Weighted Index of Recycling and Energy (WIRE) Cost for Motors in Electric Vehicles

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***Abstract*—With increasing demand of electric vehicles it is very important to recycle critical rare earth materials used in the permanent magnet motors such as Neodymium (Nd), Dysprosium (Dy) and Cobalt (Co) etc. To achieve easy recycling, focus of the motor design shall shift to design for recycling. The article presents a methodology (WIRE) to evaluate and benchmark the motor in terms of their recyclability. The method can be used to compare different motors. The method was used for evaluation of a commercial permanent magnet based HUB motor and the results are presented. A comparison between recyclability index of four different motors topology is also presented.**

***Index Terms*—Motor Recycling, Magnet Recycling, Motor Benchmarking**

I. Introduction

The demand for cleaner mode of urban transport is increasing and many countries like UK, France, Norway, Sweden etc have already announced the phasing out of diesel and petrol cars from their streets in couple of decades and likely more countries will join soon [1]. The sales of electric vehicle (EV) and hybrid electric vehicle (HEV) in recent years is growing every year and is projected to continue at higher rate in coming years [2]. At present, almost all automobile manufacturers are using permanent magnet (PM) motors to achieve high efficient vehicles [3]- [4]. The amount and quality of PM is critical for high performance motors. Therefore, to maintain the vehicle growth it is very important to have sufficient and sustainable supply of magnets. At present, Neodymium Iron Boron (NdFeB) magnets are the strongest magnets. The magnet contains critical rare earth materials like Nd and Dy. Due to limited availability of these materials it is very crucial to recycle them and use again in motors. In recent years, there has been some focus from industry and researchers on recycling of magnets. The projects like EREAN, $RARE^3$ etc are focusing on developing methods to recycle extracted magnets. The extraction of magnets from the existing electric motor design has been investigated in the project called MORE. The motor designs present today are not designed for recycling i.e. extraction of magnet is very difficult [3] & [5]. In Demeter (H2020) project one of the goals is to design motor for recycling. However, the challenge for the motor designers is to evaluate motors with respect to the recyclability and comparison of different designs. At present there is no tool to analyze the motors design for the recycling and benchmark them. In this article a method is presented to analyze and evaluate the recycling of the motors for EVs and HEVs. The method is divided in two parts. The first part evaluates recyclability of the motor considering standardization, assembly and disassembly of the motor. The second part evaluates the impact of the motor design on the performance of the motor considering energy consumption over the complete life cycle. In this article only first part is presented and discussed. The method was used to evaluate the recycling index of a commercial hub motor and the results are presented. The evaluation of four different motors designed for DEMETER project were carried out by using WIRE method. The comparison of scores are also presented and analysed.

II. Methodology

The first part of the WIRE methodology is to evaluate the ease of assembly/disassembly of electric motors. The evaluation process is divided in two parts - Standard and Cost. Each part has three categories Material, Assembly and Disassembly. Moreover, the evaluation of each material or process in each category is done in two parts. The first is **Score (S)** which depends on its relative scale in respective section. The second is **Importance (I)** which depends on material/process relative criticality in terms of recyclability of materials. The final score is the product of both i.e. **(SxI)**. The score for each activity is in the range of 1-5. For evaluation of WIRE it is recommended to have a group of 5-6 people from different fields, involved in design and manufacturing process of the motor. Figure 1 shows the evaluation sheet for the different materials of the motor for both the parts- standard and cost. Although, the evaluation largely depends on the mutual agreement of the group formed for evaluation i.e. standard and cost, certain guidelines are formed to evaluate different sections. Furthermore, the process/ materials in different sections are different depending on the criticality of the material/process. For example, the wires of sensor is important while assembling however, their importance is negligible while disassembly.

