RePED 250: Manufacturing and Market Analysis of High-Temperature Alternators

Devon Kesseli,[1] Sertaç Akar,[1] and Jody Robins[2]

1 National Renewable Energy Laboratory
2 Global Renewable Energy Solutions

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-7A40-90531
September 2024

RePED 250: Manufacturing and Market Analysis of High-Temperature Alternators

Devon Kesseli,[1] Sertaç Akar,[1] and Jody Robins[2]

1 National Renewable Energy Laboratory
2 Global Renewable Energy Solutions

Suggested Citation
Kesseli, Devon, Sertaç Akar, and Jody Robins. 2024. *RePED 250: Manufacturing and Market Analysis of High-Temperature Alternators*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-90531. https://www.nrel.gov/docs/fy24osti/90531.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-7A40-90531
September 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy (DOE), Advanced Research Project Agency-Energy (ARPA-E) under ARPA-E Award No. DE-AR0001048. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

List of Acronyms

ARPA-E	Advanced Research Projects Agency-Energy
DOE	U.S. Department of Energy
EV	electric vehicle
GOES	grain-oriented electrical steel
HPHT	high-pressure, high-temperature
LCOE	levelized cost of energy
LREE	light rare earth element
NOES	non-oriented electrical steel
NREL	National Renewable Energy Laboratory
O&G	oil and gas
RePED	repetitive pulsed electric drill
SI	substitutability index
SmCo	samarium cobalt
SRM	synchronous reluctance motor

Acknowledgments

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy (DOE). The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The authors wish to thank Bill Moeny of Tetra Innovation Institute (Tetra) for his feedback and guidance, as well as the reviewers for their comments and suggestions, including Lee Jay Fingersh, Craig Turchi, and Achilles Karagiozis from the National Renewable Energy Laboratory. The authors are also very appreciative of the industry representatives for their time and insight, including Moog, Windings, Ducommun, and Helios Electric Motors. All errors and omissions are the responsibility of the authors.

Executive Summary

The novel repetitive pulsed electric drill 250 (RePED 250) has the potential to greatly lower the costs and drilling times of geothermal projects. This tool discharges electric pulses through hard rock formations, shattering the rock in tension and allowing it to be quickly removed. One hurdle in bringing this technology to market is the RePED 250 downhole alternator. This component is essential for supplying power to the electronic drilling tool. There are currently no downhole tools on the market that meet the RePED 250 alternator's high temperature and power requirements. This report focuses on the path to commercialization for this novel alternator technology being developed as part of the RePED 250 project.

One aim of this work is to identify the geothermal market size for the RePED 250 alternator, as well as other potential markets for this technology outside of geothermal. The geothermal market is very small, with only approximately 13 wells drilled in the United States each year. The worldwide market is several times this size and growing each year. The ability of the RePED 250 technology to drastically reduce the cost of geothermal projects may also lead to an increase in this market size. When RePED 250 tool is utilized the total drilling time and cost is expected to be less than 1/3rd of the drilling time and cost of the traditional tools.

Technology developed for the high-temperature, high-power RePED 250 alternator can also be used to create high-temperature and high-power motors. These motors and alternators will have potential applications in oil and gas (O&G) drilling, a $300 billion dollar industry in the United States alone [1], as well as in more distant industries such as aircraft, weapon systems, space exploration, and electric vehicles.

Other aspects of the RePED 250 alternator's path to commercialization are also analyzed, including the supply chain for production materials and potential manufacturing methods. The supply chain and manufacturing practices for low-temperature motors and alternators are well established and require relatively minor changes for the high-temperature and high-power RePED 250 alternator. Sourcing for high-temperature materials has been identified, as well as potential supply chain risks. These most notably include electrical steel and high-temperature samarium cobalt (SmCo) magnets. Overall, these risks are not expected to be significant at the likely manufacturing scale required for the RePED 250.

Table of Contents

List of Figures

List of Tables

1 Introduction

The global potential for geothermal is limited by the speed and cost of drilling geothermal wells through hard rock formations. Drilling rates in the United States average only 125 feet per day [2], more than 40 times slower than drilling rates through softer rocks in the oil and gas (O&G) industry, though geothermal drilling speeds have been increasing in recent years [3], [4]. Novel pulsed electric drilling methods have the potential to end rotary drilling's dominance within 10 years of commercialization by drastically increasing the rate of penetration through hard rock.

The current proprietary drilling system patented by Tetra is anticipated to work in most O&G drilling applications but will need to be upgraded for geothermal applications. To reach hotter geothermal resources, drilling system components need to withstand temperatures up to 250ºC. The repetitive pulsed electric drill 250 (RePED 250) project is an effort by the National Renewable Energy Laboratory (NREL) and Tetra to adapt this pulsed electric drilling technology to 250ºC and beyond. The Department of Energy's (DOE's) Advanced Research Projects Agency-Energy (ARPA-E) initiative is supporting the effort to bring this novel drilling method to commercialization for geothermal applications.

One important component of the pulsed electric drilling system is the downhole alternator. It produces electricity from pumped fluid using a turbine and is commonly used in many traditional drilling systems. There are several challenges in adapting this component for the 250ºC pulsed electric system. Pulsed electric drilling requires relatively large amounts of power; in this case, up to 300 kW. Additionally, materials used in lower temperature downhole alternators are not stable at 250ºC. The development of this alternator is essential for the success of the RePED 250 project. In addition, a successful high temperature alternator will have impacts in other markets, ranging from O&G to electric vehicles (EV) to space exploration. The requirements for the RePED 250 alternator are listed in Table 1.

Table 1. Technical Requirements for the RePED 250 Downhole Alternator

Requirement	Unit	Value
Maximum temperature	C	250
Maximum pressure	psi	15,000
Power	kW	300
Maximum diameter	in	6.375
Maximum length	ft	40

Section 2 examines the global market and possible alternative application for the technology used in a high-power 250ºC alternator. Section 3 details the global supply chain for alternator components. Section 4 discusses the manufacturing process flow for a high-temperature alternator, including the materials and manufacturing methods used to make this component. Section 5 describes the strengths, weaknesses, risks, and opportunities of the high-temperature alternator.

2 Market Overview

The RePED 250 alternator is designed for the high-temperature, high-power drilling market. Its primary application will be for geothermal drilling, which is often through hard rock and at high temperatures. In the following subsections, primary and alternate markets for this technology are described, along with some of the major players in this industry.

2.1 Global Market Size

The geothermal drilling market is small but is expanding as the technology matures and new lower-cost drilling methods are brought to market. The global geothermal market grew by more than 43% (~6.7 GW) from 2003 to 2020 and is expected to grow another 34% (~5.4 GW) from 2020 to 2030 [5], [6], [7].

Currently, there are only approximately 13 geothermal wells drilled per year in the United States [8] and 232 per year drilled for power production globally [9], most reaching temperatures between 100º and 250ºC. Drilling to higher temperatures is more costly but leads to more efficient geothermal systems [10], [11]. One of the biggest barriers in the U.S. geothermal market is the high levelized cost of energy (LCOE) due to high drilling cost. A fast, high temperature (250ºC) drilling tool will reduce drilling times and costs, which would decrease the LCOE for geothermal projects and lead to greater geothermal deployment.

2.2 Major Players

The downhole alternator market for O&G drilling is mature and well established. A list of relevant high-temperature alternator design and manufacturing companies is shown in Table 2. Most of these companies currently produce alternators designed to operate in high-temperature, high-pressure wellbore conditions, though none meet the temperature and power requirements required for this project.

