Sustainability-Centric Rare-Earth-Free Electric Machine Design for Traction Applications

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Abstract— This paper presents a sustainability-centric design methodology for a wound-field flux-switching machine (WFFSM). The proposed design methodology considers carbon dioxide (CO_2) emissions from the production stage, especially those related to the raw materials used in active and passive components, environmental load units (ELU), cost, and recycling at the end of life of the electric machines. In addition to evaluating electromagnetic performance metrics such as torque, torque ripple, efficiency, and power density, this study proposes to assess the sustainability of active and passive components and materials (copper, magnet, laminated steel) using established equations and literature data. The paper highlights the potential for energy savings, cost reductions, and environmental benefits of the designed WFFSMs for traction applications. Comparative analysis reveals that the WFFSM achieves a 63% reduction in ELU, a 40% reduction in CO_2 emissions, and an 80% saving in raw material cost compared to the baseline flux-switching permanent magnet machine (FSPMM). Moreover, the optimized WFFSM design achieves a torque equivalent to 98% of the baseline FSPMM by integrating advanced cooling systems and higher current density levels.

Keywords—Carbon footprint, end of life, environmental load unit, externally excited synchronous machine, flux switching machine, power density, toroidal winding, rare earth magnet, recycling, sustainability, wound field electric machine.

I. INTRODUCTION

Since nearly 21% of global CO_2 emissions come from the transportation, electrifying this sector is crucial for achieving the 2050 Net Zero Emissions scenario [1]. The key to this goal is the sustainable design and development of electric powertrain systems, which aim to reduce greenhouse gas emissions at every life-cycle stage, including procurement, manufacturing, use, and recycling or disposal. Alternative solutions are being considered to partially or entirely reduce the use of materials with high CO_2 emissions and environmental loads to improve the sustainability of electric machines. For example, wound field rotor topologies are being explored as substitutes for rare-earth (RE) permanent magnets [2]-[4]. The goal is to maintain high performance and efficiency while reducing costs and greenhouse gas emissions. It is crucial to consider magnet-free machine designs for the widespread adoption of electrified transportation.

Externally excited synchronous machines (EESMs) have garnered interest in the passenger car sector in recent years due to their potential to eliminate RE permanent magnets from their design. Rotor-excited motor configurations deliver high efficiency at low torque and high-speed conditions, enhancing vehicle range during highway driving, an essential aspect of customer satisfaction. Nevertheless, this motor design necessitates advanced rotor cooling, specialized electronics for energy transfer to the rotor, and careful consideration of the rotor structure. The flux-switching machine (FSM), a type of EESM, features all excitation sources located on the stator, while the rotor carries neither windings nor magnets. This design eliminates the need for brushes and slip rings, as illustrated in Fig. 1. Based on their excitation sources, FSMs can be categorized as permanent magnet flux-switching machines (FSPMMs) and wound-field flux-switching machines (WFFSM). FSPMMs utilize permanent magnets for excitation, providing a high-power density and efficiency without needing an external power supply for field excitation. However, FSPMM comes with certain disadvantages, including complex stator structure, high magnet usage, risk of demagnetization, high cost, high CO_2 emission, and low efficiency at low-torque and high-speed conditions. WFFSMs use electromagnets, allowing for controllable flux and improved flexibility in operation. The WFFSMs possess robust stator and rotor structure, low cost, effective thermal management capability, fault tolerance, and easy flux regulation [5]-[7].

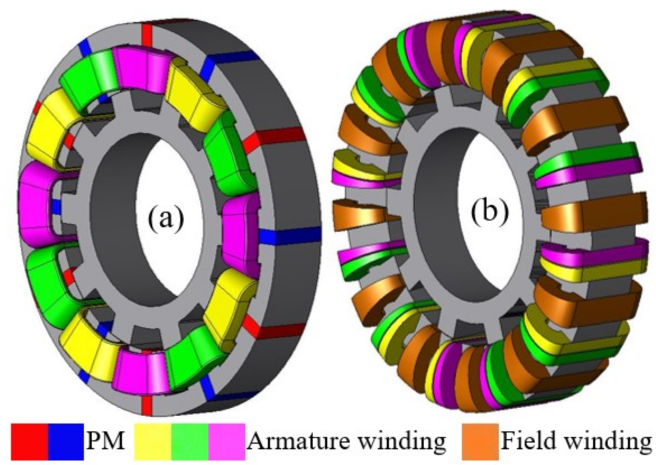


Fig. 1. 3D view of (a) FSPMM (b) WFFSM.

