Evaluation of Energy Cost Index for an Electric Vehicle Motor over a particular Drive Cycle with Recycled Magnet Concept

Pranshu Upadhayay, Adolfo G. Garcia, Ziwei Li, Amit K. Jha, Peter O. Rasmussen, Afef Kedous-Lebouc, Jean-Claude Mipo

Abstract **– Nowadays, in automotive applications, the electric vehicle motors generally utilize permanent magnet motors due to their various advantages like high torque density, high efficiency, compactness and ease of control. In this paper emphasis is given to the evaluation of energy cost index for an EV motor over a particular drive cycle during motors operational lifetime. Performance evaluation over the entire drive cycle, instead of at rated conditions, provides a better idea of the efficiency and energy consumption of an electric motor. Therefore, energy cost evaluation for the urban part of New European Driving Cycle i.e. ECE-15 is selected in this study and the energy cost index is evaluated for an EV motor for virgin and recycled magnets utilized in the machine. The comparison shows that utilizing recycled magnets can provide economical advantage over using virgin magnets albeit under certain assumptions.**

Index Terms**—automotive, cost, driving cycle, electric motors, electric vehicles, energy, finite element analysis, permanent magnets, recycle, reuse.**

I. Introduction

THE electric vehicles (EV) and hybrid electric vehicles (HEV) are the new key developments in the automotive industry with the implementation of new regulations and norms in various countries around the world. Generally, the EV machines used in automotive applications are permanent magnet (PM) machines due to various advantages like high torque density, high efficiency, compactness and ease of control [1]. The PMs deployed in these EV motors are commonly rare earth (RE) magnets i.e. Neodymium Iron Boron (NdFeB) magnets. However, due to price fluctuations and supply-demand issues of RE materials utilized in NdFeB magnets, lot of research is being undertaken to reduce or utilize RE free magnets in PM machines. In recent years, numerous studies are being carried out in recycling of critical materials, and NdFeB magnets contain a few of these critical materials i.e. Neodymium (Nd) and Dysprosium (Dy) [2]. Due to the use of NdFeB magnets in PM machines, reuse and recycle of PMs in electric motors is being re-analyzed in some of the applications around the world [3]-[4]. Nevertheless, there are challenges in developing methodologies for reuse or recycle of magnets in electric motors due to varying motor topologies, technologies, material characteristics, proper disposal at end-of-life (EoL) and economic/environmental implications.

In this regard a methodology is being developed to analyze the recyclability of PM motors with two main aspects. First, recyclability of the motor considering standardization, assembly and disassembly of the motor and second, considering energy consumption by the electric motor during its complete lifetime with variation in permanent magnet compositions [5]-[6]. In this paper a commercial PM based HUB motor is used to evaluate the second part of above methodology development. In Section II benchmarking of sample HUB motor is done by dis-assembly, experimentation and finite element (FE) analysis. Then in Section III efficiency map and energy consumption of sample HUB motor with virgin magnets for urban part of New European Driving Cycle (NEDC) i.e. ECE-15 [7] is evaluated. Similarly, machine performance and energy consumption with recycled magnets for the same ECE-15 drive cycle is evaluated in Section IV. Finally in Section V, comparison in energy consumption between virgin magnets and recycled magnets for sample HUB motor is done to obtain the energy cost index. Finally, conclusion is presented in the last section.

II. Benchmarking of Sample Electric Vehicle Motor

The sample EV motor is a commercial PM based HUB motor with outer rotor topology. The sample motor is utilized in medium speed electric 2-wheeler or small compact low speed city cars. Fig. 1 shows the sample HUB motor. The DC bus voltage for the sample motor is 72 V, maximum speed of 700 rpm and output power upto 3.5 kW. The motor

The research leading to these results has received funding from European Community's Horizon 2020 Programme ([H2020/2014-2019)] under Grant Agreement no. 674973 (MSCA-ETN DEMETER). This publication reflects only the author's view, exempting the Community from any liability. Project website: http://etn-demeter.eu/.

First four authors contributed equally to this work.

P. Upadhayay is with Valeo - Equipements Electriques Moteur, 2 rue André Boulle, 94000 Créteil, France & also with Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, 38000 Grenoble, France (e-mail: pranshulink@gmail.com).

A. G. Gonzalez is with the Department of Energy Technology, Aalborg University, Aalborg 9220, Denmark (e-mail: agg@et.aau.dk).

Ziwei Li is with Valeo - Equipements Electriques Moteur, 2 rue André Boulle, 94000 Créteil, France & also with Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, 38000 Grenoble, France (e-mail: ziwei.li@valeo.com).

A. K. Jha is with Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, 38000 Grenoble, France (e-mail: amit-kumar.jha@grenoble-inp.fr).

P. O. Rasmussen is with the Department of Energy Technology, Aalborg University, Aalborg 9220, Denmark (e-mail: por@et.aau.dk).

A. Kedous-Lebouc is with Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, 38000 Grenoble, France (e-mail: afef.lebouc@grenoble-inp.fr).

J. C. Mipo is with Valeo - Equipements Electriques Moteur, 2 rue André Boulle, 94000 Créteil, France (e-mail: jean-claude.mipo@valeo.com).

controller is a standard three-phase power electronic inverter with hall sensor inputs used for position sensing.

Fig. 1. A commercial PM based HUB motor

A. Experimental measurements

The motor was assembled on a test bench with high precision torque transducer connected to the shaft. The input power measurements were recorded using an industrial grade power analyzer so as to limit the uncertainties in measurement. Fig. 2 shows the experimental test setup utilized for the measurements and performance evaluation.