Table 2. List of Relevant High-Temperature Alternator Manufacturers

Company	Location	Products	Annual Manufacturing Capacity
Winding	New Ulm, Minnesota, USA	Custom motors, high-pressure high-temperature (HPHT) downhole alternators	Mid-scale (1-30k)
Ducommun	Santa Ana, California, USA	HPHT downhole alternators, high temperature actuators	Mid-scale (1-30k)
Moog	Buffalo, New York, USA	Precision motors, downhole motors, and alternators	Large-scale (>30k)
CDA InterCorp	Deerfield Beach, Florida, USA	Precision electronics for downhole, aviation, and defense.	Small to mid-scale
Honeybee Robotics	New York, New York, USA	Ultra-high temperature motors	Small-scale (<100)
Wittenstein SE	Igersheim, Germany	HPHT downhole alternators, high temperature actuators.	Large-scale (>30k)

Company	Location	Products	Annual Manufacturing Capacity
Printed Motor Works	Alton, United Kingdom	Custom motors and alternators	Small to mid-scale

Windings, Ducommun, and Moog are all leaders in the downhole motor and alternator industry. Representatives from each of these companies were interviewed as part of this work. These interviews provided important insight into the high-temperature motor and alternator market, as well as the manufacturing methods and global supply chain currently used in the industry. Understanding the current industry climate is essential for understanding how the RePED 250 alternator will be brought to market.

One important takeaway from these interviews is that the specialized manufacturing capabilities required to produce downhole alternators and motors can be applied to a variety of other markets, primarily in the aircraft and defense industries. In fact, for each of these companies, only a small portion of their products are used in the drilling industry, and none currently supply products for geothermal drilling. These three companies vary in size, target markets, and manufacturing capabilities. Short profiles are listed below.

- **Windings** has approximately 130 employees and specializes in low volume, niche applications of motors and alternators. They have a boutique manufacturing setup and can produce from 1–30,000 units per year based on customer needs. Each design is custom-made using a variety of novel techniques and materials to operate at the customer's specifications. They are willing to sell IP of their designs to the customer.
- **Ducommun** has approximately 200 employees and specializes in the aerospace and defense industries. Their products are based on specific customer needs, with the majority of their focus on high-temperature, low-power actuators for defense.
- **Moog** is the largest company we investigated, with 3,500 employees in the United States and nearly 10,000 worldwide. Their specialty is reliable, high-precision motors and hydraulic actuators, which are used in everything from amusement park rides to aircraft and rocket controls. At this scale, they control most of their supply chain and manufacture as many units as needed.

The ultra-high-temperature electronics industry (>300ºC) is also relevant to the RePED 250 alternator. The main market for ultra-high-temperature motors is the space industry. The players in this industry are small companies that produce extremely low volumes of custom motors.

2.3 Other Applications

Alternators work using the same principles as electric motors. While an alternator converts rotational motion to electric power, a motor uses the same process in reverse, generating torque from electricity. Because of this, the two systems use almost identical components, and the same technology used to create a high temperature alternator can be used to create a high-temperature electric motor. Looking at these two systems together presents additional options for manufacturers and broadens the possible applications for the RePED 250 alternator technology.

Alternators are used in a wide variety of industries, including drilling, automotive, aviation, and manufacturing. Applications for high-temperature alternators are rare, as in most cases the alternator can simply be moved further from the heat source. High-temperature motors and alternators can provide benefits primarily in situations where either:

1. The ambient environment itself reaches high temperature
2. Space and mass are extremely limited, and the motor or alternator cannot be moved further from the heat source in the system.

These criteria are found in several different industries described below. In many of these industries, efforts have already been undertaken to build higher-temperature components.

2.3.1 Drilling: O&G

Downhole alternators are used in both the geothermal and O&G industries to provide power to downhole equipment. While the geothermal industry stands to benefit more from high-temperature hard rock drilling tools, the O&G industry is several orders of magnitude larger and could employ the RePED 250 tool in wells that drill through hotter (>250°C) and harder than normal zones.

Although shale drilling has made up most of the O&G production increase in recent years, further recovery from mature fields and the exploitation of deep and ultra-deep water reservoirs are possible avenues for further O&G production [12]. Both applications can benefit from components rated for high temperatures and high pressures. The biggest obstacle for electronic data acquisition systems in deep wells is high temperature encountered at great depth [13]. Reliable high-temperature electronics would enable the drilling of deeper wells at a lower cost.

A wide variety of research groups and drilling tool companies have undertaken efforts to create equipment for higher-temperature drilling conditions [12], [13], [14], [15], [16], [17], [18]. These components have been tested successfully; however, they do not meet both the temperature and the power requirements for the RePED 250 alternator.

2.3.2 Aviation and Aerospace

Modern commercial aircrafts are moving away from hydraulic and pneumatic systems to a lighter, more electric architecture [19]. This architecture can be simplified by moving electric motors and actuators closer to the jet engine, where the ambient temperature is high. Hybrid electric aircrafts are also being developed [20], which make use of electric motors and storage.

In the aircraft industry, reliability and operating life are essential. These components also undergo frequent thermal cycling. In these applications, the environment can range between -50ºC and 300ºC [19], [20]. The technology used in the RePED 250 alternator should be effective in these environments.

Aerospace is a low-volume industry, but currently leads most of the ultra-high temperature (up to 450°C) motor development efforts. Reliability and temperature margins are extremely important for spacecraft components.

2.3.3 Electric Vehicles

Alternators and electric motors are used in every type of automobile, including those with internal combustion, hybrid, and electric motors. Usually, vehicles do not have the same extreme temperatures or reliability requirements as in aerospace applications, but can reach temperatures up to 160ºC or higher [19] [21], [22]. Reliability and cost will be the main factors in determining if there is a market for RePED 250 alternator technology within the electric vehicle (EV) industry. Depending on these factors in the final system design, a thermally stable RePED 250 motor or alternator could have wide applications in the traditional and EV industries. This will be especially true as EVs become more advanced and compact. Areas of particular interest are high-power truck EV motors and high-friction regenerative braking applications.

Using higher-temperature components in an EV will require nearby parts to withstand higher temperatures. The RePED 250 system will provide a good testbed for motor and alternator operation in high-temperature conditions and give this technology an advantage over other new high-temperature motor designs. However, for an EV to run at higher operating temperatures many other components must also be validated at these temperatures. This will require trade studies and cost-benefit analyses before any large-scale penetration of RePED 250 alternator technology into the EV or traditional vehicle markets is possible.

2.3.4 Other

Smoke extraction motors and vents are another possible market for high-temperature electronics. These motors are used to extract smoke from poorly ventilated areas or, in the form of electromechanical actuators, used to open ventilation shafts. They need to reliably operate at the extreme temperatures experienced during a fire [23].

3 Supply Chain

3.1 Regions

Most materials and manufacturing of high-temperature alternators and motors can be sourced from within the United States. The downhole motor and alternator companies profiled above are all based in the United States, with some manufacturing taking place in other countries. Most of the parts and raw materials used in these alternators can also be sourced from within the United States. Figure 1 shows where some of the major alternator designers, manufacturers, and component suppliers are located.