While much attention has been paid to improving performance and efficiency in FSMs [8]-[13], the sustainability

TABLE. 1. CO_2 EMISSION FACTORS, ELU, AND ESTIMATED COST OF RAW MATERIALS COMMONLY USED IN ELECTRIC MACHINES

Component	Active components					Passive components			Reference
	Magnet Wires		Magnet		Lamination	Housing	Shaft	Bearing	
Material	Copper	Aluminum	SmCo	NdFeB	Silicon steel	Al alloy	Carbon steel	Chrome steel	
CO_2 emission factor [$KgCO_2/Kg$]	4	9	25	50	2	8	3	2	[14]
Environmental load unit [ELU/Kg]	131	0.16	1200	200	1	0.16	1	1	[16]
Cost [US$/Kg]	9	2.7	50-210		2	2.5	0.8	12	[17]-[20]

aspects, such as carbon emissions from the production stage, particularly those related to raw material consumption and environmental load unit (ELU) of electric machine components remain largely unexplored. The research in [14] offers a review of carbon emissions in the manufacturing of electrical machines, and compares the emission values of various materials commonly used in different components of electric machines. The environmental impact of RE magnet and different winding materials in different electric machine topologies used in e-mobility applications are presented in [15]-[16]. This paper aims to shed light on the neglected dimension of electric machine design by providing a comprehensive review of sustainability factors, including carbon emissions, ELU, and cost in manufacturing. By comparing the carbon emission values, ELU, and costs of various materials commonly used in the main components of FSMs, we significantly contribute to the broader discussion on sustainable electric machine design.

This paper is structured as follows. Section II details the materials used to make the various parts of the electric machines. It explains the methodology used to analyze carbon emissions. The sustainability aspects of FSPMM and WFFSM, including carbon emissions, ELU, and costs, are quantified using established equations and data from the literature review. Section III evaluates the electromagnetic performance of both FSPMM and WFFSM, focusing on output torque, torque ripple, and power density. It presents the optimized WFFSM design for sustainability, highlighting the environmental benefits of this new design, such as carbon emission and ELU reduction, along with cost-saving potentials. The optimized WFFSM benefits from an advanced cooling system, which enables increased field and armature winding current densities, resulting in higher output torque comparable to the baseline FSPMM. Finally, the conclusion summarizes the key findings.

II. SUSTAINABILITY ASPECTS OF FLUX-SWITCHING MACHINES

Electric machines in traction systems are used to convert electrical energy into mechanical motion and vice versa. The increasing reliance on electric machines in this sector calls for a comprehensive design approach that goes beyond their operational phase. While enhancing efficiency is a key focus, it is equally important to consider the environmental impact of the manufacturing processes. Carbon emissions from raw materials can contribute up to 90% of the total emissions during the manufacturing phase of electric machines [14]. This section aims to concisely calculate and compare the carbon emissions and ELU of the active and passive components of FSPMM and WFFSM. By systematically evaluating these results, we can provide valuable insights for electric machine designers and encourage more sustainable and environmentally conscious practices within this industry.

A. CO_2 Emission of the Raw Materials

This subsection outlines the carbon emission factors associated with commonly used materials for both active and passive components in electric machines. Active components, such as windings, soft magnetic materials, and magnets, are crucial for energy conversion in these machines. Selecting the appropriate core, magnet, and winding materials for active components is vital, as the efficiency of the electric machine is closely linked to the energy losses from these parts. Passive components include the housing, end brackets, shaft, bearings, and insulation systems, where the main considerations are the physical and structural properties of the materials. In terms of carbon emissions, the total emission value of a material increases with both its mass and its carbon emission factor. Table 1 lists the average carbon emission factors for materials commonly used in active and passive components of electric machines. The carbon emission factors considered here would represent the average if the literature review provided a range of values for each material.