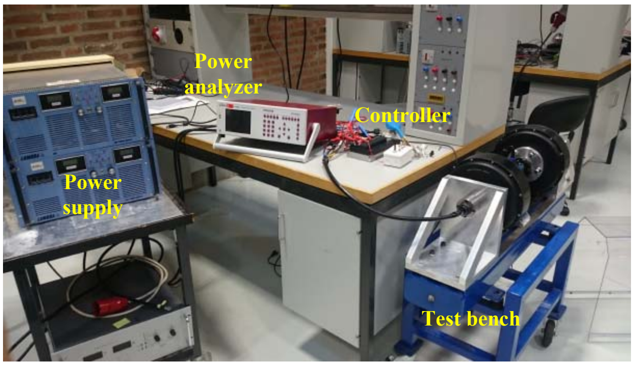

Fig. 2. Experimental test setup for performance evaluation

Two machines were assembled back to back and a resistive load was connected to the machine which would operate as a generator and load the test machine. Different resistance values were used with a set of speed variations to get the torque, speed, voltage, output power and input power of the test machine. Fig. 3 depicts the experimental torque vs. speed with the corresponding efficiency values.

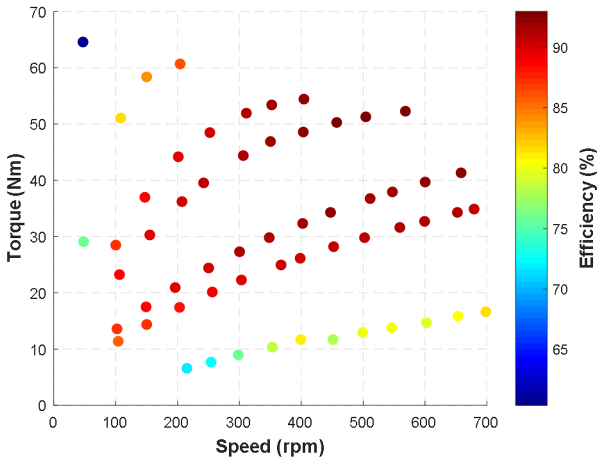

Fig. 3. Experimental torque vs. speed with corresponding efficiency values by virgin magnets

B. Disassembly and dimensions

The major dimensions, weight and materials were identified by disassembling the machine in step by step process. Fig. 4 shows the disassembled machine and the magnets. Table I depicts the main machine dimensions which would be utilized later on for 2-dimensional (2D) FE analysis so as to obtain simulated performance of the machine.

Fig. 4. Disassembled machine and permanent magnets

TABLE I
MAIN DIMENSIONS OF THE MACHINE

Parameters	Value
Stack length [mm]	40
Maximum speed [rpm]	700
Air-gap length [mm]	0.6
Magnet axial length [mm]	40
Magnet thickness [mm]	3
Magnet width [mm]	14
Stator outer diameter [mm]	253
Number of poles	56
Number of slots	63

The PMs were shaped in appropriate sizes so as to be analyzed for their magnetic properties. They were put to test in Magnetic Property Measurement System (MPMS®) from Quantum Design. It was observed that the magnetization (M) at 0 Oe applied field (H) of the magnet is around 130 emu/g which corresponds to around 1.2 T as remanence flux density (B_r) at temperature of 300 K i.e. approximately 27 °C.

C. Finite element analysis & comparison with test results

The machine was modeled in commercially available FE analysis software by using the dimensional details obtained earlier in Section II (B). The magnet properties were utilized from the MPMS measurements with 1.2 T as the B_r value. The stator lamination was a standard silicon iron soft magnetic material with loss of around 5 W/kg at 1.5 T, 50 Hz. Time-stepping 2D motion analysis was carried out to get the various performance parameters like back electromotive force (EMF), cogging torque, electromagnetic torque, iron losses, copper losses and winding voltages. Fig. 5 shows the 2D model along with the flux density plot at no-load by FE analysis.

The experimental winding current values were fed as an input in the FE analysis at various speed points to get the developed torque and losses of the machine. Finally the input power, output power, voltage and efficiency were evaluated by simulation results. In Fig. 6 it can be noticed that the comparison of simulated and experimental results for torque vs. speed with corresponding efficiency values of the machine.

It can be observed that the simulated and experimental results match fairly well and there is a maximum percentage error of 9% in torque and 5% in efficiency values.

