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OPPD
Omaha Public Power District

OPPD BOARD OF DIRECTORS

BOARD MEETING MINUTES

May 16, 2024

The regular meeting of the Board of Directors of the Omaha Public Power District ("OPPD" or "District") was held on Thursday, May 16 at 5:00 p.m. at the Omaha Douglas Civic Center, 1819 Farnam Street, 2nd Floor Legislative Chamber, Omaha, Nebraska and via WebEx audio and video conference.

Present in person at the Civic Center were Directors A. E. Bogner, M. J. Cavanaugh, M. R. Core, S. E. Howard, J. M. Mollhoff, C. C. Moody, M. G. Spurgeon and E. H. Williams. Also present in person were L. J. Fernandez, President and Chief Executive Officer, Messrs. S. M. Bruckner and T. F Meyerson of the Fraser Stryker law firm, General Counsel for the District, E. H. Lane, Sr. Board Operations Specialist, and other members of the OPPD Board meeting logistics support staff. Chair E. H. Williams presided and E. H. Lane recorded the minutes. Members of the executive leadership team present in person included J. M. Bishop, K. W. Brown, C. V. Fleener, S. M. Focht, G. M. Langel, T. D. McAreavey, L. A. Olson, M. V. Purnell, B. R. Underwood, and T. R. Via.

Board Agenda Item 1: Chair Opening Statement

Chair Williams gave a brief opening statement, including reminders for using the WebEx audio and video conferencing platform.

Board Agenda Item 2: Safety Briefing

Josh Clark, Manager, Protective Services, provided physical safety reminders. L. J. Fernandez, President and CEO, provided psychological safety reminders, including current safety focus reminders about: (i) Fire safety; (ii) Fatigue awareness; and (iii) Material handling.

Board Agenda Item 3: Guidelines for Participation

Chair Williams then presented the guidelines for the conduct of the meeting and instructions on the public comment process in the room and using WebEx audio and video conferencing features.

Board Agenda Item 4: Roll Call

Ms. Lane took roll call of the Board. All members were present in person.

Board Agenda Item 5: Announcement regarding public notice of meeting

Ms. Lane read the following:

> *"Notice of the time and place of this meeting was publicized by notifying the area news media; by publicizing same in the Omaha World Herald, OPPD Outlets*

newsletter, oppd.com and social media; by displaying such notice on the Arcade Level of Energy Plaza; and by e-mailing such notice to each of the District's Directors on May 10, 2024.

A copy of the proposed agenda for this meeting has been maintained, on a current basis, and is readily available for public inspection in the office of the District's Corporate Secretary.

Additionally, a copy of the Open Meetings Act is available for inspection on oppd.com and in this meeting room."

Board Consent Action Items:

6. Approval of the March 2024 Financial Reports, April 2024 Meeting Minutes and the May 16, 2024, Agenda.
7. Approval of the 2023 Annual Health Plan Report – Resolution No. 6647
8. SD-15: Enterprise Risk Management Monitoring Report – Resolution No. 6648
9. SD-3: Access to Credit Markets Monitoring Report – Resolution No. 6649

It was moved and seconded that the Board approve the consent action items.

Chair Williams noted the Board discussed the action items during the All Committees meeting held on Tuesday, May 14, 2024.

Chair Williams then asked for public comment. There was one comment from the public in attendance at the meeting.

David Begley, 4611 S. 96th Street, Omaha, provided comments on net zero goals, and presented materials to the board which are attached to these minutes.

Chair Williams then asked for public comment on WebEx. There were no comments.

Thereafter, the vote was recorded as follows: Bogner – Yes; Cavanaugh – Yes; Core – Yes; Howard – Yes; Mollhoff – Yes; Moody – Yes; Spurgeon – Yes; Williams – Yes. The motion carried (8-0).

Board Agenda Item 10: President's Report

President Fernandez next presented the following information:

- April 2024 Baseload Generation
- April 2024 Balancing Generation
- April 2024 Renewables
- High Banks Wind Energy Center
- Energy Assistance Program (EAP) Pop-Up Event
- Greener Together Program
- Nebraska's Safest Company Award
- Honor our Community – Arbor Day and Earth Day
- Volunteering After the Storm
- Friday April 26, 2024 Omaha Area Tornadoes - Video
- In Memoriam – Edward A. Ruhnka

Board Agenda Item 11: Opportunity for comment on other items of District Business

Chair Williams asked for comments from the public in the room on other items of District business. There were two comments.

David Begley, 4611 S. 96th Street, Omaha, provided comments on wind energy and net zero policy, and presented materials to the board which are attached to these minutes.

Mr. Laverne Treahn, Omaha, NE, provided comments on small modular reactors, and presented materials to the board which are attached to these minutes.

Chair Williams asked for comments from members of the public on WebEx. There were three comments.

David Corbin, 1002 N. 49th St, representing the Nebraska Sierra Club, provided comments on household energy burden.

Ryan Wishart, Professor, Creighton University, provided comments on net zero policy and household energy burden.

Mr. John Pollack, 1412 N. 35th Street, Omaha, provided comments on the EAP and provided a weather update.

There were no additional comments from the public in attendance at the meeting or via WebEx.

There being no further business, the meeting adjourned at 5:55 p.m.

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S. M. Focht
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S. M. Focht
Vice President – Corporate Strategy and Governance and Assistant Secretary

DocuSigned by:
Erin Lane
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E. H. Lane
Sr. Board Operations Specialist

OPPD has just contracted with NextEra Energy Resources, LLC for 600 MW of wind capacity.

On April 5, 2022, ESI Energy, LLC, a wholly owned subsidiary of NextEra Energy Resources, LLC, was convicted in Wyoming federal court and fined over $8m for killing over 150 bald and American eagles via wind turbine blades. *United States v. ESI Energy, LLC*, 22-CR-48-KHR

In the press release, both L. Javier Fernandez and Rebecca Kujawa, CEO of NextEra Energy Resources, LLC., inaccurately claimed wind energy is reliable. **2 + 2 = 5**

"Don't tell me wind turbines are reliable because it insults my intelligence and makes me very angry." Michael Corleone in *The Godfather*.

Prepared and submitted by customer-owner David D. Begley, 4611 South 96th Street, Omaha, NE

FILED

4:34 pm, 4/6/22

Margaret Botkins
Clerk of Court

UNITED STATES DISTRICT COURT FOR THE DISTRICT OF WYOMING

UNITED STATES OF AMERICA

vs

ESI ENERGY, LLC

Case Number: 22-CR-48-KHR

Defendant's Attorney(s):
Jeffrey Pope, Benjamin Wagner, Thomas Sansonetti

JUDGMENT IN A CRIMINAL CASE

THE DEFENDANT pled guilty to counts 1, 2 and 3.

ACCORDINGLY, the court has adjudicated that the defendant is guilty of the following offense(s):

Title and Section	Nature of Offense	Date Offense Concluded	Count Number(s)
16 U.S.C. §§ 703, 707(a)	Unlawful Take of Migratory Birds	January 31, 2022	1
16 U.S.C. §§ 703, 707(a)	Unlawful Take of Migratory Birds	November 17, 2020	2
16 U.S.C. §§ 703, 707(a)	Unlawful Take of Migratory Birds	December 29, 2020	3

The defendant is sentenced as provided in pages 2 through 6 of this Judgment. The sentence is imposed pursuant to the Sentencing Reform Act of 1984.

IT IS FURTHER ORDERED that the defendant shall notify the Court and the United States Attorney for this district within 30 days of any change of residence or mailing address until all fines, restitution, costs, and special assessments imposed by this judgment are fully paid.

Defendant's USM No: **N/A**

April 5, 2022
Date of Imposition of Sentence

Kelly H. Rankin
Chief United States Magistrate Judge

4/6/2022
Date

PROBATION

The defendant is hereby placed on unsupervised probation for a term of sixty (60) months, beginning April 5, 2022, subject to the following terms:

The defendant shall (A) make restitution in accordance with 18 U .S.C. §§ 2248, 2259, 2264, 2327, 3663, 3663A, and 3664; and (B) pay the assessment imposed in accordance with 18 U.S.C. § 3013. If there is a court-established payment schedule for making restitution or paying the assessment (see 18 U.S .C. § 3572(d)), the defendant shall adhere to the schedule.

The defendant shall also comply with the following additional conditions:

On or before October 1, 2022, the defendant shall make restitution of a total of Six Million Two Hundred Ten Thousand Nine Hundred Ninety-One dollars ($6,210,991.00) to the relevant agency of each state. The amount of restitution to each state is specifically:

California: $4,645,619.83
Wyoming: $403,966.94
New Mexico: $100,991.74
North Dakota: $656,446.28
Colorado: $151,487.60
Michigan: $151,487.60
Arizona: $50,495.87
Illinois: $50,495.87

Defendant is credited with already paying, through a subsidiary, to the State of California, pursuant to a prior civil agreement with the Attorney General of California and the Audubon Society Chapters of Golden Gate, Ohlone, Mount Diablo, Santa Clara Valley and Marin, and Californians for Renewable Energy, $2,206,260.00 making the final amount owed in restitution to California $2,439,359.83. Restitution will be paid to the Clerk of the Clerk for the District of Wyoming, to be paid to the relevant state agencies as directed by the U.S. Fish and Wildlife Service ("USFWS"). The defendant will not claim any of the restitution, or any other amount herein, as a tax deduction or characterize it in any manner or forum as a donation or contribution or voluntary action.

The defendant will implement the Eagle Management Plan ("EMP") set forth in Attachment B to the Plea Agreement in this matter (ECF Doc. 2), which was developed with the assistance of USFWS and the Department. The purpose of the EMP is to avoid and minimize eagle mortalities during the period between sentencing and final action on an application under the Bald and Golden Eagle Protection Act (hereinafter "Eagle Act") for an Eagle Take Permit ("ETP") for the following 50 wind facilities; Vasco Wind, North Sky River, Golden Hills, Golden Hills North, Cedar Springs I, Cedar Springs, III, Roundhouse, New Mexico Wind, Broncos Plains, Soldier Creek, Jordan Creek, Wheathridge II, Hubbard, Buffalo Ridge, Heartland Divide II, Eight Point, Irish Creek, Clearwater, Wilton, Ashtabula, Ashtabula II, Borderlands, Brady, Langdon, Langdon II, Oliver, Pheasant Run I, Skeleton Creek, Tuscola

Bay I, Tuscola Bay II, Blackwell, Crystal Lake I, Crystal Lake II, Crystal Lake III, Golden West, Green Power, Limon Wind I, Limon Wind II, Montezuma, Peetz I, Rush Springs, Sky River, Stateline, Torrecillas, White Hills, Pratt, Perrin Ranch, Lee/DeKalb, Casa Mesa and Emmons Logan (hereinafter "the Listed Facilities"). The EMP will terminate at each of these facilities upon the issuance of a final ETP decision for the facility or upon termination of any extended non-prosecution period for the facility, whichever is earlier. The EMP has been approved by the Chiefs of Migratory Birds for the relevant USFWS Regions and the Department. The EMP may be modified from time to time to the extent there is mutual agreement of USFWS and the defendant.

The defendant, USFWS, and the Department will meet at least once every six months during the first two years of the probationary period, and once every 12 months thereafter, to discuss the defendant's overall progress in implementing the EMP and to address any issues with, or proposed amendments to, the EMP. Every 12 months during the probation period, the defendant shall report in writing to the Court, USFWS, and the Department on the defendant's progress in implementing the EMP.

The defendant shall apply for ETPs for each of the Listed Facilities by the dates established in the EMP, and diligently pursue the EPTs thereafter.

As noted in the EMP, the parties recognizing that actual costs may vary from year to year based on advances in science and technology and the specific measures implemented during the term of the EMP, agree that the defendant, either directly or through its affiliates, will not be required to spend more than $27 million of the five years of probation, and no more than $7 million in either of its first two years of probation and no more than $9 million in any of the third, fourth and fifth years or probation, to implement the EMP (not including certain costs as set forth in the EMP).

Within 30 days of the entry of the plea in this matter, the defendant shall provide to USFWS its site assessments (including risk assessments) and turbine sitting plans for the four Listed Facilities not yet under construction or operation and due to become operation in 2022 and if this has not been done, shall occur immediately following entry of this Judgment.

The Court further incorporates all terms and conditions of defendants probation as expressly stated in the Plea Agreement (ECF Doc. 2). Those conditions are fully incorporated herein by reference.

FINANCIAL PENALTIES

The defendant shall pay the following total financial penalties in accordance with the schedule of payments set out below.

Count	Assessment	Restitution	Fine	
1	$50.00	$6,210,991.73	$1,861,600.00	
Notes:				
2	$50.00	$0.00	$0.00	
Notes:				
3	$50.00	$0.00	$0.00	
Notes:				
Totals:	$150.00	$6,210,991.73	$1,861,600.00	

The fine and assessments are due immediately and inclusive of all penalties and interest, if applicable.

All of the below payment options are subject to penalties for default and delinquency pursuant to 18 U.S.C. § 3612(g).

RESTITUTION

The defendant shall make restitution to the following persons in the following amounts:

Name of Payee	Amount of Restitution
Office of the Clerk United States District Court 2120 Capitol Avenue 2nd Floor, Room 2131 Cheyenne, WY 82001	$6,210,991.73

Restitution shall be paid in one lump sum on or before October 1, 2022.

The amount of restitution to each state is specifically:

California: $4,645,619.83
Wyoming: $403,966.94
New Mexico: $100,991.74
North Dakota: $656,446.28
Colorado: $151,487.60
Michigan: $151,487.60
Arizona: $50,495.87
Illinois: $50,495.87

Defendant is credited with already paying, through a subsidiary, to the State of California, pursuant to a prior civil agreement with the Attorney General of California and the Audubon Society Chapters of Golden Gate, Ohlone, Mount Diablo, Santa Clara Valley and Marin, and Californians for Renewable Energy, $2,206,260.00 making the final amount owed in restitution to California$2,439,359.83. Restitution will be deposited to the Clerk of the Clerk for the District of Wyoming, to be paid to the relevant state agencies as directed by the U.S. Fish and Wildlife Service ("USFWS"). The defendant will not claim any of the restitution, or any other amount herein, as a tax deduction or characterize it in any manner or forum as a donation or contribution or voluntary action.

SCHEDULE OF PAYMENTS

Payments shall be applied in the following order: (1) assessment; (2) fine; (3) restitution; (4) interest; (5) penalties.

The total fine and other monetary penalties shall be due in full immediately.

IT IS ORDERED the defendant shall pay a special assessment fee in the amount of $150, which shall be due immediately. Payments for monetary obligations shall be made payable by cashier's check or money order to the Clerk of the U.S. District Court, 2120 Capitol Avenue, Room 2131, Cheyenne, Wyoming 82001 and shall reference the defendant's case number, 22-CR-48-KHR. The fine shall be directed to the North American Wetlands Conservation fund as provided under 16 U.S.C. § 4406(b).

PRESS RELEASE

ESI Energy LLC, Wholly Owned Subsidiary of Nextera Energy Resources LLC, is Sentenced After Pleading Guilty to Killing and Wounding Eagles in Its Wind Energy Operations, in Violation of the Migratory Bird Treaty Act

Tuesday, April 5, 2022

For Immediate Release

Office of Public Affairs

ESI Energy Inc. (ESI) was sentenced today in Cheyenne, Wyoming, for violations of the Migratory Bird Treaty Act (MBTA), announced Assistant Attorney General Todd Kim for the Justice Department's Environment and Natural Resources Division and U.S. Attorney L. Robert Murray for the District of Wyoming.

ESI is a wholly owned subsidiary of NextEra Energy Resources LLC, which in turn is a wholly owned subsidiary of NextEra Energy Inc. ESI owns other companies, many of which operate wind energy generation facilities throughout the United States, including in Wyoming, New Mexico, Arizona, California, Colorado, Illinois, North Dakota and Michigan, as well as other states.

ESI pled guilty to three counts of violating the MBTA, each based on the documented deaths of golden eagles due to blunt force trauma from being struck by a wind turbine blade at a particular facility in Wyoming or New Mexico, where ESI had not applied for the necessary permits. ESI further acknowledged that at least 150 bald and golden eagles have died in total since 2012, across 50 of its 154 wind energy facilities. 136 of those deaths have been affirmatively determined to be attributable to the eagle being struck by a wind turbine blade.

The court sentenced ESI, pursuant to a plea agreement, to a fine of $1,861,600, restitution in the amount of $6,210,991, and a five-year period of probation during which it must follow an Eagle Management Plan (EMP). The EMP requires implementation of up to $27 million (during the period of probation; more thereafter if a written extension is signed) of measures intended to minimize additional eagle deaths and injuries, and payment of compensatory mitigation for future eagle deaths and injuries of $29,623 per bald or golden eagle. ESI also must over the next 36 months apply for permits for any unavoidable take of eagles at each of 50 of its facilities where take is documented or, in the case of four facilities not yet operational, predicted.

"The Justice Department will enforce the nation's wildlife laws to promote Congress's purposes, including ensuring sustainable populations of bald and golden eagles, and to promote fair competition for companies that comply," said Assistant Attorney General Todd Kim of the Justice Department's Environment and Natural Resources Division. "For more than a decade, ESI has violated those laws, taking eagles without obtaining or even seeking the necessary permit. We are pleased to see ESI now commit to seeking such permits and ultimately ceasing such violations."

"Wyoming is graced with abundant natural resources – including both eagles and strong winds," said U.S. Attorney L. Robert Murray for the District of Wyoming. "The sentencing today shows our commitment to both maintaining and making sustainable use of our resources. It also ensures a level playing field for business in Wyoming and ensures those receiving federal tax credits are complying with federal law."

"The U.S. Fish and Wildlife Service (USFWS) has a long history of working closely with the wind power industry to identify best practices in avoiding and minimizing the impacts of land-based wind energy facilities on wildlife, including eagles," said Edward Grace, Assistant Director of the USFWS' Office of Law Enforcement. "This agreement holds ESI and its affiliates accountable for years of unwillingness to work cooperatively with the Service and their blatant disregard of wildlife laws, and finally marks a path forward for the benefit of eagles and other wildlife resources entrusted to the Service's stewardship."

"This prosecution and the restitution it secures will protect the ecologically vital and majestic natural resources of our bald eagle and golden eagle populations," said U.S. Attorney Phillip A. Talbert for the Eastern District of California. "California has been awarded more than $4.6

million in restitution under this plea agreement for the deaths of at least 92 eagles within the state caused by the defendant and affiliated companies."

The MBTA prohibits the "taking" of migratory birds, including bald and golden eagles, without a permit from the U.S. Fish and Wildlife Service of the Department of the Interior. "Take" is defined by regulation to mean "to pursue, hunt, shoot, wound, kill, trap, capture or collect" or to attempt to do so.

Bald and golden eagles are also protected under the Bald and Golden Eagle Protection Act (the Eagle Act) which, like the MBTA, prohibits killing and wounding eagles without a permit from USFWS. USFWS is authorized to issue such eagle take permits (ETPs) only where: (1) the predicted take is compatible with the preservation of bald and golden eagles; (2) it is necessary to protect an interest in a particular locality; (3) the take is associated with, but not the purpose of, the activity; and (4) the take could not practicably be avoided. Permit applicants are required to avoid and minimize take to the maximum extent practicable, and to pay compensatory mitigation for unavoidable takes.

According to documents filed in court, it is the government's position that ESI's conduct violated both the Eagle Act and the MBTA, but the government accepted the company's guilty plea to only MBTA counts due in large part to ESI's agreement to apply for permits at 50 facilities and its prior efforts to minimize and mitigate for eagle fatalities.

ESI's and its affiliated companies' actions in Wyoming and New Mexico were taken under an admitted nationwide posture and alleged corporate policy of not applying for ETPs.

According to the information filed in this case:

- ESI and its affiliates deliberately elected not to apply for or obtain any ETP intended to ensure the preservation of bald and golden eagles, and instead chose to construct and operate facilities it knew would take eagles, and in fact took eagles, without any permits authorizing that take.
- Because ESI did not seek any ETPs, it avoided any immediate federal obligation to avoid and minimize eagle take to the maximum degree practicable and to pay for compensatory mitigation for the eagle deaths.
- Because some other wind energy companies (1) altered proposed operations as required to avoid and minimize take levels to the maximum degree practicable, (2) applied for ETPs, (3) obtained ETPs that in some cases were impacted by take levels caused by ESI's unpermitted facilities, and/or (4) paid mitigation for eagle takings, ESI, by not doing these things, gained a competitive advantage relative to those wind energy companies.
- ESI and its affiliates began commercial operations at new facilities on a schedule intended to meet, among other things, power purchase agreement commitments and qualifying deadlines for particular tax credit rates for renewable energy, and with production amounts not impacted by avoidance and minimization measures that might have been

required under an eagle take permit. ESI and its affiliates received hundreds of millions of dollars in federal tax credits for generating electricity from wind power at facilities that it operated, knowing that multiple eagles would be killed and wounded without legal authorization, and without, in most instances, paying restitution or compensatory mitigation.

According to documents filed in court, between 2018 and 2019, ESI authorized subsidiary Cedar Springs Transmission LLC (CST) to develop a multi-facility commercial wind power project in Converse County, Wyoming, consisting of the Cedar Springs I, II and III wind power facilities (collectively, the project).

On March 28, 2019, USFWS informed the defendant, through a letter to its agents, that Cedar Springs I and II, based on CST's consultant's calculations, could result in the collision mortality of 44 golden eagles and 23 bald eagles over the first five years of operations, and recommended that, because of the unusually high number of occupied golden eagle nests, the proposed wind facilities not be built. USFWS further stated that, if the facilities were built, the company should apply for an ETP under the Eagle Act as soon as possible. The defendant continued the development of the Cedar Springs facilities.

On July 17, 2019, representatives of CST met with USFWS representatives. During that meeting, USFWS recommended that, consistent with the recommendation made by USFWS in February, the wind project not be constructed due to the risk of avian fatalities. USFWS also recommended that, if the wind project was built, the project should implement seasonal curtailment during daylight hours. The defendant did not implement the recommended curtailment.

Between Sept. 10 and Sept. 23, 2019, USFWS sent additional letters to the defendant's agents, each noting that the defendant's parent company had documented that the project was anticipated to kill eagles and recommending that the facilities apply for an ETP. USFWS reiterated for the third time its recommendation that a wind project should not be constructed in the proposed area for the Cedar Springs project.

On or about Sept 28, 2020, the defendant's affiliates began some turbine operations at Cedar Springs II. Between approximately Nov 29, 2020, and Dec 1, 2020, two golden eagle carcasses were found near wind turbines at Cedar Springs II (after which it was sold).

On or about Dec. 6, 2020, the defendant authorized the commercial operation of Cedar Springs I to commence. Between April 2021 and January 2022, seven golden eagle carcasses were found near wind turbines at Cedar Springs I.

On or about Dec. 15, 2020, the defendant authorized the commercial operation of Cedar Springs III to commence. On approximately Jan. 30, 2022, a golden eagle carcass was found near a wind turbine at Cedar Springs III.

Between 2018 and 2019, ESI authorized a subsidiary, Roundhouse Renewable Energy LLC (RRE), to develop a commercial wind power facility in Laramie County, Wyoming.

In a letter dated March 28, 2019, USFWS stated that, based on RRE's consultant's calculations, Roundhouse could result in the collision mortality of 19 golden eagles and 4 bald eagles over the first five years of operation, and recommended that RRE apply for an ETP under the Eagle Act. The defendant continued the development of Roundhouse.