1) Magnet Wires

Windings is used to induce electro-motive force and produce a rotating magneto-motive force in electric machines. Copper is the most commonly used material for motor windings due to its excellent electrical conductivity, though it has a higher mass density. Aluminum, another winding material, emits 9 KgCO2/Kg on average, which is more carbon-intensive than copper, which has an average emission factor of 4 $KgCO_2/Kg$.

2) Magnets

Magnets play a crucial role in electric machines as a source of flux. Amongst the RE PMs, NdFeB is the most powerful available, with an average carbon emission factor of 25 $KgCO_2/Kg$. SmCo magnets, while comparable in strength to NdFeB, offer superior temperature stability and coercivity but emit 60 $KgCO_2/Kg$.

3) Lamination

Silicon steels, containing approximately 2% silicon, are the most commonly used soft magnetic materials for lamination. These steels have an emission factor of 2 $KgCO_2/Kg$.

4) Passive Components

This part covers the various materials used in the passive components of electric machines, such as housings, shafts, and bearings. Aluminum alloy, known for its high machinability, strength, durability, lightweight nature, and recyclability, is the most widely used material for machine housings with average carbon emission factors at 8 $KgCO_2/Kg$. Carbon steel and

TABLE 2. FLUX SWITCHING MACHINES SPECIFICATION.

Parameter	Units	Value	
		Baseline FSPMM	WFFSM
Rated speed	rpm	4,000	4,000
Stator/rotor pole	-	12/10	12/10
AC current density (J_{ac})	A/mm^2	8.5	8.5
PM type	-	SmCo	-
Stator outer diameter	mm	540	540
Air gap length (l_g)	mm	1	1
Stack length	mm	80	80

chrome steel, commonly used for shafts and bearings, have 3 and 2 KgCO_2/Kg carbon emission factors, respectively.

B. Environmental Load Unit of Raw Materials

ELU is a standardized measure used to quantify the environmental impact of various activities, products, or services. They encompass factors such as resource consumption, emissions, and ecological degradation, translating these diverse impacts into a common metric for easier comparison and assessment. By integrating multiple dimensions of environmental stress, ELUs facilitate more comprehensive and meaningful evaluations of sustainability efforts. A comparison between ELU of different materials used in FSMs is presented in Table 1. Moreover, an estimated cost of raw materials commonly used in electric machine components is also presented.

The baseline electric machine used for this study is a 12/10 stator/rotor pole FSPMM with a rated speed of 4,000 rpm designed for aerospace application, as illustrated in Fig. 1 (a). FSMs specification is presented in Table 2. The mass, carbon emission, ELU, and cost of active component materials of the baseline FSPMM are summarized in Table 3. The baseline FSPMM weighs 122.5 kg and has a total ELU of 22,130. The total carbon emission for each component is calculated by multiplying the mass of the material by its carbon emission factor. The combined material inputs produce a total carbon emission of 650 kg CO_2 for the baseline FSPMM.

A significant portion of the carbon emissions, ELU, and costs shown in Table 3 are attributable to RE magnets. To move towards more sustainable electric machine design, industry and literature suggest substituting RE magnets with electromagnets for inducing electro-motive force [2]-[4], [21]. In this study, copper has been chosen for the electromagnet windings due to its superior electrical conductivity, reliability, durability, and efficient heat transfer properties. It is important to note that while aluminum offers advantages in cost and ELU, it also has trade-offs, such as higher electrical resistivity, which results in increased winding losses and, consequently, lower efficiency.