Scoring pattern	0-5	1 - Lowest score	5 - Highest score					
		1 - Lowest score	5 - Highest score	3 = neutral score				
Assumption	The motor developed is new and for the first time and manual disassembly with high volumes i.e. 50,00							
MOTOR ID	**Hub motor for in-wheel application**							
Component/ Parts		**Standard**			**Cost**			**Recyclability SCORE**
		S	**I**	**SxI**	**S**	**I**	**SxI**	
Materials								
- Stator								
	Lamination S	5	5	25	1	5	5	30
	Copper	5	5	25	2	1	2	27
- Rotor								0
	Steel R	5	5	25	1	4	4	29
	Magnets	5	4	20	5	1	5	25
-Shaft								0
	Shaft	4	5	20	1	2	2	22
-Endshileds								0
	Drive Side	2	5	10	1	2	2	12
	Non-Drive side	2	5	10	1	2	2	12
			34	135		17	22	157
	section score			79.41 %			25.88 %	

Fig. 1: Evaluation sheet of material for standardization and cost

A. Definitions of WIRE sheet

As mentioned earlier, the WIRE evaluation is relative and hence, the accuracy of the method largely depends on the definitions of different sections. Different process/materials has different significance in the final recycling of the motor. It is important to note that the scoring is relative and hence the tool is good for comparing two motors evaluated keeping same scaling in consideration. In the following section definitions of different terms used for the evaluation are given.

- **Standard** : The category focuses on the use of standard material/processes. The evaluation for Standard category is done with the view that use of standard parts/process will simplify and encourage the recycling. Furthermore, higher the number of standard component in the motor easier it will be for recycling and further improves the quality of the recycled output.
  1) Material
     - 'S' depends on the standardization of the material. The score is higher for material, which are easily available (off the shelf) and widely used. For example, random wound copper winding are more used and widely available then rectangular strand cable of certain dimension.
     - 'I' depends on materials recyclability. For example, NdFeB magnet with and without coating is easily available however, in terms of recyclability the magnet without coating will be easier for recycling and hence its index shall be higher.
  2) Assembly
     - 'S' depends on the process/activity standardization. While scoring it is also important to consider the tools used. More non-standard tools or process used in assembly shall lower the score. For example, if special heat treatment/ or other special environment is needed for assembly, process will be non-standard and thus the index shall be lower.
     - 'I' depends on the criticality of the step/process for recycling of the part. For example, if the assembly of the copper affects the recycling of the copper. Therefore, the index shall be high.
  3) Disassembly
     - 'S' depends on the process/activity standardization. While scoring it is also important to consider the tools used. More non-standard tools or process used in disassembly shall lower the index. For example, if some chemical is needed for extraction of certain component the score shall be lower for the process.
     - 'I' depends on the criticality of the step/process for recycling of the part. Same as assembly, if disassembly process of copper make recycling easier the index shall be high.
- **Cost** : The category focuses on the cost of material/processes and its impact on recycling. The evaluation for Cost category is done with the view that higher cost of any process will increase the overall recycling cost and hence, has negative impact on the recycling. On the other hand, higher material cost incentives the recycling of that particular material like magnets and encourages recycling.
  1) Material
     - 'S' depends on the cost of the material. Higher the material cost higher the score. The processing cost of the component varies over a wide range. Therefore, to keep the tool simple and to avoid processing cost variation of the component only material cost is considered. Moreover, the non-standard design or the impact of processing will be taken care while scoring standard category. For example, NdFeB magnet is roughly 10 times costlier than the laminations in the motor. Therefore, score of magnet will be higher than the laminations. The impact of different shapes of magnet should be considered while scoring standard material category.
     - 'I' depends on the impact of the material on recycling of the whole motor. For example, if the weight of the material is very low comparing to other materials, the material recovered will be very small. Therefore, the recovery in terms of economic value will be small, even with high price of the material.
  2) Assembly
     - 'S' depends on cost required to execute the assembly process/activity. Higher the assembly cost lower the score shall be as it impacts the recycling process negatively. For example, if there

TABLE I: Scoring of Material for Standard Category

Magnet Type	S	I	Magnet Type
Rectangular small pieces with/ without coating sintered, Bonded Magnet	5	5	Rectangular small pieces or powder without coating or binder
Sintered/bonded shape parallel/radially magnetized	4	4	Sintered with coating
Halbach bonded	3	3	Sintered any shape with coating/glue
Sintered or Bonded powder but magnetised in rotor	2	2	Bonded magnets
Sintered halbach multipole	1	1	Bonded magnets with glue
Lamination Type	**S**	**I**	**Lamination Type**
Silicone iron 0.35-0.6mm, Single solid rotor	5	5	Any silicone iron lamination or solid rotor or Aluminum
Silicone steel modular type	4	4	Cobalt steel
Cobalt Steel	3	3	Amorphous Steel
Amorphous, different shapes	2	2	Soft Magnet Composites (SMC)
SMC	1	1	Any new special handling material
Winding Type	**S**	**I**	**Winding Type**
Copper / aluminium strand circular	5	5	Copper any type
Copper rectangular standard, aluminium cast rotor	4	4	Aluminium wire/Cast aluminium /Copper rotor
Copper rectangular/cricular non standard	3	2	Any new special handling material
Hollow circular copper wire	2		
Any thing special	1		

is a need of special environment for assembly, it increases the complexity and hence cost.