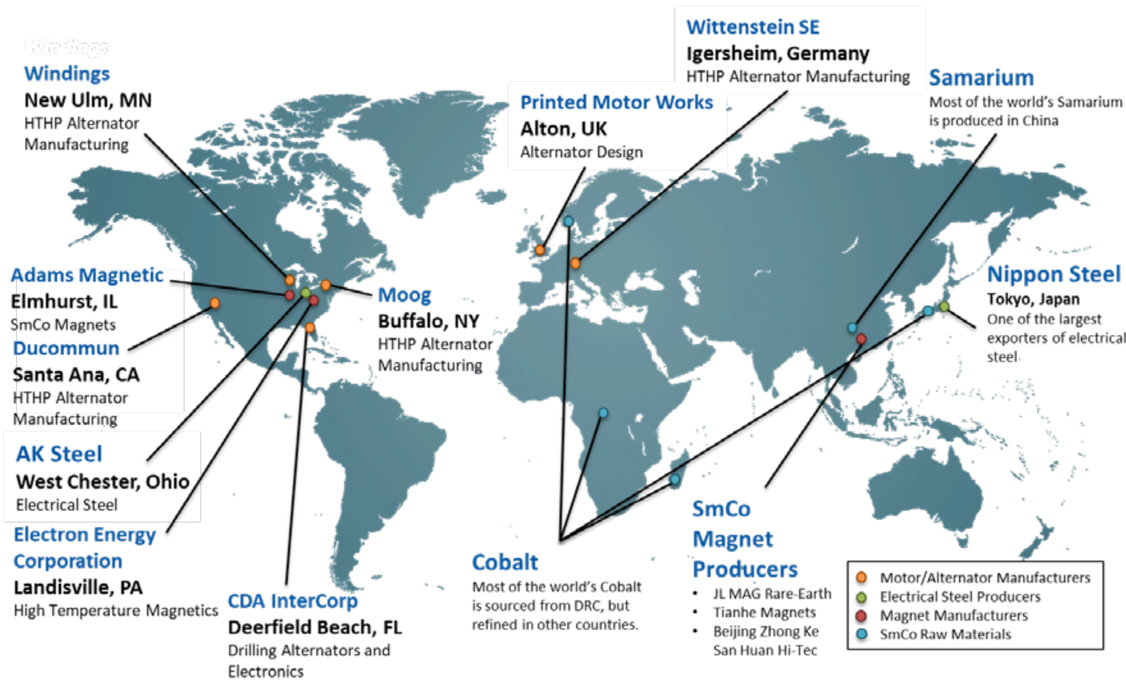


Figure 1. Global manufacturers of high-temperature alternators and relevant components

3.2 Critical Materials

Alternators and motors use many of the same components. In standard low-temperature motors and alternators, the main components are the rotor, stator, casing, and bearing seals. An example of a downhole motor is shown in Figure 2. Although this is a motor, not an alternator, and is not designed for high temperature and power, the basic RePED 250 design will likely be the same. The main components and materials used in this motor are labeled and described below.

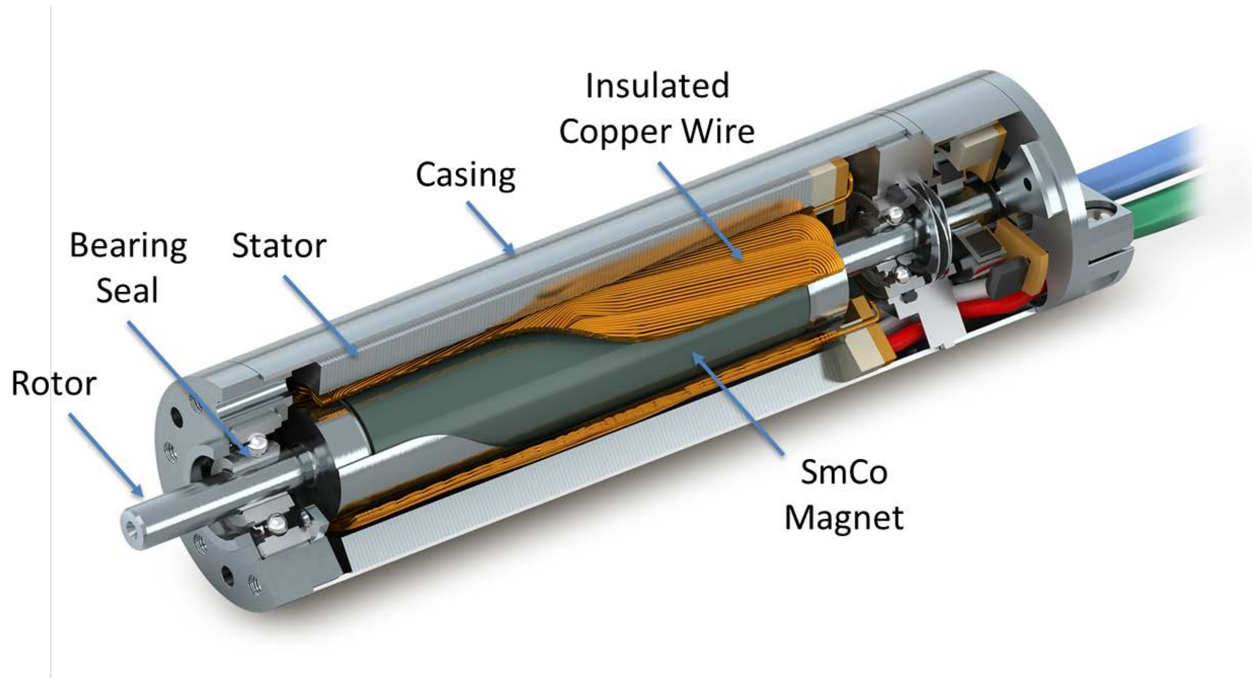


Figure 2. Image of a downhole motor provided by Maxon Group. Motors and alternators use the same basic components.

3.2.1 Magnets

Permanent magnets are used in most alternators and motors. Magnetic performance degrades at high temperatures. If magnets are to be used in a 250ºC environment, samarium cobalt (SmCo) magnets must be employed. Figure 3 shows magnet performance curves for this type of magnet at the temperature expected in the RePED 250 environment.

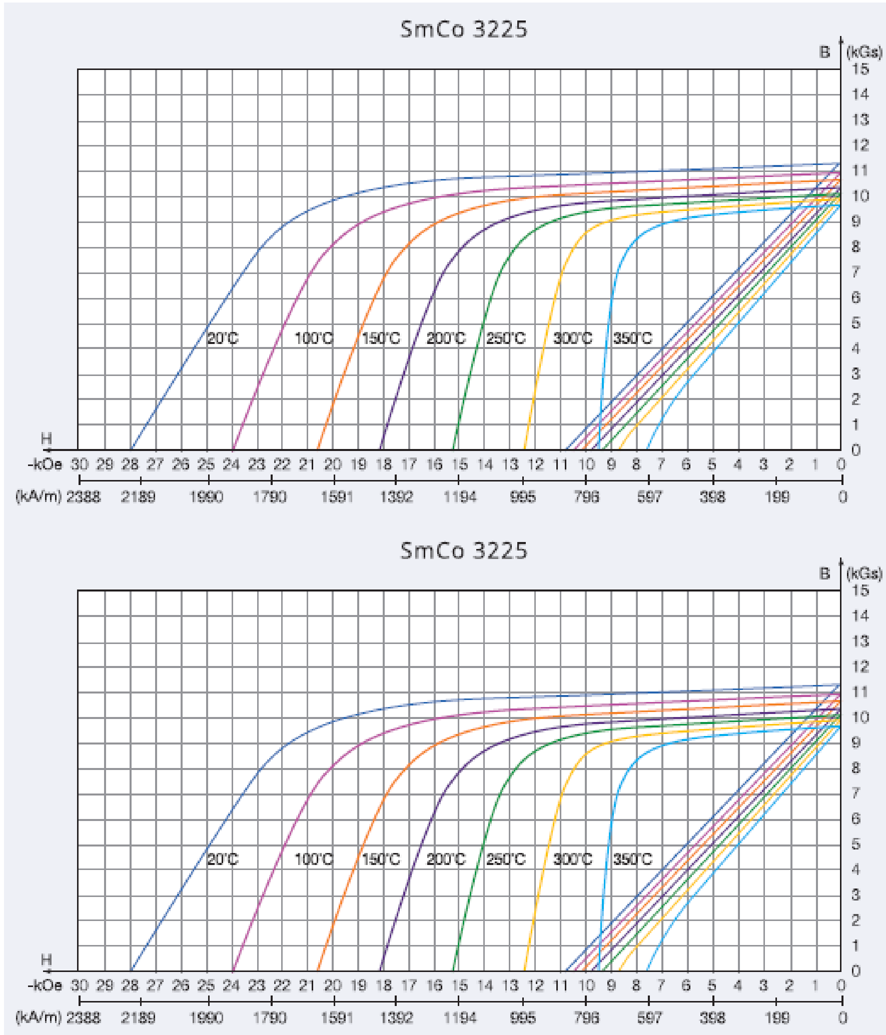


Figure 3. Performance of a 3225-grade SmCo magnet

Source: [24]