C. Copper Life Cycle Assessment

The inherent properties of copper, including its durability and excellent conductivity, position it as the preferred material for advancing the green transition. Copper holds a prominent role in various decarbonization technologies, such as electric vehicles, wind turbines, photovoltaic panels, and energy-efficient equipment. Forecasts indicate a doubling in demand for copper by 2050, rising from 25 million tonnes in 2020 to 50 million tonnes. Present estimates suggest that copper resources surpass 5 billion tonnes [22]. Therefore, copper is not considered

TABLE 3. CARBON EMISSION, ELU, AND MATERIAL COST OF FSPMM.

Parameter	Unit	Value
Total weight	Kg	122.5
Total CO_2 emission	Kg	650
Environmental load unit (ELU)	ELU	22130
Active parts raw material cost	US$	3512

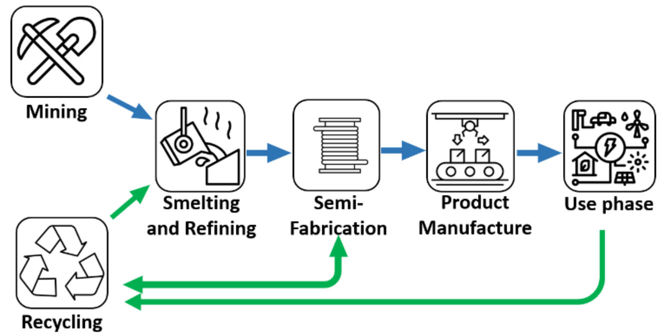


Fig. 2. Copper life cycle diagram.

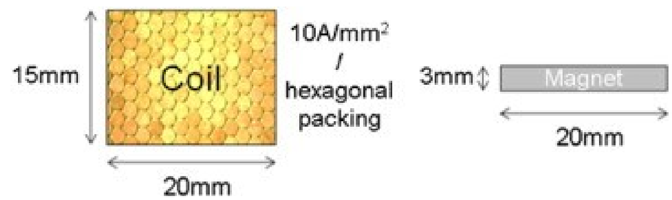


Fig. 3. Comparison between the electromagnet and RE magnet area required to produce the same magnetic field [26].

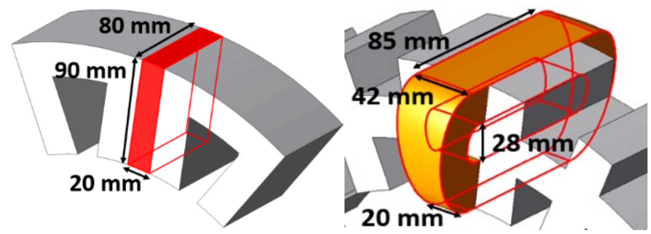


Fig. 4. Magnet and field winding dimensions in FSPMM and WFFSM.

as a critical raw material. As shown in Fig. 2, mining is the primary route of copper production that provides 70% of the demand; recycling, the secondary route, covers the other 30% of the total demand [23]. As a 100% recyclable material, copper can be reused repeatedly without losing its physical properties.

III. WOUND-FIELD FLUX-SWITCHING MACHINE DESIGN FOR SUSTAINABILITY

The WFFSM with a toroidal field and armature windings is a desirable electric machine design candidate, which simplifies the access of the copper at the end of life (design for sustainability). Besides easier winding extraction toward a recycling process, this stator type is relatively easy to manufacture with a higher winding fill factor [24]-[25]. It also provides better cooling because windings are directly exposed to the stator housing with a cooling jacket [13].

RE magnets produce a strong magnetic field within a small volume in a traction motor. The alternative would be to use electromagnets, where a magnetic field is generated by passing current through a conducting coil. It can be shown that a 3 mm thick piece of RE magnet produces the equivalent magnetic field of a coil with a current density of 10 A/mm^2, which is typical for

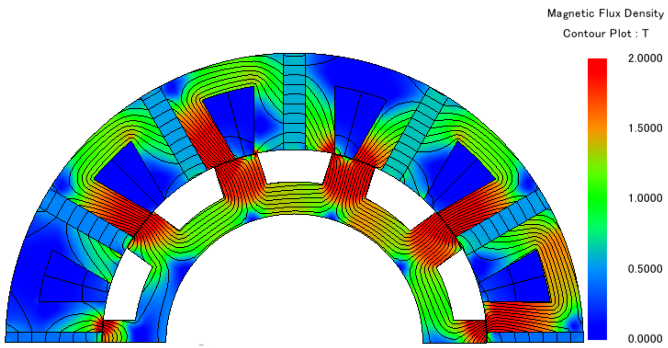


Fig. 5. Magnetic flux density and magnetic flux line of the baseline FSPMM (@ 4,000 rpm J_{ac} = 8.5 A/mm^2).