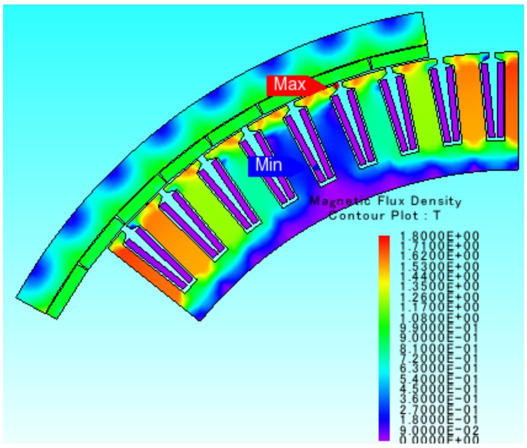

Fig. 5. Flux density plot of the sample HUB motor with virgin magnets

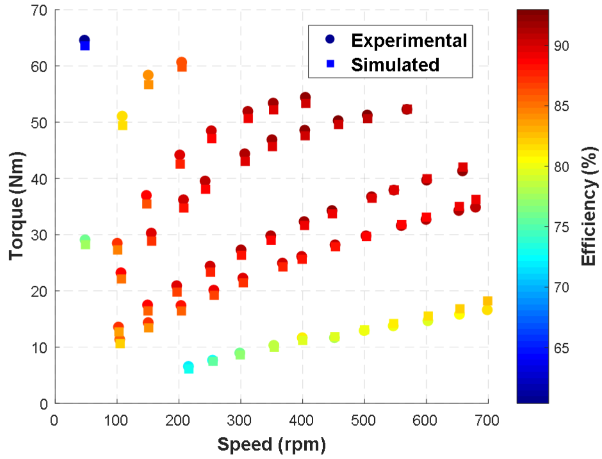

Fig. 6. Comparison of experimental & simulated torque vs. speed with corresponding efficiency values by virgin magnets

III. Efficiency Map and Energy Evaluation of the Sample HUB Motor with Virgin Magnets

Energy consumption for a reference drive cycle requires performance parameters of the machine for the complete torque vs. speed envelope. As a result, efficiency map of the motor needs to be evaluated so as to acquire the precise torque and efficiency points for the corresponding speed values in the reference drive cycle.

A. Methodology for energy consumption evaluation

A methodology has been developed to evaluate the energy consumed by the machine for a particular drive cycle. Various literatures depict the importance of evaluating the energy consumption of a machine for different drive cycles with diverse vehicle dynamics [8]-[17]. Fig. 7 shows the flow diagram of the developed methodology. In this, the machine performance is evaluated using FE analysis and utilizing the flux map of the machine, efficiency map is generated. Along with this, vehicle parameters like wheel radius, vehicle weight, rolling resistance, air density, drag coefficient and frontal area are used as input for deriving torque vs. time curve from speed vs. time of drive cycle. Now, these are used as input to the efficiency map and energy consumption for one cycle of the drive cycle is evaluated. Finally, total energy consumed in the lifetime of the machine is estimated by assuming that the motor operates for 2 hours daily for 10 years.

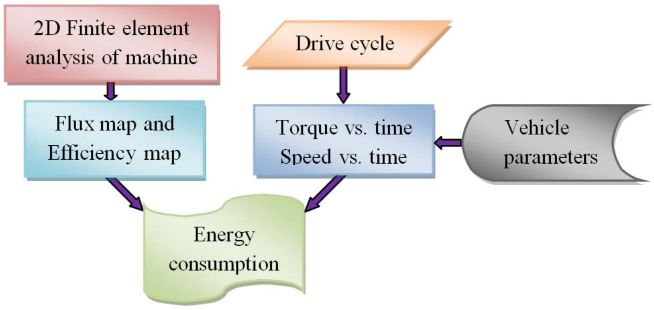

Fig. 7. Flow diagram for energy evaluation methodology

In this study it is assumed that the vehicle is a compact city car with the vehicle parameters as listed in Table II.

TABLE II
VEHICLE PARAMETERS

Parameters	Value
Vehicle weight [kg]	920
Density of air [kg/m^3]	1.225
Frontal area [m^2]	1.85
Drag coefficient	0.4
Coefficient of rolling resistance	0.01
Tyre radius [m]	0.21

B. Efficiency map and energy consumption

The efficiency mapping of the machine is evaluated by utilizing the flux map with different values of direct axis current (I_d) and quadrature axis current (I_q). Similarly, iron loss mapping is also required for various values of machine flux induction and current levels. Therefore, by utilizing optimization algorithm, the efficiency mapping is obtained for the sample motor. Fig. 8 illustrates the efficiency map of the sample motor with virgin magnets.

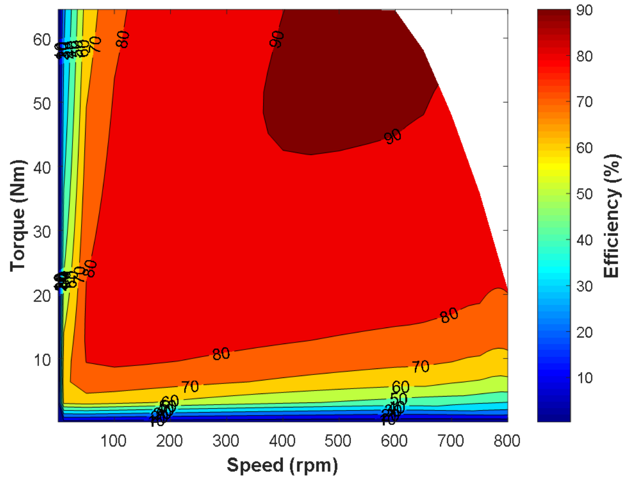

Fig. 8. Efficiency map of the sample HUB motor with virgin magnets

The drive cycle selected for this study is the urban part of the NEDC i.e. ECE-15 [7]. Fig. 9 shows the speed vs. time profile of the ECE-15 drive cycle.

The instantaneous wheel torque can be derived by using the following equation [8]-[17]:

$$T_w = \left(ma + mgC_r + \frac{1}{2}\rho_a C_d A_f v^2 \right) r_w \qquad (1)$$

where, T_w is wheel torque, m is mass of vehicle, a is acceleration, g is gravity, C_r is coefficient of rolling resistance, ρ_a is density of air, C_d is coefficient of drag, A_f is vehicle frontal area, v is velocity of vehicle and r_w is radius of the wheel. Hence, using Eq. (1), vehicle parameters as in Table II and ECE-15 drive cycle, the wheel torque vs. time profile can be obtained. Fig. 10 shows the wheel torque vs. time profile for the selected vehicle and ECE-15 drive cycle.