Magnets are sintered together, machined into shape, and then magnetized. The two main components of these magnets are samarium and cobalt, which are relatively rare materials and have potential supply chain risks. The Democratic Republic of Congo produces 70% of the world's mined cobalt and contains the majority of cobalt reserves [25] (Figure 4). This metal is mined as a byproduct of copper and nickel and often refined and re-exported by other countries, such as China and Russia. Cobalt is mainly used to make superalloys for gas turbine engines. Just under 10% of refined cobalt is used to make magnets [26].

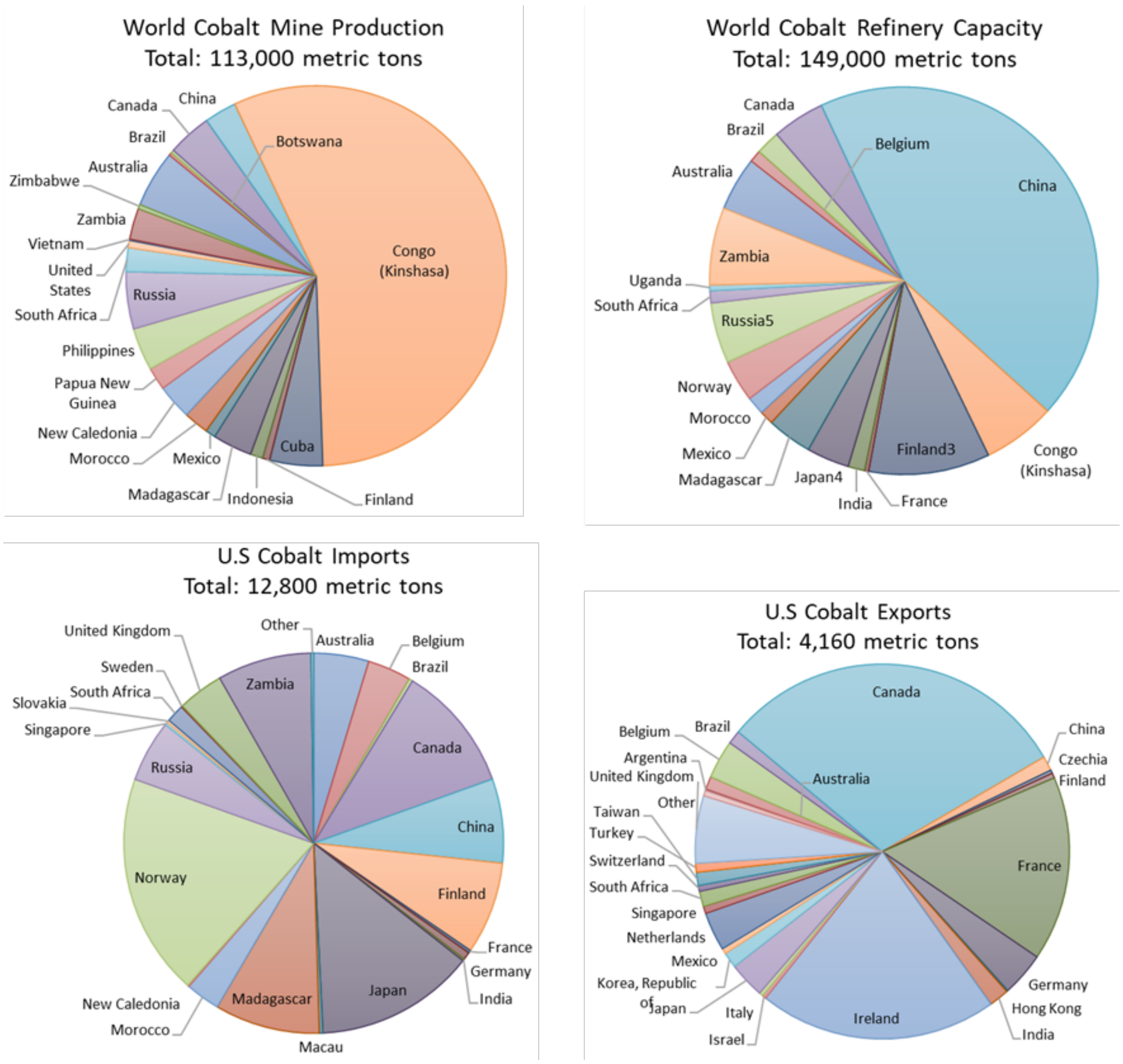


Figure 4. Summary of cobalt production, imports and exports

Source: [27]

The other component of high-temperature magnets, samarium, is categorized as a light rare earth element (LREE). The European Commission report on critical raw materials defined a substitutability index (SI) for LREEs as “a measure of difficulty in substituting the material, scored and weighted across all applications, with values are ranging between 0 and 1, with 1 being the least substitutable” [26], [28]. Samarium’s SI is calculated separately for both economic importance (SI_{EI}) and supply risk (SI_{SR}). In one study, samarium was calculated to have a SI_{EI} of 0.79 and a SI_{SR} of 0.82. These values are lower than all other LREEs, indicating that it is has the lowest supply risk of the LREEs studied [26]. Also, while China is the largest exporter of samarium, there are minable deposits in the United States [29].

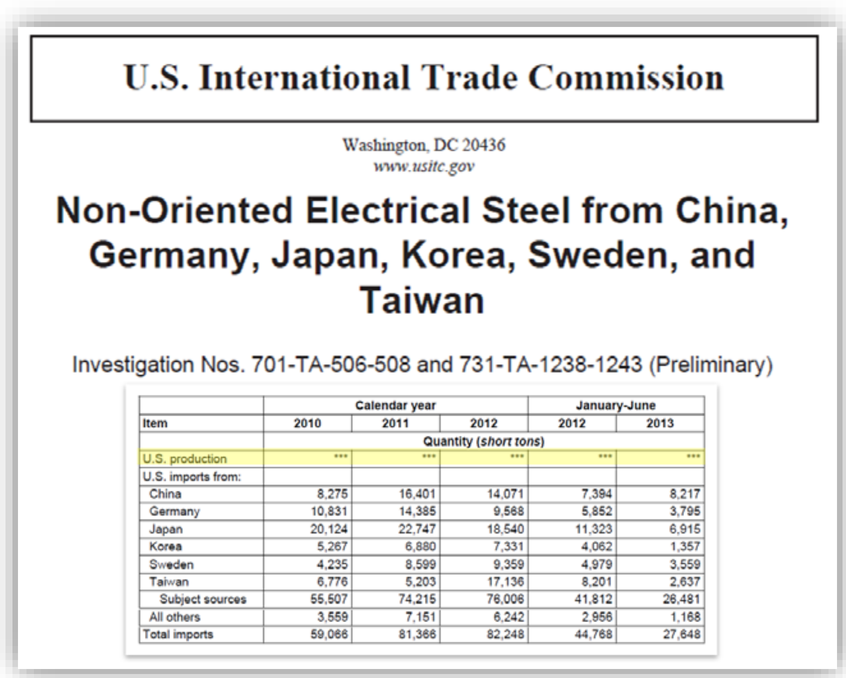
While these two materials are rare, obtaining the small quantities needed to build magnets for the high-temperature alternator market is not expected to be an issue.