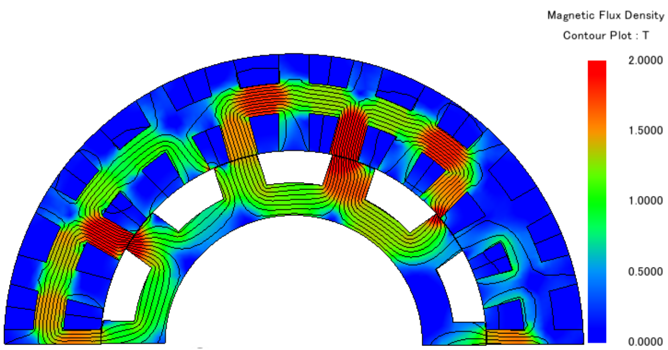


Fig. 6. Magnetic flux density and magnetic flux line of the WFFSM (@ 4,000 rpm, J_{dc} = 10.5 A/mm^2, J_{ac} = 8.5 A/mm^2).

the normal operation of a traction motor. An equivalent electromagnetic coil might have five times the cross-sectional area of the magnet, as shown in Fig. 3 [26].

In FSPMM, a stator pole consists of circumferentially magnetized PM sandwiched between two stator modules and enclosed by armature winding. PMs are replaced with toroidal field windings with a magnetic core in WFFSM. Fig. 4 shows the PM and field winding dimensions in FSPMM and WFFSM. The armature winding can also be toroidal rather than circumferential. In this case, the armature winding is wound around the stator yoke instead of the stator pole. The magnetic flux density and the magnetic flux line of the baseline FSPMM and the WFFSM are depicted in Fig. 5 and Fig. 6. The Baseline FSPMM shows saturation mostly at the rotor and stator teeth. However, the WFFSM is more saturated at stator teeth and the field windings core. Given the limited space for the field winding, achieving the same magnetic field strength would require increasing the current density to higher levels. Besides the limited slot space for the field winding, the integrated stator structure of WFFSM and the coexisting field and armature windings in the stator lead to a complex and inefficient magnetic flux path generation, resulting in higher self– and mutual inductance of armature winding, which degrade the net output torque [24]-[25]. Rotor saliency optimization is required to mitigate this issue [13].

The instantaneous torque waveforms of FSPMM and WFFSM over an electric cycle are depicted in Fig. 7. By injecting 10 A/mm^2 DC current into the field winding, the output torque of the WFFSM is 592 N.m. As shown, with a current density of 10 A/mm², the net output torque of WFFSM is 65%

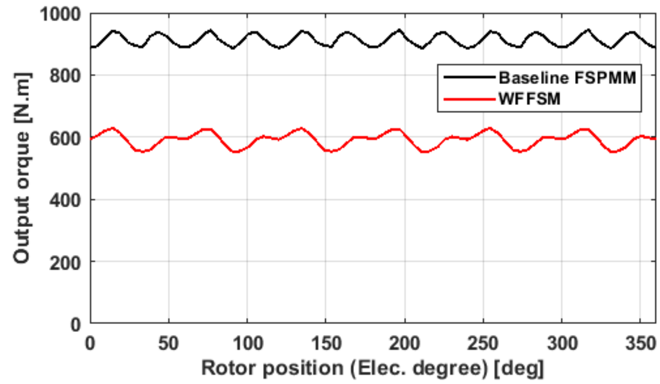


Fig. 7. Instantaneous torque waveforms of the baseline FSPMM (@ 4,000 rpm J_{ac} = 8.5 A/mm^2) and WFFSM (@ 4,000 rpm, J_{dc} = 10 A/mm^2, J_{ac} = 8.5 A/mm^2) for an electrical cycle.

