International Energy Agency
Technology Collaboration Programme
TASK 52 — ELECTRIC VEHICLES AND CIRCULARITY

ONLINE WORKSHOP:
EV traction e-motors and circularity: Activities, uncertainties, expectations

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Documentation

Part I: Introductory overview on circularity and traction e-motors

In **Part I**, three introductory presentations on different aspects of the workshop topic were held. Insights into current and future e-motor design options, a holistic approach towards circular e-motors as well as the status of End-of-Life (EOL) treatment and material criticality.

Title: Overview on e-motor design options: today and outlook

- The presentation was held by **Christian Wachter**, who is a research associate at the Institute of Vehicle Concepts, part of the German Aerospace Center (DLR), since 2015. He works in the field of electric traction drives for both road and railway vehicles, where his main activities are the mechanical design, thermal dimensioning and NVH-behavior of electric motors.

In the automotive sector, there are mainly three types of electric machines, that play a role. The first type of electric motors is the ***Permanent Magnet Synchronous Motor*** (PMSM), which has the highest share of all electric traction motors in automotive applications. The excitation for the magnetic field is created by magnets, which contain rare earth elements. The structure results in the highest efficiency and power density of all variants. Another type is the ***Electric Excited Synchronous Motor*** (EESM). The excitation is provided by copper windings in the rotor, which makes the transfer of energy via additional brushes to the rotor necessary. Here, no magnets are necessary, but the electrical losses in the rotor create heat, which has to be cooled. The EESM has a good efficiency in a broad working field and medium power density. The third type is the ***Asynchronous Motor*** (ASM). The ASM does also not contain rare earth magnets. The excitation takes place via induction in aluminium or copper cage in the rotor. It has advantages over PMSM and EESM. The production is cheaper and it is very robust against mechanical and thermal loads. But a disadvantage is the medium efficiency and lower power density.

The common design of an electric machine was shown on the example of a PMSM. The electric motor is set up of five central assembly groups. The ***housing***, made of aluminum, contains the water jacket, bearing shield and interfaces for power electronics box, and more. The ***stator*** is integrated in the main housing, mostly press-fit. It contains the laminated sheet package with copper windings and the required insulation material, e.g. paper, resin or varnish. There are two common techniques of winding. On the one hand, the windings can get wound externally and are retracted into the stator slots. Advantages are the high numbers and thin wires as well as the suitability for automating the process. But this automation takes much effort and the resulting fill factor in the stator is limited. On the other hand, the hairpin winding is inserted into the stator slot and welded to coils on the open side after forming them to an “U” shape. Here the fill factor is high, but the number of windings is lower. This process is also very good for automation. The third component of the motor is the ***rotor***. It consists of the shaft, laminated sheet package, magnets, end plates and bearings. The magnets are mostly glued into pockets in sheet package. Furthermore, the ***power electronics*** are part of the motor. The electronics are either located in a separate aluminum housing or integrated in the main housing. They mainly consist of electronic elements, circuit boards and copper conductors. Lastly the ***gearbox*** is a part. Similar to the power electronics it is either integrated in the main housing or in a separate one. It contains gears, shafts, bearings and oil.

There are **alternative design choices** existing. One the one hand, the use of alternative materials is a choice, because it has a big influence on CO_2 footprint, circularity, criticality and costs. E.g. for the bearing shield the use of secondary instead of primary aluminum would safe up to 83% of CO_2 emissions. On the other hand, another focus is **design for repairability** and easy disassembling. E.g. using screws instead of snap-on pins or bolted connections instead of press-fit are options.

Title: Stepwise approach towards circular E-motors

- The insights on this methodological approach were given by **Dr Rainer Pamminger**, who is senior scientist at the Technical University of Vienna, based in Austria where he is part of the research group on Ecodesign. He is as an experienced project manager of nationally and EU-funded projects.