In a letter dated Aug. 27, 2019, USFWS provided recommendations on opportunities to avoid and minimize impacts to eagles using the available data. USFWS again stated that the facility was predicted to take eagles even if all USFWS recommendations were implemented, however, and recommended that an ETP be sought.

On June 12, 2020, the defendant authorized the commercial operation of Roundhouse to commence. Between approximately Sept. 17, 2020, and April 17, 2021, four golden eagle carcasses were found near wind turbines at Roundhouse.

In 2003, ESI authorized a subsidiary, FPL Energy New Mexico Wind LLC (NMW), to begin operations at a commercial wind power facility in De Baca and Quay Counties, New Mexico. On or about Dec. 29, 2020, two golden eagle carcasses were found near a wind turbine at NMW.

No ETP was sought by or issued to ESI in connection with the operations or repowering of any of the above wind power facilities.

This case was investigated by the U.S. Fish and Wildlife Service Office of Law Enforcement. The prosecutions were handled by the Environmental Crimes Section of the Justice Department's Environment and Natural Resources Division with assistance from the U.S. Attorneys' Offices for the Eastern District of California, the District of Wyoming and the Northern District of California.

Updated April 4, 2024

Topics

ENVIRONMENT | **WILDLIFE**

Components

Environment and Natural Resources Division   ENRD - Environmental Crimes Section

"This is not a debate," OPPD Chairman Eric Williams, April 18, 2024

Well, yes, this is a debate. I'm trying to persuade five OPPD directors to terminate your Net Zero policy. This is politics.

Prepared and submitted by customer-owner David D. Begley, 4611 South 96th Street, Omaha, NE

Consensus Through the Years

- The Earth was the center of the galaxy.
- Slavery was a good thing.
- DDT was a good pesticide.
- Lobotomies were a good way to cure mental illness.
- Thalidomide was a good medicine for morning sickness.
- The Vietnam War was vital to the interests of the United States.

The consensus changed because some people exercised their critical thinking skills and free speech rights.

The consensus and group think can be very dangerous.

Read *The Best and Brightest.* David Halberstam's account of the Vietnam War.

Results of the Vietnam War?

- 58,220 dead and the first one was Major Dale R. Buis, a native of Pender, Nebraska.
- 303,604 wounded.
- Deep divisions in the culture.

Nutritive Value of Plants Growing in Enhanced CO_2 Concentrations (eCO_2)

Albrecht Glatzle[1]
James D. Ferguson[2]
William Happer[3]
Patrick Moore[4]
Gary Ritchie[5]
Frits Byron Soepyan[6]
Gregory Wrightstone[7]

[1]Asociación Rural del Paraguay, Asunción
[2]University of Pennsylvania School of Veterinary Medicine, USA
[3]Department of Physics, Princeton University, USA
[4]Ecologist, Ecosense Environmental Inc. Comox, BC, Canada
[5]Consultant in Forest and Environmental Sciences [ret.], Olympia, WA, USA
[6]CO_2 Coalition, Arlington, VA, USA
[7]CO_2 Coalition, Arlington, VA, USA

March 2024

CO_2 COALITION

ABSTRACT

In the present article, we strongly argue against the published notion that enhanced atmospheric concentrations of carbon dioxide (eCO_2) threaten human nutrition. We review literature and provide arguments that arrive at quite a contrary view. In accordance with Liebig's Law of the Minimum, more vigorous growth of vegetation in eCO_2 will increase plants' need for more of other nutrients. However, the resulting nutrient deficiencies caused by eCO_2 are small, compared to the nutrient shortages that agriculture and livestock routinely face because of natural phenomena, such as severe soil fertility differences, nutrient dilution in plants due to rainfall or irrigation, and even aging of crops. These problems have been satisfactorily dealt with for generations through adequate use of mineral fertilizers, most importantly nitrogen; by proper species and cultivar selection; and with food supplements for livestock and humans. The same agricultural practices will ensure that the more abundant crops that result from eCO_2 will also provide good nutrition. Over most of geological history, atmospheric CO_2 concentrations have been several times higher than today's, which are much less than optimum for most plants. We also review the contribution of eCO_2 to global warming and conclude that doubling or even quadrupling CO_2 concentrations can only cause a few percent suppression of radiation to space. The resulting temperature increase will be small, compared to the natural increases and decreases of temperature that have characterized our current interglacial period. More CO_2 is beneficial to life on Earth.

clear evidence of many periods during the Holocene that were warmer than today but had lower concentration of CO2. Most notable was the Holocene Climate Optimum during the Early and Middle Neolithic (Kalis (2003) [95]).

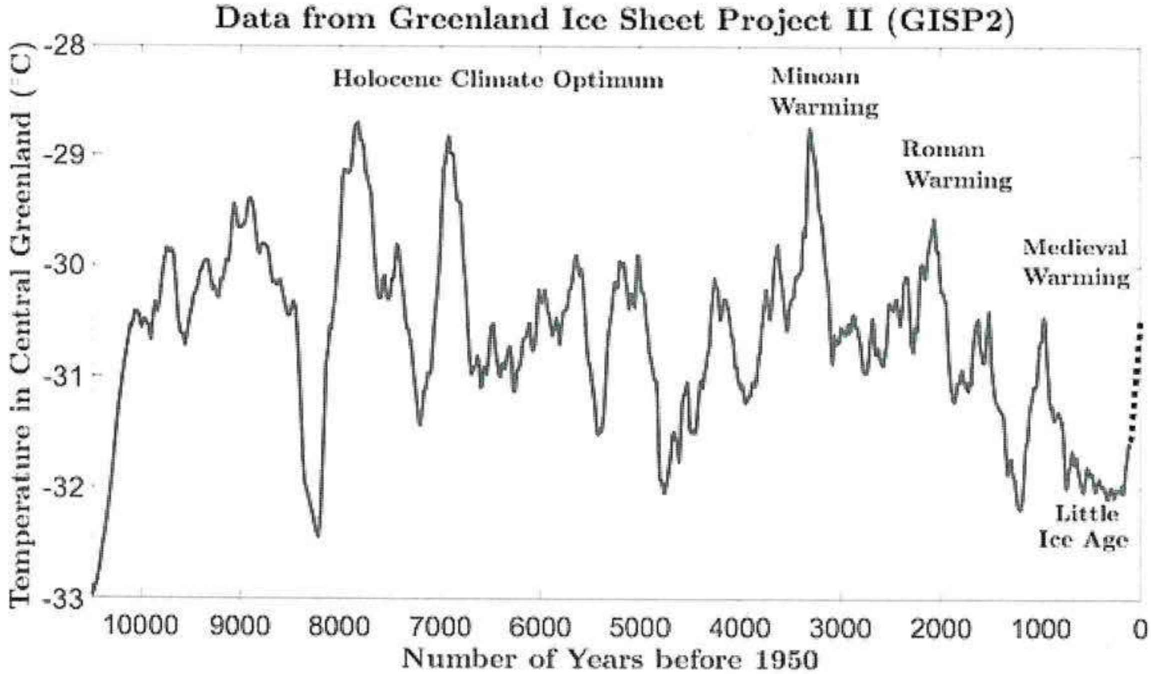


Figure 13: Estimates of the temperatures in central Greenland during the current interglacial period up to the year 1855. Even during this relatively stable climatic period, there are relatively large century-to-century variations of temperature. The large temperature variations could not have been caused by CO_2, since ice core bubbles show that CO_2 concentrations varied by no more than a few percent until about the early 1800s when a rapid increase of atmospheric CO_2 concentrations coincided with the use of fossil fuels. The estimated 1.1 °C temperature increase since 1855, shown as the black dotted line, does not differ from past temperature changes in either magnitude or duration. (Alley (2000) [91], Alley (2004) [92]). Based on Alley (2000) [91], the "present" time in the data refers to 1950. Because the data only go as far as about 95 years before the "present", then, taking the difference, the data go only as far as 1855.

The Medieval Warm Period was followed by substantial cooling which led to the Little Ice Age and to the final abandonment of Norse settlements in Greenland in the mid-1400s. The Little Ice Age, from about 1250 to 1850, was not a good time for humanity in northern Europe, where crop failures and plagues decreased the population by nearly 50%. During that period, somewhere between 200,000 and 500,000 people, 85% women, were cruelly executed as "witches" in Continental Europe (Ben-Yehuda (1980) [96]). They were blamed for bad weather and poor harvests. The end of the Little Ice Age (when Christmas markets in London used to be held on the frozen Thames) coincided more or less with the beginning of the industrial era.

SUMMARY

The significant enhancement of plant growth due to increasing CO_2 in the atmosphere is often accompanied by a slight dilution of some nutrients, notably nitrogen, in plant tissues if no attempts are made to make up for the increased demands for these nutrients with appropriate fertilizers. However, we have shown that the deficiencies in nutrients, and especially nitrogen, caused by eCO_2 are small, compared to the nutrient shortages that agriculture and livestock face because of natural phenomena, such as severe soil fertility differences, nutrient dilution in plants due to more rainfall or irrigation, and even in aging crops. These problems have been routinely dealt with for generations through adequate fertilization, proper species and cultivar selection, and food supplements for livestock and humans.

Other observed reactions to eCO_2 (such as reduced nitrate reductase activity, reduced photorespiration and reduced carotenoid biosynthesis) can be understood as a resource saving response mechanism of the plant metabolism. Generally, the additional inputs required for the correction of the nutritional deficits are tiny compared to the benefits of the higher photosynthetic rate due to eCO_2 and the associated yield increases. Moreover, there are reports that elevated CO_2 favors the accumulation of health-promoting carbon-based secondary metabolites such as antioxidants.

In addition, eCO_2 clearly promotes the efficiency of water use in plants and nitrogen fixation in legumes, which adds beneficial nitrogen to terrestrial ecosystems. Together, these two factors have led to a significant greening of Earth, particularly in arid regions. There is published evidence that gradually rising CO_2 levels have caused no additional nutrient deficiencies in the quarter of Earth's land surface that is covered with mostly arid rangelands, suitable only for grazing animals, and where fertilizer usage is ruled out for economic reasons. Grazing animals have innate "nutritional wisdom" that enables them to compensate for nutritional deficiencies by selective browsing of higher quality leaves or legumes. In addition, there are other economical ways to compensate for mineral or protein deficiencies in livestock nutrition.

In conclusion, field studies of plant growth with eCO_2, and the geological history of CO_2 and Earth's climate show that:

- Plants first appeared in the fossil record when atmospheric CO_2 levels were much higher than today. Therefore, one can be confident that plants are genetically equipped to cope with the moderate increase in CO_2 levels since the beginning of the industrial era and with additional increases of CO_2 in the future. The greening of Earth (Fig. 5) is only the beginning of benefits from more CO_2 for plants and for healthy and abundant human nutrition.

- Today's low concentration of atmospheric CO_2 is not typical of Earth's climate history, and this gaseous trace compound has not determined the fluctuations of temperature in the past and will not in the future.

- Man-made CO_2 emissions are not capable of triggering dangerous future warming. Its global warming potential is almost saturated.

- The numerous desirable and beneficial effects of more CO_2 in the atmosphere greatly outweigh "climate-damaging" or "nutrient-damaging" impacts, to the extent that these even exist. There is no "social cost of carbon," as is unfortunately and incorrectly claimed in numerous recent publications. In fact, there is a social benefit from more CO_2 in the air.

- Working in conjunction with the essential growth factors of H_2O and sunlight, CO_2 is the most important nutrient for plants and for all living organisms depending on food chains. For too long, inadequate atmospheric CO_2 has been the shortest stave of Liebig's barrel (see Fig. 4).

- Rising atmospheric concentrations of CO_2 have clearly been beneficial for the biosphere, agriculture, humanity, and particularly for global food security at very low additional cost. Still higher concentrations of CO_2 will bring additional benefits.

Today's scientific consensus re: CAGW

Academics need research funds from the federal government.

The government funds CAGW research that feeds the Left's narrative of greenhouse gases and extreme global warming.

Result?

We get the fraudulent and completely debunked "hockey stick" graph by Prof. Michael Mann; the guy who falsely claimed he won a Nobel Prize until the Nobel Committee stopped him.

SCIENCE

Same-Sex Couples Face Higher Climate Change Risks, New UCLA Study Shows

"You're a crack pot." Creighton Prof. W. Ryan Wishart to Creighton alum David D. Begley, April 18, 2024.

If Begley is a "crack pot" for not believing in CAGW, then so is the Nobel Prize winner in physics (Dr. James Clauser) the father of the hydrogen bomb (the late Dr. Edward Teller).

Who do you believe? Who knows more about science? Clauser or Wishart? I'm with the Nobel Prize winner. What about you?

Berkshire Hathaway, Inc. Report

Warren Buffett, "Scamming has always been a part of the American scene."

Dave Begley, "CAGW is the biggest scam in the history of the world."

"You can get very rich understanding the weaknesses of others." Warren Buffett commenting on Charlie Munger's wisdom

"Many people want to save the Planet." Dave Begley

"Demand for electricity doubles in Iowa by mid-2030's." Greg Abel, CEO, Berkshire Hathaway Energy, Inc.

SD – 15 Enterprise Risk Management

Reliability

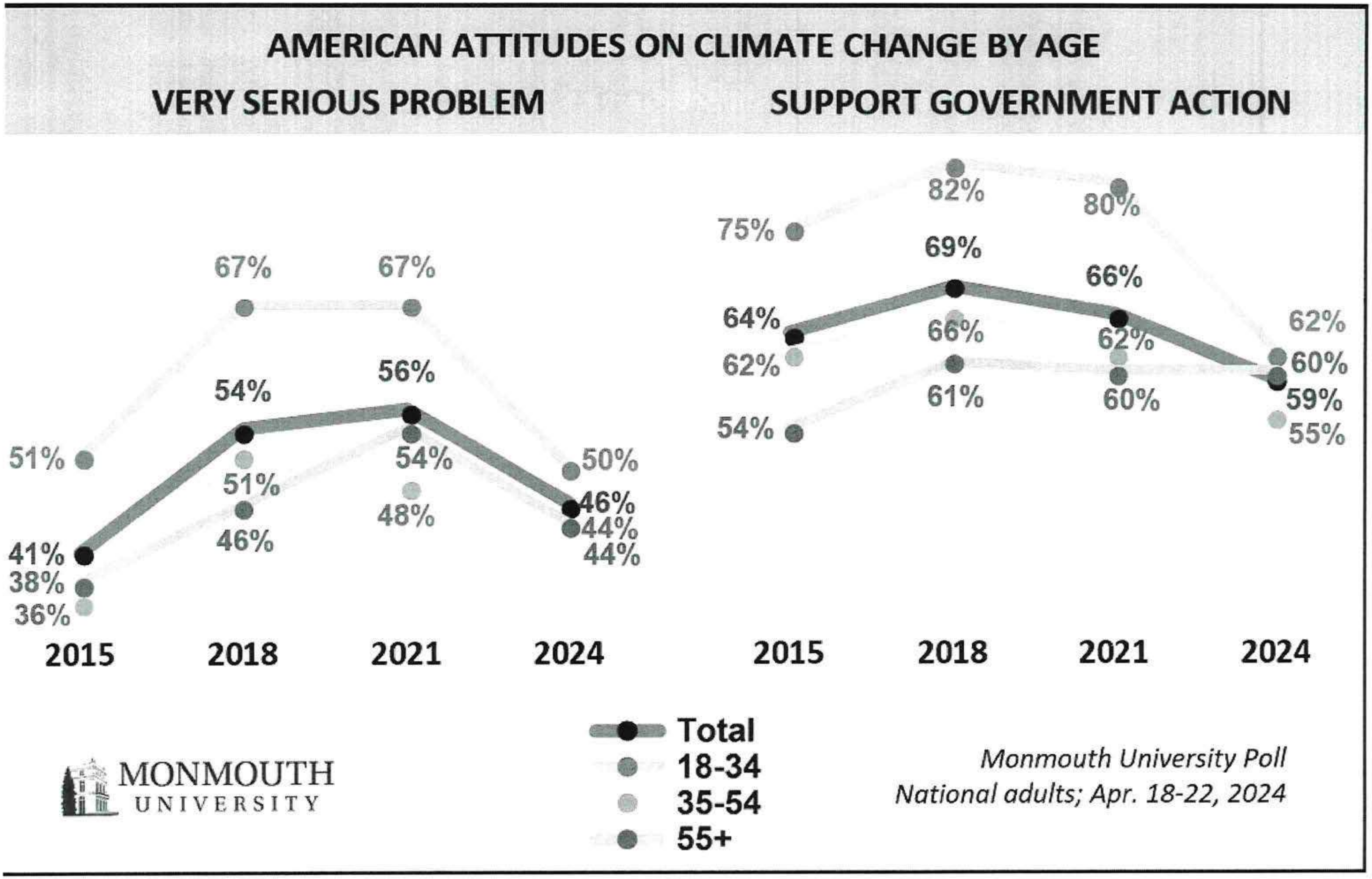
High risk that K-Junction Solar will not be built.

High risk that Cass County Solar will not be build.

High risk that Net Zero Carbon policy will cause forced blackouts in January.

Reputation

High risk that OPPD customer-owners will reject OPPD's Net Zero Carbon policy as they figure out it is a complete scam. See Monmouth University poll on American's attitude on climate change. If OPPD customer-owners were polled, I suspect that not even 25% consider that climate change is a serious problem; especially when they find out the cost.


AMERICAN ATTITUDES ON CLIMATE CHANGE BY AGE
VERY SERIOUS PROBLEM
SUPPORT GOVERNMENT ACTION
51%
41%
38%
36%
67%
54%
51%
46%
67%
56%
54%
48%
50%
46%
44%
44%
75%
64%
62%
54%
82%
69%
66%
61%
80%
66%
62%
60%
62%
60%
59%
55%
2015
2018
2021
2024
2015
2018
2021
2024
Total
18-34
35-54
55+
MONMOUTH UNIVERSITY
Monmouth University Poll
National adults; Apr. 18-22, 2024

U.S. Energy Information Administration

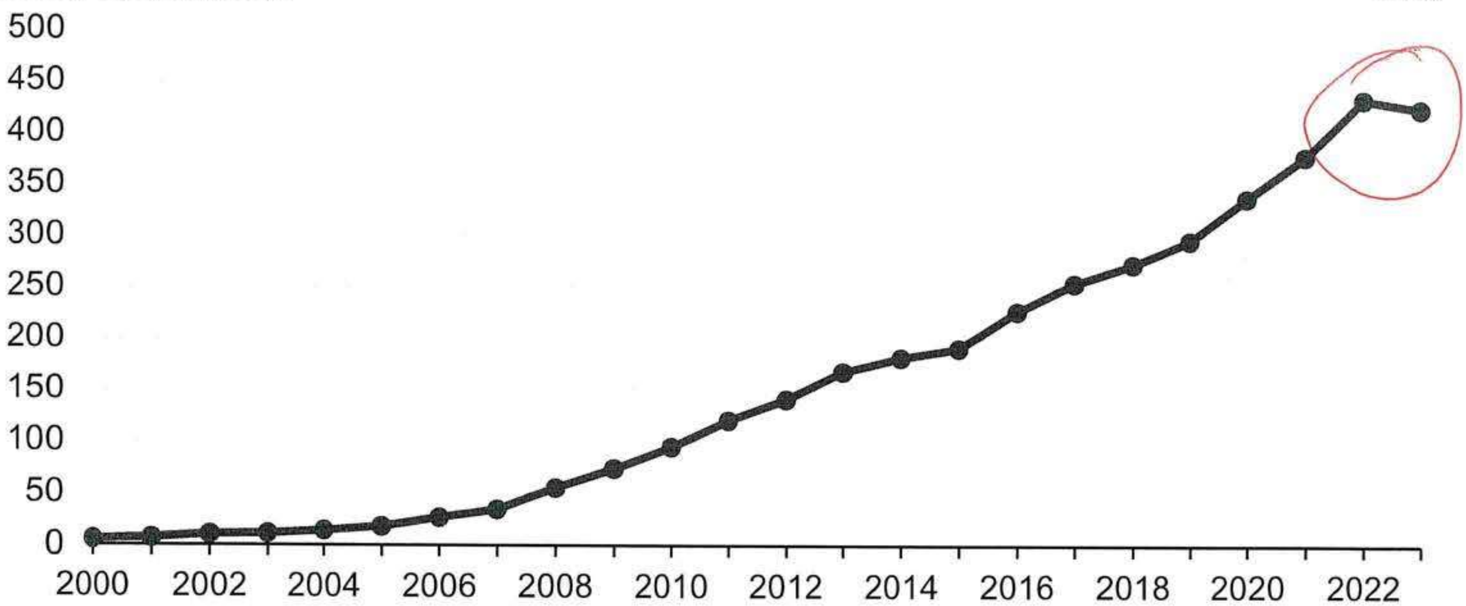
Today in Energy

IN-BRIEF ANALYSIS

April 30, 2024

Wind generation declined in 2023 for the first time since the 1990s

Annual U.S. wind generation, 2000–2023
billion kilowatthours



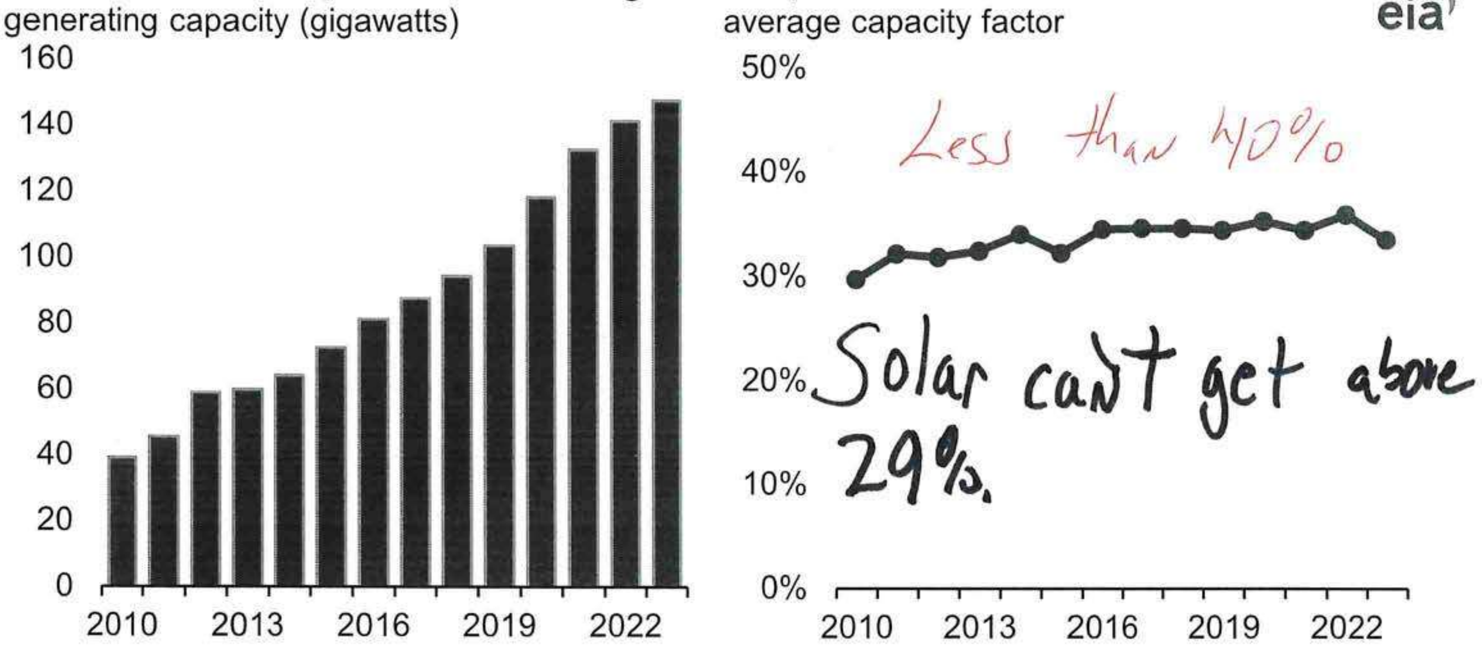
Data source: U.S. Energy Information Administration, *Electric Power Monthly*

U.S. electricity generation from wind turbines decreased for the first time since the mid-1990s in 2023 despite the addition of 6.2 gigawatts (GW) of new wind capacity last year. Data from our *Power Plant Operations Report* show that U.S. wind generation in 2023 totaled 425,235 gigawatthours (GWh), 2.1% less than the 434,297 GWh generated in 2022.

