Assessment of the Use of Sulfur Hexafluoride (SF_6) Gas Insulated Switchgears (GIS) within the Offshore Wind Sector

August 24, 2023

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MEMORANDUM

TO: US EPA, Office of Air Quality Planning and Standards

FROM: Eastern Research Group, Inc. (ERG)

DATE: August 24, 2023

SUBJECT: Assessment of the Use of Sulfur Hexafluoride (SF_6) Gas Insulated Switchgears (GIS) within the Offshore Wind Sector

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Background and Methodology:

The Environmental Protection Agency (EPA) is seeking a better understanding of the technical and economic limitations of sulfur hexafluoride (SF_6)-free switchgear on wind turbine generators (WTGs) and offshore substations (OSSs) (also known as electrical service platforms (ESPs)). SF_6 is used as an electrical and thermal insulator in electrical equipment, but it is also a powerful greenhouse gas, having a global warming potential (GWP) of 23,500 times that of carbon dioxide (CO_2).[1] SF_6 has the highest GWP out of all the greenhouse gases addressed by the Intergovernmental Panel on Climate Change (IPCC) inventory protocols. Moreover, the effects of SF_6 emissions on the climate are permanent and cumulative because of the long life of SF_6 in the in the atmosphere (estimated half-life is 3,200 years). The electrical equipment that contains SF_6 is designed to be sealed, and to minimize emissions of the gas to the atmosphere. However, SF_6 gas can escape into the atmosphere as leaks due to aging over the 20 to 35-year lifetime of the equipment. Additionally, SF_6 gas can be released during equipment manufacturing, installation, maintenance, servicing, and de-commissioning.

The information presented in this memo is current as of the time of this memo; however, the technology used in the offshore wind industry technology is advancing quickly due to the emerging demand for wind energy and for SF_6-free switchgear.

Emissions of SF_6 from equipment in U.S. electric power systems are reported annually to the EPA under the mandatory Greenhouse Gas Reporting Program (GHGRP) and the data are available online.[2] From the 2021 GHGRP data:

- Part 98, subpart DD, Electrical Transmission and Distribution Equipment Use: 2,262,542 metric tons carbon dioxide equivalents (CO_2e) SF_6 emissions.

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[1] IPCC Fifth Assessment Report (AR-5), https://www.ipcc.ch/report/ar5/syr/

[2] USEPA Facility Level Information on Greenhouse gases Tool (FLIGHT), https://ghgdata.epa.gov/ghgp/main.do

- Part 98, subpart SS, Electrical Equipment Manufacture or Refurbishment: 187,448 metric tons CO_2e SF_6 emissions.
- Total from all reporters is 2,449,990 metric tons CO_2e; subparts DD and SS combined are 0.090 percent of total GHG emissions reported in the GHGRP.

ERG performed a literature review to collect information on the availability of SF_6-free switchgear and other electrical equipment relevant to the development of the U.S. offshore wind sector. The literature included peer-reviewed journal articles, trade publications, and manufacturers literature. Information was also collected and reviewed from the websites of government agencies sponsoring research in this area (e.g., https://arpa-e.energy.gov/technologies/exploratory-topics/sulfur-hexafluoride-free-grid).

The remainder of this memo discusses the following topics as they relate to the use of SF_6 in offshore wind farms and their alternatives:

- An overview of the types of equipment that may use SF_6 in offshore wind systems.
- The purpose of SF_6 in electricity transmission equipment.
- The potential for SF_6 leakage from equipment and emissions to the atmosphere.
- Proposed uses of SF_6-containing equipment in wind turbine system projects being developed in EPA Regions 1 and 3.
- The availability of SF_6-free equipment for use in offshore wind system projects.
- An appendix describing how recent offshore wind farm permit applications have addressed the use of SF_6-containing equipment and the availability of SF_6-free alternatives.

Electricity Transmission in Offshore Wind Turbine Generating Facilities

To understand the different types of electrical equipment that may use SF_6, or an alternative insulating gas technology, it is useful to understand how electricity is transmitted from generation to the final user.

Electricity generated by power plants (whether it is fossil fuel-fired, landfill gas-fired, nuclear, waste-to-energy, hydro power, solar, or wind) is typically generated at between 11 kilovolts (kV) to 33kV alternating current (AC).[3,4]

Wind turbines consist of a rotor, gear box, generator, and switchgear. The rotor, gear box, and generator are attached to the top of a tower and the switchgear is located on the base of the tower. Wind passing over the wing-shaped rotor blades causes them to spin due to the air pressure on one side of the blade being lower than on the other side. The spinning rotor is attached to a gear box that increases the speed of the shaft from about 18 revolutions per minute

3 DOE EIA, Electricity Explained, August 11, 2022, https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php#:~:text=Electricity%20is%20delivered%20to%20consumers%20through%20a%20complex%20network,connect%20electricity%20producers%20and%20consumers.

4 Luke James, Power and Beyond: Basics of an Electrical Power Transmission System, April 21, 2020, https://www.power-and-beyond.com/basics-of-an-electrical-power-transmission-system-a-919739/

(rpm) to about 1800 rpm. The high-speed shaft from the gear box is connected to the generator, which produces electricity.

The switchgear at the base of the turbine serves several functions. It connects the wind turbine to the wind farm's network and ensures a stable frequency[5] and voltage to the rest of the network. It also converts the generator's electricity from a low voltage (LV) (about 690 V (0.69 kilovolts (kV)), although some larger turbines generate electricity at 3 kV) to medium voltage (MV) of 30 kV to 33 kV to keep transmission losses low.[6] Finally, the switchgear includes a circuit breaker to protect the generator, and to protect other wind turbines located on the same circuit.

The MV network connects multiple wind turbines to a central transformer and a large wind farm may have multiple transformers. Transformers step up the voltage for primary transmission to between 110 kV and 700kV, with the final design voltage chosen depending on the distance needed to be transmitted. In general, the longer the distance the higher the voltage chosen for transmission.[7,8] In the offshore wind industry, these transformers are often located within the wind farm on offshore substations (OSS, also known as electrical service platforms or ESPs). The larger the wind farm and the farther it is from shore (e.g., greater than 100 MW and farther than 15 km (8.09 nautical miles)), the more likely it is that the offshore windfarm will need an OSS.[9] A single offshore substation will collect the energy from multiple wind turbines in the wind farm. High voltage (HV) transmission lines will begin at the offshore substation (or, alternatively, in the case of a wind farm located a short distance from land, an onshore substation), which connect the wind farm to the existing onshore electricity grid.

The OSS is made of multiple units called "bays." A bay is the part of a substation where the switchgear and control-gear (related to a given circuit) is contained. A bay is also considered a "power line" within an electrical substation which connects a circuit (such as a power line or transformer) to a busbar; each bay typically includes circuit breakers, disconnectors, instrument transformers and surge arresters.

Primary transmission lines carry HV electricity long distances, and the electrical power is increased up to these higher voltage levels to make transmission more efficient by minimizing the energy losses that otherwise would take place when power is transmitted, in the form of heat, resulting from resistance in the lines, also known as I2R losses.[10] At higher voltages, the current is reduced relative to the voltage so that power remains constant, and the I2R losses are reduced.

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5 Alternating current (ac) frequency is the number of cycles per second at which current changes direction. It is measured in hertz (Hz), where 1 hertz is equal to 1 cycle per second.

6 Wind Energy - The Facts: Electrical Works, https://www.wind-energy-the-facts.org/electrical-works.html

7 DOE EIA, Electricity Explained, August 11, 2022, https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php#:~:text=Electricity%20is%20delivered%20to%20consumers%20through%20a%20complex%20network,connect%20electricity%20producers%20and%20consumers.