According to the European Sustainability Reporting Standards, Circular Economy is an economic system whereby the value of products, materials and other resources in the economy is maintained for as long as possible, enhancing their efficient use in production and consumption, thereby reducing the environmental impact of their use, minimizing waste and the release of hazardous substances at all stages of their life cycle. Therefore, the aim of the project **RHODAS** is to improve powertrains for heavy-duty electric transports throughout diverse measures, also containing circular design concepts. 6 steps were created to reach maximum circularity.

The first step is the **status check** on assessment of climate, circularity and criticality of an electric motor. It is to point out, that permanent magnets contribute about 50% to the GWP of electric motors. In terms of circularity, the lifetime is usually longer than the use time in vehicles and the magnets represent a high economic value with around 30% of costs. Also, for criticality the magnets are the most relevant component, especially the Neodym material. As second step the **CE-strategy selection** was carried out via a guided questionnaire. Three loops of circularity were identified, the long loop to get back raw materials, the medium loop containing remanufacturing steps and a short loop, which consists of repairing and reusing. In case repairability is given, short loop is selected. If the motor has a reduced lifetime, e.g. through defects or damage, the medium loop is chosen. Otherwise, if circularity potential is given, long loop of recycling is applied. For the electric motor the survey resulted in applying the medium loop. The third step was the **circular design assessment** using so called design cards. For the electric motors 5 important design aspects were identified. The detachability of connections should be easy, the disassembly should not be complex and suitable for automation, which also results in short disassembly time and performance feedback should be made available.

In a fourth step the **idea generation** for possible designs took place in creativity workshops. Focused on the reuse of permanent magnets four scenarios of new designs were derived. The **selection of the best solution**, as step five, was done via a performance assessment of technical feasibility, circular performance, climate performance and economic feasibility. In the last step **the circular business** model, the leasing of an electric motor, was created through a strategy game. The work resulted in three different scenarios which were evaluated. First scenario is a modular inverter with relatively low dismantling and remanufacturing rates and high disposal/recycling rates (5/95). The second scenario includes circular design concepts and take back incentives. The dismantling and remanufacturing rates are higher (20/80). The third scenario also contains the circular business model so shares result in direct reuse, dismantling/remanufacturing and disposal/recycling (30/60/10).

Looking at the impact of the different scenarios on the GWP, the reduction of CO_2-eq. is less than 10%. Regarding the criticality assessment, executing scenario 1 and 2 does only lead to a decrease in criticality by about 3%. Scenario 3, including a circular business model, leads to a reduction of around 66%. Furthermore, the circularity performance is increasing from 65,5% in scenario 1 up to 73,3% in scenario 3. In conclusion, a stepwise approach to develop circular solutions for electric motors, including use of tools. To take the right decisions, climate change, criticality and circularity potentials have to be considered at a time. It was pointed out that the improvement is the highest where high circularity potential is expected. Finally, a key to reach a significant impact on circularity, besides the right design, is the choice of the right business model. Enhancing circularity has to be thought as a holistic approach.

Title: The current situation of EOL e-motors in the United States

- The information was provided by **Dr Linda Gaines** who is an environmental scientist and systems analyst at Argonne National Laboratory in the United States. She is part of the "Energy Systems & Infrastructure Analysis" division. She is an expert on energy use and the flow of materials and processes in the energy production cycle.

The currently most used variant of electric traction motors contains permanent magnets from Rare Earth Elements (REE) in the rotor and copper in the windings in the stator. The Research & Development objective is to reduce demand and impact of these REE without negative influence on performance of the e-motors because of dependence on external stakeholders. To tackle these issues, central strategic measures firstly contain discovering alternative sources in the U.S. to be independent, as it is pursued by ARPA-E. Secondly innovative processing is another part of increasing ecological and economic efficiency, like mining, manufacturing and production techniques of magnets. Thirdly a more efficient use of materials is essential. Another important measure for increasing independence is the substitution of these critical raw materials, especially electric motor variants without rare earth magnets, like induction or externally excited motors.