U.S. wind capacity increased steadily over the last several years, more than tripling from 47.0 GW in 2010 to 147.5 GW at the end of 2023. Electricity generation from wind turbines also grew steadily, at a similar rate to capacity, until 2023. Last year, the average utilization rate, or capacity factor, of the wind turbine fleet fell to an eight-year low of 33.5% (compared with 35.9% in 2022, the all-time high).

The 2023 decline in wind generation indicates that wind as a generation source is maturing after decades of rapid growth. Slower wind speeds than normal affected wind generation in 2023, especially during the first half of the year when wind generation dropped by 14% compared with the same period in 2022. Wind speeds increased later in 2023, and wind generation from August through December was 2.4% higher than during the same period in 2022. Wind speeds had been stronger than normal during 2022.

Annual U.S. electric power sector wind generators, 2010–2023



Data source: U.S. Energy Information Administration, *Electric Power Monthly*

The decline in wind generation in 2023 was not uniform across the United States. Wind generation decreased the most in the upper Midwest, which includes the East North Central Census Division and West North Central Census Division. Wind generation in the East North Central Census Division declined by 6% compared with 2022, and it declined in the West North Central Census Division by 8%. The Mountain Census Division reported a smaller reduction of 2%. These three census divisions account for half of the installed wind capacity in the United States.

Wind generation in 2023 in other regions of the United States was slightly higher than in 2022. The West South Central Census Division had 3% more wind generation in 2023, and the Pacific Coast Census Division had 1% more. Wind generation in Texas, which has the largest wind generation fleet in the United States, increased by 4.4% in 2023. Texas had an installed wind capacity of 40.7 GW in 2023, accounting for 28% of the national total.

Principal contributors: Mark Morey, Scott Jell

SD-3: Access to Credit Markets

In order to achieve a low cost and flexible cost structure, OPPD shall maintain financial ratios and targets to ensure efficient and cost-effective access to the credit markets

Therefore:

- For OPPD's annual budgets, the Board establishes a minimum total debt service coverage* ratio of 2.0 times
- When making resource decisions, OPPD shall take into consideration long-term revenue requirements, debt-to-capitalization ratio, minimum risk-adjusted liquidity* levels, competitive position, financial risk, and financial flexibility
- OPPD's goal is to maintain an AA credit rating with the credit rating agencies consistent with the above expectations

*TERMS AND DEFINITIONS

Total Debt Service Coverage: Revenues less expenses divided by total annual senior and subordinate lien debt interest and principal payments

Liquidity: Total cash (operating and supplemental cash accounts) and unrestricted lines of credit available to meet ongoing daily cash requirements

SD – 3 Access to Credit Markets Monitoring Report

Product and Services Update.

Proposal by OPPD **to lend money directly** to customer-owners for "projects related to energy efficiency, energy related improvements, or integrated energy solutions."

OPPD has the power to buy, sell and lease personal and real property "reasonably necessary for the conduct of **its business**." Neb. Rev. Stat. §70-625.

OPPD has the power to **borrow money**. Neb. Rev. Stat. §70-631. Nothing about **lending money**.

Any surplus from OPPD's operations "shall be returned" to consumers. Neb. Rev. Stat. §70-726.

Prepared and submitted by customer-owner David D. Begley, 4611 South 96th Street, Omaha, NE

“the legal maxim "expressio unius est exclusio alterius" (the expression of one thing is the exclusion of the others)....” *Poulton v. State Farm Fire & Cas. Cos*. 267 Neb. 569, 574, 675 N.W.2d 574 (2004).

Based upon the above statutes, OPPD has no statutory authority to get into the money lending business to its customers.

I imagine every bank and finance company in Nebraska would be shocked to learn that a governmental subdivision was competing with them in the money lending business.

OPPD needs to stick to its statutorily authorized duties of generating and delivering low cost and reliable power. That’s it. **No mission creep.**

BACKGROUND

- Identified as a potential solution for helping customers to reduce energy usage during Pathways to Decarb and rates discussions
- Policy 2.03 allows funds for C&I customers for projects related to energy efficiency, energy related improvements, or integrated energy solutions
- Is a tool we can utilize to help achieve demand reduction and energy efficiency goals

ENERGY EFFICIENCY FINANCING

- Provides qualified customers financing to make energy-related improvements to their home or business
- Programs in use by utilities across the country
- **TRADITIONAL** Repayments made directly to utility as part of the monthly billing cycle
- **NON-TRADITIONAL** Repayments made directly to a 3rd party and is not directly tied to the utility

OPPD Omaha Public Power District

RESEARCH

Investigation into existing programs and solutions to understand impacts to customers and utility

INDUSTRY

Internal, Utility, Experts

Gather knowledge about what and how other utilities are executing energy efficiency financing programs.

CUSTOMER

Quantitative & Qualitative

Understand our customers' interest in an energy efficiency program and potential benefits.

FINANCE

Banks, Credit Unions, Government

Explore potential funding solutions through internal and external sources.

LEGAL

Policy Impacts & Risks

Not authorized by statute

Recognize potential program impact to policies and regulations.

OPPD
Omaha Public Power District

CONCEPTS EVALUATED

Solutions ideated (sic) and evaluated by cross-functional development team

TRADITIONAL *ON-BILL*			NON-TRADITIONAL *OFF-BILL*	
OPPD	THIRD PARTY	BLENDED	THIRD PARTY	BLENDED
✓ OPPD Funded ✓ OPPD Administered	✓ Third Party Funded ✓ Third Party Administered	✓ OPPD Funded ✓ Third Party Funded ✓ Third Party Administered	✓ Third Party Lender Referral	✓ OPPD Funded ✓ Third Party Funded ✓ Third Party Administered

HIGHEST SCORED
By core team utilizing evaluation metrics

EVALUATION METRICS

- Accessibility
- Satisfaction
- Messaging/Marketing
- Environmental Impact
- Employee Impact
- Revenue
- Expenses

OPPD
Omaha Public Power District

R.R.S. Neb. § 70-625

Archived code versions

Current currency: Code: Current through Acts of the 2nd Regular Session of the 108th Legislature (2024): LB 1, LB 16, LB 16A, LB 20A, LB 43, LB 51, LB 52A, LB 61, LB 71A, LB 78, LB 83, LB 94, LB 102, LB 102A, LB 130A, LB 139e, LB 140, LB 140A, LB 144, LB 146, LB 147, LB 151, LB 152, LB 164A, LB 184, LB 190, LB 196A, LB 198e, LB 204A, LB 247, LB 252, LB 257, LB 262A, LB 279, LB 287A, LB 299e, LB 303, LB 304, LB 308, LB 317, LB 358A, LB 461, LB 484A, LB 569e, LB 600A, LB 605, LB, 607, LB 624, LB 628, LB 631A, LB 644, LB 644A, LB 658A, LB 664, LB 716, LB 731, LB 771e, LB 771Ae, LB 829A, LB 839e, LB 844, LB 847, LB 848, LB 851e, LB 854, LB 857, LB 857A, LB 867A, LB 870A, LB 876A, LB 894, LB 895, LB 904A, LB 905, LB 905A, LB 906, LB 908, LB 909e, LB 936, LB 938, LB 940, LB 989, LB 992e, LB 992A, LB 1004e, LB 1031A, LB 1035A, LB 1074A, LB 1087, LB 1087A, LB 1102, LB 1104e, LB 1118, LB 1143, LB 1188e, LB 1200A, LB 1204A, LB 1284A, LB 1300A, LB 1301A, LB 1306A, LB 1313, LB 1329A, LB 1344A, LB 1355A, LB 1368A, LB 1394A, LB 1412, LB 1413; and 2024 ballot propositions.

Notice

This section has more than one version with varying effective dates.

§ 70-625. ***Public power district***; ***powers***; restrictions.

(1) Subject to the limitations of the petition for its creation and all amendments to such petition, a ***public power district*** has all the usual ***powers*** of a corporation for ***public*** purposes and may purchase, hold, sell, and lease personal property and real property reasonably necessary for the conduct of its business. No ***district*** may sell household appliances at retail if the retail price of any such appliance exceeds fifty dollars, except that newly developed electrical appliances may be merchandised and sold during the period of time in which any such appliances are being introduced to the ***public***. New models of existing appliances shall not be deemed to be newly developed appliances. An electrical appliance shall be considered to be in such introductory period of time until the particular type of appliance is used by twenty-five percent of all the electrical customers served by such ***district***, but such period shall in no event exceed five years from the date of introduction by the manufacturer of the new appliance to the local market.

(2) In addition to its ***powers*** authorized by Chapter 70 and specified in its petition for creation, as amended, a ***public power district*** may sell, lease, and service satellite television signal descrambling or decoding devices, satellite television programming, and equipment and services associated with such devices and programming, except that this section does not authorize ***public power districts*** (a) to provide signal descrambling or decoding devices or satellite programming to any location (i) being furnished such devices or programming on April 24, 1987, or (ii) where community antenna television service is available from any person, firm, or corporation holding a franchise pursuant to sections 18-2201 to 18-2206 or a permit pursuant to sections 23-383 to 23-388 on April 24, 1987, or (b) to sell, service, or lease C-band satellite dish systems or repair parts.

(3) In addition to the ***powers*** authorized by Chapter 70 and specified in its petition for creation as amended, the board of directors of a ***public power district*** may apply for and use funds available from the United States Department of Agriculture or other federal agencies for grants or loans to promote economic development and job creation projects in rural areas as permitted under the rules and regulations of the federal agency from which the funds are received. Any loan to be made by a ***district*** shall only be made in participation with a bank pursuant to a contract. The ***district*** and the participating bank shall determine the terms and conditions of the contract. In addition, in rural areas of the ***district***, the board of directors of such ***district*** may provide technical or management assistance to prospective, new, or expanding businesses, including home-based businesses, provide assistance to a local or regional industrial or economic development corporation or foundation located within or contiguous to the ***district***'s service area, and provide youth and adult community leadership training.

(4) In addition to the ***powers*** authorized by Chapter 70 and specified in its petition for creation as amended, a ***public power district*** may sell or lease its dark fiber pursuant to sections 86-574 to 86-578.

(5) In addition to the ***powers*** authorized by Chapter 70 and specified in its petition for creation as amended, a ***public power district*** may develop, manufacture, use, purchase, or sell at wholesale advanced biofuels and biofuel byproducts and other fuels and fuel byproducts so long as the development, manufacture, use, purchase, or sale of such biofuels and biofuel byproducts and other fuels and fuel byproducts is done to help offset greenhouse gas emissions.

(6) Notwithstanding any law, ordinance, resolution, or regulation of any political subdivision to the contrary, each ***public power district*** may receive funds and extend loans pursuant to the Nebraska Investment Finance Authority Act or pursuant to this section. In addition to the ***powers*** authorized by Chapter 70 and specified in its petition for creation, as amended, and without the need for further amendment thereto, a ***public power district*** may own and operate, contract to operate, or lease energy equipment and provide billing, meter reading, surveys, or evaluations and other administrative services, but not to include natural gas services, of ***public*** utility systems within a ***district***'s service territory.

History

Laws 1933, c. 86, § 6, p. 346; Laws 1937, c. 152, § 5, p. 583; C.S.Supp.,1941, § 70-706; Laws 1943, c. 146, § 3(1), p. 521; R.S.1943, § 70-625; Laws 1961, c. 335, § 1, p. 1045; Laws 1980, LB 954, § 62; Laws 1987, LB 23, § 1; Laws 1987, LB 345, § 1; Laws 1994, LB 915, § 2; Laws 1997, LB 658, § 8; Laws 1997, LB 660, § 1; Laws 2001, LB 827, § 15; Laws 2002, LB 1105, § 477; 2020 LB 899, § 1, effective November 14, 2020.

End of Document

70-631. Power to borrow; repayment of indebtedness; source of funds; security for indebtedness.

Any district organized under or subject to Chapter 70, article 6, shall have the power to borrow money and incur indebtedness for any corporate use or purpose upon such terms and in such manner as such district shall determine. Any and every indebtedness, liability, or obligation of such district for the payment of money, in whatever manner entered into or incurred, and whether arising from contract, implied contract, or otherwise, shall be payable solely (1) from revenue, income, receipts, and profits derived by the district from its operation and management of power plants, systems, irrigation works, hydrogen producing systems, ethanol producing systems, and from the exercise of its rights and powers with respect to utilization of radioactive material or the energy therefrom or (2) from the issuance or sale by the district of its warrants, notes, debentures, bonds, or other evidences of indebtedness, payable solely from such revenue, income, receipts, and profits, or from the proceeds and avails of the sale of property of the district. Any such district may pledge and put up as collateral security for a loan any revenue debentures, notes, warrants, bonds, or other evidences of indebtedness, issued by it. Any district may arrange for, or put up as security for notes or other evidences of indebtedness of such district, the credit of any bank or other financial institution which has been approved by the directors of such district.

Source: Laws 1933, c. 86, § 9, p. 350; Laws 1937, c. 152, § 6, p. 585; C.S.Supp.,1941, § 70-709; R.S.1943, § 70-631; Laws 1944, Spec. Sess., c. 6, § 1(1), p. 110; Laws 1959, c. 316, § 3, p. 1160; Laws 1967, c. 422, § 1, p. 1297; Laws 1981, LB 181, § 21; Laws 1983, LB 11, § 1; Laws 1986, LB 1230, § 42; Laws 2005, LB 139, § 11.

Annotations

That the statute restricts funds out of which a district may pay its liabilities to revenues derived from operation does not render unconstitutional the grant of power to condemn property prior to commencement of operations. Johnson v. Platte Valley Public Power and Irrigation Dist., 133 Neb. 97, 274 N.W. 386 (1937).

District is not exempt from payment of charges under Federal Power Act. Central Neb. P. P. & I. Dist. v. Federal Power Commission, 160 F.2d 782 (8th Cir. 1947).

70-726. Revenue; use; surplus; return to consumer.

The revenue of the corporation shall be devoted, first, to the payment of operating and maintenance expenses and the principal and interest on outstanding obligations, and thereafter to such reserves for improvement, new construction, depreciation and contingencies, as the board may from time to time prescribe. Revenue not required for the purposes set forth in this section shall be returned from time to time to the users of the services or products of such corporation on a pro rata basis according to the amount of business done with each during the period, either in cash, in abatement of current charges for electric energy, or otherwise, as the board determines; but such return may be made by way of general rate reduction to such users, if the board so elects.

Source: Laws 1937, c. 50, § 25, p. 210; C.S.Supp.,1941, § 70-825; R.S.1943, § 70-726.

The SMR 'hype cycle' hits a hurdle in Australia

Nuclear Monitor Issue:
#886
08/06/2020
Jim Green - Nuclear Monitor editor
Article

Dr. Mark Cooper, senior research fellow for economic analysis at the Institute for Energy and the Environment at Vermont Law School, writes about the small modular reactor (SMR) 'hype cycle' which shares many features with the hype that drove the 'nuclear renaissance' - the short-lived upsurge of interest in large reactors in the late 2000s.[1]

Cooper identifies three stages of the hype cycle:

1. Vendors produce low-cost estimates.

2. Advocates offer theoretical explanations as to why the new nuclear technology will be cost competitive.

3. Government authorities then bless the estimates by funding studies from friendly academics.

But the circular, self-referential SMR hype cycle has been disrupted in Australia by two government agencies, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Energy Market Operator (AEMO). The latest *GenCost* report produced by the two agencies estimates a construction cost of A$16,000 (US$10,700) per kilowatt (kW) for SMRs.[2]

The estimate has been furiously attacked by, amongst others, conservative politicians[3] involved in a federal nuclear inquiry last year, and the Bright New World (BNW) lobby group[3-5] which accepts secret donations from the nuclear industry and has a long history of spreading pro-nuclear misinformation.[6]

BNW objects to CSIRO/AEMO basing their SMR cost estimate on a "hypothetical reactor".[4] But BNW does exactly the same, ignoring real-world cost estimates for SMRs under construction or in operation. BNW starts with the estimate of US company NuScale Power, and adds a 50% 'loading' in recognition of past examples of nuclear reactor cost overruns. Thus BNW's estimate for SMR construction costs is A$9,132 (US$6,090) per kW.[5]

Two big problems: the NuScale cost estimate is bollocks, and BNW's proposed 50% loading doesn't fit the recent pattern of nuclear costs increasing by far greater amounts.

NuScale's construction cost estimate of US$4,200 per kW[7] is implausible. It is far lower than Lazard's latest estimate of US$6,900-12,200 per kW for large reactors[8] and far lower than the lowest estimate (US$12,300 per kW) of the cost of the two Vogtle AP1000 reactors under construction in Georgia (the only reactors under construction in the US).[9] NuScale's estimate (per kW) is just one-third of the cost of the

Vogtle plant – despite the unavoidable diseconomies of scale with SMRs and despite the fact that every independent assessment concludes that SMRs will be more expensive to build (per kW) than large reactors.[10] Further, modular factory-line production techniques were trialled with the twin AP1000 Westinghouse reactor project in South Carolina – a project that was abandoned after the expenditure of at least US$9 billion, bankrupting Westinghouse.[11]

Lazard estimates a levelised cost of US$118–192 per megawatt-hour (MWh) for electricity from large nuclear plants.[8] NuScale estimates a cost of US$65 per MWh for power from its first plant.[12] Thus NuScale claims its electricity will be 2–3 times cheaper than that from large nuclear plants, which is implausible. And even if NuScale achieved its cost estimate, it would still be higher than Lazard's figures for wind power (US$28–54) and utility-scale solar (US$32–44).

BNW claims that the CSIRO/AEMO levelised cost estimate of A$251–330 per MWh for SMRs is an "extreme overestimate".[3] But an analysis by WSP / Parsons Brinckerhoff, prepared for the SA Nuclear Fuel Cycle Royal Commission, estimated a cost of A$225 per MWh for a reactor based on the NuScale design.[13] Power from the Russian floating plant – the only operational SMR in the world – costs an estimated US$200 per MWh (A$300 per MWh).[14] Thus the CSIRO/AEMO figure of A$251–$330 per MWh is reasonable while BNW's figure – A$123–128 per MWh with the potential to fall as low as A$60[3] -- is an extreme underestimate.

BNW promotes[4] a 2016 study by Lovering, Yip and Nordhouse in support of its claims about nuclear construction costs – but the 2016 study was widely criticized[15] for cherry-picking, with one such critic being a former World Nuclear Association executive.[16] BNW also promotes[4] the US Energy Innovation Reform Project report[17], but the cost figures used in the report are nothing more than the optimistic estimates of companies hoping to get 'advanced' reactor designs off the ground. And BNW promotes the report by the Economic and Finance Working Group of the Canadian government-industry 'SMR Roadmap' initiative.[18] But the first-of-a-kind SMR cost estimates in the Canadian report – the most relevant being an estimated C$163 (A$177) per MWh for a 300-MW on-grid SMR – are all higher than BNW's estimate of A$123–128 per MWh.

Cost overruns

BNW proposes adding a 50% 'loading' to NuScale's cost estimate in recognition of past examples of cost overruns. Here are just some of the recent examples of much greater cost increases:

* The estimated cost of the high-temperature gas-cooled SMR (HTGR) under construction in China has nearly doubled.[19]

* The cost of Russia's floating SMR quadrupled.[20]

* The estimated cost of Argentina's SMR has increased 22–fold above early, speculative estimates.[21] and the cost increased by 66% from 2014, when construction began, to 2017.

* The cost estimate for the Vogtle project in US state of Georgia (two AP1000 reactors) has doubled to

more than US$13.5 billion per reactor and will increase further.[9] In 2006, Westinghouse said it could build an AP1000 reactor for as little as US1.4 billion[22] - 10 times lower than the current estimate for Vogtle.

* The estimated cost of about €12.4 billion[23-24] for the only reactor under construction in France is 3.8 times greater than the original €3.3 billion estimate.

* The estimated cost of about €11 billion[25] for the only reactor under construction in Finland is 3.7 times greater than the original €3 billion estimate.

* The estimated combined cost of the two EPR reactors under construction in the UK, including finance costs, is £26.7 billion (the EU's 2014 estimate of £24.5 billion[26] plus a £2.2 billion increase announced in July 2017[27]). In the mid-2000s, the estimated construction cost for one EPR reactor in the UK was £2 billion[28], almost seven times lower than the current estimate.

Timelines

BNW notes that timelines for deployment and construction are "extremely material" in terms of the application of learning rates to capital expenditure.[5] BNW objects to the CSIRO/AEMO estimate of five years for construction of an SMR and proposes a "more probable" three-year estimate as well as an assumption that NuScale's first reactor will begin generating power in 2026 even though construction has not yet begun.[4]

None of the real-world evidence supports BNW's arguments:

* The construction period for the only operational SMR, Russia's floating plant, was 12.5 years.[29]

* Argentina's CAREM SMR was conceived in the 1980s, construction began in 2014, the 2017 start-up date was missed and subsequent start-up dates were missed.[30] If the current schedule for a 2023 start-up[31] is met it will be a nine-year construction project rather than the three years proposed by BNW for construction of an SMR. Last year, work on the CAREM SMR was suspended, with Techint Engineering & Construction asking Argentina's National Atomic Energy Commission to take urgent measures to mitigate the project's serious financial breakdown.[32] In April 2020, Argentina's energy minister announced that work on CAREM would resume.[33]

* Construction of China's HTGR SMR began in 2012[34], the 2017 start-up date was missed[35], and if the targeted late-2020 start-up is met it will be an eight-year construction project.

* NuScale Power has been trying to progress its SMR ambitions for over a decade and hasn't yet begun construction of a single prototype reactor.[36]

* The large reactors under construction in the US are 5.5 years behind schedule and those under construction in France and Finland are 10 years behind schedule.

* In 2007, EDF was boasting that Britons would be using electricity from an EPR reactor at Hinkley Point to cook their Christmas turkeys in December 2017 – but construction didn't even begin until December

2018.[37]

Learning rates

In response to relentless attacks from far-right politicians and lobby groups such as BNW, the latest CSIRO/AEMO *GenCost* report makes the heroic assumption that SMR costs will fall from A$16,000 per kW to A$7,000 per kW in the 2030s. The report states that SMRs were assigned a "higher learning rate (more consistent with an emerging technology) rather than being included in a broad nuclear category, with a low learning rate consistent with more mature large scale nuclear."

But there's no empirical basis, nor any logical basis, for the learning rate assumed in the report. The cost reduction assumes that large numbers of SMRs will be built, and that costs will come down as efficiencies are found, production capacity is scaled up, etc.