8 Luke James, Power and Beyond: Basics of an Electrical Power Transmission System, April 21, 2020, https://www.power-and-beyond.com/basics-of-an-electrical-power-transmission-system-a-919739/

9 Wind Energy - The Facts: Electrical Works, https://www.wind-energy-the-facts.org/electrical-system.html

10 Farnell – Engineering Glossary, https://uk.farnell.com/i2r-loss-definition: Power loss due to resistance, which is dissipated as heat. Ohm's Law: V = IR where V = voltage (Volts) across a component, R is the component's

For very large projects (e.g., several hundred MW capacity) located far from the grid connection point (e.g., wind farms located beyond the visibility limit from land), high voltage direct current (HVDC) transmission lines are being used to avoid problems with AC cable-generated reactive power using up too much of the cable's transmission capacity.[11] The wind turbines and switchgear still use alternating current (AC), but the offshore substations include AC/DC converters (which are large installations), as well as transformers to increase the voltage. Another converter will be located at the grid end of the HVDC transmission line. The use of AC/DC converters and HVDC undersea transmission lines from offshore wind farms to reduce power losses becomes cost effective with the wind farm located between 37 to 60 statute miles (32 to 52 nautical miles) from shore.[12]

At receiving stations, including those at an onshore substation, the voltage is reduced to typically between 33kV and 66kV and sent on secondary transmission lines to electrical substations closer to load centers, such as cities, urban areas, and large factories. At substations, the voltage is reduced further to about 11kV.[13]

Neighborhood transformers further reduce the voltage,[14] and distribution lines carry electricity to houses and businesses.[15] Transformers on poles reduce voltage again before it enters houses and other similar electricity users.[16]

Purpose of SF_6 Used in Gas Insulated Switchgears

At high voltages even air can act as a conductor, and the transmission of the electric current through the gas (in this case air) results in an electrical arc. An electric arc occurs when electricity jumps from one connector to another across an open gap in the connectors, such as an open switch, unless there is sufficient distance and an insulating medium (such as air, a vacuum, or SF_6) between them. The better the insulator, the closer the conductors can be located when the switch is open without arcing.

resistance (in Ohms) and I is the current in Amps through it. Power Law: W = VI where V and I are as above, and W = power dissipated in Watts. From combining these, the loss W = (IR)I or I2R. This is also known as copper loss.

11 Wind Energy - The Facts: Electrical Works, https://www.wind-energy-the-facts.org/electrical-system.html

12 Middleton, P., Barnhart, B. 2022. Supporting National Environmental Policy Act Documentation for Offshore Wind Energy Development Related to High Voltage Direct Current Cooling Systems. Washington (DC): U.S. Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2022-023. 13 p.

13 Luke James, Power and Beyond: Basics of an Electrical Power Transmission System, April 21, 2020, https://www.power-and-beyond.com/basics-of-an-electrical-power-transmission-system-a-919739/

14 DOE EIA, Electricity Explained, August 11, 2022, https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php#:~:text=Electricity%20is%20delivered%20to%20consumers%20through%20a%20complex%20network,connect%20electricity%20producers%20and%20consumers.

15 DOE EIA, Electricity Explained, August 11, 2022, https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php#:~:text=Electricity%20is%20delivered%20to%20consumers%20through%20a%20complex%20network,connect%20electricity%20producers%20and%20consumers.

16 DOE EIA, Electricity Explained, August 11, 2022, https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php#:~:text=Electricity%20is%20delivered%20to%20consumers%20through%20a%20complex%20network,connect%20electricity%20producers%20and%20consumers.

Therefore, electric switching (switchgears)and circuit breaking at high voltages requires specialized equipment that often includes an insulating material, called a dielectric, which suppresses the ability to conduct electricity, but which can be polarized by an applied electric field. Switches, but not circuit breakers, that rely on air as an insulator can still be used if space allows, as is the case in some land-based substations where the extra space would be incorporated as part of the design of the substation.

Circuit breakers are electrical devices that automatically protect an electrical circuit when there is an overload on the line. At distribution substations that operate at medium voltage, the circuit breaker can be in a vacuum that avoids electricity being conducted in the air between contacts.

At higher voltage substations, the circuit breakers are submerged in tanks of nonconducting oil (e.g., mineral oil, vegetable-based oils, and fluorinated oils) or a dense dielectric gas, such as SF_6. Polychlorinated biphenyls (PCBs) are nonconducting oily liquids or waxy solids that were formerly used as insulators in electrical equipment. However, the production of PCBs was banned in 1979 under the Toxic Substances Control Act of 1976 because of their toxicity.[17] As a result, MV and HV electrical equipment started to utilize SF_6 gas as an insulating and arc quenching dielectric material. It is primarily used in electrical circuit breakers and high-voltage gas-insulated switchgear.

During an electrical discharge the six fluorine atoms split from the sulfur atom to capture an electron, but the SF_6 molecule quickly recombines after the discharge is quenched. One significant advantage of SF_6 gas insulated substations (GIS) and other equipment is that they can be physically more compact than, for example, air-insulated substations and equipment. While a conventional land-based air-insulated substation requires several feet of air insulation to isolate a conductor, SF_6 gas insulation needs only inches, allowing a SF_6-gas insulated facility to fit into a much smaller space than an air-insulated facility.[18]

Potential for SF_6 Leakage and Emissions to the Atmosphere

The equipment that contains SF_6 is designed to be sealed and not emit any SF_6 gas to the atmosphere. However, over the lifetime of the equipment, SF_6 gas can escape into the atmosphere as leaks from aging equipment, and gas can be released during equipment manufacturing, installation, maintenance, servicing, and de-commissioning. Unless the SF_6 that is used in the equipment is recovered and destroyed, all the SF_6 created for use on electrical equipment will eventually be emitted to the atmosphere as a greenhouse gas.

Medium voltage equipment (up to 52 kV, including some switchgear used as the base of WTGs) uses SF_6 at close to atmospheric pressure in sealed equipment for which leakage rates are estimated to be less than 0.1 percent per year. High voltage equipment (greater than 52 kV) uses SF_6 at pressure about 5 times greater than medium voltage equipment (i.e., at about 5

[17] U.S. Environmental Protection Agency. Learn about Polychlorinated Biphenyls (PCBs) https://www.epa.gov/pcbs/learn-about-polychlorinated-biphenyls-pcbs

[18] From the Revolution Wind "Export Cable and Onshore Substation - Application for a Category B Assent – 2021-07-005" (pdf page 382), http://www.crmc.ri.gov/windenergy/revolution.html

atmospheres), for which leakage rates are estimated at less than 0.5 percent per year, which is the highest allowed by relevant International Electrotechnical Commission (IEC) standards.[19]

Even if SF_6 in retired equipment is collected for destruction, the SF_6 destruction process (which relies on destroying the gas in high-temperature kilns and converting the resulting SO_2 and HF vapors to a solid by treating with calcium hydroxide solution) still releases some SF_6 to the atmosphere because it is not 100-percent efficient. Used SF_6 from retired equipment can also be collected and treated to remove impurities for reuse in GIS, but not in other industries and processes that require virgin SF_6, such as semiconductor manufacturing and magnesium production and processing.[20, 21]

Proposed Uses of SF_6-Containing Equipment in Wind Turbine Systems in EPA Regions 1 and 3

ERG has reviewed the outer continental shelf (OCS) permit applications from the Bureau of Ocean Energy Management (BOEM) for the following projects:

- Vineyard Wind 1,
- South Coast Wind (formerly Mayflower Wind),
- New England Wind 1 and 2,
- Revolution Wind,
- Sunrise Wind, and
- Coastal Virginia Offshore Wind Project (CVOW, located in EPA Region 3).

These wind farm project documents describe the use of equipment containing SF_6 on the wind turbine generators (WTGs), ESPs or OSSs, and onshore substations. The relevant information from these permit applications and, in some cases, construction and operation plans, is summarized in Appendix A. Potential emissions of SF_6 are estimated using assumed leak rates, although the applications also note that the equipment containing the SF_6 is designed to be sealed and little or no leakage is expected to occur. The permit applications also report that WTG switchgear and other equipment containing SF_6 will be equipped with integral low-pressure detectors to detect SF_6 gas leaks should they occur.

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[19] Edvard Csanyi, Electrical Engineering Portal; 34 Questions and Answers to Break the Myth About SF_6 Gas in Electrical Equipment, November 10, 2014, https://electrical-engineering-portal.com/34-questions-and-answers-to-break-the-myth-about-sf6-gas-in-electrical-equipment

[20] SF_6 & Alternatives Coalition. *Considerations for Planning an SF_6 Phase-Out.* https://www.sf6andalternativescoalition.org/wp-content/uploads/2020/10/Phase-out-Doc-FINAL.pdf

[21] J.L. Bessede, I. Huet, G. Montillet - AREVA T&D E. Barbier, J. Micozzi, - AVANTEC. *Implementation of Treatment & Recovery of the SF_6 Gas Containing a High Amount of Decomposition Products Due to High Voltage Electrical Interruptions*. https://www.researchgate.net/publication/238108111_Implementation_Of_Treatment_Recovery_Of_the_SF6_Gas_Containing_A_High_Amount_Of_Decomposition_Products_Due_To_High_Voltage_Electrical_Interruptions

New England Wind Phase 1: Outer Continental Shelf Air Permit Application, January 13, 2023, and New England Wind Phase 2: Outer Continental Shelf Air Permit Application, January 13, 2023. (The applications for the two phases have the same organization and section numbering.)