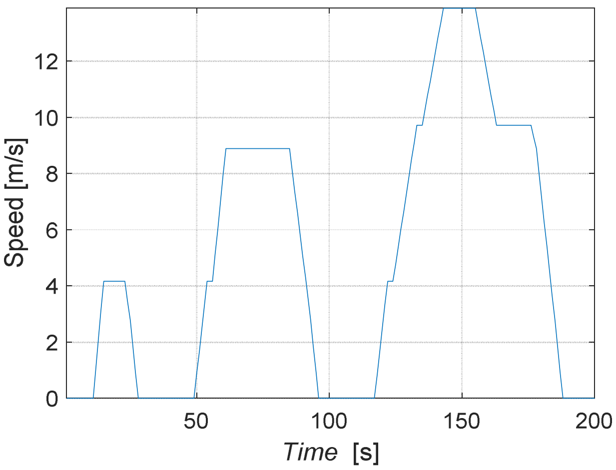

Fig. 9. Speed vs. time profile of the ECE-15 drive cycle

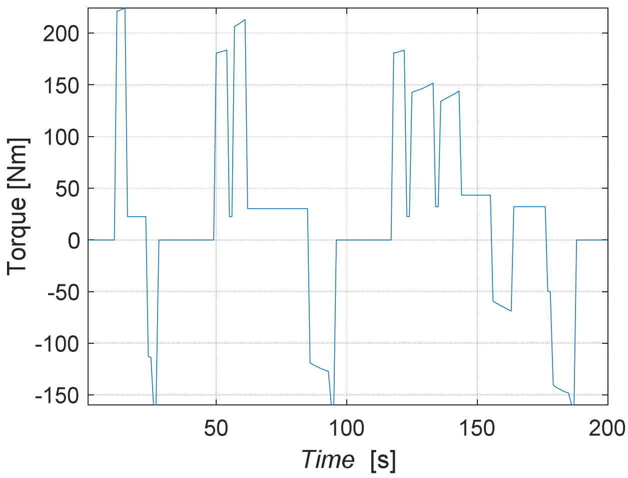

Fig. 10. Wheel torque vs. time profile for the specified vehicle and ECE-15

In typical EVs, the electrical machine is coupled to the wheels via transmission hence they have high speeds and high efficiencies. But here, it can be observed that maximum torque required at wheel is around 220 Nm. The maximum motor torque which can be delivered is around 65 Nm. Hence, it is assumed that four motors would be used in the vehicle with direct drive in-wheel configuration to achieve required vehicle wheel torque.

As per the flow diagram in Fig. 7, this torque vs. speed profile and efficiency map are employed together to get the energy consumed by one motor during the lifetime of 10 years with 2 hours of daily operation. The energy consumption can be calculated as:

$$E_c = \int_0^t E(t)dt \qquad (2)$$

where, E_c is total energy consumed, $E(t)$ is energy input as function of time and t is time. The regenerative braking and negative torque values are assumed to be zero in the energy calculations. As a result, for the sample HUB motor with virgin magnets, the total energy consumed for the complete lifetime is 3071 kWh from Eq. (2). The harmonized electricity price for Europe region is considered as 0.22 €/kWh [18]. Therefore, the energy cost for one motor with virgin magnets is € 676 for the entire assumed lifetime. The weight of total magnet in the motor is 0.7 kg, and NdFeB material price considered is 45 €/kg [19], consequently the total magnet price is € 31.5 in one motor.

The study has utilized ECE-15, but the methodology can be used to assess any drive cycle like NEDC, Urban Dynamometer Driving Schedule, Worldwide Harmonized Light Vehicles Test Procedure etc & this is considered as future work.

IV. Machine Performance with Recycled Magnets

It has been observed for past many years that rare earth material price fluctuates a lot due to regulatory factors, supply-demand issues, political and economical factors. It is for this reason recycling and reuse of rare earth materials from electronic components, computer hard drives and automotive components, have garnered a lot of interest [2]. Research is been carried out in recycling the PM scrap from various sources and fabricate recycled magnets by hydrogen decrepitation (HD) and hydrogenation, disproportionation, desorption, recombination (HDDR) [20]-[22].

In this study, magnetic property of recycled magnet considered is around 0.96 T as B_r. This is as per reference [20], where new magnet material has 1.36 T as B_r and recycled magnet has 1.08 T as B_r, hence 20% reduction in the B_r. In this study virgin magnet has 1.2 T as B_r, and taking 20% reduction for recycled magnet, the B_r evaluated is 0.96 T.

A. Performance characteristics

For the evaluation of machine performance with recycled magnets in sample motor, the methodology utilized is similar to performance calculated with virgin magnets as in Section II (C). The sample motor's dimensional parameters are kept same as that with virgin magnets; only magnet properties are altered with recycled magnet properties i.e. having 0.96 T as B_r and increased length of the motor to achieve same torque as obtained with virgin magnets. The length of stator, rotor and magnets is increased from 40mm to 46mm. Henceforth, 2D time-stepping FE analysis is carried out to get the performance characteristics like back EMF, cogging torque, electromagnetic torque, iron losses, copper losses and winding voltages. Performance has been evaluated with similar current values as used in test and simulations during the study with virgin magnets in Section II (C). Fig. 11 shows simulated torque vs. speed with corresponding efficiency values by virgin and recycled magnets. It can be observed that torque values match fairly well for virgin and recycled magnets. But the efficiency at certain points has increased with recycled magnets due to cumulative decrease of total losses, as iron losses has reduced but copper losses has increased.