Large numbers of SMRs being built? Not according to expert opinion. A 2017 Lloyd's Register report[38] was based on the insights of almost 600 professionals and experts from utilities, distributors, operators and equipment manufacturers, who predicted that SMRs have a "low likelihood of eventual take-up, and will have a minimal impact when they do arrive".[39] A 2014 report produced by *Nuclear Energy Insider*, drawing on interviews with more than 50 "leading specialists and decision makers", noted a "pervasive sense of pessimism" about the future of SMRs.[40] Last year, the North American Project Director for *Nuclear Energy Insider* said that there "is unprecedented growth in companies proposing design alternatives for the future of nuclear, but precious little progress in terms of market-ready solutions."[41]

Will costs come down in the unlikely event that SMRs are built in significant numbers? For large nuclear reactors, the experience has been either a very slow learning rate with modest cost decreases, or a negative learning rate.[42]

Real-world data

Obviously, the starting point for any logical discussion about SMR costs would be the cost of operational SMRs - ignored by CSIRO/AEMO and by lobbyists such as BNW.

There is just one operational SMR plant, Russia's floating plant. Its estimated cost is US$740 million for a 70 MW plant.[20] That equates to A$15,900 per kW - almost identical to the CSIRO/AEMO estimate of A$16,000 per kW. Over the course of construction, the cost quadrupled[20] and a 2016 OECD Nuclear Energy Agency report said that electricity produced by the Russian floating plant is expected to cost about US$200 per MWh with the high cost due to large staffing requirements, high fuel costs, and resources required to maintain the barge and coastal infrastructure.[14]

Figures on costs of SMRs under construction should also be considered - they are far more useful than company estimates, which invariably prove to be highly optimistic.

The World Nuclear Association states that the cost of China's HTGR is US$6,000 per kW.[43] Costs are reported to have nearly doubled, with increases arising from higher material and component costs, increases in labour costs, and increased costs associated with project delays.[19]

The CAREM SMR under construction in Argentina illustrates the gap between SMR rhetoric and reality. In 2004, when the reactor was in the planning stage, Argentina's Bariloche Atomic Center estimated an overnight cost of USS$1,000 per kW for an integrated 300-MW plant (while acknowledging that to achieve such a cost would be a "very difficult task").[44] When construction began in 2014, the cost estimate was US$15,400 per KW[45] By April 2017, the cost estimate had increased US$21,900 per kW.[46]

To the best of my knowledge, no other figures on SMR construction costs are publicly available. So the figures are:

A$15,900 per kW for Russia's light-water floating SMR

A$9,000 per kW for China's HTGR

A$32,800 per kW for Argentina's light-water SMR

The average of those figures is A$19,200 per kW, which is considerably higher than the CSIRO/AEMO figure of A$16,000 per kW and more than double the BNW estimate of A$9,132 per kW.

SMR hype cyclists going around in circles

The hype cycle partly explains the growth of nuclear power a half-century ago, and the short-lived resurgence 10–15 years ago.[1] Currently, SMR hype cyclists are practiced and polished and they have an endless amount of propaganda to recycle and regurgitate. But their economic claims are sharply contradicted by real-world data. And the coordinated propaganda campaign simply isn't working – government funding and private-sector funding is pitiful when measured against the investments required to build SMR prototypes let alone fleets of SMRs and the infrastructure that would allow for mass production of SMR components.

Wherever you look, there's nothing to justify the high hopes and hype of SMR hype cyclists. Argentina's SMR program is a joke. Plans for 18 additional HTGRs at the same site as the demonstration plant in China have been "dropped" according to the World Nuclear Association.[47] Russia planned to have seven floating nuclear power plants by 2015, but only recently began operation of its first plant.[29] South Korea won't build any of its domestically-designed SMART SMRs in South Korea – "this is not practical or economic" according to the World Nuclear Association[48] – and plans to establish an export market for SMART SMRs depend on a wing and a prayer ... and on Saudi oil money which is currently in short supply.[49]

Mark Cooper argues that rather than learning from past experience, nuclear hype cyclists are becoming even more deluded:[1]

"Has the nuclear industry been cured of its myopia? Not at all. In fact, there is a sense that the disease is getting worse, not better, since the characteristics that are said to make small modular technologies attractive are precisely the characteristics that make other alternatives more attractive. In the past, the refusal to look at alternatives could be explained by the fact that the advocates were looking at different

characteristics – claiming that huge baseload facilities are indispensable. They dismissed the alternatives because they are too small or too variable.

"Today, they emphasize small size and speed to market, characteristics on which the alternatives are vastly superior. At the same time they ignore the innovation that has sharply increased renewable load factors and the dramatic advances in information and control technologies that have improved the ability to forecast and integrate renewables."

Cooper's analysis is reflected in the latest CSIRO/AEMO report, which finds that SMR construction costs per kW are 2–8 times higher than costs for wind or solar.[2] Costs per unit of energy produced are 2–3 times greater for nuclear compared to wind or solar including either two hours of battery storage or six hours of pumped hydro energy storage.

Likewise, the latest Lazard's report on levelized costs of energy shows that nuclear power is more expensive than renewables:[8]

Energy Source	*Cost / MWh*
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The SMR 'hype cycle' hits a hurdle in Australia

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Article

Dr. Mark Cooper, senior research fellow for economic analysis at the Institute for Energy and the Environment at Vermont Law School, writes about the small modular reactor (SMR) 'hype cycle' which shares many features with the hype that drove the 'nuclear renaissance' - the short-lived upsurge of interest in large reactors in the late 2000s.[1]

Cooper identifies three stages of the hype cycle:

1. Vendors produce low-cost estimates.

2. Advocates offer theoretical explanations as to why the new nuclear technology will be cost competitive.

3. Government authorities then bless the estimates by funding studies from friendly academics.

But the circular, self-referential SMR hype cycle has been disrupted in Australia by two government agencies, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Energy Market Operator (AEMO). The latest *GenCost* report produced by the two agencies estimates a construction cost of A$16,000 (US$10,700) per kilowatt (kW) for SMRs.[2]

The estimate has been furiously attacked by, amongst others, conservative politicians[3] involved in a federal nuclear inquiry last year, and the Bright New World (BNW) lobby group[3-5] which accepts secret donations from the nuclear industry and has a long history of spreading pro-nuclear misinformation.[6]

BNW objects to CSIRO/AEMO basing their SMR cost estimate on a "hypothetical reactor".[4] But BNW does exactly the same, ignoring real-world cost estimates for SMRs under construction or in operation. BNW starts with the estimate of US company NuScale Power, and adds a 50% 'loading' in recognition of past examples of nuclear reactor cost overruns. Thus BNW's estimate for SMR construction costs is A$9,132 (US$6,090) per kW.[5]

Two big problems: the NuScale cost estimate is bollocks, and BNW's proposed 50% loading doesn't fit the recent pattern of nuclear costs increasing by far greater amounts.

NuScale's construction cost estimate of US$4,200 per kW[7] is implausible. It is far lower than Lazard's latest estimate of US$6,900-12,200 per kW for large reactors[8] and far lower than the lowest estimate (US$12,300 per kW) of the cost of the two Vogtle AP1000 reactors under construction in Georgia (the only reactors under construction in the US).[9] NuScale's estimate (per kW) is just one-third of the cost of the

Vogtle plant – despite the unavoidable diseconomies of scale with SMRs and despite the fact that every independent assessment concludes that SMRs will be more expensive to build (per kW) than large reactors.[10] Further, modular factory-line production techniques were trialled with the twin AP1000 Westinghouse reactor project in South Carolina – a project that was abandoned after the expenditure of at least US$9 billion, bankrupting Westinghouse.[11]

Lazard estimates a levelised cost of US$118–192 per megawatt-hour (MWh) for electricity from large nuclear plants.[8] NuScale estimates a cost of US$65 per MWh for power from its first plant.[12] Thus NuScale claims its electricity will be 2–3 times cheaper than that from large nuclear plants, which is implausible. And even if NuScale achieved its cost estimate, it would still be higher than Lazard's figures for wind power (US$28–54) and utility-scale solar (US$32–44).

BNW claims that the CSIRO/AEMO levelised cost estimate of A$251–330 per MWh for SMRs is an "extreme overestimate".[3] But an analysis by WSP / Parsons Brinckerhoff, prepared for the SA Nuclear Fuel Cycle Royal Commission, estimated a cost of A$225 per MWh for a reactor based on the NuScale design.[13] Power from the Russian floating plant – the only operational SMR in the world – costs an estimated US$200 per MWh (A$300 per MWh).[14] Thus the CSIRO/AEMO figure of A$251–$330 per MWh is reasonable while BNW's figure – A$123–128 per MWh with the potential to fall as low as A$60[3] – is an extreme underestimate.

BNW promotes[4] a 2016 study by Lovering, Yip and Nordhouse in support of its claims about nuclear construction costs – but the 2016 study was widely criticized[15] for cherry-picking, with one such critic being a former World Nuclear Association executive.[16] BNW also promotes[4] the US Energy Innovation Reform Project report[17], but the cost figures used in the report are nothing more than the optimistic estimates of companies hoping to get 'advanced' reactor designs off the ground. And BNW promotes the report by the Economic and Finance Working Group of the Canadian government-industry 'SMR Roadmap' initiative.[18] But the first-of-a-kind SMR cost estimates in the Canadian report – the most relevant being an estimated C$163 (A$177) per MWh for a 300-MW on-grid SMR – are all higher than BNW's estimate of A$123–128 per MWh.

Cost overruns

BNW proposes adding a 50% 'loading' to NuScale's cost estimate in recognition of past examples of cost overruns. Here are just some of the recent examples of much greater cost increases:

* The estimated cost of the high-temperature gas-cooled SMR (HTGR) under construction in China has nearly doubled.[19]

* The cost of Russia's floating SMR quadrupled.[20]

* The estimated cost of Argentina's SMR has increased 22–fold above early, speculative estimates.[21] and the cost increased by 66% from 2014, when construction began, to 2017.

* The cost estimate for the Vogtle project in US state of Georgia (two AP1000 reactors) has doubled to

more than US$13.5 billion per reactor and will increase further.[9] In 2006, Westinghouse said it could build an AP1000 reactor for as little as US1.4 billion[22] - 10 times lower than the current estimate for Vogtle.

* The estimated cost of about €12.4 billion[23-24] for the only reactor under construction in France is 3.8 times greater than the original €3.3 billion estimate.

* The estimated cost of about €11 billion[25] for the only reactor under construction in Finland is 3.7 times greater than the original €3 billion estimate.

* The estimated combined cost of the two EPR reactors under construction in the UK, including finance costs, is £26.7 billion (the EU's 2014 estimate of £24.5 billion[26] plus a £2.2 billion increase announced in July 2017[27]). In the mid-2000s, the estimated construction cost for one EPR reactor in the UK was £2 billion[28], almost seven times lower than the current estimate.

Timelines

BNW notes that timelines for deployment and construction are "extremely material" in terms of the application of learning rates to capital expenditure.[5] BNW objects to the CSIRO/AEMO estimate of five years for construction of an SMR and proposes a "more probable" three-year estimate as well as an assumption that NuScale's first reactor will begin generating power in 2026 even though construction has not yet begun.[4]

None of the real-world evidence supports BNW's arguments:

* The construction period for the only operational SMR, Russia's floating plant, was 12.5 years.[29]

* Argentina's CAREM SMR was conceived in the 1980s, construction began in 2014, the 2017 start-up date was missed and subsequent start-up dates were missed.[30] If the current schedule for a 2023 start-up[31] is met it will be a nine-year construction project rather than the three years proposed by BNW for construction of an SMR. Last year, work on the CAREM SMR was suspended, with Techint Engineering & Construction asking Argentina's National Atomic Energy Commission to take urgent measures to mitigate the project's serious financial breakdown.[32] In April 2020, Argentina's energy minister announced that work on CAREM would resume.[33]

* Construction of China's HTGR SMR began in 2012[34], the 2017 start-up date was missed[35], and if the targeted late-2020 start-up is met it will be an eight-year construction project.

* NuScale Power has been trying to progress its SMR ambitions for over a decade and hasn't yet begun construction of a single prototype reactor.[36]

* The large reactors under construction in the US are 5.5 years behind schedule and those under construction in France and Finland are 10 years behind schedule.

* In 2007, EDF was boasting that Britons would be using electricity from an EPR reactor at Hinkley Point to cook their Christmas turkeys in December 2017 – but construction didn't even begin until December

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Learning rates

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Stanford News (http://news.stanford.edu/)

MAY 30, 2022

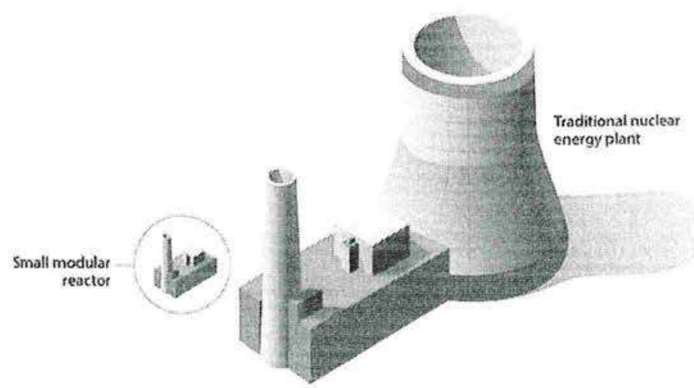
Stanford-led research finds small modular reactors will exacerbate challenges of highly radioactive nuclear waste

Small modular reactors, long touted as the future of nuclear energy, will actually generate more radioactive waste than conventional nuclear power plants, according to research from Stanford and the University of British Columbia.

BY MARK SHWARTZ

Nuclear reactors generate reliable supplies of electricity with limited greenhouse gas emissions. But a **nuclear power plant (https://www.eia.gov/energyexplained/nuclear/nuclear-power-and-the-environment.php)** that generates 1,000 megawatts of electric power also produces radioactive waste that must be isolated from the environment for hundreds of thousands of years. Furthermore, the cost of building a large nuclear power plant can be tens of billions of dollars.

To address these challenges, the nuclear industry is developing **small modular reactors (https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs)** that generate less than 300 megawatts of electric power and can be assembled in factories. **Industry analysts (https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx)** say these advanced modular designs will be cheaper and produce fewer radioactive byproducts than conventional large-scale reactors.



(https://news.stanford.edu/wp-content/uploads/2022/05/Small-modular-reactor.jpg)

Small modular reactors are about 1/10 to 1/4 the size of a traditional nuclear energy plant due to compact, simplified designs. *(Image credit: Idaho National Laboratory)*

But a study **published (https://www.pnas.org/doi/full/10.1073/pnas.2111833119)** May 31 in *Proceedings of the National Academy of Sciences* has reached the opposite conclusion.

“Our results show that most small modular reactor designs will actually increase the volume of nuclear waste in need of management and disposal, by factors of 2 to 30 for the reactors in our case study,” said study lead author Lindsay Krall, a former MacArthur Postdoctoral Fellow at Stanford University's **Center for International Security and Cooperation (CISAC) (https://cisac.fsi.stanford.edu/)**. “These findings stand in sharp contrast to the cost and waste reduction benefits that advocates have claimed for advanced nuclear technologies.”

Global nuclear power

About 440 nuclear reactors operate **globally (https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx)**, providing approximately 10 percent of the world's electricity. In the **United States (https://www.eia.gov/tools/faqs/faq.php?id=427&t=3)**, 93 nuclear reactors generate nearly a fifth of the country's electricity supply.

Unlike power plants that run on coal or natural gas, nuclear plants emit little carbon dioxide, a major cause of global warming. Advocates say that as worldwide demand for clean energy increases, more nuclear power will be needed to minimize the effects of climate change.

But nuclear energy is not risk free. In the U.S. alone, commercial nuclear power plants have **produced (https://earth.stanford.edu/news/steep-costs-nuclear-waste-us#gs.1xy0op)** more than 88,000 metric tons of spent nuclear fuel, as well as substantial volumes of intermediate and low-level radioactive waste. The most highly radioactive waste, mainly spent fuel, will have to be isolated in deep-mined geologic repositories for hundreds of thousands of years. At present, the U.S. has no program to develop a geologic repository, after spending decades and billions of dollars on the Yucca Mountain site in Nevada. As a result, spent nuclear fuel is currently stored in pools or in dry casks at reactor sites, accumulating at a rate of about 2,000 metric tonnes per year.

Simple metrics

Some analysts (https://fuelcycleevaluation.inl.gov/SitePages/Home.aspx) maintain that small modular reactors will significantly reduce the mass of spent nuclear fuel generated compared to much larger, conventional nuclear reactors. But that conclusion is overly optimistic, according to Krall and her colleagues.

“Simple metrics, such as estimates of the mass of spent fuel, offer little insight into the resources that will be required to store, package, and dispose of the spent fuel and other radioactive waste,” said Krall, who is now a scientist at the **Swedish Nuclear Fuel and Waste Management Company (https://www.skb.com/)**. “In fact, remarkably few studies have analyzed the management and disposal of nuclear waste streams from small modular reactors.”

Dozens (https://www.thirdway.org/graphic/2019-advanced-nuclear-map) of small modular reactor designs have been proposed. For this study, Krall analyzed the nuclear waste streams from three types of small modular reactors being developed by Toshiba, NuScale, and Terrestrial Energy. Each company uses a different design. Results from case studies were corroborated by theoretical calculations and a broader design survey. This three-pronged approach enabled the authors to draw powerful conclusions.

"The analysis was difficult, because none of these reactors are in operation yet," said study co-author **Rodney Ewing (https://profiles.stanford.edu/rodney-ewing)**, the Frank Stanton Professor in Nuclear Security at Stanford and co-director of CISAC. "Also, the designs of some of the reactors are proprietary, adding additional hurdles to the research."

Neutron leakage

Energy is produced in a nuclear reactor when a neutron splits a uranium atom in the reactor core, generating additional neutrons that go on to split other uranium atoms, creating a chain reaction. But some neutrons escape from the core – a problem called neutron leakage – and strike surrounding structural materials, such as steel and concrete. These materials become radioactive when "activated" by neutrons lost from the core.

The new study found that, because of their smaller size, small modular reactors will experience more neutron leakage than conventional reactors. This increased leakage affects the amount and composition of their waste streams.

"The more neutrons that are leaked, the greater the amount of radioactivity created by the activation process of neutrons," Ewing said. "We found that small modular reactors will generate at least nine times more neutron-activated steel than conventional power plants. These radioactive materials have to be carefully managed prior to disposal, which will be expensive."

The study also found that the spent nuclear fuel from small modular reactors will be discharged in greater volumes per unit energy extracted and can be far more complex than the spent fuel discharged from existing power plants.

"Some small modular reactor designs call for chemically exotic fuels and coolants that can produce difficult-to-manage wastes for disposal," said co-author **Allison Macfarlane (https://sppga.ubc.ca/profile/allison-macfarlane/)**, professor and director of the School of Public Policy and Global Affairs at the University of British Columbia. "Those exotic fuels and coolants may require costly chemical treatment prior to disposal."

"The takeaway message for the industry and investors is that the back end of the fuel cycle may include hidden costs that must be addressed," Macfarlane said. "It's in the best interest of the reactor designer and the regulator to understand the waste implications of these reactors."

Radiotoxicity

The study concludes that, overall, small modular designs are inferior to conventional reactors with respect to radioactive waste generation, management requirements, and disposal options.

One problem is long-term radiation from spent nuclear fuel. The research team estimated that after 10,000 years, the radiotoxicity of plutonium in spent fuels discharged from the three study modules would be at least 50 percent higher than the plutonium in conventional spent fuel per unit energy extracted.

Because of this high level of radiotoxicity, geologic repositories for small modular reactor wastes should be carefully chosen through a thorough siting process, the authors said.

"We shouldn't be the ones doing this kind of study," said Ewing. "The vendors, those who are proposing and receiving federal support to develop advanced reactors, should be concerned about the waste and conducting research that can be reviewed in the open literature."

Rod Ewing is also a professor in the Department of Geological Sciences in the Stanford **School of Earth, Energy and Environmental Sciences (https://earth.stanford.edu/)**. The Center for International Security and Cooperation is part of the **Freeman Spogli Institute for International Studies (https://fsi.stanford.edu/)** at Stanford.

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Media Contacts

Rod Ewing, Geological Sciences: (650) 725-8641, **rewing1@stanford.edu (mailto:rewing1@stanford.edu)**
Mark Golden, Precourt Institute for Energy: (650) 724-1629, **mark.golden@stanford.edu (mailto:mark.gol**
Lindsay Krall, Swedish Nuclear Fuel and Waste Management Company: +46 70 254 0560, **Lindsay.M.Krall@ (mailto:Lindsay.M.Krall@gmail.com)**
Allison Macfarlane, School of Public Policy and Global Affairs, University of British Columbia: 617-460-103
Allison.macfarlane@ubc.ca (mailto:Allison.macfarlane@ubc.ca)

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Nuclear waste from small modular reactors

Lindsay M. Krall, Allison M. Macfarlane, and Rodney C. Ewing Authors Info & Affiliations

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Significance

Small modular reactors (SMRs), proposed as the future of nuclear energy, have purported cost and safety advantages over existing gigawatt-scale light water reactors (LWRs). However, few studies have assessed the implications of SMRs for the back end of the nuclear fuel cycle. The low-, intermediate-, and high-level waste stream characterization presented here reveals that SMRs will produce more voluminous and chemically/physically reactive waste than LWRs, which will impact options for the management and disposal of this waste. Although the analysis focuses on only three of dozens of proposed SMR designs, the intrinsically higher neutron leakage associated with SMRs suggests that most designs are inferior to LWRs with respect to the generation, management, and final disposal of key radionuclides in nuclear waste.

Abstract

Small modular reactors (SMRs; i.e., nuclear reactors that produce <300 MW_{elec} each) have garnered attention because of claims of inherent safety features and reduced cost. However, remarkably few studies have analyzed the management and disposal of their nuclear waste streams. Here, we compare three distinct SMR designs to an 1,100-MW_{elec} pressurized water reactor in terms of the energy-equivalent volume, (radio-)chemistry, decay heat, and fissile isotope composition of (notional) high-, intermediate-, and low-level waste streams. Results reveal that water-, molten salt–, and sodium-cooled SMR designs will increase the volume of nuclear waste in need of management and disposal by factors of 2 to 30. The excess waste volume is attributed to the use of neutron reflectors and/or of chemically reactive fuels and coolants in SMR designs. That said, volume is not the most important evaluation metric; rather, geologic repository performance is driven by the decay heat power and the (radio-)chemistry of spent nuclear fuel, for which SMRs provide no benefit. SMRs will not reduce the generation of geochemically mobile ^{129}I, ^{99}Tc, and ^{79}Se fission products, which are important dose contributors for most repository designs. In addition, SMR spent fuel will contain relatively high concentrations of fissile nuclides, which will demand novel approaches to evaluating criticality during storage and disposal. Since waste stream properties are influenced by neutron leakage, a basic physical process that is enhanced in small reactor cores, SMRs will exacerbate the challenges of nuclear waste management and disposal.

In recent years, the number of vendors promoting small modular reactor (SMR) designs, each having an electric power capacity <300 MW_{elec}, has multiplied dramatically (1, 2). Most recently constructed reactors have electric power capacities >1,000 MW_{elec} and utilize water as a coolant. Approximately 30 of the 70 SMR designs listed in the International Atomic Energy Agency (IAEA) Advanced Reactors Information System are considered "advanced" reactors, which call for seldom-used, nonwater coolants (e.g., helium, liquid metal, or molten salt) (3). Developers promise that these technologies will reduce the financial, safety, security, and waste burdens associated with larger nuclear power plants that operate at the gigawatt scale (3). Here, we make a detailed assessment of the impact of SMRs on the management and disposal of nuclear waste relative to that generated by larger commercial reactors of traditional design.