- ’I’ depends on the impact of cost of the process in recycling. For example, if a motor uses powder NdFeB magnet technology. The assembly cost is higher but this cost does not impact the recycling of the magnet at the end of life (EOL) of the motor. Therefore, the index shall be neutral.

3) Disassembly

- ’S’ depends on cost required to execute the disassembly process/activity. Higher the disassembly cost lower the score shall be as it impacts the recycling process negatively. For example, if there is a need of special environment for disassembly, it increases the complexity and hence, cost which in turn discourages recyclability economically.
- ’I’ depends on the impact of cost of the process in recycling. For example, the cost of disassembly of the magnet is very critical for the recycling of the magnet. Therefore, the index shall be high for that process.

B. Calculation of Recyclability Index

The final weighted recyclability index (R) is calculated using equation 1 and 2. The R_w is in the scale of 1-5 and using equation (2) is expressed in percent, R.

$$R_w = \frac{S_1 * I_1 + S_2 * I_2 + \cdots + S_n * I_n}{\sum I} \tag{1}$$

TABLE II: S of assembly/disassembly for Cost category

Assembly / Disassembly Cost	S
Easy assembly/disassembly without any tool	5
Easy assembly/disassembly with standard tools /process	4
Complex / Hard process with standard tools or more than one person required	3
Special pre/post treatment with special tools	2
New extra method to extract magnet from rotor	1

$$R = \frac{R_w * 100}{5} \tag{2}$$

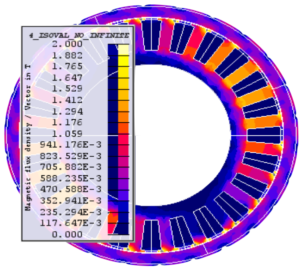
C. General Guidelines for scoring

The section provides some general guidelines, which can be used to score different sections of WIRE sheet. It is important to note here that the scores are relative and can be varied on general consensus or when scenario changes. The authors decided the scores after discussing different scenarios.

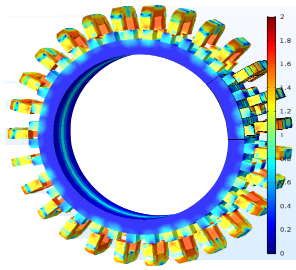
1) Scoring of materials for Standard category: Table I shows the scoring of material and its importance for recyclability with respect to their standardization. The table shows the scores for main components of the motor like lamination, magnet and copper. The materials are scored based on the definition given in section II-A.

2) Assembly/Disassembly score for Cost: Table II gives the scoring guideline for assembly/disassembly in terms of cost. Simpler the process higher the score shall be.

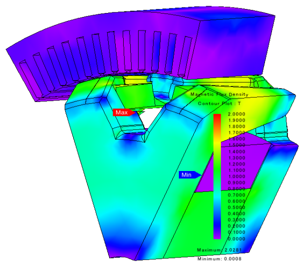
3) Assembly/Disassembly of stator and rotor: The scoring guideline for individual components (stator, rotor, bearing etc)



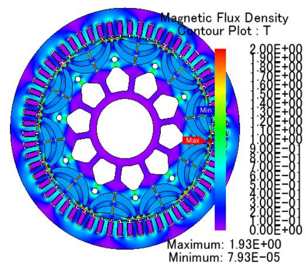
(a) Outer Rotor Motor (1)



(b) 3D Flux Hybrid Motor (2)



(c) Claw Pole Motor (3)



(d) Radial IPM Motor (4)

Fig. 2: Flux density distribution in different motors

TABLE III: Score of material cost in motor

Material Cost	S
Sintered Magnet	5
Bonded Magnet	4
SMC,Amorphous steel	3
Copper	2
Silicone Steel lamination	1