In addition, a magnet-free alternator design is being considered and would not require either of these materials. This potential supply chain benefit will be considered when selecting a final design.

3.2.2 Electrical Steel

Electrical steels are used for the lamination layers in motors and alternators. These steels are designed to have magnetic properties that minimize losses during operation. The companies interviewed sourced these materials from Asia or within the United States. Electrical steel is used in almost all power electronics, including motors and alternators.

Data about electrical steel manufacturing volumes is difficult to find due to national security concerns. Grain-oriented electrical steels (GOES) are one of the key materials used in large power transformers. These transformers are essential for maintaining electrical grid infrastructure [30], so information about U.S. production is censored. GOES and the non-oriented electrical steels (NOES) used in motors and alternators rely on the same materials and manufacturing equipment so are heavily linked [31]. Figure 5 shows a censored excerpt in a report from the United States International Trade Commission. This report identifies AK Steel and Nucor Corporation as the only known U.S. producers of electrical steel [32]. An updated report from 2019 identifies AK Steel as the sole active producer [33].


U.S. International Trade Commission

Washington, DC 20436
www.usitc.gov

Non-Oriented Electrical Steel from China, Germany, Japan, Korea, Sweden, and Taiwan

Investigation Nos. 701-TA-506-508 and 731-TA-1238-1243 (Preliminary)

	Calendar year			January-June	
Item	2010	2011	2012	2012	2013
	Quantity (*short tons*)				
U.S. production	***	***	***	***	***
U.S. imports from:					
China	8,275	16,401	14,071	7,394	8,217
Germany	10,831	14,385	9,568	5,852	3,795
Japan	20,124	22,747	18,540	11,323	6,915
Korea	5,267	6,880	7,331	4,062	1,357
Sweden	4,235	8,599	9,359	4,979	3,559
Taiwan	6,776	5,203	17,136	8,201	2,637
Subject sources	55,507	74,215	76,006	41,812	26,481
All others	3,559	7,151	6,242	2,956	1,168
Total imports	59,066	81,366	82,248	44,768	27,648

Figure 5. An example of censored U.S. electrical steel production data and international imports

Source: [32]

While detailed information about U.S. electrical steel production is difficult to find, electrical steel is not expected to pose a significant immediate supply chain risk for the RePED 250 alternator. Because of the importance of this material for national security and infrastructure, the

United States National Strategy is designed to ensure it is produced and readily available in the United States [30], [31].

Figure 6 comes from a DOE report on steel production by country [30]. While these plots do not show the U.S. or global production of electrical steel, they do offer some insight. First, in 2015 and 2016, the United States exported more electrical steel than it imported, implying that there is significant U.S. production and excess capacity. The pie chart on the right of Figure 6 shows that U.S. electrical steel imports come from a variety of countries, indicating that imports are not reliant on a single electrical steel producer, lowering the total risk.

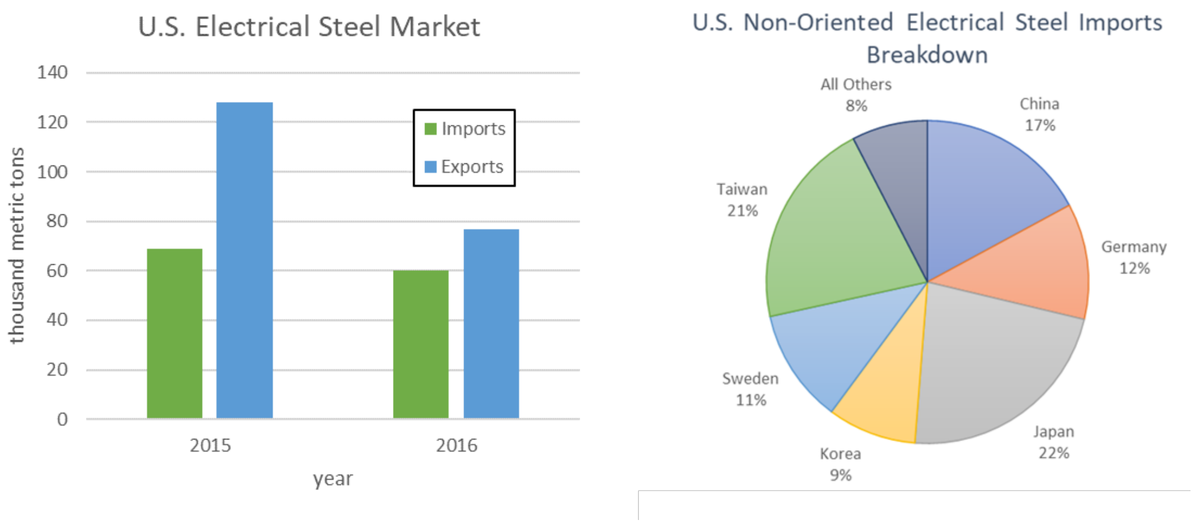


Figure 6. Summary of the 2015-2016 United States electrical steel imports and exports from [34] and of U.S. electrical steel import fractions from [32]

3.2.3 Insulation and Bearings

Insulating layers around temperature-sensitive components are essential for operation at high temperatures. High-temperature organic wire coating has a thermal class of 240°C [35], [36], which will likely be adequate for the required RePED 250 lifetime. At higher temperature, more complex ceramic coatings or other solutions would be necessary.

Coating candidates include GORE® wires, which are coated in a proprietary fluoropolymer insulation, Teflon, fiberglass, or other types of polyimide coating. Companies that design these coatings usually sell precoated wire to motor and alternator manufacturers as a part.

Bearings on the rotor shaft allow the rotor to turn freely while sealing the motor or alternator. Traditional low-temperature bearing systems use rubber seals that can deteriorate at high temperatures. Effective high-temperature bearing systems have already been developed for use in the geothermal industry [37], [38] and can likely be used for the RePED 250 alternator. These bearings replace low-temperature grease and seal materials with higher-temperature synthetic oil formulas and Kevlar fabric [38].

4 Manufacturing Analysis

The supply chain and manufacturing process for low-temperature motors and alternators is well established. High-temperature downhole alternators use many of the same components and processes but with higher-temperature materials. At the low volumes expected for the geothermal market, manufacturing will be done in small batches at one of the alternator manufacturing locations shown in Figure 1 or at a similar alternator manufacturing company. As the market grows, this process can be automated for higher production volumes at lower cost. The basic manufacturing processes are summarized below. This information was gathered from literature, specialists at NREL, and interviews with industry players.

4.1 Manufacturing Process Flow

The same basic processes are used to manufacture high- and low-temperature motors and alternators, which are well documented [21], [39], [40].

The design for the RePED 250 alternator is still under development. The selected design may be a permanent magnet machine that uses high-temperature SmCo magnets or a magnet-free design, such as an induction motor or synchronous reluctance motor (SRM). In each of these designs, the stator and alternator casing remain essentially unchanged. In an induction motor, the rotor and stator both consist of wire coils wound around a laminated core. For this design, the rotor will use the same materials and manufacturing methods outlined in the stator manufacture section below. In an SRM design, the rotor consists of a laminated core, but does not have wire windings. Here, the rotor will be manufactured like the stator manufacture described below but the wire winding step will be skipped. Lastly, in a permanent magnet design, the rotor includes SmCo magnets fixed to the rotor shaft. This is the design that is described in the rotor section below.