In section 2.2.6.2 (Generators and SF_6-Containing Equipment on the WTGs and ESP(s)), the Phase 1 and Phase 2 permit applications state that SF_6 will be used to insulate electrical equipment (e.g., switchgear) on the ESPs. The ESPs were assumed to contain a total of up to 4,120 kg of SF_6 in Phase 1 and 6,180 kg in Phase 2; the electrical equipment on each WTG could contain up to approximately 19 kg of SF_6. As stated in section 2.3.4.2, although some leaks (i.e., fugitive emissions) from the sealed systems are possible, the replacement of SF_6 during the operational period of the wind farm is not expected. Emissions were estimated using a GWP of 25,200 from IPCC's Sixth Assessment Report (2021) and a leak rate of 0.5% per year.

As stated in sections 4.3.3.22 and 4.3.3.23, the project is subject to the Massachusetts state GHG reporting requirements of 310 CMR 7.71 and the SF_6 emission limits in 310 CMR 7.72. The regulations in 310 CMR 7.72 requires all GIS owners (i.e., those who own, lease, operate, or control GIS in Massachusetts) to: (1) use GIS that is represented by the manufacturer to have a 1.0% maximum annual leak rate, (2) comply with manufacturer-recommended maintenance procedures or industry best practices to reduce SF_6 leakage, and (3) provide for the secure storage, re-use, recycling, or destruction of the SF_6.

The annual leak rate of 1% per year assumed above is the maximum allowable leak rate for non-hermetically sealed GIS established in Massachusetts Department of Environmental Protection regulations at 310 CMR 7.72.[22] The maximum allowable leak rate does not apply to hermetically sealed GIS. The Massachusetts rule defines "hermetically sealed gas-insulated switchgear" as "switchgear that is designed to be gas-tight and sealed for life. This type of switchgear is pre-charged with SF_6, sealed at the factory, and cannot be refilled by its user."

In the BACT analyses presented in section 5.3.4, the permit applications describe the use of air insulated switchgear (AIS), the use of alternative fluorinated compounds (fluorinitriles), and the use of sealed SF_6-containing equipment and leak detection systems on the WTGs and ESPs. Earlier, in section 5.1.2, the permit applications concluded that AIS and alternative fluorinated compounds were not feasible, although the permit applications acknowledged that some suppliers were marketing these alternatives for some medium and high voltage applications. In the BACT analysis in section 5.3.4, the permit applications note that in a letter to the EPA in January 2023, "requiring the use of emerging 'SF_6-free' control technologies in WTG switchgear as BACT would redefine the design of the facility and regulate the Proponent's basic business objective for Project." The permit applications conclude that the only feasible option as GHG BACT for the WTGs is to use hermetically "sealed for life" pressure switchgear that are certified by the manufacturer to meet a SF_6 leak rate of no more than 0.5% per calendar year and are equipped with leak detection systems.

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[22] Massachusetts DEP, 310 CMR 7.0: Air Pollution Control, June 1, 2022, https://www.mass.gov/regulations/310-CMR-700-air-pollution-control#current-regulations

The permit applications also conclude that GHG BACT for the ESPs is the use of "sealed for life" SF_6-insulated equipment certified by the manufacturer to meet a leak rate of no more than 0.5% per calendar year and are equipped with leak detection systems.

The permit applications state in section 5.3.4.2, that "The Proponent is unaware of control technologies employed outside the US that are not employed inside the US." However, this is counter to the information EPA has collected on the use of clean air and g^3 technology currently demonstrated on offshore wind projects outside the US.

Although the permit application noted that some leaks from the sealed systems are possible, the operators do not intend to replace any SF_6 during the operating life of the project.[23]

Coastal Virginia Offshore Wind Commercial Project. The Outer Continental Shelf Air Permit Application for Coastal Virginia Offshore Wind Commercial Project (CVOW) reports that the WTGs will use switch gear that does not contain SF_6, but the OSS platforms will have high voltage circuit breakers that contain SF_6.[24] The application states that emissions were estimated assuming a leak rate of 0.5% by weight per year, based on the International Electrotechnical Commission Standard 62271-1, 2004, [as presented in the U.S. EPA technical paper, "SF_6 Leak Rates from High Voltage Circuit Breakers - U.S. EPA Investigates Potential Greenhouse Gas Emissions Source."[25]] and the GWP for SF_6 (22,800) presented in Subpart A of 40 CR Part 98. For the completed project including three OSS storing 39,684 pounds of SF_6, SF_6 emissions were estimated to be equal to 2,262 tons/year CO_2e.

The SF_6 leak rate of 0.5% is based on a 2006 study produced by the U.S. EPA Electric Power Systems Partnership,[26] which calculated leak rates from records of SF_6 added to equipment. The 2006 Partnership study did not include equipment that was defined as "sealed-for-life." The lower bound leak rate estimated by the study was 0.2% per year, and the upper bound weighted-average leak rate ranged from 2.4% per year to a worst-case rate of 2.5% per year.

South Coast Wind. In the January 23, 2023, responses to the US EPA Comments on the Mayflower Wind [now known as South Coast Wind] Outer Continental Shelf Air Permit Application (December 23, 2022), the applicants stated that,[27]

> "Mayflower Wind has worked with its vendors to identify all equipment that is both technically and economically feasible for installation using alternatives to SF_6. SF_6-free

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[23] Phase 1 of New England Wind OCS Permit Application., p 2-23.

[24] Outer Continental Shelf Air Permit Application for Coastal Virginia Offshore Wind Commercial Project (CVOW) (January 2023), section 3.7, page 35.

[25] Appendix N: Air Emissions Calculations and Methodology. Coastal Virginia Offshore Wind Commercial Project. October 29, 2021. https://www.boem.gov/sites/default/files/documents/renewable-energy/state-activities/Appendix-N-Air-Emissions-Calculations_0.pdf

[26] EPA Additional Resources on SF_6, May 24, 2022, https://www.epa.gov/eps-partnership/additional-resources-sf6, J. Blackman, et al., *SF_6 Leak Rates from High Voltage Circuit Breakers - U.S. EPA Investigates Potential Greenhouse Gas Emissions Source.* June 2006.

[27] US EPA Comments on the Mayflower Wind [Now South Coast Wind] Outer Continental Shelf Air Permit Application – Request for Additional Information December 23, 2022; Mayflower Responses in Red – January 23, 2023

switch gear utilized in the WTGs are commercially available and Mayflower Wind can commit to using this equipment.

"On the OSPs, there are two types of switch gear – direct current and alternating current. Information provided by Mayflower Wind's potential vendors indicates that there are SF_6-free switchgear options available for the medium and high voltage alternating current applications. Per those same vendors, direct current SF_6-free equipment is currently not available.

"Mayflower Wind is evaluating the technical and economic feasibility of using the SF_6-free alternating current equipment in the OSPs. Final decisions on the OSP equipment will be made as soon as additional vendor information is available. To the extent it is technically and economically feasible, Mayflower Wind will use SF_6-free equipment in the OSPs for this offshore application."

In the Southcoast Wind Outer Continental Shelf Air Permit Application (March 2023), the applicant states on p. 3-7 that SF_6 will be present in high-voltage equipment on the OSPs, but not in the low-voltage equipment on the WTGs. The permit applicant states that the OSPs will have eighteen 220 kV GIS that will each contain 275.6 pounds of SF_6. The OSPs will contain twenty-two 66 kV GIS that will be SF_6-free. The OSPs include both DC and AC equipment, and the applicant reports that vendors are able to provide medium and high voltage AC equipment that is SF6-free, but SF6-free DC equipment is not available. The applicant reported that SF6 leak rates for modern GIS are less than 0.1% per year.

