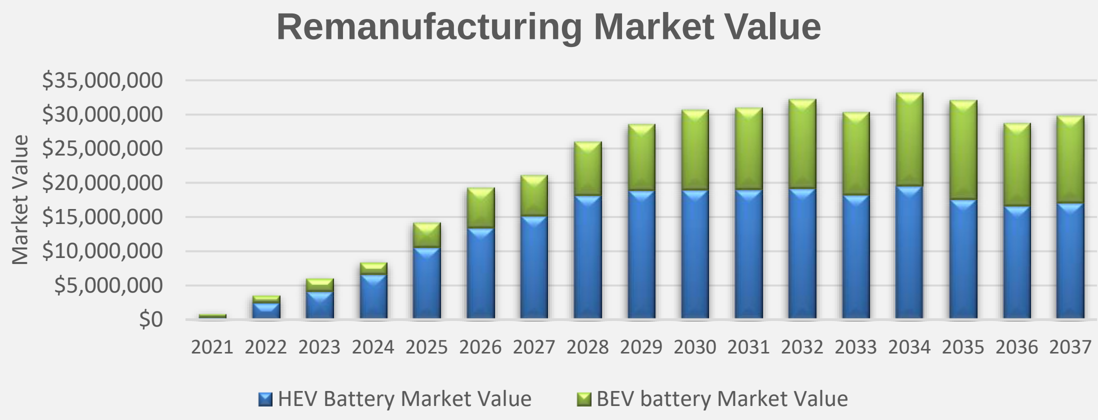


Figure 24: Spent Battery Remanufacturing Revenue Potential

[14] https://chargedevs.com/newswire/used-li-ion-batteries--repurpose-or-recycle/#:~:text=According%20to%20a%20new%20report,repurposing%2C%20and%20recycling%20efforts.%E2%80%9D

As can be seen from the figure the potential revenue from selling remanufactured batteries for EV applications is $376,153,778 over the 17-year analysis period (or $22,126,692.81 annually). Hence, resulting in 42.5% of the EV battery replacement costs to be absorbed in Jordan's economy.

It is of critical importance to note that, for such a venture to be successful, predictable and involatile availability of spent batteries and demand for replacement batteries are needed. This is because capital investments will be significant and require a steady stream of demand for sustainable operation. For Jordan, the greatest threat to achieving this stability and steady-state condition is the changing taxes and customs fees and deductions for the different types of imported vehicles.

Factor	EV consumer needs	Waste Reduction Potential	Cost	Revenue Potential	Environmental Impact	Complexity	Green Jobs Potential
Score	+3	+2	-2	+3	+3	-2	+3

4.3 Scenario comparison

The scores and revenue potential of the various scenarios are compared side-by-side to provide a holistic representation of the different EOL management practices (see Tables 2 and 3). The greatest benefits are from recycling, remanufacturing, and repurposing spent EV batteries in Jordan. Nonetheless, trade-offs do exist even among these scenarios. Hence, it is expected that the ideal scenario that would reap the greatest benefits is one that considers all of these possible EOL routes for the spent EV battery.

Table 2: Summary of criteria comparison for various EOL strategies

Scenario	Revenue potential
S1: Exporting Spent Batteries	$606,415
S2: Recycling	$13,590,853
S3: Repurposing	$21,577,142
S4: Remanufacturing	$22,126,692

A SWOT analysis is conducted to evaluate the viability and make recommendations for the proposed EOL infrastructure. The SWOT analysis is shown in Figure 25. In all, remanufacturing, repurposing, and recycling's main advantage is that there is no current competitor in Jordan and the unclaimed market is very large. Successful deployment of these EOL strategies will reduce hazardous e-waste, benefit consumers, provide a high revenue stream, and lead to job creation. Nonetheless, remanufacturing, repurposing, and recycling require complex and highly technical operations. Meanwhile, the success of these EOL strategies relies heavily on the stability of imported EVs and supply and demand balancing, which is highly impacted by quickly changing technology, politics, and market conditions.