The manufacturing processes includes four main steps: (1) materials, raw and processed; (2) parts and subassembly; (3) manufacturing (in-house machining and outsourced parts); and (4) final assembly. In Figure 7, the final product is the RePED 250 high temperature alternator using a permanent magnet design. If an induction motor version is chosen, the manufacturing processes and flow described for the stator would be applied to the rotor. If the final design is an SRM, the manufacturing process flow described for the stator, minus the winding step, will be used for the rotor.

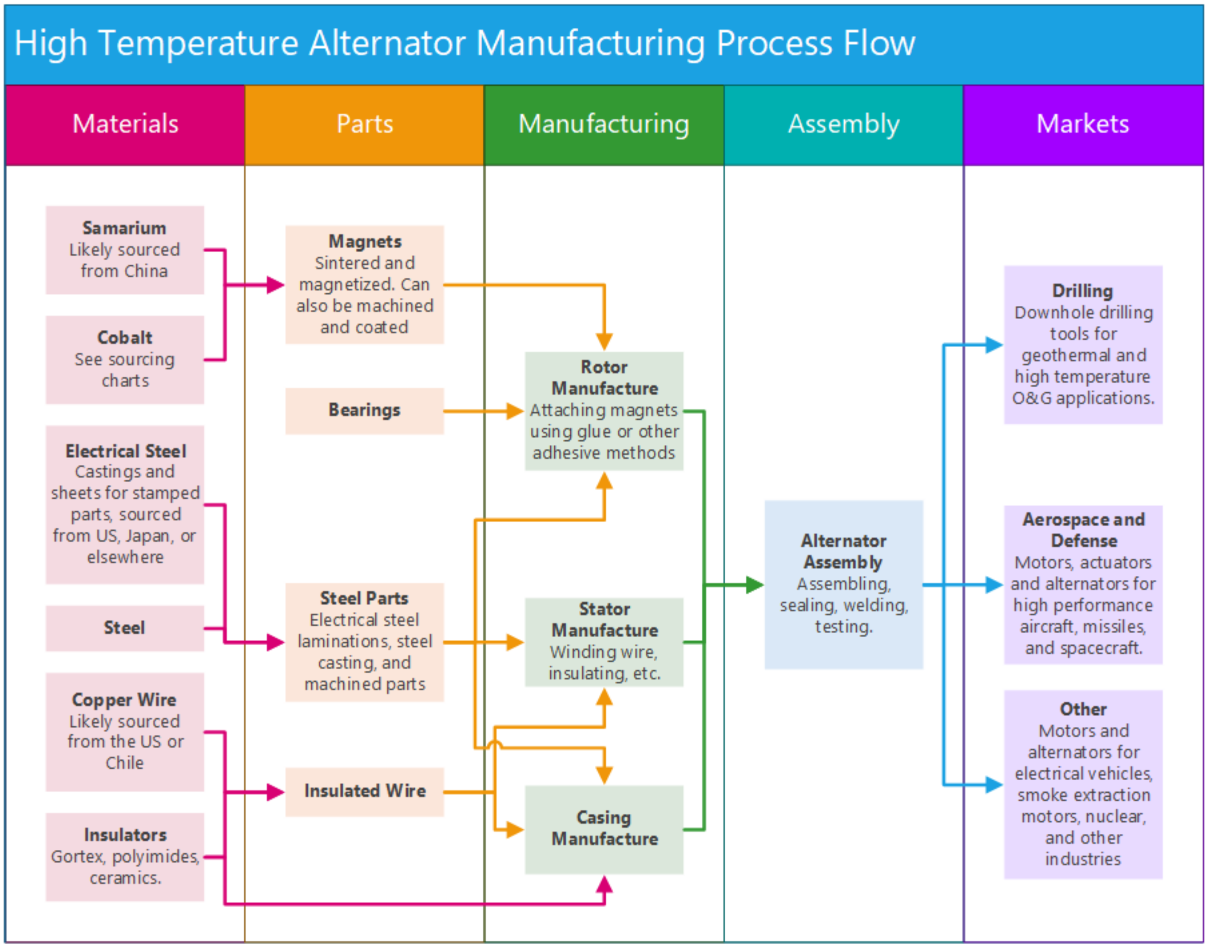


Figure 7. Flow chart showing the raw components, manufacturing, and assembly of a high-temperature alternator

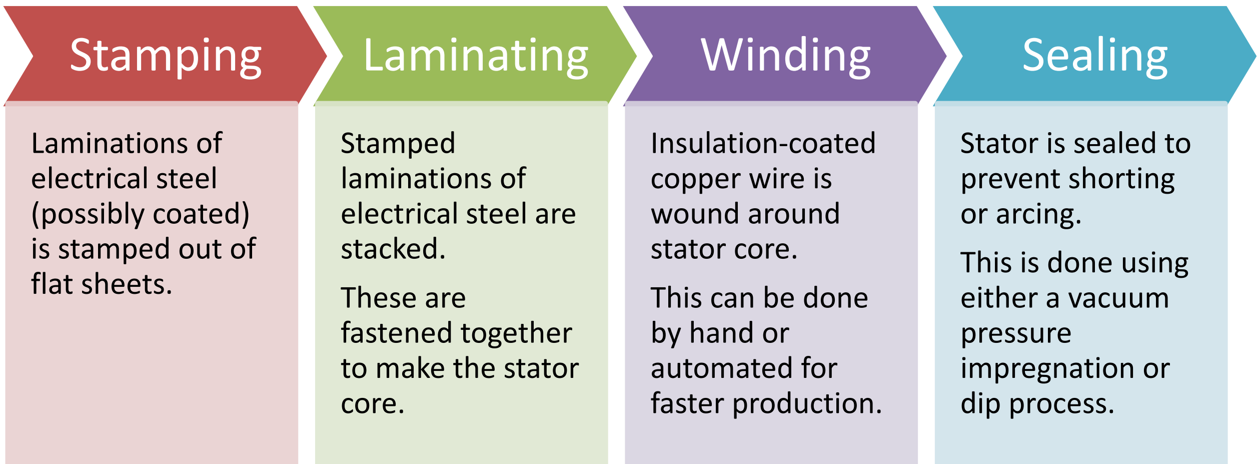
4.2 Manufacturing Processes

The RePED 250 alternator is expected to be manufactured using the same industry standard methods as low-temperature alternators but using high-temperature materials and adhesives. The main manufacturing processes for each component are described below. When manufacturing motors and alternators, the two independent rigid components, the rotor and the stator, are constructed separately and then assembled into the final product. Low manufacturing volumes are expected for the RePED 250 alternator prototypes and initial production runs. At these volumes, all the steps described below will be done by hand, with the exception of laminate stamping. Millions of motors are manufactured each year [41], so this process has been heavily automated. At high volumes, automation can be employed for the RePED 250 alternator to significantly lower manufacturing costs.

4.2.1 Stator Manufacturing

The stator structure will likely comprise a stack of electrical steel laminations, which may be coated in lacquer for insulation, and are wound with wire coils. The electrical steel laminations are stamped out of an electrical steel sheet. These laminations are stacked in layers to make up the stator body, which prevents eddy currents in the stator. Next, wire loops are wound onto the stator. This wire will be purchased from a wire manufacturer already coated with a high-temperature insulating material. After installing wire coils onto the stator, epoxy resin is used to fill the gaps between coils to prevent leaks and arcing. Dipping and vacuum pressure impregnation forces this resin through the stator coils. The entire stator will likely be baked to allow the high temperature epoxy resin to cure [42]. That said, it is possible that the vacuum pressure impregnation (VPI) sealing will not work at RePED 250 temperature. Figure 8 shows a flow chart of the main components and processes that will be used to manufacture the stator.