SF_6 Emissions from Gas Transfers and SF_6 Production

The SF_6 emissions are not exclusively from what is usually considered a leak associated with faulty, damaged, or otherwise compromised equipment in which the SF_6 escapes to the atmosphere. Alternatively, the SF_6 may be emitted during transfers between SF_6 gas cylinders and the GIS, for example during initial charging and recharging. If the switchgear has a technical problem that requires all the SF_6 to be removed in order to be repaired, then some may be emitted during transfers from the equipment to SF_6 gas cylinders. The SF_6 emissions during charging and transfers will come from purging air from the transfer lines after they are connected between the gas cylinder and the GIS, and from the residual SF_6 in the lines and fittings after the transfer is completed. Similar loss mechanisms occur throughout the lifecycle of the GIS equipment as it is filled, repaired, and retired and the SF_6 is reclaimed for reuse or for destruction.

One producer of SF_6-free medium voltage switchgear (Nuventura) notes that SF_6 is typically sent to switchgear manufacturers in a 45.5 kg bottle. The same company also estimates that the production of a bottle of virgin SF_6 generally results in leakage emissions of 1.5 kg to 3.6 kg of SF_6, while the production of a bottle of reconditioned SF_6 typically emits 0.29 kg of SF_6 due to leakage.[28] If it is assumed as an example, that a 145 kV GIS will use about 85 kg of SF_6, or about

[28] Nuventura, "What happens to used SF_6?" November 12, 2021, https://www.nuventura.com/post/what-happens-to-used-sf6

2 bottles, those SF_6 leakage emission rates would be equivalent to 14 metric tons CO_2e (15.4 tons) per 145 kV GIS using reconditioned SF_6 and 70 to 170 metric tons CO_2e (77 to 187 tons) per 145 kV GIS using virgin SF_6 that is needed to initially charge equipment or to recharge it after a repair. The leakage emissions based on reconditioned SF_6 could also be equated with the minimum end-of-life emissions from an SF_6-containing GIS even if all the SF_6 is recovered for recycling.

For comparison, the permit application for Phase 1 of the New England Wind project reported that the switchgear in each WTG may use and contain up to approximately 19 kg (42 lb) of SF_6 on each WTG and that the ESP(s) will use SF_6 and may contain a total of up to 4,120 kg (9,063 lbs) of SF_6.[29] Applying the same SF_6 leakage rates to the Phase 1 of the New England Wind project would be equivalent to about 2.8 metric tons CO_2e per WTG using reconditioned SF_6 and 15 to 35 metric tons CO_2e (16.5 to 38.5 tons) per WTG using virgin SF_6 for the Phase 1 WTG. For all the ESP(s) in Phase 1, the SF_6 leakage would represent about 617 metric tons CO_2e (679 tons) using reconditioned SF_6 and 3,192 to 7,660 metric tons CO_2e (3,511 to 8,426) using virgin SF_6.

Potentially Applicable SF_6-Free Equipment for Offshore Wind Generating Turbines (WTGs) and Offshore Substations (OSSs)

General Electric (GE) Grid Solutions

Green Gas for the Grid (g^3) Alternatives from GE The GE F35g GIS[30] is also available in an SF_6-free alternative known as the Green Gas for the Grid (g^3) alternative. GE's F35g is a g^3-gas-insulated substation available up to 145 kV but only available as of March 2023 at a frequency of 50 Hz. GE's F35g is the first SF_6-free g^3-gas-insulated substation up to 145 kV to complete an Energy Networks Association (ENA) assessment in the UK. The GE website also reports that equipment using the g^3 alternative that has been developed so far has the same physical footprint and general dimensions as equipment using SF_6. However, information available from OCS permit applicants indicate that GE's SF_6-free medium-voltage switchgear line, the F35g, is only presently available in a 50 Hz International Electrotechnical Commission (IEC) configuration (for use in the European Union and Asian markets) and is, therefore, not compatible with the 60 Hz electrical standard here in the United States.[31]

The g^3 alternative gas is based on the use of a combination of CO_2, O_2, and C_4F_7N (Novec™ 4170 gas, which is a fluoronitrile gas). Novec 4170 has an atmospheric lifetime of 30 years and a GWP of 2,100, compared to 3,200 years and a GWP of 23,500 for SF_6.[32] GE Grid Solutions estimates that the g^3 alternative gas mixture presents a 99-percent GWP reduction compared to

29 New England Wind Phase 1 Outer Continental Shelf Air Permit Application. January 13, 2023. p. 2-16.

30 GE Grid Solutions F35g SF_6-free g^3-Gas-Insulated Substations up to 145 kV. https://www.gegridsolutions.com/hvmv_equipment/catalog/f35g.htm

31 Memorandum to: Patrick Bird, US EPA Region 1, from: Justin Krebs, AKRF Environmental, Planning, and Engineering Consultants. February 24, 2023. Response to Sunrise Wind, LLC Outer Continental Shelf Air Permit Application – Request for Additional Information, received December 2, 2022.

32 3M, Novec 4710 Insulating Gas, https://multimedia.3m.com/mws/media/1132124O/3m-novec-4710-insulating-gas.pdf

SF_6 over a 100-year time horizon. Emissions were estimated by GE Grid Solutions based on an assumed emission rate of 0.5 percent per year over 40 years. GE Grid Solutions reports that recycling of the g^3 mixture and recovery of the Novec 4170™ gas are still being developed and disposal is now the only available end-of-life option.

According to documents on the GE website, g^3 alternative equipment has been used in South Korea, which operates their power grid at 60 hertz, the same frequency as in the U.S.[33, 34]

GE Grid Solutions reports that recycling of the g^3 mixture and recovery of the Novec 4170™ gas are still being developed and disposal is now the only available end-of-life option.

GE Grid Systems reports that the first g^3 products were built in 2015 and the first energizations occurred in 2017, and that Europe and South Korea have g^3 installations that include lines, substations, instrument transformers, and circuit breakers. As of 2021, g^3 product installations included the following in Europe and South Korea, however the available literature did not indicate if any of these were at offshore wind farms:[35]

- 145 kV g^3 gas insulated substations at 16 sites including 100 bays;
- 420 kV g^3 gas insulated substations at 1 site including 9 bays;
- 420 kV g^3 gas insulated lines at 8 sites including over 5,000 meters;
- 123 kV g^3 live tank circuit breakers at 5 sites including 14 circuit breakers.

Siemens Energy

Siemens Energy is a provider of electrical equipment for both onshore and offshore applications, including gas insulated switchgear, circuit breakers, transformers, and offshore grid connections (i.e., substations), among many others. Siemens Gamesa is a related company that is a producer of offshore and onshore wind turbines. Siemens reports that due to increased offshore wind turbine power, there is an increased trend for using higher voltages within the wind turbine network in order to decrease the current and the cable losses during transmission. As a result, more compact gas-insulated high-voltage switchgear is needed.

Siemens has developed gas insulated switchgear air insulated switchgear for offshore applications. Some SF_6-free equipment is about 25% larger than SF_6-containing equipment but is still able to meet the space requirements on the WTG and OSS. The higher costs because of the larger size would be offset by lower operating and end of life costs, according to Siemens. Siemens estimates that the switchgear represents about 1% to 2% of the capital costs for a typical offshore wind farm.

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33 g^3 Insulating & Switching Gas Roadmap (English). g3-Roadmap-Infographic-GEA-33147F-202303-R02.pdf https://www.gegridsolutions.com/app/resources.aspx?prod=g3&type=5

34 International electrical Commission site showing voltage and frequency by country, and the types of consumer electrical plugs used. https://www.iec.ch/world-plugs

35 GE, SF_6-free Solution in Practice, https://resources.gegridsolutions.com/sf6-free-solutions/white-paper-g3-the-sf6-free-solution-in-practice#main-content

8VM1 Blue GIS™

Siemens has developed gas insulated switchgear using vacuum interrupting technology and clean air insulation, designated as 8VM1 Blue GIS™, available up to 72.5kV for offshore wind turbine applications.[36,37] Siemens reports that due to increased offshore wind turbine power, there is a trend to using higher voltages within the wind turbine network to decrease the current and, therefore, the cable losses. As a result, more compact gas-insulated high-voltage switchgear is needed. 8VM1 Blue GIS™ is rated for 50 Hz and 60 Hz (United States). However, according to the "Sunrise Wind OCS Application Response to comments 2023 02 24" document (specifically, the response to comment 2(i) that starts on page 3), the Siemens 8VM1 is a single 3-phase breaker/switching device and is not available in a bus configuration. According to the Sunrise Wind application, this makes it well-suited for use on individual WTGs (and will be used by SRW on the WTGs [see response to comment 5]), but it is not suited for use on the OCS-DC, which requires a bus configuration. (In electric power distribution, a bus or busbar is a metallic strip or bar, typically housed inside switchgear, panel boards, and busway enclosures for local high current power distribution. They are also used to connect high voltage equipment at electrical switchyards,)

Vacuum interrupting technology allows the use of clean air as an insulating medium in gas-insulated switchgears. The term "clean air" refers to a mixture composed of 80 percent nitrogen and 20 percent oxygen that is cleaned and free of humidity; it contains no fluorinated gases. Siemens reports that some units are available for both onshore and offshore wind turbine installations, but they are not available for all sizes and types of applications (e.g., voltages, frequencies, and current types). Other advantages of these units are that specially trained personnel are not needed for the transport, handling, or operation of the clean air GIS, and there are no expenses related to the purchasing, handling, and recycling of SF_6 or other gases. The expected lifetime of the equipment is greater than 50 years, with first inspection at 25 years, which is the same as for conventional SF_6-containing equipment.