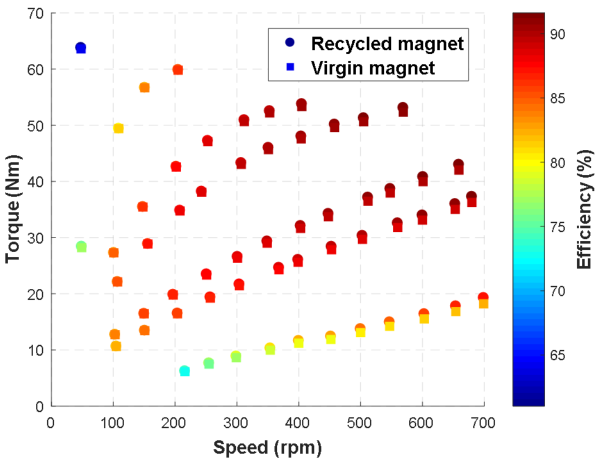

Fig. 11. Simulated torque vs. speed with corresponding efficiency values by virgin and recycled magnets

B. *Efficiency map and energy consumption*

The efficiency map and energy consumption of the sample motor with recycled magnets is evaluated similarly as done while using virgin magnets in Section III (B). By utilizing the flux map with different values of I_d and I_q and iron loss map for various values of machine flux induction and current levels, the efficiency map is generated for the motor with recycled magnets. Fig. 12 illustrates the efficiency map of the sample motor with recycled magnets.

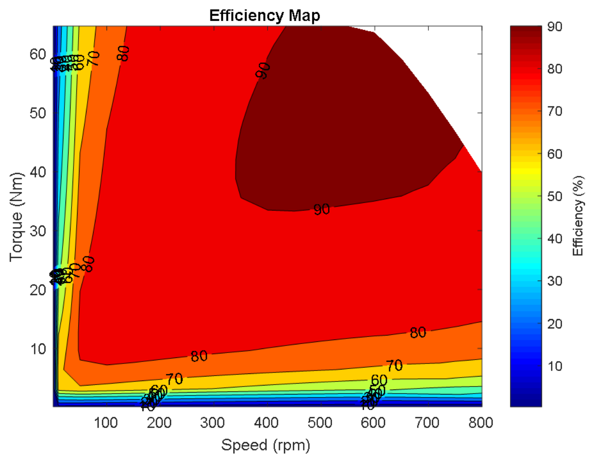

Fig. 12. Efficiency map of the sample HUB motor with recycled magnets

Hereafter employing the flow diagram in Fig. 7, torque vs. speed profile and efficiency map together can provide energy consumed by one motor during the lifetime of 10 years with 2 hours of daily operation with recycled magnets. Consequently, for sample motor with recycled magnets, total energy consumed for complete lifetime is calculated as 2995 kWh from Eq. (2). Similarly, assuming the harmonized electricity price for Europe region as 0.22 €/kWh [18], the energy cost for one motor with recycled magnets is € 659 for the assumed lifetime.

It is difficult to comment on the price of recycled magnets as it is subject to ongoing research studies. But as it is assumed to be prepared from scrap PMs the price is assumed to be lower compared to virgin PMs. Due to increased length the PM weight increases from 0.7 kg to 0.81 kg with recycled magnets. Therefore, assuming the price of recycled magnet material as half of virgin magnets i.e. 22.5 €/kg with certain estimates, the total PM price calculated would be € 18.23 since motor contains 0.81 kg of magnets.

V. Energy Cost Index and Comparison between Virgin and Recycled Magnets

Energy cost evaluation considering the machine performance on a particular drive cycle or duty cycle gives more insights than evaluating machine performance at rated loads. Since machine performance could be optimized for rated conditions but their operation may not be subjected to rated conditions during a specific duty cycle. Therefore, comparing machine performance at a particular drive cycle with different magnet scenarios would provide information about the importance of energy and magnet cost.

For this purpose, an index has been proposed to compare the energy cost in relation to magnet cost. The temperature for both the machines has been assumed the same. For instance, in this study energy consumption cost with virgin magnets is € 676 and magnet cost is € 31.5 for the sample motor. Considering this as the base scenario and naming it as Scenario 1 and/or Scenario base. The energy cost computed with recycled magnets is € 659 and magnet cost is € 18.23 for the sample motor; and naming it as Scenario 2. The energy cost index is defined as follows:

$$EC_i = \left(\frac{E_c(j)}{E_c(b)}\right).\left(\frac{Mag_c(j)}{Mag_c(b)}\right) \quad (3)$$

where, EC_i is the energy cost index, $E_c(j)$ is energy cost for Scenario *j*, $Mag_c(j)$ is magnet cost for Scenario *j*, $E_c(b)$ is energy cost for Scenario base and $Mag_c(b)$ is magnet cost for Scenario base. As a result, energy cost index for Scenario 2 as per Eq. (3) is evaluated as 0.564. From Fig. 13 it can been observed that the design with recycled magnets has low efficiency in low speed high torque region and high efficiency in high speed low torque region as compared to efficiencies with virgin magnets. However, the drive cycle has most of the points in high speed low torque region; hence energy consumption is low with recycled magnets for this drive cycle. Hence, it can be deduced that energy consumption depends on both drive cycle and machine design.