Figure 8. Breakdown of the steps and processes in the manufacture of the stator



Note: This diagram is essentially the same for all possible alternator designs. The same process is followed for magnet-free rotor designs.

At the low production volumes (~5 to 10 parts per year) expected for the initial RePED 250 alternator, the lamination stack and wire winding will likely be done by hand. At higher production volumes (~10 to 50 parts per year), both processes can be automated.

4.2.2 Rotor Manufacturing

Depending on the design, the rotor will consist of laminated stacks like in the stator or a solid shaft with attached or embedded permanent magnets. In a magnet free design, the rotor assembly looks almost identical to the stator process flow shown in Figure 8, either as described, with wire windings on the rotor (induction motor) or without windings (SRM). At the RePED 250 temperatures, permanent magnets are expected to be the best choice. For this design, SmCo magnets would be pre-magnetized and coated as required for 250ºC operation. The rotor shaft will be likely be made of aluminum or another common metal. At low manufacturing volumes, the rotors would be assembled by hand; however, this process could be automated for high manufacturing volumes.

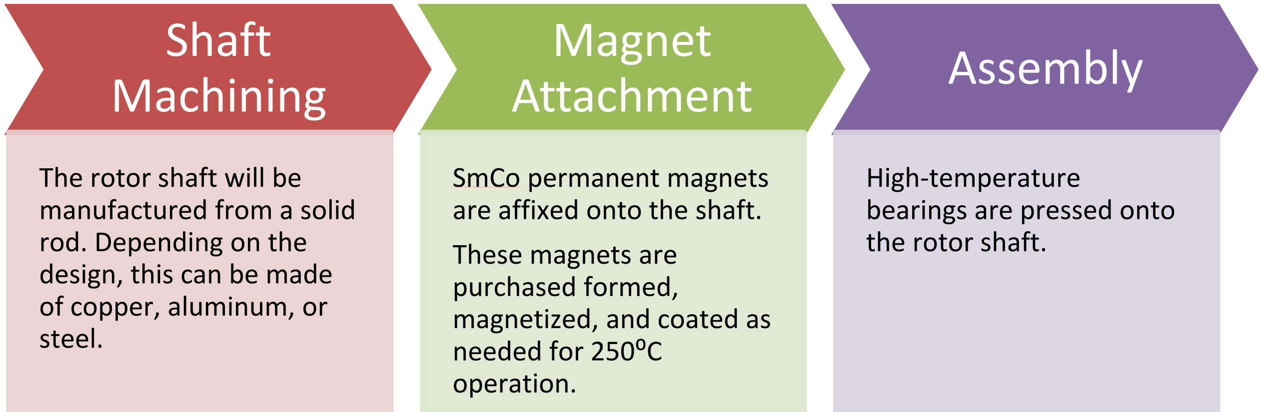


Figure 9. Breakdown of the steps and processes in the manufacture of a permanent magnet rotor

Note: The stator flow chart in Figure 8 is used for a magnet-free rotor design.

4.2.3 Casing and Assembly

Once the rotor and stator are assembled separately, they are combined and fit into a metal casing. The casing is usually steel, or aluminum and heat shrunk onto the outside of the stator. The final steps include sealing the casing, fitting and sealing the bearings onto the rotor, and connecting any necessary electrical leads, controls, and drives. The alternator seals are checked, and the completed assembly is tested.

5 Strengths, Weaknesses, Risks, and Opportunities

The industry representatives we spoke with helped to identify the most significant risks for this product. One of the primary market barriers for the RePED 250 technology is the speed at which the industry will adopt new technology. For O&G drilling projects, the risks associated with using a new technology can make major operators hesitant to utilize new drilling tools. A committed partner in the O&G industry will lower this risk. One minor market risk for the RePED 250 is the extended life cycle of developing new drilling tools. This leads to a long sales cycle (months to years) and slow market penetration of new technology.

Risks in supply chain and manufacturing are minimal. Low-temperature alternators are a $5.19 billion industry [43] with well-established supply chains and manufacturing practices. High-temperature and high-power alternators would use many of the same materials and manufacturing methods as their low-temperature counterparts. Most of the materials in the RePED 250 alternator can be sourced from within the United States. The principal supply chain risk is the high temperature SmCo magnets. Samarium is a rare earth element that is sourced primarily from China; however, at the scales expected (~5 to 10 parts per year) for RePED 250, it is not anticipated that obtaining this material will be difficult. Cobalt is another rare material, but is refined by a wide variety of countries, including the United States, and is not expected to be a concern at the quantities required for the RePED 250 alternator. The manufacturing methods that will be used for the RePED 250 alternator are mostly the same regardless of temperature and can be scaled up to meet market volumes with little difficulty. As quantities increase, these methods can be automated, lowering costs. This analysis will continue to be refined as the alternator design is finalized.

The RePED 250 alternator requirements are unusual in both the operational temperature and total power. This unique tool will allow for drastically faster and lower-cost drilling through hard rock at the temperatures needed for efficient geothermal power. Although it is growing, the primary geothermal market for the RePED 250 alternator is relatively small. The RePED tool will lower the barriers in capital costs for new geothermal projects, creating huge potential for industry growth. In the past, geothermal has relied on drilling tools designed for the O&G industry. Having field-tested tools designed specifically for geothermal will also decrease the risk for new drilling projects.

There are a variety of other potential markets for this tool, including O&G drilling, electric vehicles, aviation, space exploration, and defense. These additional markets represent promising potential areas of growth, but the aircraft and drilling industries are both risk-averse and slow to adopt new technology. While this could make penetrating the market difficult, the technology used in this novel alternator would be well tested in the geothermal industry, setting it up for rapid expansion into future markets.

References

[1] IBISWorld, “Oil Drilling & Gas Extraction Industry in the US - Market Research Report,” Apr. 2020. [Online]. Available: https://www.ibisworld.com/united-states/market-research-reports/oil-drilling-gas-extraction-industry/

[2] Z. Frone and L. Boyd, “Baseline Metric for Domestic Geothermal Drilling Rates,” *GRC Trans.*, vol. 42, 2018.

[3] A. Samuel *et al.*, “Improvement in Rate of Penetration in FORGE Drilling Through Real Time MSE Analysis and Improved PDC Technology,” in *47th Workshop on Geothermal Reservoir Engineering*, Stanford, California: Stanford University, Feb. 2022, p. 8.

[4] J. C. Robins, D. Kesseli, E. Witter, and G. Rhodes, “2022 GETEM Geothermal Drilling Cost Curve Update,” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022.

[5] B. Matek, “2016 Annual US Global Geothermal Power Production,” *PDF Doc. URL Httpgeo-Energy Orgreports Aspx Accessed 529 17*, 2016.

[6] S. Akar, C. R. Augustine, P. Kurup, and M. K. Mann, “Global value chain and manufacturing analysis on geothermal power plant turbines,” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2018.

[7] R. Bertani, “Geothermal power generation in the world 2010–2014 update report,” *Geothermics*, vol. 60, pp. 31–43, 2016.

[8] A. Robertson-Tait, W. Harvey, S. Hamm, and L. Boyd, “The United States of America Country Update 2020 – Power Generation,” in *Proceedings World Geothermal Congress 2020*, Reykjavik, Iceland, May 2020.

[9] G. W. Huttrer, “Geothermal Power Generation in the World 2015-2020 Update Report,” in *World Geothermal Congress; International Geothermal Association: Reykjavik, Iceland*, 2020.

[10] R. DiPippo, “Ideal thermal efficiency for geothermal binary plants,” *Geothermics*, vol. 36, no. 3, pp. 276–285, 2007, doi: https://doi.org/10.1016/j.geothermics.2007.03.002.