Siemens is also able to provide equipment that is rated for frequencies of either 50 Hz or 60 Hz. The electricity grid in the U.S. uses 60 Hz and in Europe it uses 50 Hz. Therefore, the Siemen's equipment is available for systems in both the U.S. and Europe. Siemens reported that as of August 2022, the following equipment was available as part of their Blue equipment portfolio:[38]

- Gas insulated switch gear at 72.5, 145, and 420 kV (the 420 kV units are gas insulated busducts);
- Live tank circuit breakers at 72.5 and 145 kV;
- Dead tank circuit breakers at 145 kV; and

36 Siemens Energy, 8VM1 Blue GISD up to 72.5, 2021, https://assets.siemens-energy.com/siemens/assets/api/uuid:8ab94721-6342-4309-b8a7-5be8baf33f5e/flyer-8vm1-blue-gis-72-5kv-non-eu.pdf?ste_sid=e4db292789ad3186e17872a14bb3dabf

37 Clean Air High Voltage Switchgear for Offshore Wind Application: Exchange with US Environmental Protection Agency Region 1 and ERG Questions by ERG and Answers, September 19th, 2022

38 Siemens Energy Blue High-voltage Products, 2022, https://assets.siemens-energy.com/siemens/assets/api/uuid:1e83b691-89a5-42f0-a42a-8d70c62832b7/2020-08--siemens-energy-blue-portfolio-customer-presentation-en-.pdf

- Instrument transformers at 72.5, 145, 245, and 420 kV.

Siemens reports the following status of units using vacuum and clean air technology as of August 2021:[39]

- 8VM1 Wind Tower Blue GIS® up to 72.5 kV: 72.5 kV switchgear for application in wind turbines, with vacuum circuit breaker and clean air insulation. Units contracted: 974; in operation: 201.
- 8VN1 Blue GIS® up to 145 kV: World's first 145 kV GIS with vacuum circuit breaker and clean air insulation. Units contracted: 349; in operation: 25.
- Blue VT up to 420 kV: World's first 420 kV voltage transformer with clean air insulation; Same footprint as SF_6 product; Current transformers and combined devices available on lower voltage levels. Units contracted: 288; in operation: 109.
- 3AV1 Blue Live Tank CB up to 145 kV: World's first 145 kV LT vacuum circuit breaker with clean air insulation; Same footprint as SF_6 products. Units contracted: 140; in operation: 110.
- 3AV1 Blue Dead Tank CB up to 145 kV: World's first 145 kV DT vacuum circuit breaker with clean air insulation; Same footprint as SF_6 products (identical connections and main dimensions). Units contracted: 15; in operation: 6.
- Blue Station Service VT up to 420 kV & 167 kVA[40]: World's first 420 kV station service transformer with clean air insulation; Output power up to 167 kVA / phase; Same footprint as comparable SF_6 product. Units contracted: 6.

Siemens also reports that they have completed two offshore wind power projects using SF_6-free GIS: [41]

- East Anglia One (North Sea, United Kingdom): 102 turbines with an installed capacity of 714 MW; no SF_6 GIS; all are SF_6-free 8VM1 Blue GIS® for 72.5 kV.
- Nissum Bredning Vind (Nissum Bredning estuary, Denmark): four 7 MW wind turbines; installation of four bays of SF_6-free 8VM1 Blue GIS® for 72.5 kV.

As of August 2022, Siemens reports that they have installed clean air systems in the U.S., Europe, Asia, and Australia. More than 3,000 units have been ordered, more than 1,850 have been delivered, and more than 1,000 units are in operation. In offshore wind farms, units for more than 1,000 bays have been ordered and more than 450 are in operation in both WTG and in OSS. This equipment includes circuit breakers, GIS bays, gas-insulated busducts, and instrument transformers operating at up to 420 kV. Siemens has provided all SF_6-free GIS for WTG for two wind farms in Europe:

- 165 SF_6-free 72.5 kV GIS bays at the Hornsea 2 wind farm off the Yorkshire, UK, coast in the North Sea (in full operation since August 2022); and

[39] *Id.*

[40] kVA = 1,000 volt-amps. The volt-amps are the voltage (the force that moves electrons on a circuit) multiplied by the amps (the electrical current); the kVA measures the apparent power of a generator.

[41] *Id.*

- 140 Clean Air 72.5 kV GIS bays at the Hollandse Kust Zuid wind farm in the North Sea off the north coast of the Netherlands.[42]

However, it is important to note that these four examples are for systems in Europe operating at 50 Hz, and wind farms in the US will be operating at 60 Hz. Therefore, not all equipment can be assumed to be available or demonstrated for the US system at 60 Hz.

Siemens reports that they plan to develop a full “climate neutral” portfolio with the latest sales release date of 2030. This portfolio will include gas insulated switchgear, live tank circuit breakers, and dead tank circuit breakers up to 550 kV; and instrument transformers up to 420 kV. As of September 2022, SF_6-free products were fully available up to 145 kV and partially available up to 245 kV:

- Gas-insulated switchgear: GIS available at 72.5 and 145 kV, gas-insulated busducts available at 420 kV; still to be developed: 420 kV back parts (i.e., disconnector, earthing switch, voltage transformer, busbar…), circuit breakers at 420 kV, GIS at 245 and 550 kV.
- Live tank circuit breakers: available at 72.5 and 145 kV; still to be developed at 245, 420, and 550 kV.
- Dead tank circuit breakers: available at 145 kV; still to be developed at 72.5, 245, 362, and 550 kV.
- Instrument transformers: available at 72.5, 145, 245, and 420 kV.

SF_6-free products include the 8VM1 Blue GIS™ for 72.5 kV for offshore are available and in operation. However, it should be noted that this GIS is not available in a bus configuration which might preclude it from being used on the OCS-DC, which requires a bus configuration.

For 145 kV WTG and OSS, SF_6-free products are available; however, according to OCS permit applicants,[43] these are only available for AC applications and not for DC applications. The AC applications will be used on the WTGs, but DC equipment is needed for some applications on the OSS. SF_6-free products for OSS at 245 and 420 kV are still in development and will be available in the next 5 years, according to Siemens.

In addition, Siemens reports that SF_6-free products for DC systems on the OSS are available up to 300 kV and that products up to 500 kV are in development. There are two types of switch gear – direct current (DC) and alternating current (AC). On the WTGs, AC equipment is always used; on the OSS, DC technology may be used in addition to AC technology, which is needed to handle the power coming from the WTG. Siemens reports that SF_6-free products for DC systems on the OSS are available up to 300 kV and that products up to 500 kV are in development. It is

[42] Clean Air High Voltage Switchgear for Offshore Wind Application: Exchange with US Environmental Protection Agency Region 1 and ERG Questions by ERG and Answers, September 19th, 2022.

[43] US EPA Comments on the Mayflower Wind [Now South Coast Wind] Outer Continental Shelf Air Permit Application – Request for Additional Information December 23, 2022; Mayflower Responses in Red – January 23, 2023.

currently not known whether these are presently available for 60 Hz systems and for offshore use.