TABLE IV: Importance of Assembly/Disassembly process

Process	Standard Importance	Cost Importance
Assembly of stator lamination	3	3
Assembly of copper winding	3	3
Assembly of rotor lamination	3	3
Assembly of magnet and rotor	5	3
Assembly of sensor wires	1	3
Assembly of rotor and stator	3	3
Assembly of end shields	3	3
Assembly of shaft	3	3
Disassembly of end shields	3	3
Separation of rotor and stator	4	4
Disassembly of copper	3	4
Disassembly of stator	3	3
Disassembly of magnets from rotor	5	5
Disassembly of rotor	3	3

is shown in Table II. However, there is one more critical step in assembly/disassembly, which is separation of a rotor from a stator. The complexity of the process is even higher in PM motors. The ease of assembly / disassembly mainly depends on the force of extraction and its size. Therefore, to scale the process following method is used. Larger the volume and airgap flux density i.e. power of the motor, separation of rotor and stator will be difficult and hence, the score shall be lower. Mathematically it can be presented by equation 3. Figure 2 shows the flux density distribution in motor for 4 different topologies designed in framework of DEMETER project. Motor 3 has lowest flux density and hence, disassembly will be much easier compared to other motors.

$$\mathbf{S} \propto \frac{1}{V * B_\delta^2} \tag{3}$$

where, V is volume of the motor and B_δ is the airgap flux density.

4) Scoring 'I' of material for Cost category: The scoring of 'I' depends on the weight of the material in the motor. Higher the weight of the material higher will be the recovery of material from recycling. The proposed method to estimate that is as follows. Lets assume, the motor has W_c kg of Copper, W_s kg of Stator steel, W_r kg of rotor steel and W_m weight of Magnet and the weight (W_s) of stator steel is maximum. The I score for stator steel W_s is 5 and the rest is scaled in proportion to the W_s. The fraction numbers are rounded to nearest integer.

I for magnet is $\frac{W_m * 5}{W_s}$

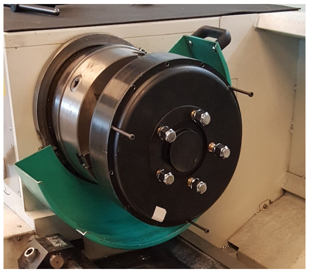
I for copper is $\frac{W_c * 5}{W_s}$

Table III shows the relative score of material used in the motors.

5) 'I' of assembly/disassembly for Standard & Cost category: The criticality of each step during assembly and disassembly is shown in table IV. While indexing, the recycling of steel, copper and magnet was considered important and hence, the process affecting their recycling was index accordingly. If some step of assembly is very important for recycling of that material then it shall have high indexed. For example, assembly of magnet and rotor is very significant for extraction of magnet and hence, has high index.

III. WIRE EVALUATION FOR HUB MOTOR

The developed methodology was used for evaluating commercial permanent magnet based HUB motor. The motor was disassembled manually with standard tools and the process was observed keeping in mind the recycling of the parts. Figure 3 shows the different stages while disassembly of the motor. After complete disassembly of the motor the WIRE sheet, was filled by the authors. For simplicity many assembly/disassembly steps are clubbed together and score and importance were given. The scores of standard and cost of the WIRE evaluation is shown in figure 4. The final cost index is lower than the final standard index. The motor is a commercial motor and has used more standard parts and processes. The index for cost of the material is lower compared to assembly and disassembly. It is important to note here that the index is relative and in absolute terms cost of material can be higher than the assembly and disassembly of the motor. As mentioned earlier the method is developed to compare different motors recyclability. The final recycling index (R) of the motor is