[11] K. Yost, A. Valentin, and H. H. Einstein, “Estimating cost and time of wellbore drilling for Engineered Geothermal Systems (EGS) – Considering uncertainties,” *Geothermics*, vol. 53, pp. 85–99, 2015, doi: https://doi.org/10.1016/j.geothermics.2014.04.005.

[12] A. Chen, R. B. Ummaneni, R. Nilssen, and A. Nysveen, “Review of electrical machine in downhole applications and the advantages,” in *2008 13th International Power Electronics and Motion Control Conference*, IEEE, 2008, pp. 799–803.

[13] B. W. Ohme, M. T. Johnson, J. C. Hansen, J. Riekels, M. N. Ericson, and M. Bobrek, “Updated Results from Deep Trek High Temperature Electronics Development Programs,” *Oil Nat. Gas Technol.*, 2007.

[14] A. Chen, “Investigation of Permanent Magnet Machines for Downhole Applications: _ Design, Prototype and Testing of a Flux-Switching Permanent Magnet Machine,” 2011.

[15] T. F. Price, “Development of a High-Pressure/High-Temperature Downhole Turbine Generator,” Dexter Magnetic Technologies Inc, 2007.

[16] Windings Electromagnetic Solutions, “From Evolution to Revolution: Electric Motors in Oil and Gas Exploration.” Mar. 2019. [Online]. Available: https://www.windings.com/download/whitepaper/whitepaper-oil-gas-windings.pdf

[17] M. Hooker, C. Hazelton, and K. Kano, “High-Temperature Motor Windings for Downhole Pumps Used in Geothermal Energy Production,” 2010, doi: 10.2172/1011754.

[18] H. Guo, Z. Lv, Z. Wu, and B. Wei, “Multi-physics design of a novel turbine permanent magnet generator used for downhole high-pressure high-temperature environment,” *IET Electr. Power Appl.*, vol. 7, no. 3, pp. 214–222, 2013.
[19] C. Buttay *et al.*, “State of the art of high temperature power electronics,” *Mater. Sci. Eng. B*, vol. 176, no. 4, pp. 283–288, 2011, doi: https://doi.org/10.1016/j.mseb.2010.10.003.
[20] H. Zhang, C. Saudemont, B. Robyns, and M. Petit, “Comparison of technical features between a more electric aircraft and a hybrid electric vehicle,” in *2008 IEEE Vehicle Power and Propulsion Conference*, IEEE, 2008, pp. 1–6.
[21] C. L. Whaling, R. Holcomb III, S. Johnson, and F. Hanratty, “North American Electric Traction Drive Supply Chain Analysis: Focus on Motors,” presented at the US Department of Energy’s Annual Merit Review (AMR) meetings, Synthesis Partners, LLC, Reston VA, Jun. 07, 2016. Accessed: Apr. 03, 2020. [Online]. Available: https://www.energy.gov/sites/prod/files/2016/06/f32/edt032_whaling_2016_o_web.pdf
[22] R. A. Normann, “First high-temperature electronics products survey 2005.,” Sandia National Laboratories, 2006.
[23] A. Zbrowski and T. Samborski, “Study on electromechanical drives used in ventilation and smoke extraction systems,” *Eksploat. Niezawodn.*, vol. 16, pp. 367–376, 2014.
[24] “Magnetic products for engineering performance, innovation and design.” Adams Magnetic Products. Accessed: Jul. 01, 2020. [Online]. Available: https://www.adamsmagnetic.com/sites/default/files/Adams-Materials-Catalog.pdf
[25] “Mineral commodity summaries 2020,” Reston, VA, Report, 2020. doi: 10.3133/mcs2020.
[26] A. Tkaczyk, A. Bartl, A. Amato, V. Lapkovskis, and M. Petranikova, “Sustainability evaluation of essential critical raw materials: cobalt, niobium, tungsten and rare earth elements,” *J. Phys. Appl. Phys.*, vol. 51, no. 20, p. 203001, 2018.
[27] United States Geological Survey, “2016 Minerals Yearbook: Cobalt [Advanced Release].” 2019. Accessed: May 06, 2020. [Online]. Available: https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-cobal.pdf
[28] G. Blengini *et al.*, “Methodology for Establishing the EU List of Critical Raw Materials: Guidelines,” *Eur. Commision Join Res. Cent. Bruss. Belg.*, 2017.
[29] United States Geological Survey, “2016 Minerals Yearbook: Rare Earths [Advanced Release].” 2019. Accessed: May 06, 2020. [Online]. Available: https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-raree.pdf
[30] P. Hoffman and W. Bryan, “Large power transformers and the US electric grid,” *Rep. US Dep. Energy*, 2012.
[31] S. A. Jones and B. B. Bay, “WRITTEN COMMENTS OF AK STEEL CORPORATION,” United States Department of Commerce, Bureau of Industry and Security, Investigation No. 232, May 2017. Accessed: Jun. 30, 2020. [Online]. Available: https://www.bis.doc.gov/index.php/232-steel-public-comments/1924-ak-steel-public-comment/file
[32] U.S. International Trade Commission, “Non-Oriented Electrical Steel from China, Germany, Japan, Korea, Sweden, and Taiwan.” Dec. 2013.
[33] U.S. International Trade Commission, “Non-Oriented Electrical Steel From China, Germany, Japan, Korea, Sweden, and Taiwan; Scheduling of Full Five-Year Reviews.” Nov. 01, 2019.

[34] United States Geological Survey, "2016 Minerals Yearbook: Iron and Steel [Advanced Release]." 2019. Accessed: May 06, 2020. [Online]. Available: https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-raree.pdf
[35] V. Iosif, D. Roger, S. Duchesne, and G. Vélu, "Experimental characterization of the maximum turnto-turn voltage for inorganic high temperature motor," in *2014 IEEE Electrical Insulation Conference (EIC)*, 2014, pp. 69–73.
[36] V. Iosif, D. Roger, S. Duchesne, and D. Malec, "Assessment and improvements of inorganic insulation for high temperature low voltage motors," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2534–2542, 2016.
[37] A. Stefánsson *et al.*, "A 300 Degree Celsius Directional Drilling System," in *IADC/SPE Drilling Conference and Exhibition*, Society of Petroleum Engineers, 2018.
[38] S. Orazzini *et al.*, "New roller cone bit technology for geothermal application significantly increases on-bottom drilling hours," *Geotherm. Resour. Counc. Trans.*, vol. 35, pp. 215–224, 2011.
[39] F. Caniato, R. Golini, and M. G. M. Kalchschmidt, "Global supply chain configurations and management: evidences from the electric motors industry," in *Annual Meeting of the Decision Science Institute*, 2011.
[40] M. Lowe, R. Golini, and G. Gereffi, *Manufacturing Climate Solutions Carbon-Reducing Technologies and U.S. Jobs*. 2010. doi: 10.13140/RG.2.1.4124.3922.
[41] "Top 20 Electric Motor Manufacturers in the World 2019," technavio Blog. Accessed: Jun. 30, 2020. [Online]. Available: https://blog.technavio.com/blog/top-20-electric-motor-companies#:~:text=More%20than%20300%20million%20electric,large%20buildings%2C%20and%20industry%20globally.
[42] R. Mills, C. Payne, and K. Younsi, "Insulation cure monitoring on global VPI large AC motors," in *Conference Record of the the 2002 IEEE International Symposium on Electrical Insulation (Cat. No. 02CH37316)*, IEEE, 2002, pp. 492–496.
[43] Frost & Sullivan, "Global Alternator Market, Forecast to 2020," Feb. 2017. [Online]. Available: https://store.frost.com/global-alternator-market-forecast-to-2020.html