From information exchanges with US EPA on February 11, 2022, and September 19, 2022, Siemens estimated that the total cost of ownership of SF_6-free equipment (based on vacuum and clean air technology) is less than 100 percent of the total cost of ownership of SF_6-based equipment:

- The capital cost of vacuum and clean air-insulated equipment is estimated to be greater than 125 percent of SF_6-based equipment. The increased capital cost will depend on the voltage level of the equipment; however, the cost of the electrical equipment that uses SF_6 represents only about 1 to 2 percent of the total capital cost of an offshore wind farm. There is no significant difference in the installation costs.
- The operation and maintenance (O&M) costs of vacuum and clean air technology is estimated to be less than that of SF_6-based equipment.
- The end-of-life costs of vacuum and clean air technology is estimated to be zero percent of SF_6-based equipment. The clean air can be released to the atmosphere. On the other hand, SF_6 and other GHG alternatives must be removed and transported to shore for destruction or recycling, and the cost and environmental impact of destruction and recycling are not well known.

Siemens estimates that the increased capital cost of the SF_6-free equipment is offset by its reduced O&M and end-of-life costs over the life of the equipment. Siemens did not indicate that this estimate was limited to any particular voltage rating or frequency (50 Hz or 60 Hz) of equipment.

Siemens estimates that the additional lifecycle costs for GHG-free equipment, such as for a 145 kV GIS would be $0 per metric ton of GHG reduced in metric tons CO_2e, and that the additional investment for GHG-free equipment (i.e., the capital cost) would be about $33 per ton of GHG reduced (metric ton CO_2e). Siemens estimates that for a 145 kV GIS, which would be suitable for either a wind turbine or an offshore substation, the capital cost would be about $70,000 higher per bay for a clean air technology. This would avoid using 85 kg of SF_6, which equals 2,100 tons of CO_2e, or a cost of $33/ton CO_2e avoided, assuming that all of the SF_6 is eventually emitted if it is created to be used in the GIS. This cost-effectiveness is about the same as the overall cost per ton CO_2e reduced for high penetration wind power and solar photovoltaic (PV) power.[44]

Siemens also estimates that a wind farm with 100 turbines that uses SF_6-free equipment would avoid 252,000 tons CO_2e, assuming 100 kg SF_6 is used per turbine and that all the SF_6 is eventually emitted.

[44] Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve. ©2009 McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/pathways-to-a-low-carbon-economy

Hitachi Energy Switzerland Ltd

Hitachi Energy is currently deploying SF_6-free GIS under the name of EconiQ.[45] The equipment includes 72.5, 145, and 420 kV GIS. These GIS use an alternative gas that is a blend of fluoronitriles, carbon dioxide, and oxygen. The website indicates that the 145 and 420 kV GIS are applicable for offshore wind power connections. However, the website also notes that for the 72.5 and 145 kV GIS, "compact solutions and 60 Hz" systems will not be available until 2023 and 2024, implying that they were first available only for 50 Hz systems. The Hitachi EconiQ website shows a timeline out to 2025 to offer a complete SF_6-free portfolio.

Input from Industry Applications Related to Available of Equipment from GE, Siemens, and Hitachi

Several applicants have clarified the availability of different types of equipment for use on the WTGs and OSS in their responses to EPA questions on permit applications.

According to one applicant (Sunrise Wind, SRW), although ~66kV HVAC SF_6-free switchgear is becoming more commercially available, these types of switchgear are not necessarily technically feasible for all applications in an offshore wind farm. [46] The applicant noted that the Siemens 8VM11 is a single 3-phase breaker/switching device and is not available in a bus configuration. [A bus (or busbar) configuration is one that is used for high voltage power distribution as found in an electrical substation. The busbar itself is a solid metal bar or tube used to connect medium or high-voltage equipment. This is different from the configuration found at the base of the WTGs.] According to the applicant, the 8VM11 is well-suited for use on individual WTGs and is being used by SRW on the WTGs, but it is not suited for use on the OCS-DC, which requires a bus configuration.

According to the same SRW response, GE's SF_6-free medium-voltage switchgear line, the F35g, is only presently available in a 50 Hz International Electrotechnical Commission (IEC) configuration (for use in the European Union and Asian markets) and is, therefore, not compatible with the 60 Hz electrical standard in the United States.

The same SRW response stated that the Siemens 8VN15 has been deemed to be not technically feasible due to increased size (~25%) and weight (~50%) over the SF_6 switchgear currently being planned for the OCS-DC. The applicant stated that the OCS-DC topside structure is pre-built onshore, and then transported to the pre-installed foundation at the final location. According to the applicant, only two vessels exist globally that are capable of lifting the completed topside into position as currently designed; redesigning to a larger footprint and with greater mass would likely exceed the capacities of even these vessels and/or the installed foundation.

[45] Hitachi Energy EconiQ™ Eco-efficiency high energy portfolio. https://www.hitachienergy.com/us/en/products-and-solutions/high-voltage-switchgear-and-breakers/econiq-eco-efficient-hv-portfolio

[46] Memorandum to: Patrick Bird, US EPA Region 1, from: Justin Krebs, AKRF Environmental, Planning, and Engineering Consultants. February 24, 2023. Response to Sunrise Wind, LLC Outer Continental Shelf Air Permit Application – Request for Additional Information, received December 2, 2022.

Finally, the SRW response notes that the SRW OCS-DC is utilizing 320 kV High-Voltage Direct Current (HVDC) transmission for transmitting power collected from the offshore wind farm to shore. The response states that at the present time, there is no alternative to SF_6 for HVDC switchgear. The response notes that Siemens remains the market leader for HVDC switchgear, but they do not have any SF_6-free options at this time.

Similarly, according to SRW, the g3 switchgear from GE is for High-Voltage Alternating Current (HVAC) transmission only and is, therefore, not compatible with the SRW OCS-DC.

For the Revolution Wind project, Hitachi provided a Statement of Non-Availability of SF_6-free Products.[47] This statement was cited in a response from Orsted in December 2022 to comments from EPA related to the Revolution Wind project.[48] According to Hitachi, they do not offer 275kV (300kV) non- SF_6 GIS (EconiQ) product in the portfolio because it has only a limited market outside of the offshore wind segment and, therefore, priority is given to other voltage levels, for instance to 145 or 420kV.

According to Hitachi, for 66 or 145 kV equipment, the SF_6-free EconiQ equipment transition was not launched until April 2021, so it was not available for projects that had already completed the design phase of the project and committed to purchasing specific equipment from vendors. The SF_6-free GIS at 145 kV was available in 2021, but it was still in a pilot phase of development and only available for a few small projects, according to Hitachi.

The developers of Revolution Wind (Ørsted) noted that they had committed to purchasing equipment from Hitachi before they had launched the transition to SF_6-free technology, so they would have had to redesign the project and negotiate new agreements with the equipment vendors. This change would also create a 19-month delay in the project, according to Ørsted, and would have delayed the displacement of CO_2e produced by fossil fuel sources. Ørsted noted that the opportunity cost of this delay, in terms of CO_2e emitted per year from fossil fuels, would far outweigh the potential CO_2e from the use of SF_6 in currently available equipment.

California Regulatory Action

The California Air Resources Board (CARB) has established standards (Cal. Code Regs. Tit. 17 Subarticle 3.1 - Regulation for Reducing Greenhouse Gas Emissions from Gas-Insulated Equipment)[49] that will limit emissions of SF_6 from gas insulated equipment and will also gradually prohibit acquiring new equipment that uses SF_6 as an insulating gas. The phaseout

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47 Letter from Martin Wieser, Hitachi Energy Switzerland Ltd, to Andreas Anders Gade, Ørsted Wind Power. Statement Non-Availability of SF6-free Products for Ørsted's US projects (REV01&OCW01). September 26, 2022.

48 Memorandum to: Patrick Bird, Manager, EPA Region 1 – Air Permits, Toxics, and Indoor Programs Branch; from: Whitney Marsh, Ørsted. Subject: Revolution Wind OCS Air Permit Application – Response to November 14, 2022 Comments. December 14, 2022

49 California Code Subarticle 3.1 – Regulations for Reducing Greenhouse Gas Emissions from Gas-Insulation Equipment, https://casetext.com/regulation/california-code-of-regulations/title-17-public-health/division-3-air-resources/chapter-1-air-resources-board/subchapter-10-climate-change/article-4-regulations-to-achieve-greenhouse-gas-emission-reductions/subarticle-31-regulation-for-reducing-greenhouse-gas-emissions-from-gas-insulated-equipment

provisions were incorporated in rule amendments that were effective on January 1, 2022. The first phase of the prohibition begins on January 1, 2025, and the last phase begins on January 1, 2033. The earliest phaseout dates for new equipment are for lower voltage capacity (less than 35 kV) and the later dates apply to higher voltage capacity. By January 1, 2033, acquiring SF_6-containing equipment greater than 245 kV would be prohibited.