Nuclear technology developers and advocates often employ simple metrics, such as mass or total radiotoxicity, to suggest that advanced reactors will generate "less" spent nuclear fuel (SNF) or high-level waste (HLW) than a gigawatt-scale pressurized water reactor (PWR), the prevalent type of commercial reactor today. For instance, Wigeland et al. (4) suggest that advanced reactors will reduce the mass and long-lived radioactivity of HLW by 94 and ~80%, respectively. These bulk metrics, however, offer little insight into the resources that will be required to store, package, and dispose of HLW (5). Rather, the safety and the cost of managing a nuclear waste stream depend on its fissile, radiological, physical, and chemical properties (6). Reactor type, size, and fuel cycle each influence the properties of a nuclear waste stream, which in addition to HLW, can be in the form of low- and intermediate-level waste (LILW) (6–8). Although the costs and time line for SMR deployment are discussed in many reports, the impact that these fuel cycles will have on nuclear waste management and disposal is generally neglected (9–11).

Here, we estimate the amount and characterize the nature of SNF and LILW for three distinct SMR designs. From the specifications given in the NuScale integral pressurized water reactor (iPWR) certification application, we analyze basic principles of reactor physics relevant to estimating the volumes and composition of iPWR waste and then, apply a similar methodology to a back-end analysis of sodium- and molten salt–cooled SMRs. Through this bottom-up framework, we find that, compared with existing PWRs, SMRs will increase the volume and complexity of LILW and SNF. This increase of volume and chemical complexity will be an additional burden on waste storage, packaging, and geologic disposal. Also, SMRs offer no apparent benefit in the development of a safety case for a well-functioning geological repository.

1. SMR Neutronics and Design

A nuclear reactor is designed to sustain criticality, a chain reaction of fission events that generates energy (~200 MeV per fission event) and extra neutrons that can cause fission in nearby fissile nuclides. The neutron "economy" of a reactor depends on the efficiency of the chain reaction process; the fate of neutrons absorbed by abundant nuclides, such as ^{238}U or ^{232}Th; the fission of newly generated fissile nuclides, such as ^{239}Pu and ^{233}U; and the loss of neutrons across the fuel boundary. These "lost" neutrons can activate structural materials that surround the fuel assemblies. Each of these physical processes generates radioactive waste. Thus, the final composition of the SNF and associated wastes depend on the initial composition of the fuel, the physical design of the fuel, burnup, and the types of structural materials of the reactor.

The probability of neutron leakage is a function of the reactor dimensions and the neutron diffusion length, the latter of which is determined by the neutron scattering properties of the fuel, coolant, moderator, and structural materials in the reactor core (12). The neutron diffusion length will be the same in reactors that use similar fuel cycles and fuel–coolant–moderator combinations; thus, the neutron leakage probability will be larger for an SMR than for a larger reactor of a similar type (*SI Appendix*, section 1).

For thermal-spectrum reactors, the neutrons undergo elastic scattering with the water or graphite moderator, leading to neutron diffusion lengths that are short relative to the core dimensions. Here, leakage grows quadratically with decreasing core radius and reactor size (*SI Appendix*, section 1). For instance, a 3,400-MW_{th} PWR will leak <3% of its free neutrons, whereas a 160-MW_{th} iPWR may leak >7% (9). Leakage from fast reactors is also high, at least 4% and up to 25%, depending on the fuel composition and other aspects of core design (13). Overall, both water and nonwater SMRs entail increased neutron leakage as compared with a gigawatt-scale light water reactor (LWR) (*SI Appendix*, section 1).

Small increases in neutron leakage have a significant effect on core criticality and power output and will lead to reduced SNF burnup (a measure of fuel efficiency expressed in units of energy extracted per mass of heavy metal in the initial fuel; e.g., megawatt-days per kilogram, or MWd/kg) (*SI Appendix*, section 1) (9, 14) unless compensated for by design changes to the reactor and/or fuel, including

- utilizing a fuel enriched to >5 wt % initial ^{235}U or ^{239}Pu to increase the initial fissile loading and the probability of neutron absorption by a fissile element,
- introducing a neutron reflector to redirect a fraction of leaked neutrons back into the core, and/or
- foregoing a neutron moderator or using graphite rather than water.

Most of the SMR designs listed in the IAEA Aris database incorporate one or all these strategies to improve the core neutron economy (Table 1).

Table 1.

Select SMRs and full-scale reactors to illustrate differences in fuel enrichment, burnup, and reactor materials

Reactor type	MW_{th}	Enrichment (%)	burnup (MWd/kg)	Vessel lifetime (y)	Moderator (if not water)	Coolant (if not water)	Re
Boiling water							

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n/a, not applicable.

In this paper, we describe how these changes manifest in water-, sodium-, and molten salt–cooled SMR designs and their impact on the volume, composition, and geologic disposal of SNF/HLW and LILW.

2. Framework for Waste Comparison

The management and disposal of nuclear waste are influenced by the formation and distribution of radionuclides throughout a reactor, which in turn, depend on the geometry, composition, and flow paths of reactor, fuel, moderator, and coolant materials. These specifications were tabulated for 16 SMR designs (Table 1). Of these, the NuScale iPWR, the Toshiba 4S sodium-cooled fast reactor, and the Terrestrial Energy Integral Molten Salt Reactor (IMSR) were selected for in-depth, quantitative and qualitative waste assessments, because reliable reactor and fuel cycle specifications for these designs have been published in (pre-)license and patent application materials. Where proprietary design parameters were redacted from these materials, gaps in the availability of technical data were filled through explicit assumptions, through reference to similar designs analyzed in the scientific literature, or through derivation using known design parameters.

2.1. Metrics.

The quantitative comparison aimed to determine whether advanced reactors will generate less nuclear waste than existing LWRs. SNF and LILW volumes were calculated for each of the three SMR designs, and the results were normalized to the thermal energy generated by the respective reactor or fuel cycle, roughly the reactor power integrated over the reactor lifetime or fuel cycle length (sections 3 and 4). This metric, the energy-equivalent waste volume (in cubic meters per gigawatt thermal-year, or m^3/GW_{th}-y), was used to compare SMR and PWR waste volumes relative to their respective energy benefits. Fuel burnup and core geometry specifications were used to estimate the SNF volumes (sections 3.2 and 4), whereas neutron flux and primary coolant loop specifications were used to estimate the volume of reactor material that will become neutron activated or contaminated to result in long- or short-lived decommissioning LILW (sections 3.3, 4.1, and 4.2).

The metrics "volume" and "energy-equivalent volume," however, do not reflect the radionuclide composition and speciation, much more important parameters for the proper evaluation of the impact on the safety of a geologic repository. Nuclear reactors generate several distinct waste streams, which contain variable concentrations of radionuclides that have a range of half-lives from hours to millions of years and a variety of very different nuclear and chemical properties. Thus, in addition to calculating the SMR waste volumes, we characterize the radiochemical compositions of SNF and LILW streams (sections 3 and 4) and then, discuss their management and disposal as SNF or LILW in a geologic repository (section 4).

2.2. LILW.

Decommissioning LILW that contains low or very low concentrations of short- or long-lived radionuclides (half-lives less than or greater than 30 y, respectively) may qualify for disposal as "short-lived LILW" in a near-surface disposal facility. However, "long-lived LILW" that contains intermediate concentrations of long-lived radionuclides and/or short-lived radionuclides in concentrations high enough to warrant radiation-shielded packaging should be disposed of in a geologic repository that has multiple natural and engineered barriers (6).

In this paper, we classify reactor materials that may become neutron activated via neutron leakage from the active core as long-lived decommissioning LILW (sections 3.3.1 and 4.2), whereas materials that may become contaminated by contact with the primary reactor coolant are classified as short-lived LILW (sections 3.3.2 and 4). Where possible, we refer to neutron flux models or to previous waste characterization studies to justify these SMR LILW classifications. However, in practice, these classifications should be verified through an iterative safety assessment process. This involves sampling and analysis of reactor materials to constrain the source term as well as site-specific radionuclide transport simulations that consider the temporal evolution of a proposed repository, including its natural hydrogeochemistry, as coupled with an engineered barrier system (section 4).

2.3. HLW or SNF.

Similar to LILW, the safe management and disposal of SNF or HLW must take into account metrics beyond mass, volume, or radioactivity. Therefore, we compare the SNF that will be generated by SMRs with that discharged by LWRs in terms of

- the chemistry of the SNF matrix and its radionuclide contents, which influences the environmental mobility of radionuclides and their consequent potential to deliver radiation doses to humans in the biosphere;
- the heat generated by radioactive decay, which can damage the SNF matrix, as well as other components of the barrier system (e.g., the stability of backfill clays used to inhibit radionuclide transport); and
- the concentrations of fissile isotopes in the SNF, which influence its potential to sustain a heat-generating critical chain reaction that can damage the fuel and barrier systems in a geologic repository.

These variables depend on the SNF radiochemical composition (i.e., the radionuclide amount and type, including their chemical properties, half-lives, decay modes, and daughter products), which in turn, depends on the initial fuel composition, its final burnup, and the time elapsed since it was discharged from the reactor. In addition, the in-core neutron energy spectrum affects the types and amounts of radionuclides formed in the fuel and reactor materials, such that the composition of SNF generated by a moderated thermal-spectrum reactor will differ from that generated by a fast reactor. SMR and LWR fuel burnups and compositions are compared in terms of repository design and long-term safety assessments in section 4.

2.4. Waste Chemistry.

Whether a particular nuclear material can be stored or disposed of at a specific facility is, in part, governed by its radiochemical and bulk chemical compositions. LWRs generate decommissioning LILW and SNF in the nominal forms of concrete, steel, zirconium cladding, and UO_2. Since these materials do not react rapidly or violently under ambient conditions, they can be stored or disposed of at appropriately designed facilities. On the other hand, non-LWR SMRs employ chemically exotic fuels and coolants (e.g., metallic sodium, metallic uranium, and uranium tetrafluoride) that react rapidly with water and/or atmospheric oxygen. Since experience with handling and disposing of these chemically unstable waste streams is limited, we refer to decommissioning reports from previous experimental reactors to infer the implications that novel SMR materials will have for the direct disposal of their wastes (sections 4). Prior to disposal, exotic spent fuel, coolant, and/or moderator materials will require treatment and conditioning. However, the properties of the by-products and infrastructure associated with these processes are uncertain, so the additional waste streams generated by treatment and conditioning processes are not quantified in this study.

This study also neglects to consider reprocessing, recycling, and dilution because these treatments will not eliminate the need for the storage, transportation, treatment, and disposal of radioactive materials.

3. SMR Waste Streams: Volumes and Characteristics

3.1. Novel SMR Design Features.

Many SMRs adopt an "integral" design, wherein the reactor core and certain auxiliary systems (e.g., steam generators, pressurizers, and/or heat exchangers) are all contained within a reactor vessel (*SI Appendix*, Figs. S2 and S3). Several SMRs may be colocated at a single power station. For instance, a NuScale iPWR station may host up to 12 160-MW_{th} iPWRs, each submerged in a common reactor pool that shares water with the SNF cooling pool (15, 16).

Primary coolant (e.g., in the form of water, molten salt, or sodium) will be heated at the core and circulated upward through the center of the reactor vessel. At the upper portion of the reactor vessel, the primary coolant is redirected downward to flow over heat exchangers, which warm a secondary coolant that ultimately supports the power train. The primary coolant comes in direct contact with the active core and so, represents an important conduit that, under normal operating conditions, can contaminate the reactor vessel and its contents with radionuclides.

In the case of sodium- and molten salt–cooled SMRs, the primary coolant will be chemically reactive (section 3.4.3), heated to temperatures >500 °C, and highly radioactive (2). Under these extreme conditions, reactor components can have a shorter lifetime than the standard PWR (60 y), and this will increase decommissioning LILW volumes. In addition, nonlight water SMRs will introduce uncommon types of LILW in the form of neutron reflectors and chemically reactive coolant or moderator materials.

The following sections show how the difference between SMR and full-scale reactor core geometries, primary coolant flow paths, and refueling procedures will impact the generation of short- and long-lived decommissioning LILW.

3.2. SNF: burnup, Mass, and Volume.

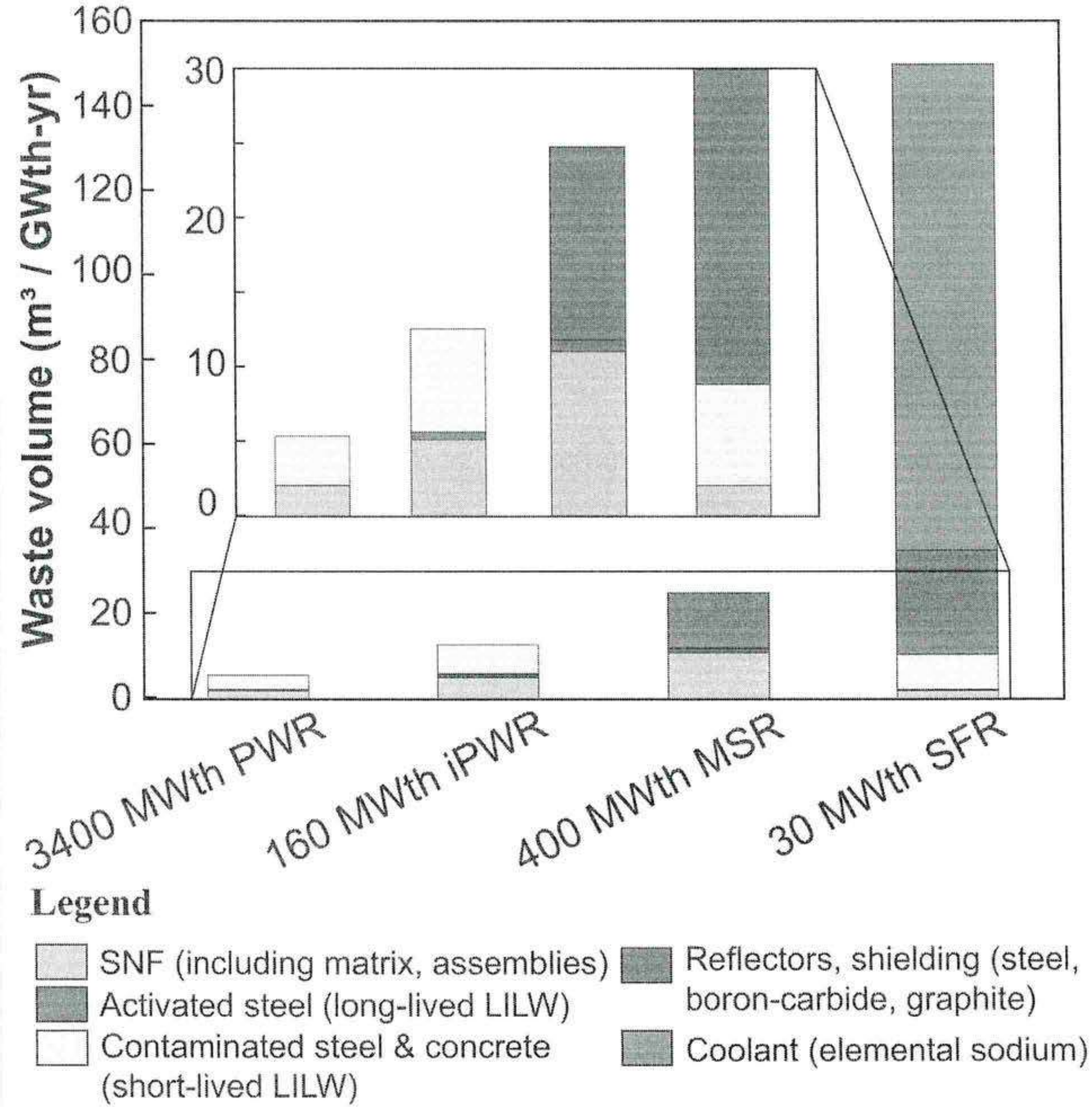
For PWR and iPWR designs that each employ UO_2 fuel enriched to ~5 wt % ^{235}U, previous investigators report that neutron leakage (section 2) will reduce fuel burnups from ~55 MWd/kg, as achieved by PWRs, to 26 to 34 MWd/kg for an iPWR (9, 15). Since burn-up details were redacted from the publicly available license application of the NuScale reactor, a burnup of ~34 MWd/kg is here calculated using the fuel rod dimensions, linear power density, and reactor operating parameters provided for this iPWR (*SI Appendix*, Table S2) (17). Operating as recommended by NuScale, a 12-module iPWR station (1,900 MW_{th}) would discharge ~21 MT SNF/y, which is similar to a power station that hosts a single 3,400-MW_{th} PWR (burnup of 57 MWd/kg) (*SI Appendix*, Table S2). Per energy equivalent, the mass of SNF that will be discharged by an iPWR is 1.7-fold greater than that discharged by a gigawatt-scale PWR (*SI Appendix*, Table S2).

Like the NuScale iPWR, molten salt– and sodium-cooled SMRs will experience enhanced neutron leakage (section 2 and *SI Appendix*, section 1). Although these SMR designs may seek to offset the leakage by using neutron reflectors and/or fuel enriched to >5 wt % initial fissile concentration, fuel burnups will be lower than for larger molten salt– and sodium-cooled reactors (Table 1). For instance, the use of 19 wt % initial fissile fuel in a 2-, 30-, or 135-MW_{th}

sodium SMR will achieve burnups of <10, 34, or 90 MWd/kg, respectively (Table 1). ThorCon's 560-MW_{th} molten salt SMR also calls for a fuel enriched to ~20 wt % fissile isotopes that is claimed to achieve a burnup of 250 MWd/kg. However, 3%-enriched ^{235}U fuel in Terrestrial Energy's 400-MW_{th} molten salt SMR will achieve a burnup of only 14 MWd/kg (Table 1).

The energy-equivalent mass of SNF generated by these SMRs can be calculated from the inverse of the respective burnup. Whereas a PWR with a burnup of 55 MWd/kg discharges ~6.5 MT SNF/GW_{th}-y, a nonwater-cooled SMR may discharge 1.5 to >36 MT SNF/GW_{th}-y. These figures, however, solely reflect the mass of uranium, actinides, and fission products in the SNF and neglect contributions from salt or sodium constituents in or around the fuel matrix. Such low-density materials contribute little to mass-based SNF estimates but nevertheless, will contribute to volume-based estimates. For the 160-MW_{th} NuScale, the 400-MW_{th} Terrestrial Energy, and the 30-MW_{th} Toshiba SMR designs, volumetric discharges of 5.1, 11, and 2.0 m^3 SNF/GW_{th}-y, respectively, have been calculated as compared with 2.0 m^3 SNF/GW_{th}-y for a PWR (Fig. 1 and *SI Appendix*, section 2). The management and disposal implications for low–burnup SMR fuel are discussed in section 4.

Fig. 1.



Energy-equivalent waste volumes, by waste type, for various SMR designs—including the NuScale iPWR, the Terrestrial Energy IMSR, and the sodium-cooled Toshiba 4S SMRs.

3.3. Long-Lived LILW: Activated Steel from Reactor Vessels and Neutron Reflectors.

In general, long-lived LILW consists of near-core reactor components that have become radioactive or "activated" after absorbing neutrons leaked from the core (18, 19) (section 2). This activated steel contains radioisotopes with half-lives longer than several thousand years (e.g., ^{59}Ni, ^{14}C, ^{94}Nb, ^{99}Tc, ^{93}Zr, ^{93}Mo, and ^{36}Cl) and so, should be disposed of in a geologic repository that will limit and delay the introduction of radionuclides to the surface ecosystem (Table 2) (7, 20, 21).

Table 2.

Activation products and half-lives of core barrel, moderator, neutron reflector, shielding, and coolant materials for various SMR designs

Material	Activation product ($t_{1/2}$, y)	Notes	Ref.
Stainless steel	^{54}Mn (0.85), ^{55}Fe (2.7), ^{60}Co (5.3), ^{63}Ni (1.0e2), ^{93}Mo (4.0e3), ^{14}C (5.7e3), ^{94}Nb (2.0e4), ^{59}Ni (7.6e4), ^{99}Tc (2.1e5), ^{36}Cl	Depends on the composition of steel	19, 20

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FLiBe, a mixture of fluorine, lithium, and beryllium.

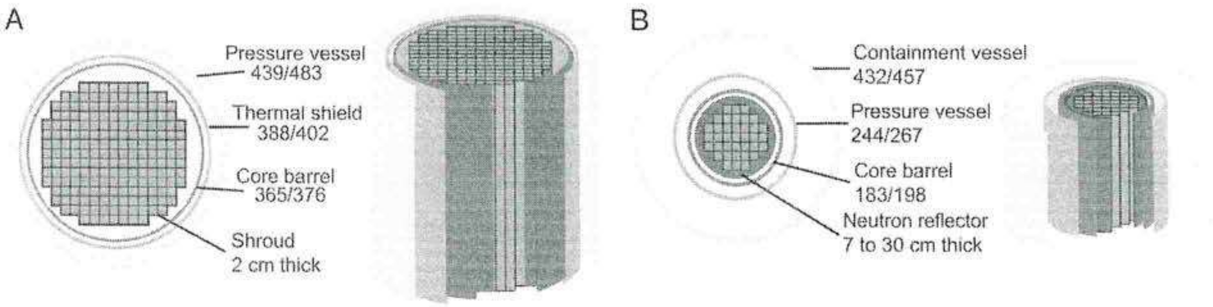
3.3.1. Near-core iPWR components.

The degree of activation in near-core reactor steel is directly proportional to the time-integrated flux of neutron exposure or the neutron "fluence" (21). Although a NuScale iPWR generates 95% less heat than a full-scale PWR, the total neutron flux at the periphery of an active iPWR core will be similar to that of the AP1000 (>10^{14} neutrons/cm^2-s) (18, 22).

Activation models that account for the geometry and composition of PWR cores indicate that exposure to a thermal neutron fluence >10^{21} neutrons/cm^2 (i.e., a neutron flux >10^{12} neutrons/cm^2-s for 60 y at 70% capacity factor) will qualify a component as long-lived LILW or Greater-than-Class-C waste, as defined by the US Nuclear Regulatory Commission (*SI Appendix*, Fig. S1) (19, 21).

NuScale indicates that the iPWR pressure vessel, located ~35 cm from the active core, is exposed to a thermal neutron flux of $2.4 \cdot 10^{11}$ neutrons/cm^2-s (Fig. 2 and *SI Appendix*, Fig. S1) (18). This exceeds the thermal flux at the pressure vessel of a PWR ($5.3 \cdot 10^{10}$ neutrons/cm^2-s) by a factor of 4.5 (23). If the iPWR operates for 60 y at 95% capacity (18), the neutron fluence at the iPWR pressure vessel, ~$4.3 \cdot 10^{20}$ neutrons/cm^2, will approach the long-lived LILW activation limit of 10^{21} neutrons/cm^2. Hence, NuScale iPWR components located between the core and the pressure vessel, including the core barrel and the neutron reflector (*SI Appendix*, Fig. S1), may warrant geologic disposal as long-lived LILW at decommissioning. Whether the NuScale iPWR pressure vessel will also reach long-lived LILW activation levels is uncertain and may vary according to nation-specific regulations.