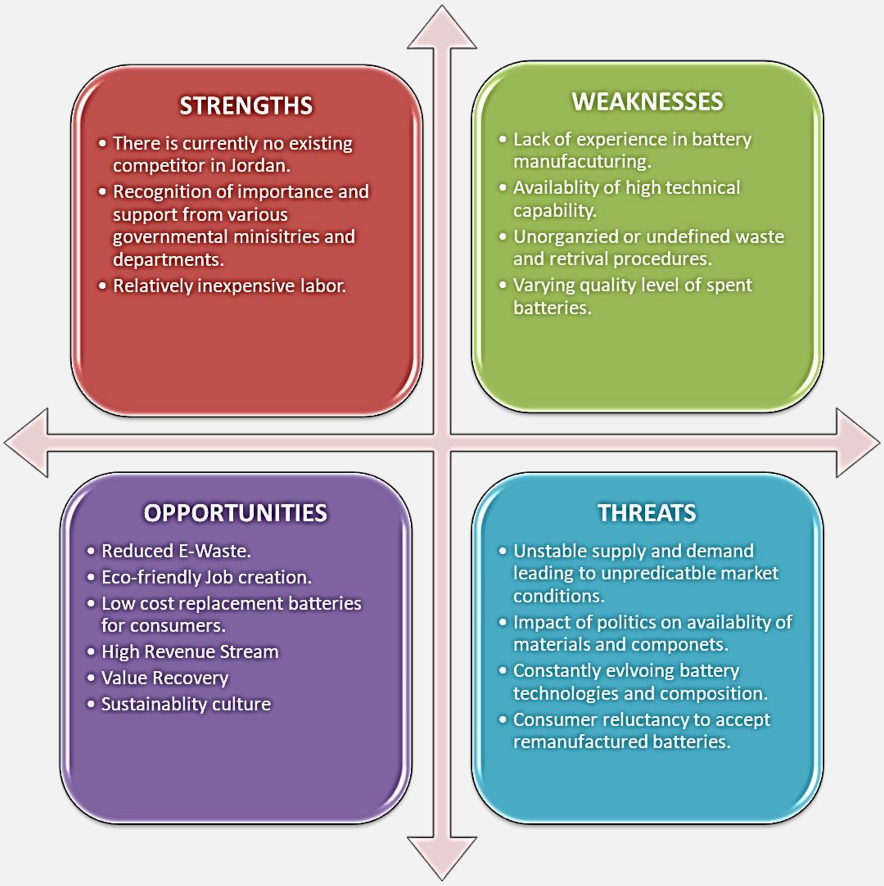


Figure 25: SWOT Analysis for Recommended Infrastructure

	Scenario	EV consumer needs	Waste Reduction Potential	Cost	Revenue Potential	Environmental Impact	Complexity	Green Jobs Potential
0	Disposing	-3	-3	-1	0	0	+1	0
1	Exporting	-1	0	-1	-1	-2	0	0
2	Recycling	0	+2	-3	+1	+2	-3	+2
3	Repurposing	-1	+1	-1	+3	+3	-1	+1
4	Remanufacturing	+3	+2	-2	+3	+3	-2	+3

Table 3: Summary of Revenue Potential for Various EOL Strategies in Jordan

5. Conclusions and Recommendations

5.1 Potential Pathway for a Sustainable EOL Ecosystem in Jordan

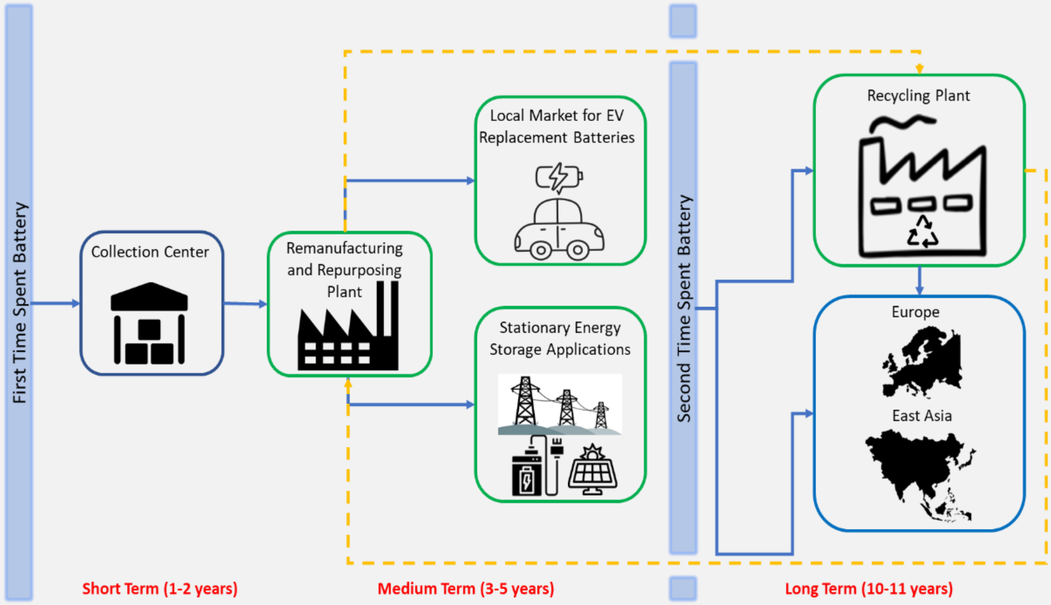


Figure 26: Recommended Infrastructure for Jordan

The suggested infrastructure for EV battery EOL management is shown in Figure 26 and is summarised as follows. In the short-term horizon (1-2 years), there is a critical need to train and educate EV owners, EV mechanics, and private sector stakeholders on sustainable best practices for EV batteries and proper handling at the EOL. Meanwhile, it is necessary to open up collection centres in Jordan to collect these spent batteries. Moreover, policies and regulations supported via an incentive system by the government must be put into place to encourage the proper discarding of EV batteries.

Next, in the medium-term horizon (3-5 years), a sustainable EOL strategy for Jordan could include a remanufacturing and repurposing plant. It is recommended that the primary focus of the plant is on producing replacement batteries for EV owners. Meanwhile, batteries that are not able to be restored to a quality level acceptable for automotive applications, can be repurposed or stationary energy storage applications.