(a) Motor

(b) Motor without End-shields

(c) Stator

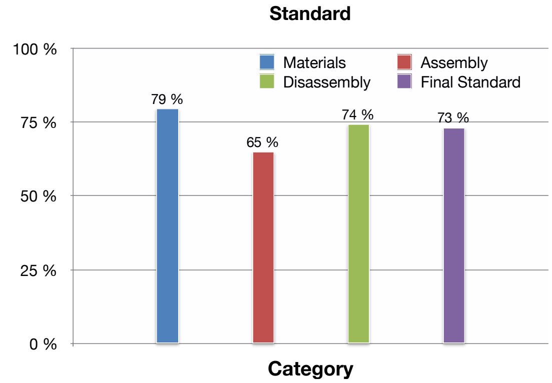
(d) Rotor

Fig. 3: HUB Motor Diassembly

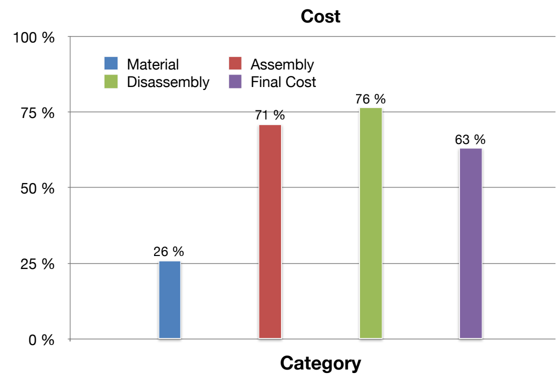
68.5%. The low index was expected as motor is not designed for recycling.

IV. Comparison of Recyclability Index of four motors

Figure 4 shows the four different motors designed for (H)EVs with ease of recycling in the framework of DEMETER project. Motor 1 is an outer rotor topology motor with an ideal Halbach magnet manufactured using bonded magnet. Motor 2 is a 3D flux hybrid motor using modular amorphous steel stator core and the rotor has sintered magnet placed between rotor laminations. Motor 3 is a permanent magnet based claw pole motor topology designed for easy extraction of magnet for mild hybrid vehicle. Motor 4 is an interior PM(IPM) motor using thermoplastic type bonded magnets and can be magnetized inside a rotor core. The motors were evaluated using WIRE method to compare the recyclability index. Figure 6 presents the index of all 4 motors in standard and cost category for assembly, disassembly and material. It can be seen that motor 3 has highest score in assembly subcategory because the process for the claw pole is highly industrialized and the design change made for easy recycling is minor. On the other side motor 2 has lowest score because the 3D flux machine has U core laminations for stator which requires special process to assemble. Moreover, due to the magnets position and glue that used for magnet fixing, the rotor assembly is also more complicated than the rest. The disassembly of motor 1 has maximum score because of simple rotor structure and no glue is used for magnet assembly, whereas motor 2 has the lowest because to extract magnet special processing is required. The material used in all 4 motors are standard and hence, have similar scores. The material cost of motor 2 has the highest



(a) Standard Distribution



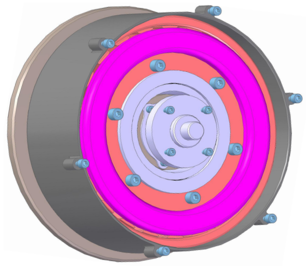
(b) Cost Distribution

Fig. 4: Distribution of Recycling index of the sample motor

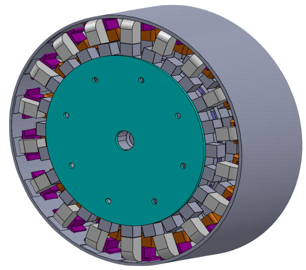
score shows that the recovery of high valued material from motor 2 is maximum compared to others. For assembly and disassembly in terms of cost the trend is same for all the motors. Motor 1 has the highest score because of simple structure. Thus, the disassembly process does not need any special treatment of magnets before extraction. Whereas, some pretreatments are required for other motors to extract magnet, which contributes to lower indexes. The final recyclability index of four motors are 71%, 63%, 71% and 64% respectively

V. Conclusion and Discussion

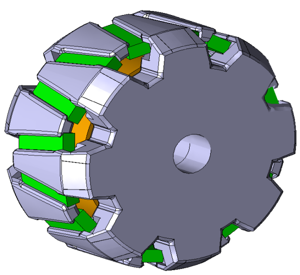
The WIRE method is developed for indexing the recyclability (R) and energy impact of the motors. In this article recyclability part of the method is presented. The method is simple to use and can be modified as per the requirement. The methodology takes standardization and cost into consideration for determining the recyclability of the motor. The recycling of any motor depends on the materials used, assembly and disassembly. The evaluation is relative in nature and hence, will be effective in comparison of motors done keeping the scaling same. To make method evaluation objective, different scoring guidelines is also presented and can be modified if the evaluating team finds suitable. The motor designed for recycling should have higher standard components with easy assembly and disassembly process.