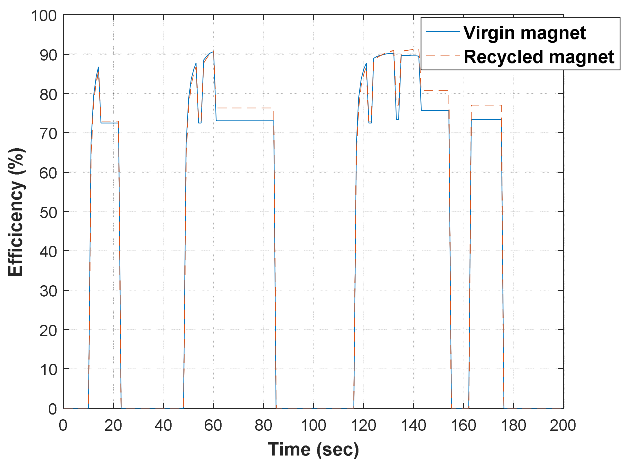

Fig. 13. Efficiency vs. time profile for virgin and recycled magnets

For analysis purpose, few more scenarios are assumed, for example, Scenario 3 where energy cost is € 676 (energy cost for virgin magnets) and magnet cost is € 18.23 (magnet cost for recycled magnets) and Scenario 4 where energy cost is € 659 (energy cost for recycled magnets) and magnet cost is € 31.50 (magnet cost for virgin magnets). Table III represents the comparison of energy cost index for different scenarios, computed using Eq. (3).

TABLE III
COMPARISON OF ENERGY COST INDEX FOR DIFFERENT SCENARIOS

	Energy cost (€)	PM material price (€/kg)	Magnet cost (€)	Energy cost index
Scenario 1	676	45.0	31.50	1.000
Scenario 2	659	22.5	18.23	0.564
Scenario 3	676	22.5	18.23	0.579
Scenario 4	659	45.0	31.50	0.975
Scenario 5	700	37.6	30.46	1.000

Hence, it can be observed that the energy cost index for Scenario 3 is 0.579 and Scenario 4 is 0.975. This indicates that lower the energy cost index, better is the machine in economic aspects and is advantageous as compared to base scenario. Considering one more hypothetical scenario (Scenario 5), where the recycled magnet cost is approximately equal to virgin magnets i.e. € 30.46 and energy cost is € 700; the energy cost index computed is 1.000, as shown in Table III. This is equal to energy cost index of base scenario, indicating that even if the price of recycled magnet are similar to virgin magnet and have higher energy consumption, the economic impact is same. Other than the above cited advantages, with recycled magnets one can observe one more advantage which is that, they have low environmental impact as compared to virgin magnets. The mining of rare earth materials have negative repercussions in terms of environmental and human conditions. The preparation of recycled magnets has lower implications on human labour aspects as no mining is required. Additionally they have environmental benefits like reduction in air and water pollution. It can be argued that even for the preparation of recycled magnets a number of environmental hazards are possible like storage of hydrogen gas and its use in HD and HDDR process, and use of certain chemicals for separation of materials. But if both the circumstances are weighed together, the authors assume that mining would have higher negative impact than producing recycled magnets from scrap [23]. The authors recommend future studies and research into economic-environmental comparison between virgin and recycled magnet production and usage phase.

A general representation of the index is tabulated in Table IV, where energy cost index varies with the cost of virgin and recycled magnets. In this the E_c virgin magnet is € 676, E_c recycled magnet is € 659 and weight of virgin magnet is 0.7 kg and weight of recycled magnet is 0.81 kg. Hence, it can be observed that as the PM material price varies for virgin and recycled magnets the index varies accordingly. The greener the index it is better economically when compared to red coloured cells in Table IV. Similar, hypothesis can be generated with variable energy costs for different grades of magnets and the index would indicate the cases which are economically more advantageous.

TABLE IV
ENERGY COST INDEX WITH VARYING MAGNET COSTS

			VIRGIN MAGNETS					
	PM. mat. price(€/kg)		**20**	**35**	**50**	**65**	**80**	**95**
		PM. cost (€)	**14.0**	**24.5**	**35.0**	**45.5**	**56.0**	**66.5**
RECYCLED MAGNETS	**5**	**4.05**	0.282	0.161	0.113	0.087	0.071	0.059
	20	**16.20**	1.128	0.645	0.451	0.347	0.282	0.237
	35	**28.35**	1.974	1.128	0.790	0.607	0.494	0.416
	50	**40.50**	2.820	1.611	1.128	0.868	0.705	0.594
	65	**52.65**	3.666	2.095	1.466	1.128	0.917	0.772
	80	**64.80**	4.512	2.578	1.805	1.388	1.128	0.950
	95	**76.95**	5.358	3.062	2.143	1.649	1.340	1.128

VI. CONCLUSION

In this paper, the energy cost index evaluation methodology over ECE-15 drive cycle for an EV motor with PMs has been presented. The methodology is utilized to present different scenarios where virgin magnets and recycled magnets were employed and energy cost index was computed. It has been observed that the recycled magnets can provide better economical advantage than virgin magnets as it is assumed that the cost of recycled magnets would be lower than virgin magnets in this case study. Lower the energy cost index, the machine is better in terms of economic evaluation as compared to base scenario. The recycled magnets also provide benefits in terms of environmental aspects as they would be less polluting in their production than virgin magnet materials mined from various sources around the world. The methodology for energy cost index evaluation is a comparative tool and can be adjusted as per the individuals' needs and calculations. The scenarios can vary from motor design and different drive cycles, which can provide varied results and conclusions. Thus, generating an index for comparison provides reasonably good inspiration on using recycled magnets in electrical machines. Future work is planned with experimental utilization of recycled PMs in electrical machine designs.