Finally, in the long-term horizon (10-11 years) as remanufactured batteries reach their EOL (end of "second" life for the battery), it is recommended that they are recycled or shipped to other countries for processing. Hence, a recycling facility will be needed. Meanwhile, the recycling plant can, not also receive batteries at their "second" EOL, but also receive scrap from the remanufacturing centre. Meanwhile, the material recovered from the recycling plant and be used by the remanufacturing facility or exported.

The long-term goal is to move away from one-by-one refurbishment efforts and move toward standardized and quality-controlled remanufacturing operations. Moreover, opening a remanufacturing plant holds the potential of creating green jobs in line with the

Government of Jordan's Economic Modernization Vision 2033. These jobs can be at multiple stages in the supply chain (i.e., collection centres, remanufacturing facilities, sales, etc.). For the remanufacturing plant, the economic value that can be allocated for these jobs is estimated according to the following assumptions: First, the average annual profit margin is assumed to be 10.5%. Next, using the above market value estimations and assumed profit margin, the total remanufacturing costs were assumed. Considering that labour costs account for 30% of the total manufacturing costs, over the 17-year analysis period an economic value of $ 100,997,289 or an average of $ 5,941,017 per year. The yearly green jobs allocation is shown in Figure 27.

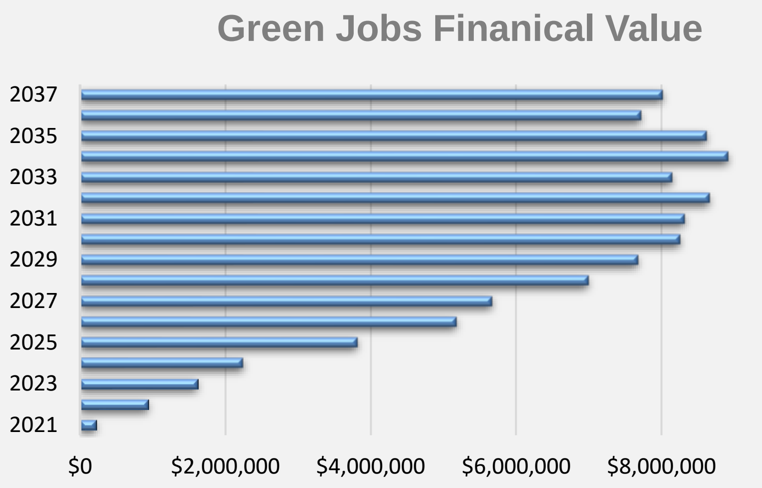


Figure 27: Green Jobs Allocations for Remanufacturing

5.2 Recommendations

Recommendations for EV use and spent EV battery returns:

- EV owners should be educated on the optimal use conditions of their EVs to avoid premature EOL of their batteries, as well as on the proper EOL disposal methods for EVs.

- For mechanic shops working on EVs, vocational training specifically on battery replacement and repair is necessary so that the life extension is maximises and safety concerns regarding the appropriate disassembling of batteries are considered. From a policy level, EV mechanics working on the battery should be required to obtain a license to work on the EV battery. This license should be issued to mechanics that have undergone the appropriate training related to the optimal replacement and repair of EV batteries. Moreover, the EV mechanic should show proof that they have a designated safe and secure place for disassembling the battery.

- Designated collection centres solely for EV batteries are needed. The collection centres need to sort batteries according to model, type, and capacity. A method for retrieval of spent batteries is needed to aid the collection of spent batteries.

This can be done via an incentive system in which a voucher or financial enticement is given to the EV owner (or mechanic) upon the proper return of batteries to a designated collection centre.

Recommendations on imports of EVs and LIBs:

- The Customs Department and the Ministry of Environment need to work together to specify the appropriate battery performance thresholds (such as the age of the battery, remaining useful capacity, DOD, SOC, etc.). Such standards should be kept for both batteries being imported with an EV or standalone batteries.

- The Customs Department needs to enforce the inspection of the battery performance. Hence, certified battery inspection methods need to be identified and added to the import requirements. This should be done before the battery enters Jordan to avoid the accumulation of waste batteries in Jordan Customs-Free zones.

- Current regulations in Jordan for importing EV batteries prohibit standalone batteries from entering (i.e., must be accompanied by another parts ex. engine). This regulation should be revised since it increases the inventory of unnecessary parts in Jordan. Moreover, this constraint puts barriers for consumers seeking to import batteries from battery manufacturers/remanufactures which will have a longer life than a used battery already installed on an EV or engine.

Recommendations on information availability and data collection

- A reliable and open-access information repository and database should be developed. This is needed at multiple levels, i.e., user level, workshop level, policy and regulations, incentives, etc.

- Traceability should be imposed on EV batteries to allow more sustainable handling and proper decision-making for EV batteries. Traceability involves following the batteries retrospectively by looking back at past processing, state, and usage. Meanwhile, tracking involves following the future path and conditions of the battery.

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