Lastly, the EOL treatment of used permanent magnets is a part of these strategic measures. One approach is the reusing or remanufacturing of magnets, where the preservation of the magnet's structure is the goal. It is possible to either reuse the whole magnet assembly or the disassembled magnets. Although it would result in lower energy and material cost, challenges as clean scrap streams and the nondestructive evaluation of magnet integrity have to be tackled. Another approach is the recycling of used magnets mainly via pyrometallurgical and hydrometallurgical recycling with specific advantages and disadvantages. Pyrometallurgical recycling means recovering REE via high-temperature reduction and separation. The trade-off between robustness and high energy demand has to be considered. Hydrometallurgical recycling is recovering the REE from dissolved magnets in solutions. On the one hand high recovering rates for REE are possible, but on the other hand it causes chemical waste and is energy and reagent intensive. It has to be said, that according to study recycling REE magnets can compensate up to 16% of magnet demand in 2030.

Focusing on whole electric motors, there is no high demand on replacing expected due to the long lifespan in comparison to cars. Because of longer lifespan EV motors could be repurposed into other applications, e.g. airport ground support vehicles. The question is how current seen emerging markets increase and whether used motors and magnets can be internationally exported. Regarding the higher scrap value, recycling could be a solution, but is not an established industry, yet, as disassembling is still manually and the overall volume of feedstock is missing.

Part II: Exchange on specific aspects of traction e-motors circularity

Part II was designed to discuss on three different topics in the field of electric motors and circularity in smaller groups of the plenum. Therefore, three breakout sessions were held on the following topics:

1. Session: Technology choice and design of e-motors, incl. design for recycling

The focus was set on the design- and development phase:
The effect of Design for Circularity on these phases and companies
Innovative design options and barriers for reaching market potentials

At the beginning, five guideline questions were presented, which were prioritized by a vote of the participants.

- Where is electric motor technology heading and what does that mean for circularity?
- What limits disassembly, reuse and product value retention of electric machines?
- How embedded is Design for Circularity in today’s development process?
- Which trade-offs define circular electric machines today?
- How do materials choices shape circular outcomes?

Due to time constraints, the two most important questions were discussed in more detail.
At the beginning, the participants focused on the question of the **future development of electric motors and the impact on circularity**.
One focus was on the introduction of a **"Machine Passport"** - a digital document that could be comparable to the Digital Product Passport (DPP). This passport would contain key information about the materials used and the mechanical steps for repair and recycling. The participants recognized that such a tool could play a central role for Original Equipment Manufacturers (OEMs) in the implementation of the circular economy, **provided it can support business models**. However, significant challenges were also identified. One of the biggest hurdles is the **handling of confidential information**. As many manufacturers protect sensitive technical know-how, the question arises as to how sufficient access to the necessary information can be guaranteed for recycling and repair companies. One possible solution would be to **license recycling companies** to allow them access to the Machine Pass while maintaining the integrity

of trade secrets. Such licensing would require a certain amount **of knowledge transfer regarding recycling and repairing**.
Another key issue was the development of **technologies that use less or no REE**. The material criticality of REE was identified as a decisive factor for the future sustainability of e-motors. A promising alternative is the use of **ferrite magnets**, which are easier to handle and recycle in EOL process. A problem there is the small energy density of ferrite magnets, which leads to heavier machines. In addition, the variety of motor typologies was emphasized, in particular drive concepts such as **asynchronous motors** (ASM) or **externally excited synchronous motors** (EESM) could be promising alternatives. A deeper discussion was focusing on the **synchronous reluctance motor** (SynRM). This variant is not based on permanent magnets, but utilizes the principles of reluctance - i.e. the tendency of magnetic fields to choose the path with the lowest line of magnetic resistance. These motors offer promising potential. New developments for this variant show an increased efficiency that is almost comparable to that of PMSMs. This is offset by the cost-intensive power electronics required due to a positive and high-power factor. Nevertheless, these costs could be compensated for by not having REE magnets and therefore not requiring cooling equipment. In addition, the susceptibility to faults is also significantly lower compared to PMSMs. Ultimately, this motor with mechanical fixings and no adhesive connections is cheaper and more efficient to recycle and is therefore fully recyclable.
The last important trend for enhancing circularity for e-motors is the **modularization of the design**. Rotors and stators could be designed swappable for easier repairing and recycling.