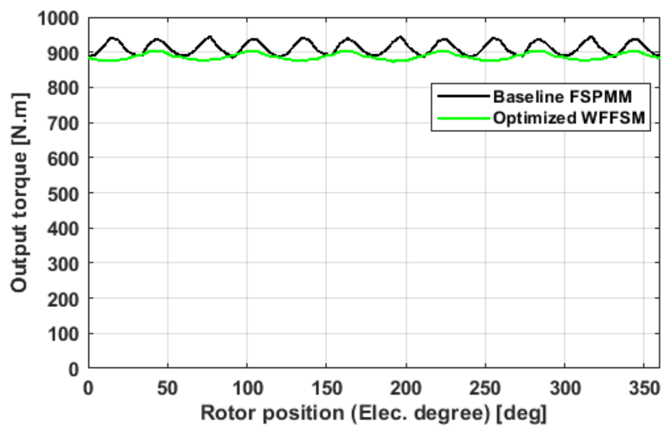
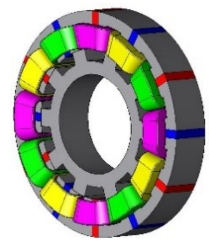
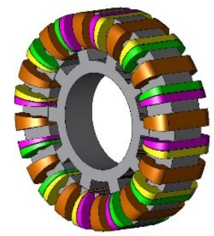
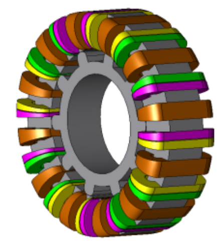


Fig. 8. Instantaneous torque waveforms of the baseline FSPMM (@ 4,000 rpm, J_{ac} = 8.5 A/mm^2) and optimized WFFSM for an electrical cycle (@ 4,000 rpm, J_{dc} = 17 A/mm^2, J_{ac} = 17 A/mm^2).

of that of the baseline FSPMM (908 N.m). Considering the better cooling capability of toroidal winding, with advanced winding cooling techniques, the optimized WFFSM can reach higher output torque by pushing field and armature current densities. Additionally, within the stator core of the optimized WFFSM, the outer teeth do not play a significant role in electromagnetic performance [13]. Consequently, keeping the same outer diameter makes it possible to remove these outer teeth in the stator and push the stator yoke outward, thus providing additional space for accommodating advanced winding cooling techniques. It is evident that this approach also reduces the stator core loss. The instantaneous torque waveforms of the FSPMM and the optimized WFFSM over an electric cycle are plotted in Fig. 8. By incorporating an advanced cooling system and higher current density levels, the optimized WFFSM achieves a torque output of 890 N.m, that is 98% of the baseline FSPMM.

The electromagnetic performance and sustainability aspects of the baseline FSPMM, WFFSM, and the optimized WFFSM are summarized in Table 4. This comparative analysis raises the question of which FSM topologies is better. FSPMM offers higher power density with the same current density, relatively lightweight, and compact structure. WFFSM shows the net output torque 65% of the baseline FSPMM. However,

TABLE 4. COMPARISON OF FSMS WITH IDENTICAL GEOMETRY AT LOADED CONDITION (@ 4,000 RPM).