Fig. 2.



To-scale drawing of (A) 1,000-MW_{elec} PWR and (B) 50-MW_{elec} NuScale iPWR cores showing inner and outer diameters of cylindrical components (in centimeters) and color coded according to anticipated status as short-lived (yellow) or long-lived (light red and maroon) LILW. Orange color indicates uncertainty with respect to short- or long-lived LILW status.

Since the NuScale iPWR components discussed will consist of stainless steel with a composition similar to that of a PWR (i.e., type 304/304L stainless steel) (8, 19), these long-lived LILW estimates are not sensitive to differences in the steel composition and associated neutron absorption cross-sections.

The volume of long-lived LILW that might arise from decommissioning a 160-MW_{th} iPWR was estimated and compared with the corresponding figures for a 3,400-MW_{th} PWR (19) (*SI Appendix*, Table S3). One iPWR will generate 0.29 or 0.53 m^3/GW_{th}-y depending on whether the pressure vessel will be activated to long-lived LILW levels. Compared with a PWR ($3.1 \cdot 10^{-2}$ m^3/GW_{th}-y), the NuScale iPWR would increase the energy-equivalent volume of long-lived decommissioning LILW waste in need of geologic disposal by a factor of 9 to 17 (*SI Appendix*, Table S3).

3.3.2. Corroded vessels from molten salt reactors.

Molten salt reactor vessel lifetimes will be limited by the corrosive, high-temperature, and radioactive in-core environment (23, 24). In particular, the chromium content of 316-type stainless steel that constitutes a PWR pressure vessel is susceptible to corrosion in halide salts (25). Nevertheless, some developers, such as ThorCon, plan to adopt this stainless steel rather than to qualify a more corrosion-resistant material for the reactor vessel (25).

Terrestrial Energy may construct their 400-MW_{th} IMSR vessel from Hastelloy N, a nickel-based alloy that has not been code certified for commercial nuclear applications by the American Society of Mechanical Engineers (26, 27). Since this nickel-based alloy suffers from helium embrittlement (27), Terrestrial Energy envisions a 7-y lifetime for their reactor vessel (28). Molten salt reactor vessels will become contaminated by salt-insoluble fission products (28) and will also become neutron-activated through exposure to a thermal neutron flux greater than 10^{12} neutrons/cm^2-s (29). Thus, it is unlikely that a commercially viable decontamination process will enable the recycling of their alloy constituents. Terrestrial Energy's 400-MW_{th} SMR might generate as much as 1.0 m^3/GW_{th}-y of steel or nickel alloy in need of management and disposal as long-lived LILW (Fig. 1, Table 1, and *SI Appendix*, Fig. S3 and section 2).

3.3.3. Damaged reflectors and shielding from fast-spectrum SMRs.

Since fast-spectrum SMRs—cooled by gas or by molten sodium, lead, or salt—forego a neutron moderator, these designs employ neutron reflectors and shielding to mitigate damage to the reactor vessel caused by fast neutron bombardment (Table 1) (30, 31). Although neutron absorption cross-sections are, in general, lower for fast than for thermal neutrons, fast neutron fluxes in sodium-cooled SMRs will exceed 10^{15} n/cm^2-s (32). Thus, the need to manage and dispose of activated reflector and shielding subassemblies as long-lived LILW can be anticipated. For example, after operating for 20 y, the 750-MW_{th} BN-350 sodium-cooled fast reactor (Kazakhstan: 1973 to 1993) generated ~13 m^3 of activated steel that contained long-lived ^{59}Ni and ^{94}Nb radionuclides in concentrations sufficient to warrant geologic disposal of its reflectors and shielding as long-lived LILW (33).

Common reflector and shielding materials include steel and boron carbide, respectively, but beryllium, magnesium, lead, and other materials have also been considered (31). Although some of these materials form few long-lived activation products, they will be clad by steel cladding that does form long-lived activation products and will be lifetime limited by fast neutron damage (Table 2) (32, 34). Given the 30-y core lifetime and dimensions stated by Toshiba, a 30-MW_{th} sodium-cooled SMR will generate up to 25 m^3/GW_{th}-y of activated reflector and shielding assemblies that may be classified as long-lived LILW (Table 1 and *SI Appendix*, Fig.

S3 and section 2; see Fig. 1).

3.4. Short-Lived LILW.

3.4.1. Contaminated iPWR components.

Short-lived LILW is primarily generated by surface contamination of structural materials that have been in contact with the reactor coolant, which carries radioisotopes sourced by ruptured fuel rods and activated corrosion products (35). Inventory reports indicate that a 3,400-MW_{th} PWR in Sweden will generate ~600 m^3 (3.3 m^3/GW_{th}-y) of short-lived decommissioning LILW in the form of contaminated steel and activated concrete (*SI Appendix*, Table S3) (36, 37).

Short-lived LILW from a NuScale iPWR will be dominated by steel from the pressure and containment vessels (Fig. 2) that will become contaminated by radionuclides carried by water in the primary coolant and the reactor pool. Ultimately, the iPWR pressure and containment vessels will generate 17 and 43 m^3 of short-lived decommissioning LILW, respectively, equivalent to 6.9 m^3/GW_{th}-y (*SI Appendix*, Table S3). This neglects the iPWR internal components (e.g., the steam generators) and contributions from structural materials in the reactor–SNF pool and so, represents a lower-limit estimate. Therefore, per energy equivalent, a 160-MWth iPWR will generate at least a twofold larger volume of short-lived decommissioning LILW than a 3,400-MW_{th} PWR.

3.4.2. Graphite moderators from molten salt reactors.

Thermal-spectrum molten salt reactor designs tend to employ graphite as both a neutron moderator and reflector (Table 2). This graphite may occupy 60 to 80% of the core volume, the remainder of which will be occupied by a liquid fuel–coolant salt that flows through hollow tubes in the graphite matrix, carrying with it dissolved fuel isotopes and fission products (38). Graphite in the Oak Ridge Molten Salt Reactor Experiment (MSRE) acquired surface contamination by Mo, Te, Ru, and Nb fission products, whereas tritium, Cs, and Sr radioisotopes (generated via decay of Xe and Kr fission products) diffused into the porous structure of the graphite (39, 40). Whether and where this graphite has been disposed of are unclear, although the management and disposal of graphite moderators recovered from Magnox and Reaktor Bolsjoj Mosjnosti Kanalnyj (RBMK) reactors have been complicated by the presence of both short- and long-lived isotopes—including tritium, ^{14}C, corrosion/activation products, fission products, and actinides (Table 2) (41).

Since graphite tends to expand and crack during prolonged irradiation, its lifetime in an SMR will be limited (42). Depending on the magnitude of its neutron flux exposure, graphite lifetimes for the molten salt SMR designs pursued today will range from 2.5 to 30 y (39) (Table 1). Given a stated lifetime of 7 y, the 400-MW_{th} IMSR (Terrestrial Energy) will discharge ~13 m^3/GW_{th}-y of radioactive graphite that will require geologic disposal (Fig. 1, Table 1, and *SI Appendix*, section 2).

3.4.3. Liquid metal and salt coolants.

When an LWR is decommissioned, many of the radionuclides in its cooling water (section 3.3.1) can be removed by filters and ion exchange resins (43). However, storage, decontamination, and disposal of radioactive sodium- and molten salt–based coolants will need to account for their chemical complexity and tendency to generate explosive or corrosive by-products upon contact with air or moisture.

At the experimental sodium-cooled fast reactors operated during the late twentieth century, decommissioning was complicated by the large volumes of metallic sodium coolant that became contaminated by a ^{22}Na activation product and by Cs isotopes leached from ruptured fuel elements (34). This pyrophoric sodium was deactivated through a pilot-scale water-based process that was performed under an inert atmosphere to prevent the explosion of a hydrogen by-product. Ultimately, the sodium coolant generated several hundred cubic meters of low-level radioactive waste (34). The 30-MW_{th} Toshiba 4S reactor might generate 115 m^3/GW_{th}-y of contaminated pyrophoric sodium coolant in need of treatment, conditioning, and disposal (Fig. 1, Table 1, and *SI Appendix*, section 2).

Similar decommissioning challenges can be anticipated for molten salt reactors that utilize a liquid fluoride–based fuel–coolant salt into which the fissile isotopes are directly dissolved (Table 1). This fluoride salt readily reacts with water to form corrosive hydrofluoric acid and becomes highly radioactive as fission and activation products accumulate over the course of operation. After the 8-MW_{th} MSRE was shut down in 1969, volatile UF_6 complexes formed via radiolytic decomposition of the solidified fuel salt that was stored on-site at Oak Ridge National

Laboratory. This presented a criticality risk that prompted the removal of fissile material from the solidified salt mass (44), but the continued presence of highly radioactive salt-soluble fission products has stymied further decommissioning. A report that the authors recovered through the Freedom of Information Act indicates that the US Department of Energy, rather than decommissioning and off-site disposal of the salt and reactor components, may entomb this legacy waste on-site (*SI Appendix*, section 3).

4. Management and Disposal of SMR Waste

The excess volume of SMR wastes will bear chemical and physical differences from PWR waste that will impact their management and final disposal. Although SMR developers tend to describe their waste production in terms of HLW or SNF mass and total radiotoxicity, repository design and postclosure safety analysis depend more on the solubility, environmental mobility, and sorption properties of specific radionuclides and the decay power or heat generation rate of the packaged wastes as well as the recriticality potential of the fissile materials that they contain (45). These parameters correlate to the waste stream radiochemistry and bulk chemical composition, which in turn, depend on the initial fuel composition and enrichment, discharge burnup, and in-core neutron energy spectrum, which are different for SMRs than for PWRs.

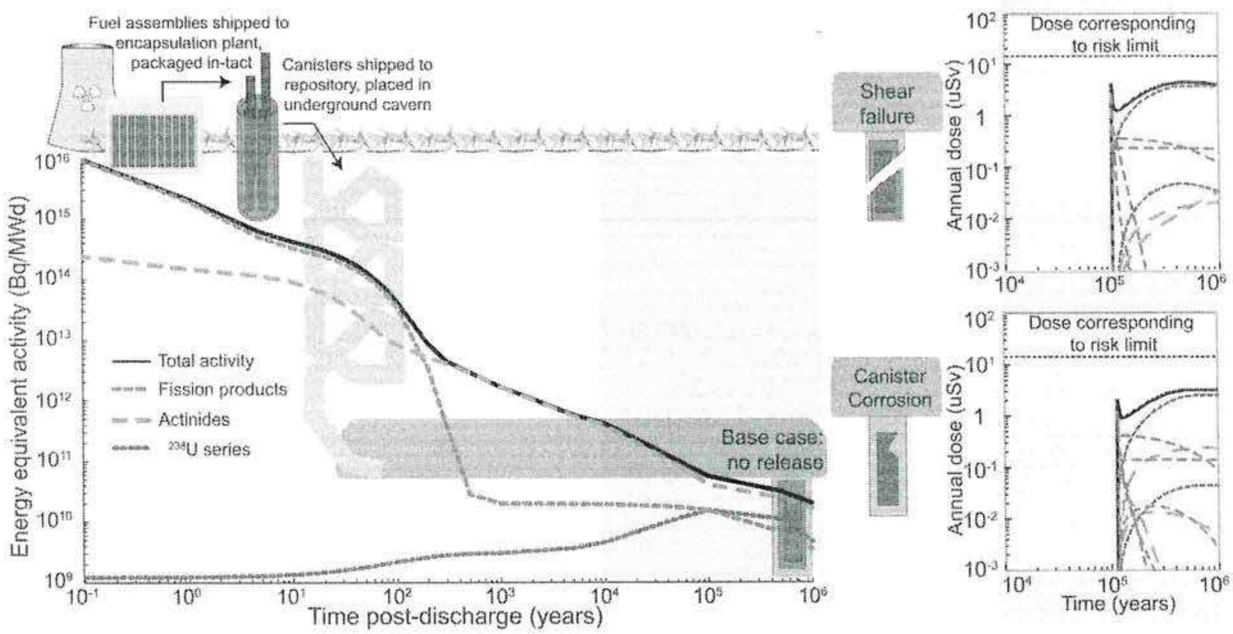
4.1. SNF Management and Disposal.

4.1.1. Fuel composition and durability.

PWRs utilize ~5 wt %–enriched ^{235}U fuel bound in a durable (under reducing conditions) UO_2 matrix contained within zirconium-clad fuel rods and supported by steel assembly structures. Over the course of irradiation, uranium atoms fission into a bimodal distribution of lighter fission products and transmute into heavier transuranic elements, such as plutonium. LWR fuel irradiated to a burnup of ~50 MWd/kg contains ~4 wt % fission products and ~1 wt % plutonium, although these concentrations increase with the fuel burnup. In addition, the fuel cladding and assembly structural materials contain activation products formed through neutron absorption reactions.

The fission products dominate the radioactivity, dose risk, and decay heat generation of newly discharged SNF, which is initially stored in actively cooled water pools to inhibit the physiochemical degradation of the fuel and cladding, otherwise driven by heat and radiation (Fig. 3). Although ~95% of this radioactivity decays within a few decades, the fission product fraction consists of a host of isotopes that show significant variation in half-life and chemistry and therefore, are relevant to repository design (section 4.1.3) and to long-term dose risk (section 4.1.2) in addition to SNF storage and handling. Repository performance models indicate that long-lived geochemically mobile fission products, although a small fraction of the long-term SNF radioactivity, can deliver a significant portion of the far-field dose under several repository failure scenarios (Fig. 3 and section 4.1.2) (46, 47).

Fig. 3.



Temporal evolution of radioactivity in LWR fuel by contribution from fission products, actinides, and daughters in the uranium series (Left) as compared with calculated future doses under the two different scenarios of repository failure after 10,000 y (Right). Adapted from refs. 46 and 47.

The transuranic isotopes contain the bulk of the long-term SNF radioactivity (Fig. 3) but form a relatively small number of actinide elements, many of which are chemically bound in the UO_{2+X} fuel matrix (48, 49). Therefore, the long-term chemical behavior of SNF in a geologic repository will be roughly analogous to that of crystalline UO_2 (50). The solubility of uranium with respect to crystalline UO_2 in pure pH-neutral water is very low, $<10^{-9}$ M, although this increases to ~10^{-7} M in the presence of dissolved oxygen (50–52).

Non-LWR SMRs will generate a similar array of radioisotopes for disposal but will employ fuels with markedly different bulk chemistries. Lacking fuel cladding, the liquid fuel envisioned for molten salt reactors will release gaseous fission products—including isotopes of Xe that decay to high-activity or long-lived isotopes of Cs—to an off-gas system, forming an HLW stream (8, 53). Noble metal fission products, on the other hand, will precipitate throughout the reactor structures (section 3.3.2). Nevertheless, the molten fuel salt will retain the salt-soluble fission products and actinides that, eventually, will solidify into a mass of nominal UF_4. In pure water, crystalline UF_4 readily hydrates to a $UF_4 \cdot 2.5H_2O$ phase that, compared with uranium-oxide, is orders of magnitude more soluble (10^{-4} M) (54). In water that contains dissolved oxygen, the reaction of crystalline UF_4 produces corrosive, hydrofluoric acid (55). This unfavorable chemistry formed the basis of a US Department of Energy (DOE) decision to convert depleted uranium, stored as UF_6, to a more stable uranium-oxide rather than dispose of the material as crystalline UF_4 (56).

Sodium-cooled SMR designs employ a solid fuel, although for many of the designs listed in Table 1, this is envisioned to consist of stainless steel–clad uranium metal and elemental sodium, both of which classify as pyrophoric. Citing the failure of this type of fuel to meet the waste acceptance criteria for a geologic repository, the US DOE has decided to convert the SNF discharged by previous experimental sodium reactors to a more stable chemical form (8).

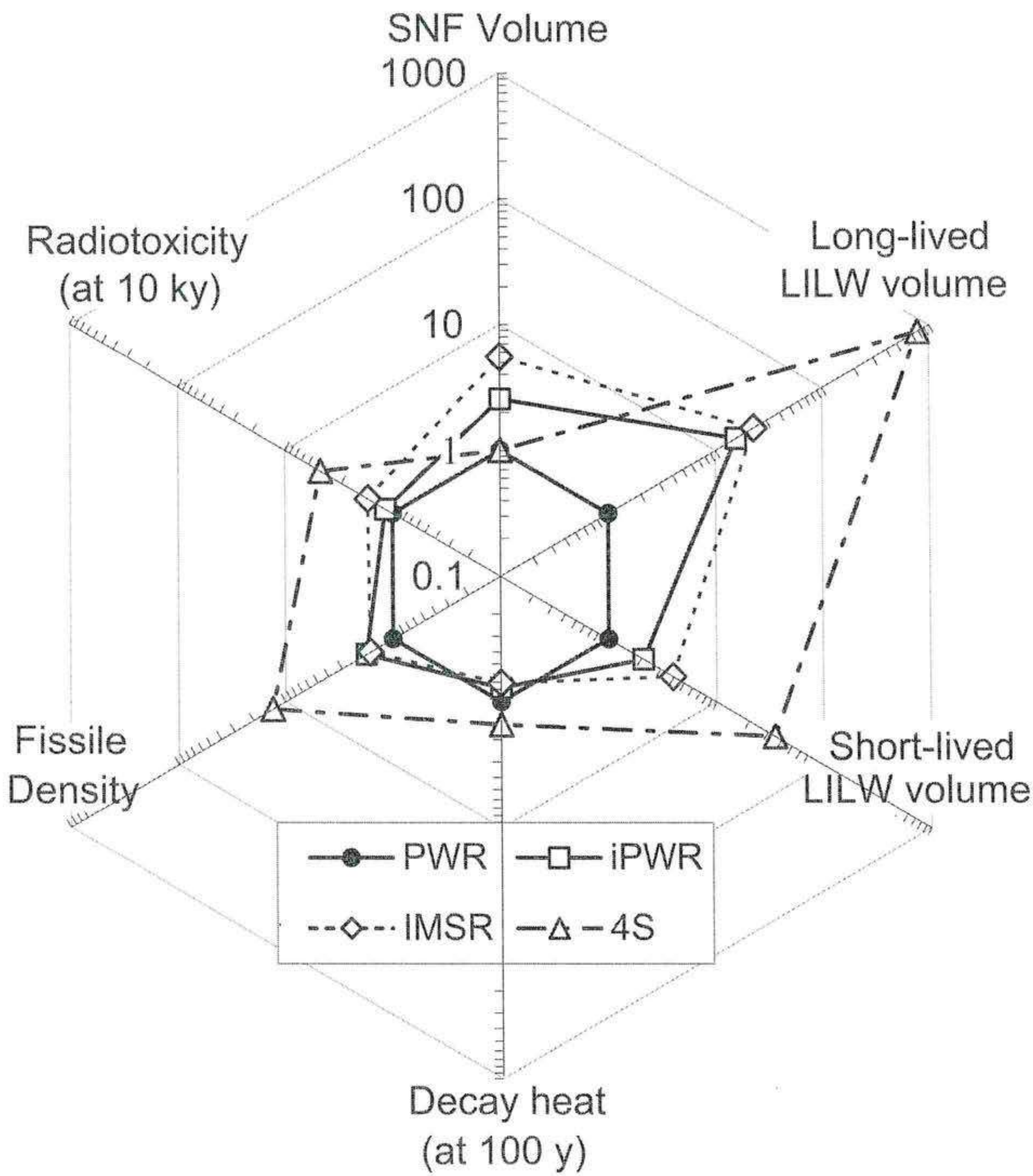
Due to their high chemical reactivities, these SMR fuels will need to be processed into a waste form that is suitable for geologic disposal, an objective that the US DOE has suggested might be met using pyroprocessing technology (8). SNF reprocessing facilities generate additional long- and short-lived technological, structural, process, and decommissioning wastes (57). Furthermore, before disposal in a geologic repository, the separated radionuclide streams should be solidified in a durable matrix, such as a radiation-resistant ceramic waste form (58). Although limited data are available to quantify the waste consequences associated with reprocessing and conditioning facilities, the following sections describe the implications for disposal of actinide- and fission product–containing SMR fuel.

4.1.2. Ingestion radiotoxicity vs. repository far-field dose.

Reactor developers sometimes compare the waste burden of different reactors and fuel cycles against the total "ingestion radiotoxicity" of their SNF or HLW. This metric, calculated in Sievert units, reflects the theoretical dose consequence of ingesting a particle of SNF or HLW, including all radionuclides present in the waste at a particular point in time (59). In the first ~100 y postirradiation, the total radiotoxicity of LWR fuel is dominated by short-lived fission products, whereas ^{239}Pu and ^{240}Pu dominate the long-term SNF radiotoxicity (between 1,000 and 100,000 y postdischarge) (*SI Appendix*, section 2) (47).

Since the fraction of fission products in SNF is linearly proportional to the fuel burnup, the energy-equivalent fission product radiotoxicity is similar for low– and high–burnup SNF. However, low–burnup SNF contains a higher energy-equivalent concentration of ^{239}Pu and ^{240}Pu, so the radiotoxicity of iPWR SNF (burnup of 33 MWd/kg) is ~50% higher than that of a PWR (burnup of 50 MWd/kg) at 10,000 y postdischarge (Fig. 4 and *SI Appendix*, section 2). A similar inverse relation between long-term actinide radiotoxicity and reactor size/burnup will prevail among small non-LWR SMRs, including thermal-spectrum molten salt reactors and sodium fast reactors (60). Fast reactors breed more plutonium than do thermal-spectrum reactors, so the SNF discharged by fast-spectrum SMRs will have a higher energy-equivalent long-term radiotoxicity than thermal-spectrum reactors (*SI Appendix*, section 2) (61). Overall, SMRs will lead to an increase in long-term SNF ingestion radiotoxicity (Fig. 4).

Fig. 4.



"Radar" chart comparing waste calculation results for various SMRs normalized against respective results for a 3,400-MW_{th} PWR displayed on a logarithmic axis. "SNF Volume" reflects the entire volume of the active core as divided by the total thermal energy produced during one fuel cycle. For the IMSR, the fluoride-based fuel–coolant salt factors into this volume. Short-lived LILW for the IMSR and 4S reactors includes the graphite moderator and sodium coolant, whereas activated reflectors and shielding materials from the 4S reactor are categorized as long-lived LILW. Decay heat and radiotoxicity are shown at 100 and 10,000 y, respectively, similar to the timing of peak buffer temperature and canister failure under an accelerated corrosion scenario for a repository in crystalline rock. Categorizations and calculations are further explained in section 4 and SI Appendix, section 3.

This metric, however, provides little insight into future doses from a geologic repository, where various geochemical processes, complemented by multiple engineered barriers, can limit radionuclide transport from the repository to the surface ecosystem (47). Since many of the actinides are chemically incorporated into the insoluble UO_{2+x} fuel matrix, future releases of the most long-lived and radiotoxic SNF constituents will be low if disposed of in a repository sited in a favorable hydrogeochemical environment. Low-redox conditions are essential to the inhibition of SNF dissolution, as are pH, salinity, and bicarbonate concentrations (49, 50). Hydrology, including hydraulic head, fracture frequency, and matrix permeability, is important to limiting radionuclide advection rates and temporal variations in geochemistry. Hydrogeochemical conditions are highly site specific but in general, are most favorable at depths of a few hundred meters below Earth's surface. If in the future, groundwater chemistry changes to a composition that destabilizes UO_{2+x}, then many radionuclides will partition onto mineral surfaces through coprecipitation, adsorption, and ion exchange processes. This will further limit far-field radionuclide advection and consequent biological exposures (48, 49, 61).