In addition, the **limits for disassembling, reusing and product value retention of e-motors** were considered as the second important topic for discussion. Important aspects from multiple perspectives were identified.
First of all, R-strategies other than recycling can only be established if these approaches, such as reusing and remanufacturing, present a **positive business case for companies** along the value chain. In terms of the overall vehicle, current OEM strategies also see a clear advantage in selling new vehicles instead of reconditioning and reusing used ones. But even if it would be a positive business case already, looking at possible EOL vehicles, about one third is exported from EU or is not feasible for this EOL treatment, so recycling volumes are low. Making sure the vehicle will stay in the EU would be necessary. A second important aspect is the **design of the engine**. Currently, in many cases it would only work to use the same model or platform because there are no standardized interfaces for reusing. However, recycling and disassembly must also be simplified in future in order to separate the most valuable parts. Last but not least, the **legal situation** is currently still in its infancy. A stronger focus based on recycling or reusing quotas, for example, could help. A pioneering role in the EU could reach important players worldwide. In this way, the establishment of these EOL approaches could also be promoted in China or India, for example. The challenges are therefore manifold in technical, political, market and legal terms.

2. Session: End-of-Life treatment of e-motors, different approaches

The focus was set on different EOL treatment approaches:
Technical, market & political barriers to realize these approaches
Possible solutions to tackle these barriers

A voting by the participants at the beginning of the session showed the current focus on certain R-strategies for EV electric motors. The predominant focus is currently on EOL treatment, such as recycling and remanufacturing. This information was then used to formulate thoughts and questions about the R-strategies using guiding questions and collected on the digital concept board. In this way, a picture of current challenges and ideas for solving them could be collected. These contributions were then clustered and assigned topics.

The first defined cluster relates to the ***market potential and requirements*** of EOL approaches. The importance of positive business models is recognizable in the information compiled. Suitable markets must exist for this. With regard to these potential markets, the question of the right R strategy arises. Is it possible to determine under which circumstances, for example, recycling or remanufacturing is favored? Conditions must therefore be identified that make these strategies and dismantling appear economically viable. The second cluster includes ***legislation and communication***. There are laws and directives in the European Union that do not relate specifically to electric motors, but which have an indirect influence on the development and EOL handling of these motors. These include, for example, the EOL Vehicles Directive 2000/53/EC and the Critical Raw Materials Act. Communication has also been recognized as important in paving the way for more recyclable engines and strategies. Raising awareness of circularity through higher R strategies such as Reduce and Rethink. Independent of the specific EOL treatment approach, ***data management and communication***, in this case between stakeholders in the life cycle process, were discussed. The importance of data management and the communication of this technical data, such as material compositions or the condition of components between stakeholders, is a key requirement for an efficiently functioning circular economy. The Digital Product Passport (DPP) is an instrument for documenting such data in a transparent and standardized manner, from production through use to EOL. This is currently under development. It is therefore important to identify the necessary information that EOL processes require. Appropriate legislation may help to integrate this information into the DPP. The ***disassembling and dismantling*** are important steps in the recycling process route of EV traction motors. Dismantling is currently considered to be very costly compared to the expected revenue to be generated. Suitable measures to reduce costs and thus generate a positive business case have been addressed. The introduction of standardization and, building on this, automation of the dismantling process are relevant topics that need to be worked on. In addition, possible ***emission reduction potentials*** were analyzed. Finally, the last cluster highlighted ***barriers and doubts*** regarding the realization of a holistic, circular EV traction motor approach. These barriers are manifold. Possible performance losses in the quality and energy density of the motors were emphasized as relevant for reusing, for example. Technical hurdles also exist in the processing of certain materials, such as electrical steel. Green steel is also relevant for the holistic approach, although it is only available to a limited extent.

In the session, important topics relating to the implementation of various EOL treatment approaches were identified, also independently of the strategy. Within these clusters, relevant questions and existing hurdles were formulated that need to be addressed in order to progress towards a more circular EV traction motor. It also emerged that the current focus is more on R strategies, such as recycling or remanufacturing, which affect later life cycle phases.