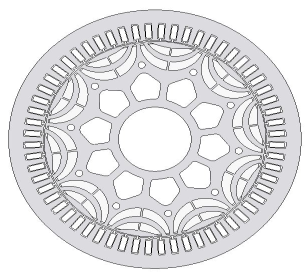
(a) Outer Rotor Motor (1)



(b) 3D Flux Hybrid Motor (2)



(c) Claw Pole Motor (3)

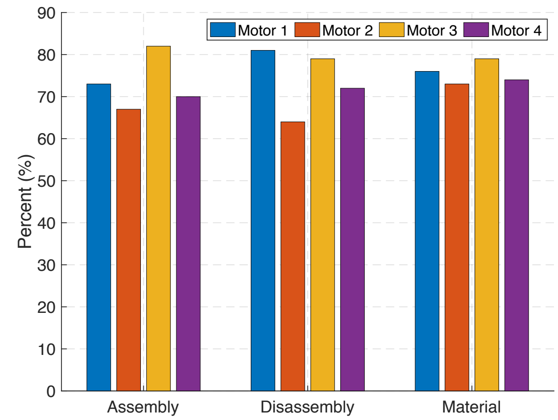


(d) Radial IPM Motor (4)

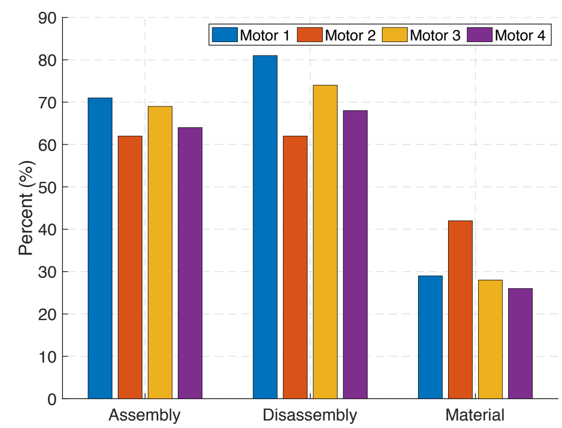
Fig. 5: Four Different Motors Designed in DEMETER project

The evaluation was done for a commercial hub motor and the scores are presented. Many processes in assembly/disassembly were clubbed together to keep the evaluation simple due to lack of certain information. The recycling index for the motor is 68.5%, which is low as motor is not designed for the recycling and the index can be improved by modifying small design changes.

The final recyclability index of four motors are 71%, 63%, 71% and 64% respectively. The scores obtained reflect that the method is able to distinguish the features of motor for easy recyclability. The WIRE score comparison of the 4 motors show that the recyclability increases with the high utilization of standard materials. It further improves if machine design is such that it can be assembled and disassembled using conventional process and tools. The use of glue for magnet assembly makes recovery of magnet from motor difficult and lowers the recyclability index. Furthermore, use of complicated motor structure also lowers the recyclability index. However, one has to keep in mind the method by its nature scores lower for new / innovative designs / method as can be seen in the case of motor 2. Therefore, the designers must strive to use conventional/ standard method of assembly and disassembly with magnet assembly without any glue to make motor easier for recycling.



(a) Score of Standard category for 4 motors



(b) Score of cost category for 4 motors

Fig. 6: WIRE evaluation scores for all four motors

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REFERENCES

[1] Countries are announcing plans to phase out petrol and diesel cars. is yours on the list? [Online]. Available: https://www.weforum.org/agenda/2017/09/countries-are-announcing-plans-to-phase-out-petrol-and-diesel-cars-is-yours-on-the-list/

[2] Internaltion Energy Agency, Ed., *Global EV Outlook 2017*.

[3] T. Elwert, D. Goldmann, F. Rmer, M. Buchert, C. Merz, D. Schueler, and J. Sutter, "Current developments and challenges in the recycling of key components of (hybrid) electric vehicles," *Recycling*, vol. 1, no. 1, pp. 25–60, 2015. [Online]. Available: http://www.mdpi.com/2313-4321/1/1/25

[4] L. Kumar and S. Jain, "Electric propulsion system for electric vehicular technology: A review," *Renewable and Sustainable Energy Reviews*, vol. 29, no. Supplement C, pp. 924 – 940, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032113006734

[5] U. Bast, R. Blank, M. Buchert, T. Elwert, F. Finsterwalder, G. Hornig, T. Klier, S. Langkau, F. Marscheider-Weidemann, J.-O. Muller, C. Thurigen, F. Treffer, and T. Walter, "Recycling von komponenten und strategischen metallen aus elektrischen fahrantrieben," Aug-2014.