VII. ACKNOWLEDGMENT

The research leading to these results has received funding from European Community's Horizon 2020 Programme ([H2020/2014-2019)] under Grant Agreement no. 674973 (MSCA-ETN DEMETER). This publication reflects only the author's view, exempting the Community from any liability. Project website: http://etn-demeter.eu/.

Special thanks to Prof. Sylvie Hebert and Prof. Antoine Maignan for helping in the characterization of the magnets at CRISMAT lab of ENSICAEN.

VIII. REFERENCES

[1] T. Elwert, D. Goldmann, F. Romer, M. Buchert, C. Merz, D. Schueler, and J. Sutter, "Current developments and challenges in the recycling of key components of (hybrid) electric vehicles," *Recycling Journal*, vol. 1, no. 1, pp. 25– 60, October 2015.

[2] Y. Yang, A. Walton, R. Sheridan, K. Guth, R. Gauß, O. Gutfleisch, M. Buchert, B. M. Steenari, T. V. Gerven, P. T. Jones, and K. Binnemans, "REE recovery from end-of-life NdFeB permanent magnet scrap: A critical review," *Journal of Sustainable Metallurgy*, vol. 3, no. 1, pp. 122–149, Mar 2017.

[3] M. Kimiabeigi, R. S. Sheridan, J. D. Widmer, A. Walton, M. Farr, B. Scholes, and I. R. Harris, "Production and Application of HPMS Recycled Bonded Permanent Magnets for a Traction Motor Application," *IEEE Trans. on Industrial Electronics*, vol. 65, no. 5, pp. 3795-3804, May 2018.

[4] 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," MORE Project report, Aug 2014.

[5] A. K. Jha, Z. Li, A. Garcia, P. Upadhayay, P. O. Rasmussen, A. Kedous-Lebouc, and L. Garbuio, "Weighted index of recycling and energy (WIRE) cost for Motors in electric vehicles," International *Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)* 2018, pp. 1-6, June 2018.

[6] A. G. Gonzalez, A. K. Jha, Z. Li, P. Upadhayay, and P. Rasmussen, "Validation of Efficiency Maps of an Outer Rotor Surface Mounted Permanent Magnet Machine for Evaluation of Recyclability of Magnets," *INTERMAG 2018*, pp. 1-4, April 2018.

[7] T. J. Barlow, S. Latham, I. S. McCrae, P. G. Boulter, *A reference book of driving cycles for use in the measurement of road vehicle emissions*, version. 3, United Kingdom: IHS, 2009, pp. 21.

[8] P. Lazari, J. Wang, and L. Chen, "A Computationally Efficient Design Technique for Electric-Vehicle Traction Machines," *IEEE Trans. on Industry Applications*, vol. 50, no. 5, pp. 3203-3213, Sep.-Oct. 2014.

[9] K. Kiyota, H. Sugimoto, and A. Chiba, "Comparing Electric Motors: An Analysis Using Four Standard Driving Schedules," *IEEE Industry Applications Magazine*, vol. 20, no. 4, pp. 12-20, July-Aug. 2014.

[10] Qi Li, Tao Fan, Ye Li, Z. Wang, X. Wen, and Jing Guo, "Optimization of external rotor surface permanent magnet machines based on efficiency map over a target driving cycle," *20th International Conference on Electrical Machines and Systems (ICEMS) 2017*, pp. 1-5, Aug. 2017.

[11] P. D. Walker, and H. M. Roser, "Energy consumption and cost analysis of hybrid electric powertrain configurations for two wheelers," *Applied Energy Journal*, vol. 146, pp. 279-287, May 2015.

[12] C. Krasopoulos, M. Beniakar, and A. G. Kladas, "Comparison of Three Different In-Wheel SMPM Motor Configurations Based on the Urban NEDC," *Materials Science Forum*, vol. 856, pp. 233-238, May 2016.

[13] Ganji B., Kouzani A. Z., Trinh H. M., "Drive Cycle Analysis of the Performance of Hybrid Electric Vehicles," In: Li K., Fei M., Jia L., Irwin G.W. (eds) *Life System Modeling and Intelligent Computing. Lecture Notes in Computer Science*, vol. 6328, pp. 434-444, Springer, Berlin, Heidelberg, 2010.

[14] J. O. Estima, and A. J. M. Cardoso, "Efficiency Analysis of Drive Train Topologies Applied to Electric/Hybrid Vehicles," *IEEE Trans. on Vehicular Technology*, vol. 61, no. 3, pp. 1021-1031, Mar. 2012.

[15] E. Carraro, M. Morandin, and N. Bianchi, "Traction PMASR Motor Optimization According to a Given Driving Cycle," *IEEE Trans. on Industry Applications*, vol. 52, no. 1, pp. 209-216, Jan.-Feb.. 2016.