Accounting for the geochemical mobility of the various radionuclides in SNF, repository evolution models typically attribute most of the dose consequence of a failed SNF canister to long-lived and geochemically mobile fission and activation products, namely ^{59}Ni, ^{129}I, ^{79}Se, ^{36}Cl, and ^{14}C (Fig. 3) (48, 62). In general, these travel as negatively charged chemical species that do not adsorb onto mineral surfaces that are positively charged, a process that would otherwise slow their transport. In addition, the ^{226}Ra progeny of ^{238}U in the SNF may present a far-field exposure risk for repositories constructed in low-redox, fractured crystalline bedrock environments, although exposures will be lower than those associated with natural ^{226}Ra in these environments (48).

Since the energy-equivalent activities of fission and activation products are similar for low– and high–burnup SNF, SMR fuel may not significantly increase the future exposure risks unless the SNF packaging (section 4.1.4) and site selection plans neglect the differences in actinide contents. For instance, the performance assessment for a proposed repository sited in a seismically active and geochemically oxidizing environment (Yucca Mountain, NV) did attribute much of the long-term dose to ^{239}Pu, ^{242}Pu, and ^{237}Np (63). At the Yucca Mountain site, UO_{2+x} and its actinide constituents are relatively soluble, so the dose consequence of SMR fuel disposal would be higher than that of LWR fuel due to relatively high ^{239}Pu and ^{240}Pu contents in low–burnup fuel.

4.1.3. SNF/HLW thermal load and repository size.

After SNF is discharged from a reactor, decaying radionuclides in the fuel emit alpha, beta, and gamma radiation that is absorbed into nearby materials and converted to heat. To preserve the thermal hydraulic, mechanical, and chemical integrity of the repository system, the capacity and spacing of SNF disposal canisters will be configured to dissipate decay heat. Most repositories are designed to maintain temperatures less than 100 °C in the engineered barrier system. Yucca Mountain, however, was designed as a "hot" repository, wherein the temperature of groundwater would exceed the boiling point for a few hundred years postclosure. Consequently, repository dimensions—along with the associated packaging and excavation costs—are, in part, governed by decay heat rather than by waste volume (64, 65).

The duration of interim storage is factored into repository dimension calculations because the SNF decay power decreases over time. The predominant source of decay heat evolves from the fission products ^{137}Cs and ^{90}Sr and their ^{137m}Ba and ^{90}Y daughters at 10 to 100 y postdischarge to ^{241}Am and ^{238}Pu at 100 to 1,000 y postdischarge (46). In a repository that will accept SNF/HLW aged 20 to 60 y, near-field temperatures will peak at ~10 y postclosure. Therefore, fission product decay heat imposes a significant constraint on repository dimensions (46, 66).

In a thermal-spectrum reactor, the energy-equivalent concentration of ^{238}Pu increases with fuel burnup. Thus, for up to 100 y postdischarge, the energy-equivalent decay power is ~30% higher for 50-MWd/kg burnup than for 33-MWd/kg SNF burnup (Fig. 4 and *SI Appendix*, section 2). The thermal character of low–burnup SNF implies that, despite the increased volumes associated with SMRs, their impact on the dimensions of an SNF repository may be small.

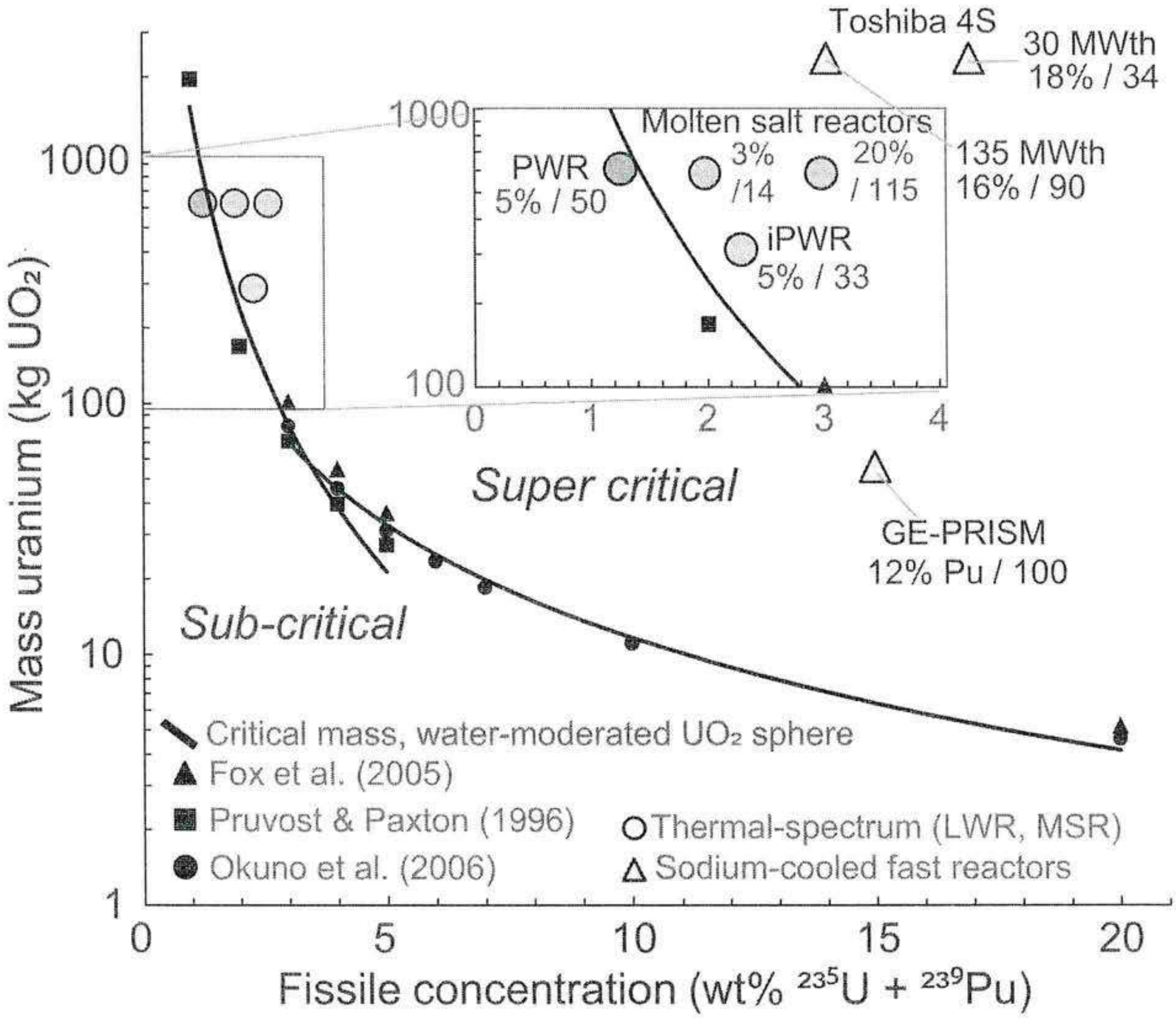
Models indicate that at 100 y postdischarge, the thermal output of SNF generated by a plutonium-fueled fast SMR (similar to the Toshiba 4S design) will be ~50% higher than the energy-equivalent PWR fuel (Fig. 4 and *SI Appendix*, section 2). Thermal data for uranium-fueled fast SMRs are scarce, although large sodium-cooled fast reactors (Table 1) are said to fission minor actinides, like ^{241}Am and ^{238}Pu, more efficiently than thermal-spectrum LWRs and molten salt reactors (61). However, the persistence of short- and long-lived fission products in these fuel cycles will limit their theoretical benefit for repository dimensions. HLW streams that predominately consist of fission products, typically conditioned into borosilicate glass, may require a repository up to 50% as large as a repository for LWR SNF (58). Since repository excavation and backfill account for only ~10% of the cost of a decommissioning and SNF disposal program (66), a fuel cycle that seeks to reprocess Pu will not significantly reduce nuclear waste management and disposal costs.

4.1.4. Fissile isotopes and recriticality.

As a primary safety objective, SNF should be stored and disposed of in a subcritical configuration to inhibit its ability to sustain a fission chain reaction. Since the critical mass of water-moderated UO_2 decreases exponentially if its fissile isotope concentration increases from 1 to 5% (figure 8 in ref. 67), the mass of SNF that can be loaded into a disposal package is limited by the concentration of fissile ^{235}U, ^{239}Pu, and ^{241}Pu in the SNF. In LWR SNF, the net concentration of these isotopes correlates positively to initial fuel enrichment and negatively to final burnup. Calculations performed to assess long-term criticality safety for several geologic repository designs indicate that fresh 5 wt % ^{235}U–enriched PWR fuel should be irradiated to a burnup >39 MWd/kg to maintain subcritical conditions in canisters loaded with four or more PWR assemblies (68–70).

Since iPWRs will irradiate 5 wt % ^{235}U–enriched fuel to a burnup of <34 MWd/kg, iPWR SNF will not meet the criticality safety standards for existing repository designs (71–75) (Fig. 5 and *SI Appendix*, section 2). Likewise, sodium-cooled SMR designs, which call for irradiation of fresh fuel with ≫10 wt % ^{235}U or ^{239}Pu to burnups ranging from 10 to 100 MWd/kg, will generate SNF with high fissile isotope concentrations (Fig. 5, Table 1, and *SI Appendix*, section 2). Quoted fuel enrichments and burnups for molten salt SMR designs are more variable, and published depletion models that estimate the fissile isotope composition of the SNF are scarce. Therefore, we assumed that the isotopic evolutions of fuel in an LWR and a molten salt reactor are similar because both reactors operate under the thermal neutron spectrum. Under this assumption, SNF generated by the Terrestrial Energy IMSR-400, which calls for 3 wt % ^{235}U–enriched fuel irradiated to a burnup of 14 MWd/kg, will contain 2.1 wt % ^{235}U + ^{239}Pu. Like that generated by the NuScale iPWR (2.3 wt %) and the Toshiba 4S SMR (17 wt %), this contains fissile isotopes in higher concentrations than the SNF generated by a PWR (1.3 wt %) (Fig. 4 and *SI Appendix*, section 2). The case is likely similar for many of the SMR designs listed in Table 1, considering the quoted fuel enrichments and burnups.

Fig. 5.



Concentration of fissile isotopes in SNF ("Fissile concentration") vs. mass of fuel in each assembly ("Mass uranium") for various reactors plotted alongside a criticality curve generated from the data of refs. 67, 72, and 73 to illustrate the sensitivity of SNF canister loading to the fissile isotope composition of the SNF. Inset shows enlargement of clustered points, labelled according to reactor-type and the associated initial fuel enrichment and burnup. Derivation of fissile concentration is explained in SI Appendix, section 2 or obtained from refs. 74 and 75. The molten salt SMR designs studied here contain several to tens of metric tons of uranium or thorium fuel that is not bound within structural assemblies and so, are here assigned an assembly mass similar to a PWR. "GE-PRISM" refers to the Power Reactor Innovative Small Module design by GE Hitachi Nuclear Energy.

In general, for a given SNF composition, each canister should contain a subcritical mass of SNF. However, critical masses are very small for materials containing more than a few weight percent fissile isotopes. Whereas a critical mass of PWR SNF is >1,000 kg, critical masses for iPWR and sodium-cooled SMR SNF are only ~200 and <10 kg, respectively (Fig. 5). Recriticality boundaries and management processes are rarely assessed for unconventional SNF types with elevated fissile isotope concentrations. However, Hicks and Baldwin (71) indicate that SNF from the UK Prototype Fast Reactor would pose a recriticality risk even if disposal canister capacities were limited to a single SNF assembly (burnup of 190 MWd/kg, initial/final ^{239}Pu concentrations of 30/15 wt %). Therefore, novel approaches to canister design and loading will need to be developed for the SMR designs analyzed here and listed in Table 1.

Canisters designed to accommodate the existing PWR SNF inventory have a capacity of four or more assemblies per canister, whereas canisters for iPWR and sodium-cooled SMR SNF might accommodate only one assembly or a fractional assembly, respectively.

Molten salt reactor SNF packaging will likewise deviate from the existing concepts. Vendors typically suggest that the spent liquid fuel salt remains inside the reactor vessels while it solidifies. However, the recriticality incident that almost occurred at the shutdown MSRE as a result of formation and migration of volatile actinide–fluoride complexes (section 3.4.3) (45) illustrates the need to process the actinides in this salt mass, including the fissile ^{235}U, ^{239}Pu, and/or ^{233}U, into a more stable ceramic waste form. Although the DOE eventually accomplished this through a pilot-scale fluoride volatility treatment, no methods to segment and package the remainder of the fission product–containing MSRE salt mass have been developed, as illustrated by the DOE preference to entomb the MSRE on-site at Oak Ridge National Laboratory (section 3.4.3 and *SI Appendix*, section 3).

The need for SNF segmentation and/or a larger number of disposal canisters and associated packaging operations support the notion that the back end of SMR fuel cycles, as discussed in section 3, entails increased handling of radiologic and fissile material. These packaging challenges will be compounded by the relatively large, energy-equivalent volumes of SMR SNF (sections 1 and 3.2) and will introduce costs and radiation exposure risks to the nuclear fuel cycle.

4.2. LILW Management and Disposal.

SMRs will generate larger, energy-equivalent volumes of LILW than a PWR (Fig. 1 and sections 3.3 and 3.4). Some of this waste may be suited for disposal in a near-surface, short-lived LILW repository (<30-m deep) (7). However, neutron-activated, long-lived LILW is more complicated to manage because radiation exposures must be mitigated on both operational and geologic timescales.

Due in part to the need to limit worker exposures to the radiation emanating from activated LWR components, especially that emitted by the ^{60}Co ($t_{1/2}$ = 5.3 y) activation product of steel (76), decommissioning represents ~20% of LWR waste management and disposal costs (67). Since SMRs will generate >10-fold more neutron-activated steel than the energy-equivalent LWR and will introduce the need to chemically treat radioactive sodium and molten salt coolants, they may significantly increase the costs and exposure risks associated with nuclear decommissioning.

After ^{60}Co has decayed, activities of long-lived ^{59}Ni, ^{63}Ni, ^{14}C, ^{94}Nb, and ^{93}Mo will remain sufficiently high to warrant the geologic disposal of activated LWR components (Table 2) (77). Nickel isotopes are soluble under acidic conditions (78), so cementitious barrier materials are employed in LILW repositories to impose alkaline conditions (79) that limit nickel dissolution in the repository groundwater (80). More mobile than nickel, models suggest that ^{14}C and ^{93}Mo will be the dominant contributors to future doses from a repository for activated decommissioning waste (81). Activated SMR and LWR steel will bear similar radiochemical compositions, so ^{14}C and ^{93}Mo may dominate future doses from SMR waste repositories, although such doses, like the energy-equivalent radionuclide inventory, may be higher for SMR wastes. Since few studies focused on constraining the radionuclide inventories of irradiated graphite, molten salt, and sodium are available, the future dose consequence for these waste streams remains unclear.

5. Conclusions

This analysis of three distinct SMR designs shows that, relative to a gigawatt-scale PWR, these reactors will increase the energy-equivalent volumes of SNF, long-lived LILW, and short-lived LILW by factors of up to 5.5, 30, and 35, respectively. These findings stand in contrast to the waste reduction benefits that advocates have claimed for advanced nuclear technologies. More importantly, SMR waste streams will bear significant (radio-)chemical differences from those of existing reactors. Molten salt- and sodium-cooled SMRs will use highly corrosive and pyrophoric fuels and coolants that, following irradiation, will become highly radioactive. Relatively high concentrations of ^{239}Pu and ^{235}U in low-burnup SMR SNF will render recriticality a significant risk for these chemically unstable waste streams.

SMR waste streams that are susceptible to exothermic chemical reactions or nuclear criticality when in contact with water or other repository materials are unsuitable for direct geologic disposal. Hence, the large volumes of reactive SMR waste will need to be treated, conditioned, and appropriately packaged prior to geological disposal. These processes will introduce significant costs—and likely, radiation exposure and fissile material proliferation pathways—to the back end of the nuclear fuel cycle and entail no apparent benefit for long-term safety.

Although we have analyzed only three of the dozens of proposed SMR designs, these findings are driven by the basic physical reality that, relative to a larger reactor with a similar design and fuel cycle, neutron leakage will be enhanced in the SMR core. Therefore, most SMR designs entail a significant net disadvantage for nuclear waste disposal activities. Given that SMRs are incompatible with existing nuclear waste disposal technologies and concepts, future studies should address whether safe interim storage of reactive SMR waste streams is credible in the context of a continued delay in the development of a geologic repository in the United States.

Data Availability

All study data are included in the article and/or *SI Appendix*.

Acknowledgments

We acknowledge Julien de Troullioud de Lanversin for his review of section 1 and *SI Appendix*, section 1. This research was supported by the John D. and Catherine T. MacArthur Foundation through fellowships (to L.M.K.) at George Washington University and at the Center for International Security and Cooperation, Stanford University.

Supporting Information

Appendix 01 (PDF)

DOWNLOAD 1.23 MB

References

CO2 emissions of nuclear power: the whole picture

Nuclear Monitor Issue:
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Article

'Nuclear power is a clean means to generate electricity. At least, it causes no CO2 emissions.' Based on this view some environmental activists became proponents of nuclear power, for fear of the disastrous consequences of climate change. At first glance they seem to be right: nuclear power stations are silent, clean and (usually) operate reliably day and night, summer and winter. But alas, also in this case it's no free lunch. Nuclear power causes CO2 emissions indeed, and at a growing rate.

In a nuclear reactor enriched uranium is being fissioned, releasing heat. The heat is converted into electricity by means of steam turbines. Enriched uranium, the fuel for the nuclear reactor, is produced from uranium ore by means of a sequence of industrial processes. Uranium ore is recovered from the earth's crust at several places in the world.

When a certain portion of the uranium has been fissioned, the nuclear fuel has to be removed from the reactor, because the fuel is not suitable anymore for energy production. About once every year the spent fuel has to be replaced by fresh nuclear fuel. The question arises: what happens with the spent nuclear fuel?

Process chain

The technical system aimed at generating electricity from uranium has three components:

1. Upstream processes: needed to produce nuclear fuel from uranium ore in the earth's crust.

2. Mid-section: construction and operation of the nuclear power plant.

3. Downstream processes: needed for safe disposal of all radioactive wastes generated during the operational life of the nuclear power plant.

The three-component structure of a process chain – upstream processes, mid-section and downstream processes – is also valid for fossil-fueled power stations, actually for nearly all production processes.

Upstream part of the nuclear process chain

The upstream processes comprise the recovery of uranium from the earth's crust, transport, refining and conversion into a gaseous uranium compound, enrichment and fabrication of fuel elements that can be placed into the nuclear reactor. Without these upstream processes nuclear power would be impossible. Without nuclear power these processes would not exist. Each process consumes energy (electricity and fossil fuels) and emits CO2 into the atmosphere. Especially the recovery of uranium from the earth's crust consumes large amounts of fossil fuels and produces much CO2.

The average uranium content of the globally exploited ores decreases as more ore is mined, due to the fact that the easiest accessible and richest available ores are mined firstly. The richest ores offer the highest return on investment for the mining companies. The lower the uranium content, the more rock has to be mined and chemically treated and the more energy is consumed to extract one kilogram of uranium. Below a certain ore grade, the recovery of 1 kg uranium consumes as much energy as can be generated from 1 kg uranium in a nuclear power plant. This phenomenon is called the energy cliff of uranium ore. This conclusion is based on a physical analysis of data published by uranium mining companies during many years.

Construction

Construction of a modern nuclear power plant consumes about 850,000 tons of concrete and about 150,000 tons of steel, plus thousands of tons of other materials. The production of these construction materials and of the equipment of the plant consumes a lot of energy, accompanied by substantial CO2 emissions. The construction activities themselves contribute also to the CO2 emissions.

Operation, maintenance and refurbishments

The nuclear reactor is the sole component of the nuclear process chain that does not emit CO2. This fact may be the source of the incorrect view that nuclear power would be CO2 free. All other processes of the nuclear system, without which a nuclear power plant cannot produce electricity, do emit CO2.

During the fission process in the reactor, the radioactivity of the nuclear fuel and the surrounding materials increase a billion-fold. This increase is caused by the generation of fission products and activation products. Activation is the phenomenon that non-radioactive materials, such as concrete and steel, become radioactive by irradiation by neutrons from the fission process. It is impossible to artificially reduce the radioactivity of a material, or to make it less harmful. Radioactivity is harmful to all living organisms.

Numerous radioactive components of the power plant have to be replaced one or more times during the operational lifetime of the plant. In the end the reactor vessel may be one of the few original components that are not replaced. Operation, maintenance and refurbishments of a nuclear power plant consume considerable amounts of energy and emit CO2.

Downstream part of the nuclear process chain

An old Latin verb says: 'In cauda venenum', in the tail is the venom. This verb might apply to nuclear power. Due to the generation of large amounts of human-made radioactivity the spent nuclear fuel is strongly radioactive and remains so for long periods. The specific activity of spent fuel decreases with time due to natural decay of the radionuclides. After 1,000 years the specific activity of spent fuel is still a million times higher than the lethal level for human beings. An operating nuclear power plant generates each year an amount of artificial radioactivity corresponding to more than 1000 times the amount that is released by the explosion of one nuclear bomb of 15 kilotons (Hiroshima bomb).

The largest part of the human-made radioactivity is retained in the spent fuel elements at the moment of discharge from the reactor. In addition, a considerable amount of radioactivity is dispersed in thousands of tons of construction materials. These materials are released at the decommissioning and dismantling of the nuclear power plant after closedown. What should happen with these radioactive materials?

During the past decades various concepts have been proposed for definitive disposal of radioactive materials. According to the nuclear industry the radioactive waste issue is not a problem. However, a fact is that after 70 years of civil nuclear power, all human-made radioactive materials are still stored at vulnerable temporary storage facilities.

The sole way to prevent more dispersal of radioactive materials into the human environment is to isolate the materials from the biosphere for periods of hundreds of thousands of years. There are designs of definitive disposal facilities in galleries deep in geologically stable formations. Nowhere on earth is such a geologic repository operational for high-level nuclear wastes. Sweden and Finland are the farthest with the construction of geologic repositories for spent fuel and for other radioactive wastes. Construction of a geologic repository and sequestering the radioactive wastes are energy-intensive and produce large amounts of CO2.

Another important part of the downstream processes is the decommissioning and dismantling of the nuclear power plant at the end of its operational lifetime. Globally some 600 nuclear power plants are to be dismantled some day. The mass of radioactive debris and scrap released from one nuclear power station may amount to some 100,000 tons at various levels of radioactivity. The radioactivity is caused by neutron irradiation and contamination with radionuclides during the operational life of the plant. Some 10,000 tons are expected to be classified as high-level waste.

In addition, many thousands of cubic meters of contaminated soil are to be considered radioactive waste, due to leaks and small accidents. First estimates of dismantling nuclear power plants in the UK and in Switzerland point to a cost as high as the construction cost, or even higher. It is not clear if these estimates include cleanup of the plant site and final disposal of the radioactive debris and scrap.

According to the nuclear industry, dismantling should occur many decades after final shutdown and will take a period of at least 10 years. How much energy and human effort will be needed? Who will pay these activities some 60–100 years after final shutdown?