3. Session: Hurdles in improving circularity: Current practices and conditions

The focus was set on legislative, economic conditions and standards:
Current status of regional and worldwide legislation and directives
Supportive measures and collaboration to promote circularity

Participants of this session are working in research, consultancy and in organization for sustainable transport. Firstly, a list of international relevant directives, legislations and guidelines, which have a direct or indirect impact on the lifecycle of electric motors, was created via a first brainstorming. The noted regulations are primarily valid for the European Union, although they influence actions and strategies of companies worldwide, which are part of the European market. The relevant regulations are as follows:

The EU End-of-Life Vehicles Regulation (ELV) covers the collection, treatment and recycling of EOL vehicles in order to avoid waste and increase recycling rates in the automotive sector. Additionally, the **Ecodesign for Sustainable Products Regulation (ESPR)** creates cross-product requirements for sustainability, reparability, recyclability and information obligations over the entire life cycle of products. The **Ecodesign rules for electric motors** define requirements for the energy efficiency of electric motors in order to reduce power consumption and CO_2 emissions. **The EU Battery Regulation (2023/1542)** is not directly related to electric motors, but defines sustainability, safety, recycling and due diligence requirements for all batteries placed on the EU market, which could be a reference for future activities on e-motors. There are also worldwide, not standardized, defined **CO_2 emissions standards for passenger cars & vans**, which set binding fleet limits for vehicle manufacturers to reduce greenhouse gas emissions from new vehicles. Furthermore, there are regulations on specific relevant materials like the **REACH-regulation**. It regulates the registration, evaluation, authorization and restriction of chemical substances to protect humans and the environment from hazardous chemicals. The **RoHS Directive** is focusing on restricting the use of certain hazardous substances in electrical and electronic equipment in order to reduce environmental and health risks. The **Trade Defense & Foreign Subsidy Rules are** measures against unfair trade practices and competition-distorting third-country subsidies in the EU internal market. Lastly, **Economic Security and Supply Chain Resilience** has to be considered, to minimize risks in critical supply chains and avoid economic dependence.

In the further process of the session a row of guiding questions on the legislative and market situation of electric motors were faced. Firstly, the **current status of worldwide legislations and directives** was discussed. It was stated out that regulations and directives exist in the EU, as also mentioned in the brainstorming. The EU Critical Raw Materials Act and a draft regulation on circularity requirements for vehicle design and on management on EOL vehicles as well as the new EOL vehicle regulation have direct or indirect influence on the electric motors. In addition, the Digital Product Pass serves as a measure of data management to also ensure legislative requirements. Outside of the EU there were no specific regulations and directives mentioned. E.g. in the US, the topic of circularity is not addressed in legislation, yet. Secondly, the **current situation of EOL markets** was discussed. Looking at the regional situation, there is no market of recycling of e-motors in Europe, yet. Different barriers were identified. The potential structure of a market is still facing a lack of links in the business chain. E.g. a holistic collection system has to be installed. Therefore, possible new players have to join the market. Expanding the EOL market, reusing is an alternative approach of treatment. As the motors have a longer expected lifetime than the vehicles, used electric motors are still functional and could be reused, e.g. in ground support vehicles at airports. A key impact on implementing a lasting EOL market is the existence of positive business cases for participants. Therefore, a higher economic value of used e-motors and higher prices for virgin materials would be drivers of such a development. Thirdly, **possible supportive measures** were evaluated. On the one hand the clarification of responsibilities is essential. E.g. all producers have to take care of their used products, which comes with the implementation of the extended producer responsibility (EPR). But in that case the legislation still has to be clearer. On the other hand, the data management is important when creating efficient business chains. The European Digital Product Pass (DPP) for electric motors could support. It has to be included in the legislation. Another tackled topic in this session was the **necessary collaboration** to promote circularity. The collaboration has to include stakeholders throughout the entire value chain of the e-motor, but especially dismantlers, remanufacturers and recyclers. This communication contains different aspects of knowledge transfer through the integration of the aforementioned design-for-recycling, material-flow analysis and sorting techniques and technologies. Using this knowledge the development of possible joint business models is part of the solution. Nevertheless, there are **risks and uncertain events** that could impact this transition towards circularity. A current issue for realizing positive business models is the so called “valley of death”-problem. There is a significant time gap between now and needed high recycling volumes, due to long lifetime of e-motors. In addition to that there is an uncertainty, whether the current approaches are still economic viable in the future without standardization, e.g. permanent magnet disassembling standards. Besides an international competition for scrapped components, the risk of contradictive legislations can cause barriers. E.g. higher motor efficiencies and material avoidance strategies could cause conflicts. These uncertainties could slow down private investments as a consequence. Finally, a short glimpse at **dependencies of regulations** was made. It has to be considered, that the handling of regulations and actions might be different between passenger cars and heavy-duty vehicles.