Type	Baseline FSPMM	WFFSM	Optimized rotor WFFSM with advanced cooling
Machine design			
Output torque [Nm]	908	592	890
Torque ripple [%]	6.2	17.8	3.4
Cogging torque [Nm]	66	56	32
Field current density (J_{dc}) [A/mm^2]	-	10	17
Armature current density (J_{ac}) [A/mm^2]	8.5	8.5	17
Efficiency [%]	94	91.5	92.7
Active parts power density [Kw/L]	25	12.5	23
Active parts torque density [Nm/L]	59.8	29.7	54.5
Lamination weight [Kg]	72.6	73.7	71.9
Copper weight [Kg]	35.4	61.8	61.8
PM weight [Kg]	14.5	0	0
Total weight [kg]	122.5	135.5	133.7
Total CO_2 emission [kg]	650	394.9	391
Environmental load unit (ELU)	22130	8180	8178
Active parts raw material cost [US$]	3512	704	700
Design features	✓ High power density. ✓ Relatively high efficiency. ✓ No winding overlaps. • Modular stator structure. • High cost. • Demagnetization. • No field regulation.	✓ No winding overlaps. ✓ Short end winding. ✓ Higher filling factor ✓ Better cooling capability. ✓ Field regulation capability. ✓ Low cost. ✓ Easy winding extraction at the EoL. • Lower efficiency. • Lower power density. • Local saturation. • Voltage harmonics.	✓ No winding overlaps. ✓ Short end winding. ✓ Higher filling factor ✓ Better cooling capability. ✓ Field regulation capability. ✓ Low voltage harmonics. ✓ Low cost. ✓ Easy winding extraction at the EoL. ✓ Higher current density. • More complicated cooling system.

considering the environmental footprint of electric machine manufacturing, the WFFSMs exhibit a reduction of 63% in ELU and 40% in CO_2 emissions compared to the FSPMM. Optimizing the WFFSM with advanced cooling also results in an output torque comparable to 98% of the baseline FSPMM. Furthermore, the material costs of WFFSMs are only 20% of that of FSPMM. The spider graph comparing the normalized sustainability aspect and electromagnetic performance of the baseline FSPMM, WFFSM, and the optimized WFFSM are plotted in Fig. 9. The WFFSMs improve sustainability aspects such as ELU, carbon emission, and cost. The optimized WFFSM shows a comparable power density and efficiency with FSPMM.

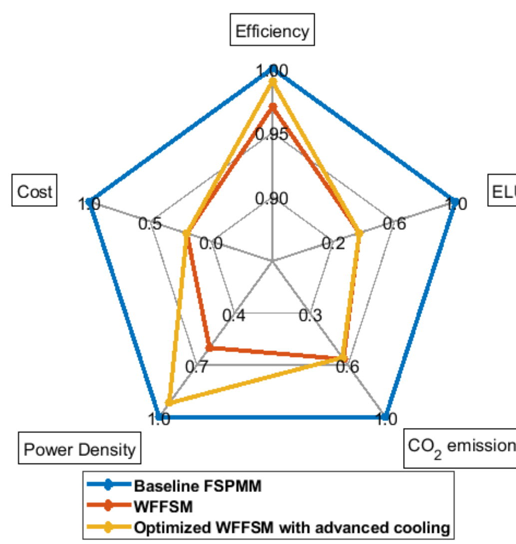


Fig. 9. Normalized sustainability aspects and electromagnetic performance comparison of FSPMM and WFFSMs.

IV. CONCLUSION

Rare earth magnets possess unique magnetic characteristics and are widely used in electric propulsion systems. However, due to their high cost, limited availability, and environmental concerns, it is crucial to explore alternative technologies to replace rare-earth-based magnets in electric motors. A toroidal winding wound-field flux-switching machine is an externally excited synchronous machine offering several benefits, such as a simple and robust rotor structure, improved thermal management capabilities, field regulation capability, and low cost. From a sustainability perspective, this study examined the impact of replacing rare earth magnets with field windings. The proposed electric machine topology is designed with sustainability in mind. It emphasizes advantages such as energy savings, cost reduction, lower environmental footprint, and easier material recycling at the end of life. Comparative analysis shows that the wound-field flux-switching machine achieves a 63% reduction in ELU, a 40% reduction in CO_2 emissions, and an 80% saving in raw material costs compared to the baseline flux-switching permanent magnet machine. The optimized wound-field flux-switching machine design also achieves a torque equivalent to 98% of the baseline flux-switching permanent magnet machine by integrating advanced cooling systems and higher current density levels.

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