No new technology is needed to adequately finish the downstream processes. Geologic repositories are similar to deep underground mines. Energy consumption and CO2 emissions of other downstream processes can reliably be estimated based on similar industrial processes without radioactive materials. Energy consumption and CO2 emission of all downstream processes together prove to be about as large as those of the upstream processes including construction and operation of the nuclear power plant.

Contemporary CO2 emissions and latent CO2 emissions of nuclear power

The CO2 emissions of the upstream processes, construction and operation are called the contemporary CO2 emissions, because they occur before and during the operation of the nuclear power plant. By means of a physical analysis of all processes and activities separately it is possible to reliably estimate the contemporary CO2 emission of nuclear power. The methodology was developed during the 1970s and 1980s and has been peer reviewed extensively by international peer groups. The used data originate exclusively from the nuclear industry. The model nuclear power plant in this analysis corresponds with the newest nuclear power plants presently operating. The assumed lifetime electricity production is higher than the current global average. Energy consumption and CO2 emission of uranium mining plus milling is calculated based on data published by the mining industry.

The CO2 emission of the downstream processes, that is inextricably coupled to the present application of nuclear power, will occur in the future, long after closure of the nuclear power plant. For that reason these postponed emissions are called the latent CO2 emissions of nuclear power. The latent emissions are hidden in the future and are usually not taken into account.

A physical analysis of the complete nuclear process chain comes to estimates of the contemporary CO2 emission of 65–116 grams CO2 per kilowatt-hour delivered electricity, and of the latent emission of 74 g CO2/kWh. The spread of the figures of the contemporary emissions is caused by differences of the presently operational uranium mines. The differences result from different properties of the mined uranium ore, such as the ore grade and the chemical composition of the ore. The CO2 emissions of the uranium mining plus milling increase as more ore is mined, because the richest ores are mined first, so the remaining ores are leaner.

Table 1. Contemporary CO2 emissions of nuclear power

PROCESS	g CO2/kWh
uranium mining + milling, low, rich ores	7.1
average	32.3
high, lean ores	57.4
refining + conversion	2.8
enichment (ultracentrifuge)	2.6
conversion + fuel element fabrication, including zircalloy production	3.4
construction of the nuclear power plant	24.9
operation + maintenance + refurbishments of the	24.4

power plant	
sum emissions of contemporary processes – low	*65*
average	*90*
high	*116*

Table 2. Latent (future) CO2 emissions of nuclear power

PROCESS	g CO2/kWh
definitive isolation of the radioactive waste of the upstream processes	14,0
conversion and definitive isolation of depleted uranium	5.7
dismantling of the nuclear power plant, inclusief definitive isolation of the debris	40.9
interim storage and definitive isolation of the spent fuel	8.2
rehabilitation of a proportional part of the uranium mine	4.8
sum emissions of future processes	*74*

CO2 trap of nuclear power

To keep the global nuclear capacity constant at the present level, about 370 GWe, each year until 2060 nine new nuclear power plants should be connected to the grid. The present construction rate is far lower than nine plants a year for a period of 40 years. During the coming four decades nearly all currently operating nuclear power plants would reach the end of their technical lifetime and have to be closed down.

Assumed that the global nuclear capacity would remain constant, the average CO2 emissions of nuclear power would become higher than 400 g CO2/kWh after the year 2070. With this figure nuclear power comes into the same emission range as fossil fuelled power stations. This phenomenon is called the CO2 trap of nuclear power. The chance is dim of discovery of major new rich uranium ore deposits, by which the CO2 trap could be postponed to a later year. During the past four decades no such deposits have been discovered, despite extensive exploration.

Visibility of upstream and downstream activities

The downstream processes of the nuclear energy system are usually invisible to the public, because they occur at other places far from the nuclear power plant, often on different continents. Moreover, large time differences may play a part: downstream processes can be invisible because they have not yet taken place.

These facts may contribute to the incorrect view that a nuclear power plant is a stand-alone system, and consequently that for calculation of the CO2 emissions of nuclear power only the power plant itself has to be taken into account. Usually construction, operation and maintenance of the power plant are also left outside the scope. Actually the specific CO2 emissions of nuclear power is identical to the emissions of the whole cradle-to-grave sequence of processes that makes nuclear power generation possible.

Nuclear legacy

The downstream part of the nuclear chain involves a nuclear legacy for future generations. During the disasters of Chernobyl and Fukushima jointly an amount of artificial radioactivity has been globally dispersed about equal to the production of one nuclear power plant during one year. This amount corresponds with only 0.01% of the amount of human-made radioactivity that is temporarily stored within the biosphere at vulnerable temporary storage facilities. Further dispersion of the human-made radioactive materials will certainly occur, potentially causing disasters that may dwarf Chernobyl and Fukushima, if man does not invest adequate amounts of energy and human effort to prevent that. The Second Law of thermodynamics is relentless.

Prospects of nuclear power

In 2018, the global gross energy production of all energy sources jointly was 585 exajoule. The share of nuclear power was 10 exajoule, not more than 1.7%. From these figures it follows that globally the nuclear contribution to CO2 reductions is minor, even if nuclear power was free of CO2 emissions.

How are the prospects for nuclear power? The most advanced types of currently operational nuclear power plants cannot fission more than 0.5% of the uranium nuclei present in natural uranium as found in nature. Since the dawn of civil nuclear power in the 1950s, the nuclear industry is working on nuclear energy systems, based on a uranium-plutonium cycle, that would be able to fission 30-50% of the nuclei in natural uranium.

However, an operating nuclear power plant that could fulfil this promise has never been realized in practice. After seven decades of research in seven countries and investments of hundreds of billions of dollars, this type of nuclear power plant is fading off the scene. This failure can be explained by reason of technical problems and limitations arising from phenomena governed by the Second Law of thermodynamics.

Research on the use of thorium as a net energy source, based on a thorium-uranium cycle, started also in 1950s. Thorium is not fissionable and has to be converted into fissionable uranium in a nuclear reactor The technical problems and limitations arising from the Second Law of thermodynamics apply all the more so to nuclear power plants based on thorium. Development of thorium-based energy systems was halted during the 1970s.

From the above observations it follows that nuclear power in the future has to rely exclusively on the currently operational nuclear reactor technology.

Conclusions

The view that nuclear power is free of CO2 emissions turns out to be a fallacy, originating from disregarding construction, operation, maintenance, upstream processes and downstream processes of a nuclear power plant.

Actually, the specific CO2 emission of nuclear power is the same as the joint emission of all processes without which nuclear power would be impossible.

The cradle-to-grave CO2 emission of nuclear power is 139-190 g CO2/kWh, the sum of the contemporary emissions (65-116 g CO2/kWh) and the latent emissions (74 g CO2/kWh). These figures are the result of a comprehensive physical analysis of data on all involved processes published by the nuclear industry during the past years.

CO2 trap. The CO2 emission of nuclear power will rise in the future, due to depletion of rich uranium ores. If the world nuclear capacity would remain constant at the present level, the nuclear CO2 emission will surpass the emission of gas-fired power plants after the year 2070.

Nuclear legacy. The downstream processes of nuclear power plants must be performed in such an effective way that nuclear disasters will be prevented that may dwarf the disasters at Chernobyl and Fukushima.

Energy debt. The present use of nuclear power leaves behind a substantial energy debt for the future generations. It comprises the future energy investments required to complete the downstream processes adequately.

In 2018 the world energy supply of all energy sources jointly was 585 exajoule. The share of nuclear power was 10 exajoule, not more than 1.7%.

The most advanced types of nuclear power plants that are currently operational, or will become operational, cannot fission more than 0.5% of the uranium nuclei present in natural uranium.

Net energy production by reactor systems that, according to the nuclear industry, could fission 30-50% of the uranium nuclei in natural uranium proved to be infeasible.

Thorium-based nuclear power plants proved to be infeasible as well.

Failures of both the uranium-plutonium and the thorium-uranium systems can be attributed to phenomena governed by the Second Law of thermodynamics.

Also in the future nuclear power has to based solely on the present reactor technology.

Background documents

Descriptions of the processes, calculations, methodology and references to used publications can be found in the following reports which can be downloaded from www.stormsmith.nl/reports.html. It should be emphasized that all data used in this analysis originate from publications of the nuclear industry and associated official institutions and from uranium mining companies.

Global context and prospects of nuclear power

Uranium-plutonium breeder systems

Thorium for fission power

Contemporary CO2 emissions of advanced nuclear power

Decommissioning and dismantling

Methodology of energy analysis

Energy debt, latent CO2 emissions, latent entropy

Emission of non-CO2 greenhouse gases

Life-cycle nuclear CO2 emissions

Advanced reference reactor and EPR

Uranium mining + milling

Uranium for energy resources

Unconventional uranium resources

Uranium from seawater

Energy cliff and CO2 trap

Industrial views on radioactive waste

Geologic repositories and waste conditioning

Problems for the future – message to the future

Construction and OMR of nuclear power plants

Radioactive waste management – future CO2 emissions

Uranium mine rehabilitation

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How are the prospects for nuclear power? The most advanced types of currently operational nuclear power plants cannot fission more than 0.5% of the uranium nuclei present in natural uranium as found in nature. Since the dawn of civil nuclear power in the 1950s, the nuclear industry is working on nuclear energy systems, based on a uranium-plutonium cycle, that would be able to fission 30-50% of the nuclei in natural uranium.

However, an operating nuclear power plant that could fulfil this promise has never been realized in practice. After seven decades of research in seven countries and investments of hundreds of billions of dollars, this type of nuclear power plant is fading off the scene. This failure can be explained by reason of technical problems and limitations arising from phenomena governed by the Second Law of thermodynamics.

Research on the use of thorium as a net energy source, based on a thorium-uranium cycle, started also in 1950s. Thorium is not fissionable and has to be converted into fissionable uranium in a nuclear reactor The technical problems and limitations arising from the Second Law of thermodynamics apply all the more so to nuclear power plants based on thorium. Development of thorium-based energy systems was halted during the 1970s.

From the above observations it follows that nuclear power in the future has to rely exclusively on the currently operational nuclear reactor technology.

Conclusions

The view that nuclear power is free of CO2 emissions turns out to be a fallacy, originating from disregarding construction, operation, maintenance, upstream processes and downstream processes of a nuclear power plant.

Actually, the specific CO2 emission of nuclear power is the same as the joint emission of all processes without which nuclear power would be impossible.

The cradle-to-grave CO2 emission of nuclear power is 139-190 g CO2/kWh, the sum of the contemporary emissions (65-116 g CO2/kWh) and the latent emissions (74 g CO2/kWh). These figures are the result of a comprehensive physical analysis of data on all involved processes published by the nuclear industry during the past years.

CO2 trap. The CO2 emission of nuclear power will rise in the future, due to depletion of rich uranium ores. If the world nuclear capacity would remain constant at the present level, the nuclear CO2 emission will surpass the emission of gas-fired power plants after the year 2070.

Nuclear legacy. The downstream processes of nuclear power plants must be performed in such an effective way that nuclear disasters will be prevented that may dwarf the disasters at Chernobyl and Fukushima.

Energy debt. The present use of nuclear power leaves behind a substantial energy debt for the future generations. It comprises the future energy investments required to complete the downstream processes adequately.

In 2018 the world energy supply of all energy sources jointly was 585 exajoule. The share of nuclear power was 10 exajoule, not more than 1.7%.

The most advanced types of nuclear power plants that are currently operational, or will become operational, cannot fission more than 0.5% of the uranium nuclei present in natural uranium.

Net energy production by reactor systems that, according to the nuclear industry, could fission 30-50% of the uranium nuclei in natural uranium proved to be infeasible.

Thorium-based nuclear power plants proved to be infeasible as well.

Failures of both the uranium-plutonium and the thorium-uranium systems can be attributed to phenomena governed by the Second Law of thermodynamics.

Also in the future nuclear power has to based solely on the present reactor technology.

Background documents

Descriptions of the processes, calculations, methodology and references to used publications can be found in the following reports which can be downloaded from www.stormsmith.nl/reports.html. It should be emphasized that all data used in this analysis originate from publications of the nuclear industry and associated official institutions and from uranium mining companies.

Global context and prospects of nuclear power

Uranium-plutonium breeder systems

Thorium for fission power

Contemporary CO2 emissions of advanced nuclear power

Decommissioning and dismantling

Methodology of energy analysis

Energy debt, latent CO2 emissions, latent entropy

Emission of non-CO2 greenhouse gases

Life-cycle nuclear CO2 emissions

Advanced reference reactor and EPR

Uranium mining + milling

Uranium for energy resources

Unconventional uranium resources

Uranium from seawater

Energy cliff and CO2 trap

Industrial views on radioactive waste

Geologic repositories and waste conditioning

Problems for the future – message to the future

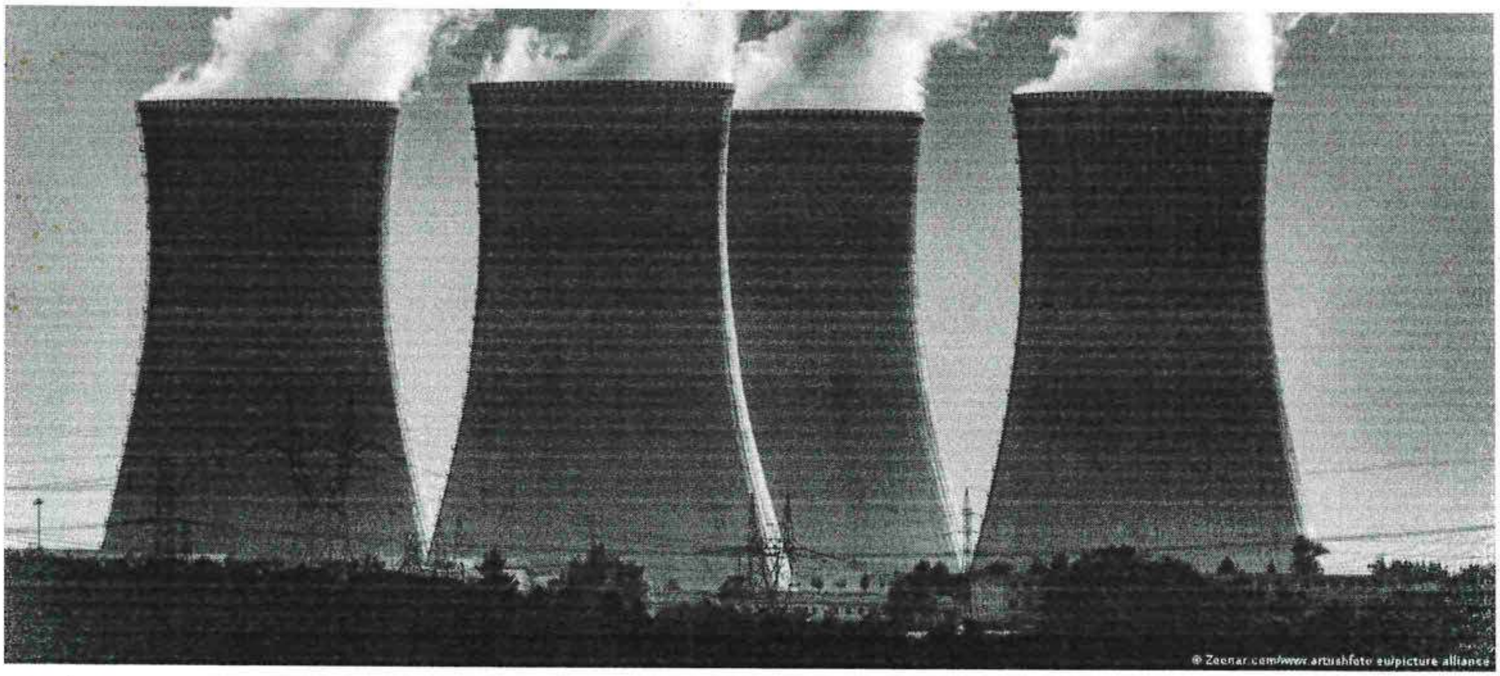
Construction and OMR of nuclear power plants

NATURE AND ENVIRONMENT | GLOBAL ISSUES

Fact check: Is nuclear energy good for the climate?

Joscha Weber
11/29/2021

Supporters of nuclear energy say it can help us wean our economies off polluting fossil fuels. No surprise, it's a heated issue. But what about the facts? Can nuclear power really help save the climate?



Nuclear power is expensive, especially when follow-up costs are taken into account — Image: Zoonar.com/www.artushfoto.eu/picture alliance

The latest figures on global carbon dioxide emissions call into question the world's efforts to tackle the climate crisis. **CO2 emissions are set to soar 4.9% in 2021**, compared with the previous year, according to a **study** published earlier this month by the Global Carbon Project (GCP), a group of scientists that track emissions.

In 2020, emissions dropped 5.4% due to the COVID-19 pandemic and associated lockdowns. Most observers expected a rebound this year — but not to such an extent. The energy sector continues to be the largest emitter of greenhouse gases, with a share of 40% — and rising.

But **what about nuclear**? Supporters of the controversial energy source say it's a climate-friendly way to generate electricity. At the very least, it's something we could use **until we're able to develop comprehensive alternatives**. In recent weeks, particularly during the **COP26 climate summit**, advocates have been creating a stir online with statements like "if you're against nuclear energy, you're against climate protection" and "**nuclear energy** is about to make a comeback." But is there anything to it?

Explainer: Nuclear power to the rescue?

Is nuclear power a zero-emissions energy source?

No. Nuclear energy is also responsible for greenhouse gas emissions. In fact, no energy source is completely free of emissions, but more on that later.

When it comes to nuclear, uranium extraction, transport and processing produces emissions. The long and complex construction process of nuclear power plants also releases CO_2, as does the demolition of decommissioned sites. And, last but not least, nuclear waste also has to be transported and stored under strict conditions — here, too, emissions must be taken into account.

Dismantling nuclear power plants — as seen here in Mülheim-Kärlich, Germany — also produces CO2 Image: Thomas Frey/dpa/picture alliance

And yet, interest groups claim nuclear energy is emission-free. Among them is Austrian consulting firm ENCO. In late 2020, it released a **study prepared for the Dutch Ministry of Economic Affairs and Climate Policy** that looked favorably at the possible future role of nuclear in the Netherlands.

"The main factors for its choice were reliability and security of supply, with no CO2 emission," it read. ENCO was founded by experts from the International Atomic Energy Agency, and it regularly works with stakeholders in the nuclear sector, so it's not entirely free of vested interests.

At COP26, environmental initiative Scientists for Future (S4F) presented a **paper** on nuclear energy and the climate. The group came to a very different conclusion. "Taking into account the current overall energy system, nuclear energy is by no means **CO2 neutral**," they said.

Ben Wealer of the Technical University of Berlin, one of the report's authors, told DW that proponents of nuclear energy "fail to take into account many factors," including those sources of emissions outlined above. All the studies reviewed by DW said the same thing: Nuclear power is not emissions-free.

How much CO2 does nuclear power produce?

Results vary significantly, depending on whether we only consider the process of electricity generation, or take into account the entire life cycle of a nuclear power plant. A **report** released in 2014 by the UN's **Intergovernmental Panel on Climate Change** (IPCC), for example, estimated a range of 3.7 to 110 grams of CO2 equivalent per kilowatt-hour (kWh).

It's long been assumed that nuclear plants generate an average of 66 grams of CO2/kWh — though Wealer believes the actual figure is much higher. New power plants, for example, generate more CO2 during construction than those built in previous decades, due to stricter safety regulations.

Studies that include the entire life cycle of nuclear power plants, from uranium extraction to nuclear waste storage, are rare, with some researchers pointing out that data is still lacking. In one life cycle **study** , the Netherlands-based World Information Service on Energy (WISE) calculated that nuclear plants produce 117 grams of CO2 emissions per kilowatt-hour. It should be noted, however, that WISE is an anti-nuclear group, so is not entirely unbiased.

However, other **studies** have come up with similar results when considering entire life cycles. Mark Z. Jacobson, director of the Atmosphere / Energy Program at California's Stanford University, calculated a climate cost of 68 to 180 grams of CO_2/kWh, depending on the electricity mix used in uranium production and other variables.

How climate-friendly is nuclear compared to other energies?

If the entire life cycle of a nuclear plant is included in the calculation, nuclear energy certainly comes out ahead of fossil fuels like coal or natural gas. But the picture is drastically different when compared with renewable energy.

According to new but still unpublished data from the state-run German Environment Agency (UBA) as well as the WISE figures, **nuclear power** releases 3.5 times more CO_2 per kilowatt-hour than **photovoltaic solar panel** systems. Compared with onshore wind power, that figure jumps to 13 times more CO_2. When up against electricity from hydropower installations, nuclear generates 29 times more carbon.

Could we rely on nuclear energy to help stop global warming?

Around the world, nuclear energy representatives, as well as some politicians, have called for the expansion of atomic power. In Germany, for example, the right-wing populist **AfD party** has backed nuclear power plants, calling them "modern and clean." The AfD has called for a return to the energy source, which Germany has pledged to phase out completely by the end of 2022.

Other **countries** have also supported plans to build new nuclear plants, arguing that the energy sector will be even more damaging for the climate without it. But Wealer from Berlin's Technical University, along with numerous other energy experts, sees takes a different view.

"The contribution of nuclear energy is viewed too optimistically," he said. "In reality, [power plant] construction times are too long and the costs too high to have a noticeable effect on climate change. It takes too long for nuclear energy to become available."

Mycle Schneider, author of the **World Nuclear Industry Status Report** , agrees.

"Nuclear power plants are about four times as expensive as **wind** or solar, and take five times as long to build," he said. "When you factor it all in, you're looking at 15-to-20 years of lead time for a new nuclear plant."

He pointed out that the world needed to get greenhouse gases under control within a decade. "And in the next 10 years, nuclear power won't be able to make a significant contribution," added Schneider.

"Nuclear power is not being considered at the current time as one of the key global solutions to climate change," said Antony Froggatt, deputy director of the environment and society program at the international affairs think tank Chatham House in London.

He said a combination of excessive costs, environmental consequences and lack of public support were all arguments against nuclear power.

Nuclear funding could go toward renewables

Due to the high costs associated with nuclear energy, it also blocks important financial resources that could instead be used to develop renewable energy, said Jan Haverkamp, a nuclear expert and activist with environment NGO Greenpeace in the Netherlands. Those renewables would provide more energy that is both faster and cheaper than nuclear, he said.

"**Every dollar invested in nuclear energy** is therefore a dollar diverted from true urgent climate action. In that sense, nuclear power is not climate-friendly," he said.

In addition, nuclear energy itself has been affected by climate change. During the world's increasingly hot summers, several nuclear power plants have already had to be temporarily shut down or taken off the grid. Power plants depend on nearby water sources to cool their reactors, and with many rivers drying up, those sources of water are no longer guaranteed.

The much vaunted "renaissance of nuclear power" is anything but when all the facts are taken into consideration, Mycle Schneider told DW. He said the nuclear industry has been **shrinking** for years.

"In the last 20 years, 95 nuclear power plants have gone online and 98 have been shut down. If you take China out of the equation, the number of nuclear power plants has shrunk by 50 reactors in the last two decades," Schneider added. "The nuclear industry is not thriving."

Additional reporting by Jo Harper and Gero Rueter

This article was translated from German by Martin Kübler

Correction, November 30, 2021: A previous version of this article unintentionally omitted one of two sources in the graphic 'How does electricity affect the environment?'. The Umweltbundesamt and WISE are the sources of the data. DW apologizes for the error.

Radioactive waste storage in Germany

A newly-formed commission will start working on a plan for a permanent nuclear waste storage site in Germany soon. The issue is something that has divided the country for decades.

10 images