[16] O. Karabasoglu, and J. Michalek, "Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle powertrains," *Energy Policy Journal*, vol. 60, pp. 445-461, Sep. 2013.

[17] M. Novak, J. Novak, and Z. Novak, "Methodology for Efficiency Mapping of Permanent Magnet Synchronous Motors," *19th International Conference on Electrical Drives and Power Electronics (EDPE) 2017*, pp. 205-210, Oct. 2017.

[18] Electricity price statistics, http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

[19] Alliance LLC, Commodity prices. http://www.allianceorg.com/magnetandmaterialcosts.html

[20] R .S. Sheridan, A. J. Williams, I. R. Harris, and A. Walton, "Improved HDDR processing route for production of anisotropic powder from sintered NdFeB type magnets," *Journal of Magnetism and Magnetic Materials*, vol. 350, pp. 114-118, Jan. 2014.

[21] R. S. Sheridan, R. Sillitoe, M. Zakotnik, I. R. Harris, and A. J. Williams, "Anisotropic powder from sintered NdFeB magnets by the HDDR processing route," *Journal of Magnetism and Magnetic Materials*, vol. 324, no. 1, pp. 63-67, Jan. 2012.

[22] M. Zakotnik, I. R. Harris, and A. J. Williams, "Multiple recycling of NdFeB-type sintered magnets," *Journal of Alloys and Compounds*, vol. 469, no. 1-2, pp. 314-321, Feb. 2009.

[23] H. Jin, P. Afiuny, S. Dove, G. Furlan, M. Zakotnik, Y. Yih, and J. W. Sutherland, "Life Cycle Assessment of Neodymium-Iron-Boron Magnet-to-Magnet Recycling for Electric Vehicle Motors," Environ. Sci. Technol. Journal, 52 (6), pp 3796–3802, 2018.

IX. BIOGRAPHIES

Pranshu Upadhayay was born in Jorhat, Assam, India in 1986. Following a B. Tech degree (2007) in Electrical Engineering from Nirma University, India, he received M. S. (Research) in Electrical Engineering (2015) from the Indian Institute of Technology Delhi, India. He is currently working towards his Ph.D. degree from G2Elab, Grenoble INP, Université Grenoble Alpes, and is also associated with Valeo - Equipements Electriques Moteur, Créteil, France.

From 2007 to 2015 he was associated with multinational companies like Schneider Electric India Pvt. Ltd., and Crompton Greaves Ltd., at Mumbai, India. He has published 8 papers in International conference proceedings. His fields of interest include electrical machines and drives, design & FE analysis of special electrical machines, 3D flux claw-pole machines and rare earth magnet reuse and recycling concept in EV and HEV applications.

Adolfo Garcia Gonzalez received his M.Sc. degree in Electrical Engineering from KTH Royal Institute of Technology, Sweden, in 2015. He is currently working toward a Ph.D. degree at the Section of Electrical Machines of the Department of Energy Technology at Aalborg University.

His research interests include modelling and design of electrical machines with 3D-Flux and non-traditional materials for traction applications.

Ziwei Li received his M.Sc. degree in Electrical Engineering from KTH Royal Institute of Technology, Sweden, in 2015. He is currently working towards a Ph.D degree at the laboratory of G2Elab, Grenoble INP, Grenoble and Valeo - Equipements Electriques Moteur, Créteil, France.

His research interests include modeling and optimization of radial flux electrical machines with rare earth magnets recycling concepts for electrical vehicle applications.

Amit Kumar Jha, received B.E degree (2008) in Electrical and Electronics Engineering from Birla Institute of Engineering, Mesra, India and M.Sc. degree (2012) in Electrical Power Engineering from Royal Institute of Technology, Stockholm, Sweden. He is currently working as Ph.D. researcher at G2Elab, Grenoble, France focusing on design of electrical motor with easy recycling for electric vehicles.

Prior to PhD, he has worked in different companies like Bombardier Transportation AB, Vasteras, Sweden, Xylem water solutions, Stockholm, Sweden and Schneider Electric Pvt. Ltd, India. His fields of interest are design of electric motor and its drives for different motor applications and study system performance.

Peter Omand Rasmussen was born in Aarhus, Denmark, in 1971. He received the M.Sc.E.E. and Ph.D. degrees from Aalborg University, Aalborg, Denmark, in 1995 and 2001, respectively.

In 1998, he became an Assistant Professor, and in 2002, he became an Associate Professor at Aalborg University. His research areas are the design and control of switched reluctance, permanent-magnet machines, and magnetic gears.

Afef Kedous-Lebouc has received her Electrical Engineering and Ph.D. degrees from Grenoble Institute of Technology (former Institut National Polytechnique de Grenoble) in 1982 and 1985. She is a Senior CNRS Researcher at Grenoble Electrical Engineering Laboratory G2Elab.

She managed its MADEA Team "Advanced Materials and electromagnetic devices" from 2004 to 2012. She is expert in magnetism, magnetic materials and application in electrical engineering devices. She managed more than 35 industrial projects and participated in many international research programs. She is expert within the International Electrotechnical Commission (IEC TC 68). She has more than 250 publications (80 international journals and 28 invited conferences). She has a large experience in PhD training (35 PhD, 30 already defended).

Jean-Claude Mipo received the Ph.D. degree in electrical engineering from the University "Pierre et Marie Curie", France. Since 1998, he has been with Valeo - Equipements Electriques Moteur, where he is currently Advanced Technical Manager.