CARB also reports that, according to feedback received from equipment manufacturers and users, the non-SF_6 equipment can have a lower lifetime cost of ownership for similar reasons to those identified by Siemens, creating financial incentives for businesses to transition to non-SF_6 equipment. These incentives are already resulting in a switch to non-SF_6 equipment among conventional power companies, according to CARB.[50] CARB estimated a cost-effectiveness of $33 per metric ton CO_2e reduced for the Proposed Amendments to the Regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear.[51]

The same standard also establishes maximum allowable emission limit in metric tons CO_2e for all existing equipment in a system containing greenhouse gases, including, but not limited to, SF_6. Before the amendments effective on January 1, 2022, the standard established a maximum allowable SF_6 emission rate that became more stringent over time, with an allowable emission rate of 10% in calendar year 2011 and a rate of 1% in 2020 and each calendar year thereafter.

[50] State of California Air Resources Board Public Hearing to Consider the Proposed Amendments to the Regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear. Staff Report: Initial Statement of Reasons. Date Of Release: July 21, 2020. p. 129.

[51] *Id*. p. 133.

Appendix A: Excerpts from Permit Application and Construction and Operation Plans

Additional information on specific projects, including links to up-to-date permit applications and construction and operation plans (COP) for each project, can be found at the Bureau of Ocean Energy Management's (BOEM) web page for state renewable energy projects: https://www.boem.gov/renewable-energy/state-activities.

From Vineyard Wind 1 Air Permit Application (8-17-2018):[52]

p. 4-10:

"Once electrical equipment (switchgear) located on the WTGs and ESPs is installed, there may be fugitive emissions of sulfur hexafluoride (SF_6) (a clear, odorless, and non-flammable greenhouse gas used to insulate switchgear). Vineyard Wind's engineers indicated that there would be approximately 13 kg of SF_6 on each WTG. The ESPs are expected to contain a total of eighteen 220 kV gas insulated switchgear (GIS) and twenty-two 66 kV GIS. The 220 kV GIS are anticipated to contain 125 kg of SF_6.[[53]] The 66kV GIS are expected to contain 85 kg of SF_6. The GIS is sealed equipment, with little or no leakage of SF_6 expected to occur."

p. 4-28:

"Emissions of SF_6 used to insulate electrical equipment (primarily switchgear) on the WTGs and ESPs were estimated based on the storage capacity of SF_6 within the equipment and a conservative annual leak rate of 1%, which is the maximum allowable SF_6 emission rate beginning in the 2020 calendar year (310 CMR 7.72(5)(a)). However, the GIS is sealed equipment, with little or no leakage of SF_6 expected to occur."

p. 340 of PDF: SF_6 emissions estimated at 2,808 tpy CO_2e.

p. 350 of PDF: SF_6 emissions for 800 MW, based on 100 WTGs:

- 11,949 lb of SF_6 in associated equipment;
- 1% per year leaking assumed, 119.49 lb/yr emitted;
- At 23,500 GWP of SF_6, emissions are 1,404 tpy CO_2e and 42,120 over the 30-year life span of the project.

[52] https://www.boem.gov/vineyard-wind; https://www.regulations.gov/document/EPA-R01-OAR-2019-0355-0098

[53] Industry literature (e.g., from Siemens) indicates that vacuum clean air (SF_6-free) gear is currently available only up to 72.5 kV.

From New England Wind (formerly Vineyard Wind South) COP (10-29-2021):[54]

p. 3-44: (Phase 1)

"The Phase 1 *onshore* [emphasis added] substation will house two 220–275/345 kV "step-up" transformers, switchgear, and other necessary equipment. The onshore substation is expected to use a gas insulated substation (GIS) design. A GIS is enclosed within a structure that uses sulfur hexafluoride (SF_6) gas to insulate the substation equipment. Use of SF_6 gas to insulate the substation's electrical equipment rather than ambient air enables a more compact substation layout. The SF_6 gas will be used in new circuit breakers, which are designed to be gas-tight and sealed for the life of the equipment."

p. 3-119, section 3.3.3.4 Decommissioning Plan and Procedures:

"Prior to dismantling the WTGs, they would be properly drained of all lubricating fluids, according to the established operations and maintenance procedures and the Oil Spill Response Plan (OSRP) (see Section 3.3.4.3). Removed fluids would be brought to a port for proper disposal and/or recycling. Any SF_6 in gas insulated switchgear would be carefully removed for reuse. Next, the WTGs would be deconstructed (down to the foundation) in a manner closely resembling the installation process. The blades, rotor, nacelle, and tower would be sequentially disassembled and transported to port for processing using vessels and cranes similar to those used during construction."

p. 3-120:

"The ESP(s) [are expected to be disassembled in a similar manner as the WTGs, using similar vessels. Prior to dismantling, the ESP(s) would be properly drained of all oils, lubricating fluids, and transformer oil according to the established O&M procedures and OSRP. Removed fluids would be brought to port for proper disposal and/or recycling. Similarly, any SF_6 in gas insulated switchgear would be carefully removed for reuse. Before removing the ESP(s), the offshore export cables and inter-link cables would be disconnected, as discussed for the inter-array cables above."

From Revolution Wind Farm Outer Continental Shelf Air Permit Application (August 12, 2022):[55]

Page 2-21: Each of the Offshore Substations (OSS) will contain a maximum of 40 lbs (18 kg) of SF_6 for medium and high voltage gas insulated switchgear. OSS devices containing SF_6 will be equipped with integral low-pressure detectors to detect SF_6 gas leakages should they occur.

Page 3-28: The WTGs will not have SF_6 within the switchgears.

Page 6-89: The BACT and LAER analysis states that

> "Sulfur hexafluoride (SF6) is used as an electrical and thermal insulator in electrical equipment and has a global warming potential (GWP) of 23,500 times that of carbon

[54] https://www.boem.gov/renewable-energy/state-activities/new-england-wind-formerly-vineyard-wind-south
[55] https://www.boem.gov/renewable-energy/state-activities/revolution-wind

dioxide. SF_6 is expected to be used for insulation purposes on each of the OSSs. The maximum potential quantity of SF6 per OSS is 40 lbs (see Section 2.2.3) and fugitive emissions are possible. However, OSS devices containing SF_6 will be equipped with integral low-pressure detectors to detect SF6 gas leakages should they occur. This BACT analysis includes SF_6 emissions as a secondary GHG component. The control technologies identified for GHG as SF_6 control from the database searches are as follows.

- Sealed with leak detection systems and alarms
- Leak detection shall be repaired within five (5) days of discovery
- Leak rate no more than 0.5% per year"

Page 6-91: GHG as SF_6 BACT: Revolution Wind proposes to utilize sealed systems with leak detection systems and alarms to control GHG as SF_6.

From Revolution Wind Farm Construction and Operation Plan, July 21, 2022:[56]

PDF p. 143:

"Sulfur hexafluoride ("SF_6") gas will be used for electrical insulation in some switchgear components; OnSS [onshore substation] devices containing SF_6 will be equipped with integral low-pressure detectors to detect SF_6 gas leakage, which will notify the dispatch center for response should they occur."

Maximum Potential Quantities of Oils, Fuels, Lubricants, and SF_6 for the Onshore Substation

Oil/Fuel/Lubricant/ Gas Type	Maximum Quantity
SF6	40,000 pounds (lbs) (18,144 kg)

PDF p. 177:

"Each of the OSSs [offshore substations] will require various oils, fuels, and lubricants to support its operation; SF_6 will also be used for insulation purposes.[57] Table 3.3.5-2 provides a summary of the maximum potential quantities of oils, fuels, lubricants and SF_6 per OSS. The spill containment strategy for each OSS is comprised of preventive, detective, and containment measures. The OSSs will be designed with a minimum of 110 percent of secondary containment of all identified oils, grease, and lubricants. These measures are discussed in more detail in the ERP/OSRP provided in Appendix D. Additionally, OSS devices containing SF_6 will be equipped with integral low-pressure detectors to detect SF_6 gas leakages should they occur."

[56] https://www.boem.gov/renewable-energy/state-activities/revolution-wind

[57] The COP says the same about the OnSS (Onshore Substation) with respect to containment and low pressure detectors for SF_6 gas leakage.