Part III: Discussion of results and closing

The final part of the workshop was used to present the results developed in the breakout sessions to all participants in order to discuss these results in plenary. To wrap this workshop up, a short summary with the most essential learnings is provided here.

One key towards more circularity of EV traction e-motors is the **design for circularity** located in the development phase of the motor’s life cycle. Facing **criticality of REE**, design choices without rare earth materials and therefore permanent magnets are coming into focus. An example is the **Synchronous Reluctance Motor (SynRM)** using a sheet metal as a rotor, which follows an external magnetic field synchronously. In combination with using **mechanical fixation** and **mono materials**, EOL treatment, like disassembly, is easier to realize. A key for broad acceptance and use of these types of motors is the ability of matching the **technical performance requirements** of conventional e-motors like PMSM. Another key could be the introduction of a **machine pass**, similar to the battery pass, which includes information on material and mechanical information for EOL treatment. But questions of confidential information and authorization of recycling companies to get access to this pass still have to be faced.

Central elements to reach more circularity for e-motors are existing markets for EOL treatment, which means a **commercialization of EOL activities**. First companies are starting **pilots for recycling PM or reusing e-motors** in different fields of use, but broad markets are not existing, neither for recycling, nor reusing, refurbishing or remanufacturing. To establish these markets, **positive business cases** for the partners throughout the whole supply chain have to be realized. Firstly, the required scaling process to reach commercialization could face the lack of EOL e-motors due to long lifetimes and thus small amounts in the next years. Secondly, the EOL treatment, such as **disassembly** still faces technical issues regarding **automatization**, referring to missing information on materials and mechanical composition and possible **standardization**. Without being **cost-efficient**, realizing prices that are competitive to primarily produced e-motors is still hard. Thirdly, the **reverse supply chain** is not existing in big scale because links between participants are not established, yet.

Regulatory policy should play an important role to enhance the move towards a circular market for e-motors. Looking at the current situation, a specific **regulation on EV traction e-motors**, similar to the new European Battery Regulation, **is not existing**, neither in the EU nor in other regions of the world. More general regulations on circularity exist, e.g. **EU EOL Vehicle Regulation** and the **Raw Materials Act** for ensuring the material supply in the EU, but are not referring to e-motors explicitly. Possible directives and regulations on e-motors have to directly or indirectly **ensure several developments**, e.g. through definition of guiding incentives or mandatory recycling quotas of materials or components. To mention two: The **economic value of 2nd-use e-motors and recycled materials** has to be competitive to new produced ones. Clear **responsibilities** have to be defined to establish **transparent, reliable and standardized reverse supply chains**, e.g. through **EPR**. In sum, the legislation should be an enabler to the development of circular markets. An additional key of enhancing circularity for e-motos is to **resolve contradictory regulations**, e.g. the request for more motor efficiency, which could slow down progress in avoidance strategies (e.g. PM).

Nevertheless, there are already a number of different measures in place to promote the circularity of e-motors. Progress is being made both in the area of motor development and the creation of new business models. Ultimately, it is essential that all stakeholders, industry, research, legislatures, NGOs and others collaborate to create a holistic framework for EOL treatment of EV traction e-motors.

Respectfully submitted by Jonas Peschke