Summary of Maximum Potential Quantities Oils, Fuels, Lubricants, and SF_6 per OSS

OSS Equipment	Oil/Fuel/Lubricant/ Gas Type	Maximum Quantity per OSS
Medium and High-Voltage Gas- insulated Switchgears	SF_6	40 lbs (18 kg)

PDF p. 184:

"Each of the WTGs will require various oils, fuels, and lubricants to support the operation of the WTGs; SF_6 may also be used for insulation purposes. Table 3.3.8-2 provides a summary of the maximum potential quantities of oils, fuels, lubricants, and SF_6 per WTG. The spill containment strategy for each WTG is comprised of preventive, detective and containment measures. These measures include 100 percent leakage-free joints to prevent leaks at the connectors; high pressure and oil level sensors that can detect both water and oil leakage; and appropriate integrated retention reservoirs capable of containing 110 percent of the volume of potential leakages at each WTG. Additionally, WTG switchgear containing SF_6 will be equipped with integral low-pressure detectors to detect SF_6 gas leakages should they occur."

Summary of Maximum Potential Quantities Oils, Fuels, Lubricants, and SF_6 per WTG

WTG System/Component	Oil/Fuel/Lubricant/ Gas Type	Maximum Quantity per WTG
Switchgear	SF_6	Up to 13 lb (6 kg)

Sunrise Wind Farm Project OCS Permit Application (February 24, 2023):

Page 18 of pdf: "… the OCS-DC [offshore converter station] will have gas-insulated switchgears containing sulfur hexafluoride (SF_6), which is a potent greenhouse gas. These are manufactured to be completely sealed and would likely result in little or no SF_6 emissions. They will be equipped with gas density monitoring devices to detect SF_6 gas leakages should they occur."

Page 21 of pdf: "The operation of the WTGs will not generate air emissions as they will not contain diesel generators (or have switchgear with SF_6)."

Page 25 of pdf: "Potential fugitive emissions [of SF_6] from switchgear on the OCS-DC are conservatively assumed to be 19.8 lbs annually; it is further assumed that these emissions during the first year will be during the construction phase, and in the O&M phase in subsequent years."

Potential annual emissions of SF6 are estimated in Table A11.

- The total quantity of SF6 = 3,960 lbs in the OCS-DC equipment.
- At a 0.5% annual leak rate, annual emissions are 19.8 lbs or 0.010 tons.
- CO_2e would be 233 tons/year.

Pages 65 to 66 of pdf: (in Section 6.5 BACT and LAER Analyses):

"6.5.4 SF6 from Electrical Equipment

Gas-insulated switchgears are manufactured to be completely sealed and would likely result in little or no SF_6 emissions. Devices containing SF_6 will be equipped with integral low-pressure detectors to detect SF_6 gas leakages should they occur.

6.5.4.1 Step 1 – Identify All Control Technologies

The RBLC and other information sources (including online research findings) were reviewed to identify all potentially applicable control technologies. The SF_6 control technologies listed were as follows:

- Leak prevention with manufacturer-guaranteed leak rate no more than 0.5% per year.
- Equipped with leakage detection systems and alarms.
- Equipped with low-pressure alarms and a low-pressure lockout where the alarms are triggered when 10% of the sulfur hexafluoride (SF_6) (by weight) has escaped.
- Using equipment without SF_6, although this alternative was not identified in the RBLC search.

6.5.4.2 Step 2 – Eliminate Technically Infeasible Options

The OCS-DC will contain a medium voltage (66 kV HVAC) and higher voltage (320 kV HVDC or higher) gas-insulated switchgear (GIS) using SF_6 and will be equipped with integral low-pressure detectors to detect SF_6 gas leakages, should they occur. The switchgears will have a manufacturer-certified leak rate of less than 0.5 percent per year. The Project's WTGs will not use SF_6 in any fashion and therefore will not emit or have the potential to emit any SF_6. The switchgear located at the base of each WTG will be insulated using clean, dry air.

SRW is aware that alternatives to SF_6-containing GIS are emerging. While it is true that ~66kV HVAC SF_6-free switchgear is becoming more commercially available, these types of switchgear are not necessarily technically feasible for SRW. The medium voltage switchgear for OCS-DC requires a bus configuration. The Siemens 8VM1 switchgear is a single 3-phase breaker/switching device but is not available in a bus configuration. In addition, the Siemens 8VN1 switchgear has been deemed to be not technically feasible due to increased size (~25%) and weight (~50%) over the SF_6 switchgear currently being planned for the OCS-DC. Finally, GE's switchgear line is only presently available in a 50 Hz International Electrotechnical Commission (IEC) configuration and is therefore not compatible with the 60 Hz electrical standard here in the United States.

The SRW OCS-DC is utilizing 320 kV High-Voltage Direct Current (HVDC) transmission for transmitting power collected from the offshore wind farm to shore. At the present time, there is no alternative to SF_6 for HVDC switchgear. Siemens remains the market leader for HVDC switchgear, but they do not have any SF_6-free options at this time. Therefore, use of equipment without SF_6 is not considered a technically feasible option for the OCS-DC and will not be discussed further.

6.5.4.3 Step 3 – Rank Remaining Control Technologies by Control Effectiveness

The control technologies ranked in order of effectiveness (from most effective to least effective) are as follows:

- Equipment with manufacturer-guaranteed leak rate of no more than 0.5% per year.
- Equipped with leakage detection systems and alarms.
- Equipped with low-pressure alarms and a low-pressure lockout where the alarms are triggered when 10% of the sulfur hexafluoride (SF_6) (by weight) has escaped.

6.5.4.4 Step 4 – Evaluate Most Effective Controls and Document Results

Electric switchgear using SF_6 with manufacturer certified leak rate less than 0.5 percent per year is the most effective control technology. Installation of leak detection and repair system and low-pressure alarms are also equally effective and will minimize SF_6 emissions.

6.5.4.5 Step 5 – Select BACT

BACT for the switchgears on the OCS-DC is considered to be completely sealed gas-insulated switchgears with manufacturer certified leak rate of less than 0.5 percent per year. BACT should include installation of the leakage detection systems and alarms, and low-pressure detectors to detect SF_6 gas leakages. The equipment should be operated following manufacturer recommendations for maintenance and repair.

This is supported by the findings in the RBLC search results.

Sunrise Wind Farm COP (8-19-22):[58]

PDF p. 10:

"Gas-insulated switchgears are manufactured to be completely sealed and would likely result in little or no SF_6 emissions. Switchgears containing SF_6 on the WTG, OCS–DC [offshore converter station], and OnCS–DC [onshore converter station] will be equipped with integral low-pressure detectors to detect SF_6 gas leakages should they occur."

Summary of Maximum Potential Volumes, Oils, Fuels, Gas and Lubricants for the Onshore Converter Station

Onshore Converter Station Equipment/System	Oil/Fuel/Gas Type	Total Oil/Fuel/Gas Volume
Gas-Insulated Switchgear Bay	Sulfur Hexafluoride (SF6)	3,500 lbs

58 https://www.boem.gov/renewable-energy/state-activities/sunrise-wind

Summary of Maximum Potential Volumes Oils, Fuels, Gases and Lubricants for OCS–DC

Offshore Converter Station	Oil/Fuel/Gas Type	Oil/Fuel/Gas Volume
Medium and High-Voltage Gas-insulated	Sulfur Hexafluoride	3,960 lbs (1,796 kg)

In an earlier (August 23, 2021) draft of the COP, Table 3.3.8-2 Summary of Maximum Potential Volumes Oils, Fuels, Gases and Lubricants per WTG, showed that each WTG would have contained 6 kg (13 lb) of SF_6. The August 19, 2022, draft of the COP shows that the WTGs will not contain any SF_6.

PDF p. 339:

"Medium- and high-voltage gas-insulated switchgears associated with the OCS–DC [Offshore Converter Station] could contribute up to 0.020 tons of SF_6 each year [470 tons CO_2e/yr]. However, gas-insulated switchgears are manufactured to be completely sealed and would likely result in little or no SF_6 emissions."

PDF p. 341:

"During the O&M phase, fugitive emissions of SF_6 may occur at a rate of 1 percent annually from the gas-insulated switchgear bay associated with the OnCS–DC [Onshore Converter Station] resulting in up to 0.018 tons of SF_6 each year. However, gas-insulated switchgears are manufactured to be completely sealed and would likely result in little or no SF_6 emissions. Additionally, OnCS–DC devices containing SF_6 will be equipped with integral low-pressure detectors to detect SF_6 gas leakages should they occur.